DISS. ETH NO. 25337

Fostering Technological Change for a Sustainable Built Environment: The Role of Policy, System Design and Performance

A thesis submitted to attain the degree of
DOCTOR OF SCIENCES of ETH ZURICH
(Dr. sc. ETH Zurich)

presented by
DAVID GROSSPIETSCH
Dipl.-Wi.-Ing., Karlsruhe Institute of Technology (KIT)
born on 06.11.1985
citizen of Germany

accepted on the recommendation of
Prof. Dr. Volker H. Hoffmann
Prof. Dr. Martin Patel

Zurich, 2018

“Es ist nicht genug, zu wissen, man muss auch anwenden;
es ist nicht genug, zu wollen, man muss auch tun.”

(Knowing is not enough; we must apply.
Wishing is not enough; we must do.)

Johann Wolfgang von Goethe

Acknowledgements

With the thesis at hand, this wonderful academic journey comes to an end, which allows me to express my gratitude to the people who have made it possible and have supported my decision to follow this path. I am well aware that it is a mammoth task to ensure that this section's list is comprehensive, and it is doomed to fail. However, little by little, I will try to list the (groups of) individuals I feel deeply indebted to for directly or indirectly accompanying me on my dissertation endeavor.

I am sincerely grateful to:

- Volker Hoffmann, for giving me the opportunity to write both my diploma and doctoral thesis with you and your amazing team of highly talented and passionate researchers. After knowing the group for seven years now, I feel profoundly rooted in the fruitful SusTec environment. Thank you for providing enormous flexibility, also for challenges off the academic track – I truly could not imagine a better Doktorvater!
- Martin Patel, for kindly agreeing to co-examine my dissertation and for the enjoyable project collaboration in the context of the SCCER. I highly appreciate your efforts.
- Stefan Feuerriegel, for your willingness to accept my request to be the chairperson (head of the examination committee) for my dissertation's defense. Thank you for your commitment.
- Bastien Girod, for supervising my dissertation and for teaching me how to navigate the academic terrain. Thank you for making such a huge effort to shape this period of my life and for showing me how to master the trade-offs between scientific rigor, relevance and pragmatism – and doing it all with apparent ease while excelling in countless tasks in parallel. You are truly a role model!
- Benedikt Battke, Tobias Schmidt and Jörn Hoppmann, for your decision back in 2011 to bring me aboard as a young and naive student. Thanks to you, I could embark on this colorful, intellectual journey. I have learned a great deal from all of you – thank you for that.
- Christof Knoeri, for enriching both my academic and athletic journeys. You are a dinosaur when it comes to experience in research on energy-efficient buildings and in all sorts of epic long-distance (triathlon) races. Thanks for the countless hours discussing and swimbikerunning.
- Jan Ossenbrink, for being a loyal companion, the most rigorous researcher I know, a close friend, a hilarious office mate, and a constant source of creative excuses. Thanks for the great company since the first day we met in early 2012, when we conquered Uetliberg during a lunch break.
- Simon Sinsel, for a fantastic time with numerous facets (e.g., at Lake Thun) and sensitizing me for more diplomatic behavior aside from the binary mode. Thanks for the shared path.
- Fanny Frei, for keeping up the Swiss flag (including style, language and customs), for being both a rejoicing and a suffering comrade on the final stretch of the dissertation, and for being a role model in balancing parental responsibilities with personal liberties. Merci vielmol.
- Annegret Stephan, for being a close friend, KIT fellow and mountain bike partner in crime, as well as for knowing every single footnote of any imprint desired. Thank you for the great time.
- Hendrik Clausdeinken, for being a like-minded number cruncher in the office, for a great sense of black humor, and for the intrinsic spark that you carry. Thanks and keep the fire burning.
- Monica Heinz, for being SusTec's good-hearted soul and the most efficient problem solver. Thank you for eliminating all administrative hurdles in the blink of an eye and always with a smile.

- The rest of the SusTec Family (alphabetically): Catharina Bening, Nicola Blum, Petrissa Eckle, Aoife Brophy Haney, Jens Hamprecht, Jörn Hünteler, Alejandro Nunez-Jimenez, Julian Kölbel, Tillmann Lang, Jochen Markard, Johannes Meuer, Florian Nägele, Christina Nakhle, Evan Petkov, Falko Petzold, Jakob Prüss, Marius Schwarz, Marija Spokaite, Valeria Superti, and Ann-Kristin Zobel. Thank you for the numerous fruitful discussions and the constructive feedback that clearly helped this thesis. I have enjoyed your great spirit whether in paper sessions, lunch seminars, quarterly retreats or Samichlaus Schwumms.
- All the Masters/semester students and research assistants whom I have had the honor to work with during my stay at SusTec. Thank you for being a constant source of scientific knowledge, methodological novelties and extracurricular curiosities. In particular, Philippe Thömmes needs to be mentioned, because he was always eager to sacrifice his last hair – you rock!
- The academic projects IMES and SCCER FEEB&D, for financially supporting this dissertation. To be precise, special thanks to Innosuisse and its Swiss Competence Center for Energy Research (SCCER) on Future Energy Efficient Buildings and Districts (FEEB&D) (Grant No. 1155000149), and to the Swiss National Science Foundation (SNF) under the National Research Program (NRP70) Energy Turnaround (Grant No. 407040-153781). Embedded in these projects I had the honor to meet and collaborate with exceptionally gifted scholars from different disciplines, among them Paolo Gabrielli and Portia Murray. Thank you for the great work.
- The D-MTEC affiliates: Hilde Brune, Sonja Förster, Vivianna Fang He, Judith Holzheimer, Erik Jentges, Xavier Mundet, Georg Windisch, Martin Würmseher, and many more. Thanks for providing inspiration, motivation, and distraction along and aside from the academic track.
- My athletic community at ETH and beyond: Paul Börner, Maximilian Braun, Philipp Buchli, Jan Bürger, Alex Edenstrasser, Stefan Gabriel, Robert Galbraith, Markus Hübner, Arne Josten, Jussi Kastu, Mark Pfeiffer, Daniel Rapp, Mathias Rebholz, Roman Richthammer, Andreas Ueberrhein, and many more fellows. Thank you for the thrilling moments we experienced together; they are worth remembering. A perfect momentary distraction from the non-linearity of academic research. Please continue to follow these roads: Dream big. Be daring. Keep tri-ing.
- Ralph Lange, for his dedication as one of the best and quirkiest roomies ever. Thanks for bringing glamour back to science and for the numerous volumes of MöhrliMadness – what a life!
- Rosalie Mutter, for her patience and warm-hearted support, especially during the last months. Thank you for the fantastic time we have shared together so far – more to come.
- My friends from near and far, for being there whenever opinions or drinks were needed. You are my reason to be happy. I feel very fortunate to call you my friends. Thanks to all of you!
- My family, namely, my sister Larissa, my mother Rosita and my father Jost, for your love, trust and continuous support throughout all the years. You made all this possible. My deepest gratitude is due to you: Thanks for everything!

Abstract

Climate change is arguably the most pressing challenge of this century. The reduction of energy demand and greenhouse gas emissions from buildings play a pivotal role in mitigating climate change. Due to the building sector's large share of almost one third of total final energy use and carbon dioxide emissions, aiming for a sustainable built environment is essential for reaching energy and emission reduction targets. However, decarbonizing society in general, and establishing a sustainable built environment in particular, requires substantial societal and technological change that encompasses the invention, innovation and diffusion of new products and processes. In the built environment, technological change and the advent of so-called low-carbon technologies allow for: i) a considerable reduction of energy demand via energy efficiency technologies (e.g., insulation of building envelopes), and ii) a drastic reduction of emissions on the supply side through the integration of renewable energy sources, which replace conventional, fossil-fueled solutions. For the latter measure, decentralized energy systems are regarded as promising options, yet their potential contributions, which are subject to system design and performance, are still unclear. Despite the huge potential of technological change, its rate and direction remain uncertain, but these can be induced by institutional action, such as public policy intervention. Thus, the overarching objective of this dissertation is to improve the understanding of *how system design and performance can contribute to a sustainable built environment* and to develop a better grasp of *how technological change can be supported by policy.*

To address these questions, this thesis applies a mix of quantitative and qualitative methods and empirically draws on two research cases: decentralized energy systems and energy efficiency technologies. On the one hand, the case of decentralized energy systems is used to quantitatively assess the level of technological change they could provide, that is, their cost and potential contribution to energy strategy targets and, thus, a sustainable built environment. Since decentralized energy systems are considered to be in the innovation phase, the question of system design and performance is a fundamental one and is tackled in detail within the first part of this thesis (articles I, II, and III). On the other hand, the case of energy efficiency technologies applies a qualitative analysis to explore the link between policy support and technological change. More precisely, the second part of this thesis (article IV) examines the diffusion phases of three energy-efficient building technologies, which have been substantially shaped by policy. The temporal scope of this thesis is two-fold. The predominant focus on the innovation phase of decentralized energy systems and the assessment of their potential contributions requires a prospective view (2004–2050), whereas the observation of the diffusion phases and the related policy support for energy efficiency technologies requires a retrospective view (1970–2015). The spatial scope is primarily limited to Switzerland with partial outlooks from a global perspective. The Swiss context represents an ideal research setting, as Switzerland has been one of the lead markets for energy-efficient building technologies and has a pioneering role in the development and initial deployment of decentralized energy systems.

This thesis is composed of four individual articles, each of which addresses a distinct literature gap derived from the overarching objective of this dissertation. The first article investigates the concept

of decentralized energy systems and provides a comprehensive review and comparison of the state-of-the-art in both literature and practice. The second article examines the role of decentralized energy systems in off-grid applications and evaluates how, when, and where energy self-sufficient neighborhoods can become competitive. The third article focuses on the optimal system design and its techno-economic and environmental performance in an urban and rural grid-connected neighborhood under three future scenarios. Lastly, the fourth article studies cases in which policies have been successfully adapted to the specificities of energy efficiency technologies in order to accelerate their diffusion.

Based on the insights of the individual articles, this thesis makes the following five contributions to the literature. First, it helps to improve the common understanding of the concept of decentralized energy systems by analyzing the four key aspects of terminology, motivation/scope, application, and technical configuration. Second, it provides model-based assessments of the techno-economic and environmental performance of decentralized energy systems, including technical configurations and applications. Third, it extends the existing literature in several methodological aspects, namely, an optimization based on a full annual time horizon resolution, more sophisticated and realistic depictions of conversion technologies, and reflections on conceivable future developments for uncertain input parameters. Fourth, it adds to the literature on policy-induced diffusion by applying a multiple case study design within a single national context, thereby allowing for the disentanglement of the impact of policy types on the diffusion of different kinds of technologies. Fifth, it provides initial conceptual guidance for the tailoring of technology-specific policy support along the dimensions of technological maturity and diffusion status.

Finally, this dissertation makes the following implications for practitioners and policy makers, providing valuable insights for more informed decisions. First, decentralized energy systems have already been proven in practice with various applications and their techno-economic and environmental performance (e.g., systems with solar photovoltaics, heat pump and battery) can outperform conventional, fossil-based solutions in many areas. Therefore, they constitute viable alternatives to the conventional methods for supplying buildings with energy, and thus can overhaul traditional business models and render existing assets and capabilities obsolete. Second, decentralized energy systems can successfully contribute to the achievement of political energy strategy targets. This thesis sketches out options to foster both their further development and large-scale deployment. In addition, this thesis has identified several critical factors (e.g., retrofit rate, renewable potential, feed-in remuneration) that affect the successful contribution of decentralized energy systems to climate change mitigation. These factors can and should be influenced by policy makers in order to support decentralized energy systems. Third and lastly, while a comprehensive set of support policies is instrumental for the diffusion of some technologies, singular support measures can be sufficient for others. This underlines the need for policy makers to adjust their support to the specific nature of an innovation, which requires them to precisely assess and periodically re-evaluate an innovation's maturity level and diffusion status before designing corresponding support measures.

Zusammenfassung

Die Abschwächung des Klimawandels ist eine der dringlichsten Herausforderungen dieses Jahrhunderts. Um diese zu meistern, bedarf es einer deutlichen Reduktion des Energiebedarfs und der Treibhausgasemissionen, bei der Gebäude eine zentrale Rolle einnehmen. Der Gebäudesektor weist einen hohen Anteil von fast einem Drittel am gesamten Energieverbrauch und an den Kohlendioxidemissionen auf, weshalb ein nachhaltiger Gebäudesektor als Schlüssel zum Erreichen der Energie- und Emissionsreduktionsziele gilt. Die Dekarbonisierung der Gesellschaft im Allgemeinen sowie insbesondere das Etablieren eines nachhaltigen Gebäudesektors erfordern einen erheblichen gesellschaftlichen und technologischen Wandel, welcher die Invention, Innovation und Diffusion von neuen Produkten und Prozessen beinhaltet. Der technologische Wandel und das damit verbundene Aufkommen sogenannter kohlenstoffarmer Technologien ermöglichen dem Gebäudesektor i) den Energiebedarf beträchtlich zu senken und ii) Emissionen auf der Energieversorgungsseite durch die Integration von erneuerbaren Energiequellen – und der damit verbundenen Ablösung konventioneller, fossil-befeuerter Lösungen – drastisch zu reduzieren. Während i) mithilfe von Energieeffizienztechnologien, wie beispielsweise einer verbesserten Wärmedämmung der Gebäudehülle, erreicht werden kann, stellen dezentrale Energiesysteme eine vielversprechende Option für ii) dar. Allerdings ist deren Beitrag zur Abschwächung des Klimawandels abhängig von Systemaufbau (d.h. technische Zusammensetzung, Dimensionierung) und Systemleistung (technisch, ökonomisch, ökologisch) derzeit noch unklar. Trotz dieses großen Potentials, das dem technologischen Wandel beigemessen wird, ist dessen Geschwindigkeit und Richtung ungewiss, kann jedoch durch institutionelle Maßnahmen, wie die Intervention durch den Gesetzgeber, beeinflusst werden. Aus diesem Grund ist die übergeordnete Zielsetzung dieser Dissertation, das Verständnis zu verbessern, wie Systemaufbau und -leistung zu einem nachhaltigen Gebäudesektor beitragen können und wie technologischer Wandel durch Politikmaßnahmen gefördert werden kann.

Um diese Zielsetzung zu adressieren, bedient sich die vorliegende Arbeit quantitativer und qualitativer Methoden und baut empirisch auf zwei Fallstudien auf: dezentrale Energiesysteme und Energieeffizienztechnologien. Auf der einen Seite wird die Fallstudie zu dezentralen Energiesystemen genutzt, um quantitativ den Grad von technologischem Wandel zu bestimmen, welchen diese bereitstellen könnten. Dies umfasst die Beurteilung von deren Kosten und deren möglichen Beitrag zu Energiestrategiezielen. Da sich dezentrale Energiesysteme in der Innovationsphase befinden, ist die Frage nach Systemaufbau und -leistung essentiell und wird detailliert im ersten Teil dieser Arbeit behandelt. Auf der anderen Seite untersucht die Fallstudie zu Energieeffizienztechnologien mithilfe einer qualitativen Analyse die Verbindung zwischen verschiedenen Fördermaßnahmen und technologischem Wandel. Genauer gesagt beleuchtet der zweite Teil dieser Arbeit die Diffusionsphasen von drei energieeffizienten Gebäudetechnologien, die wesentlich von Fördermaßnahmen begünstigt wurden. Dabei beinhaltet der zeitliche Betrachtungsrahmen dieser Dissertation zwei Perspektiven. Der Fokus auf die Innovationsphase dezentraler Energiesysteme und die Bewertung von deren möglichen Beitrag erfordert eine prospektive Sichtweise (2004-2050), wohingegen die Betrachtung der Diffusionsphasen und der damit verbundenen Fördermaßnahmen für

Energieeffizienztechnologien die retrospektive Sichtweise (1970-2015) vorgeben. Der geographische Betrachtungsrahmen liegt im Wesentlichen auf der Schweiz, ergänzt um Ausblicke auf globaler Ebene. Die Schweiz stellt ein ideales Forschungsumfeld dar, da sie einer der Vorreitermärkte für energieeffiziente Gebäudetechnologien war und ist und zusätzlich eine Pionierrolle bei der Entwicklung und Ersteinführung von dezentralen Energiesystemen einnimmt.

Die vorliegende Dissertation setzt sich aus vier Artikeln zusammen, von denen jeder eine bestimmte Literaturlücke – abgeleitet aus der übergeordneten Zielsetzung dieser Arbeit – adressiert. Der Fokus des ersten Teils dieser Arbeit liegt auf dezentralen Energiesystemen (Artikel I, II und III), während der zweite Teil die Diffusion von Energieeffizienztechnologien analysiert (Artikel IV). Dabei untersucht Artikel I das Konzept dezentraler Energiesysteme und erarbeitet einen Überblick und Vergleich zwischen dem Stand der Wissenschaft und dem der Praxis. Artikel II analysiert die Rolle dezentraler Energiesysteme in netzentkoppelten Anwendungen und bewertet, wie, wann und wo energieautarke Nachbarschaften wettbewerbsfähig werden könnten. Der Fokus von Artikel III liegt auf der Bestimmung des optimalen Systemaufbaus sowie der techno-ökonomischen und ökologischen Leistung einer urbanen und einer ländlichen netzgekoppelten Nachbarschaft unter drei Zukunftsszenarien. Artikel IV erforscht, wie Fördermaßnahmen in erfolgreichen Fällen an die Besonderheiten einzelner kohlenstoffarmer Technologien angepasst wurden, um deren Diffusion zu beschleunigen.

Auf den Erkenntnissen der einzelnen Artikel basierend, erarbeitet die vorliegende Dissertation die folgenden fünf Beiträge zur bestehenden Literatur. Erstens hilft sie das gemeinsame Verständnis für das Konzept dezentraler Energiesysteme durch die Analyse von vier wesentlichen Elementen (Terminologie, Motivation/Betrachtungsumfang, Anwendung und technische Zusammensetzung) zu verbessern. Zweitens erarbeitet sie eine model-basierte Einschätzung des Systemaufbaus und der techno-ökonomischen und ökologischen Leistung dezentraler Energiesysteme mit einem breiten Spektrum an verschiedenen Aspekten, darunter die technische Zusammensetzung und die Anwendung. Drittens erweitert sie die bestehende Literatur in mehreren methodischen Punkten, beispielsweise eine Optimierung mit zeitlicher Auflösung eines ganzen Jahres, eine ausgereiftere und realitätsnähere Abbildung von Umwandlungstechnologien und die Berücksichtigung denkbarer Entwicklungen der unsicheren Eingangsparameter in der Zukunft. Viertens ergänzt sie die Literatur zu politikinduzierter Diffusion, indem sie vergleichende Fallstudien im selben nationalen Kontext anwendet, um den Einfluss verschiedener Förderarten auf die Diffusion unterschiedlicher Technologien herauszustellen. Fünftens bietet sie eine erste konzeptionelle Orientierungshilfe für das Maßschneidern technologiespezifischer Fördermaßnahmen entlang der beiden Dimensionen, technologische Reife und Diffusionsstatus.

Abschließend leitet die Arbeit Implikationen für Entscheidungsträger in Politik und Unternehmen her. Erstens sind dezentrale Energiesysteme bereits heute in verschiedensten Anwendungen in der Praxis erprobt. Zudem übertrifft deren techno-ökonomische und ökologische Leistung, wie beispielsweise von Systemen mit solarer Photovoltaik, Wärmepumpe und Batterie, die von konventionellen, fossil-befeuerten Lösungen bereits in einigen Bereichen. Aus diesen Gründen stellen sie eine zukunftsfähige Alternative zum konventionellen Weg der Energieversorgung von Gebäuden dar. Traditionelle Geschäftsmodelle könnten daher überholt und bestehende Anlagen und Fähigkeiten obsolet werden. Zweitens können dezentrale Energiesysteme zum Erreichen politischer energiestrategischer Ziele beitragen. Diese Arbeit identifiziert verschiedene Möglichkeiten, um die Weiterentwicklung und Diffusion dezentraler Energiesysteme zu unterstützen. Zusätzlich werden einige wichtige Faktoren, zum Beispiel die Sanierungsrate, das Potential erneuerbarer Energiequellen oder die Einspeisevergütung, identifiziert, welche den erfolgreichen Beitrag dezentraler Energiesysteme zur Abschwächung des Klimawandels beeinflussen. Entscheidungsträger in der Politik können und sollten auf diese Faktoren einwirken, sofern sie die Unterstützung dezentraler Energiesysteme anstreben. Drittens und letztens zeigt diese Arbeit, dass vollumfängliche Fördermaßnahmen zielführend für die Diffusion bestimmter Technologien sein können, während für andere Technologien einzelne, ausgewählte Fördermaßnahmen ausreichen können. Das unterstreicht die Notwendigkeit für Entscheidungsträger in der Politik, die Fördermaßnahmen an die Technologiespezifika anzupassen. Sie sollten folglich den technologischen Reifegrad und den Diffusionsstatus von Technologien genau und regelmässig evaluieren, bevor sie entsprechende Fördermaßnahmen gestalten.

Table of Contents

Acknowledgements IV

Abstract VI

Zusammenfassung VIII

1 Introduction 1
  1.1 Towards a Sustainable Built Environment in Response to Climate Change 1
  1.2 Policy Support for Low-Carbon Technologies 2
  1.3 Overarching Research Question and Framework 4

2 Theoretical Background 6
  2.1 Fundamentals of Technological Change 6
  2.2 The Role of Policy in Fostering Innovation and Diffusion 8

3 Research Cases 10
  3.1 Decentralized Energy Systems 10
  3.2 Energy Efficiency Technologies 13

4 Research Framework and Objectives 16

5 Methods and Data 18
  5.1 Methods 18
  5.2 Data Sources 20
  5.3 Overview 21

6 Summary of Results 22
  6.1 Article I: Matching Decentralized Renewable Energy Production and Local Consumption: A Review of Energy Conversion and Storage Systems 22
  6.2 Article II: How, When, and Where? Assessing Renewable Energy Self-Sufficiency at the Neighborhood Level 24
  6.3 Article III: A Comparison of Storage Systems in Neighborhood Decentralized Energy System Applications from 2015 to 2050 26
  6.4 Article IV: The Role of Policy in Fostering the Diffusion of Low-Carbon Innovations 28

7 Conclusion 30
  7.1 Contributions to Literature 30
  7.2 Implications for Practitioners and Policy Makers 32
  7.3 Limitations and Further Research 33

8 Overview of Articles 35

References 36

Annex: Articles 45

Article I 46

Article II 78

Article III 120

Article IV 172

1 Introduction

This section introduces the motivation and the background for this dissertation. First, the challenge of global climate change and the potential contribution of a sustainable built environment to its mitigation is outlined (1.1). Second, an argument is presented for why policy support for low-carbon technologies is necessary to follow the path towards a sustainable built environment (1.2). Lastly, the overarching research question is derived and the basic research framework is presented (1.3).

1.1 Towards a Sustainable Built Environment in Response to Climate Change

Anthropogenic greenhouse gases substantially contribute to global warming according to the ample evidence collected, for instance, by the Intergovernmental Panel on Climate Change (IPCC) (IPCC, 2018). In fact, climate change has become one of the major challenges facing humankind, and will be even more of a challenge for upcoming generations. Rising annual mean temperatures cause disastrous incidents, such as extreme weather events (e.g., droughts, floods, hurricanes), decreased agricultural yields, and melting polar ice caps and glaciers, which results in a rising sea level (IPCC, 2014). At the same time, the growing world population and the global pursuit of economic wealth are accompanied by an increased demand for mostly fossil-based energy (UN, 2017). As a consequence, there is a pressing need for climate change mitigation and reduction measures for greenhouse gas emissions, of which carbon dioxide (CO_2) accounts for almost three quarters (IEA, 2017a). International treaties, such as the Kyoto Protocol and the Paris Climate Accord, have laid out the regulatory basis for the collective commitment to tackling these challenges. The Paris Climate Accord represents a recent milestone with the agreement of 195 countries that emphasize their willingness to reduce CO_2 emissions to a level that would limit global warming to “well below” 2.0 °C (UNFCCC, 2015).

While the global Herculean effort to decarbonize requires the participation of every sector of the economy, the building sector is a promising target as it makes up almost a third of total global final energy use (and as much as 40% in the European Union) and represents an equally important source of CO_2 emissions (Gynther et al., 2015; IEA, 2013a; Lucon et al., 2014). Growth in energy use and emissions per capita has halted in both residential and commercial buildings within the last decade owing to extensive technological progress (Le Quéré et al., 2016; Lucon et al., 2014). This is mostly due to two developments. First, on the supply side, renewable energy sources (RES) have made large contributions by replacing fossil-based energy supplies. Second, on the demand side, more and more energy efficiency measures have been implemented in new buildings and are progressively making their way into the existing building stock via retrofitting. While the potential on the demand side has widely been addressed via large-scale deployments of energy-efficient technologies (e.g., appliances, insulation, lighting, heating) over the last three decades, there is still a major possibility to reap the emission reduction potential of buildings on the supply side. Today, state-of-the-art technologies are capable of rendering new buildings “net-zero energy” efficient or even turning them into “net-positive energy buildings”, that is, buildings that produce more energy than they require, which enables exporting the surplus to other buildings or systems (Cole and Fedoruk, 2015). By achieving this, (systems of) buildings are considered to be promising options to facilitate the system integration of RES (Guen et al., 2018; Vieira et al., 2017). In addition to the external driver of RES integration to support climate change mitigation, innovation activity in the building industry, an industry that is oftentimes classified as sluggish (Kulatunga et al., 2006; Seaden and Manseau, 2001), seems to gain momentum with the advent of novel (digitalized) technologies (e.g., smart meters or homes), new business models (e.g., shared-economy approaches) and innovative concepts (e.g., “prosumer”) (European Patent Office, 2018). Despite these developments, an accelerated approach is needed to realize the required 83% CO_2 emission reductions by 2050 (against the baseline scenario) that the building sector must achieve to be on track to effectively curb global warming (IEA, 2010).

1.2 Policy Support for Low-Carbon Technologies

Numerous scholars have emphasized the decisive role that policy plays in escaping the “carbon lock-in” (Unruh, 2002, 2000) by fostering technological change as an important piece in the climate change mitigation puzzle. Even though the ambitious targets agreed upon in the Paris Climate Accord can be technically and economically achieved, a policy roadmap for rapid decarbonization is essential (Rockström et al., 2017) given that “the scale of the challenge demands enhanced action and coordination between all actors, including national and sub-national governments” (OECD, 2015, p. 18). Policy has been proven to substantially spur technological change, as demonstrated by prominent cases in domains unrelated to climate change mitigation, such as the development of the global positioning system (GPS), the internet or airbags (Mazzucato, 2013). In the realm of decarbonization there are also numerous examples of policy intervention, ranging from a market-based cap and trade system (cf. emissions trading system by the European Union) to various forms of technology-specific support. Among many others, examples of low-carbon technologies[1] that have largely benefitted from governmental efforts for accelerated development and deployment include solar photovoltaics (PV) in Germany (Hoppmann et al., 2014, 2013) and electric vehicles in Norway (Figenbaum, 2017). Thus, it is acknowledged that “policies have played, and will continue to play, a fundamental role in attracting investments, increasing deployment and driving cost reductions” (IRENA, 2015a, p. 26).

Policy efforts can be effective at each of the three stages of technological change – invention, innovation, and diffusion (Jaffe et al., 2002; Kemp and Pontoglio, 2011) – and can be classified with different taxonomies (e.g., technology-push vs. demand-pull) and specific types or instruments (e.g., labels, performance standards) (Grübler et al., 2012a; IEA, 2018; Nemet, 2009). Despite the broad scope that technological change covers, the diffusion stage remains the largest challenge for low-carbon technologies as it requires a “widespread adoption by non-governmental entities […] [and] the

---

[1] The term low-carbon technology refers to means and methods that lead to an absolute reduction in CO_2 emissions. Low-carbon technologies can be clustered as carbon reduction technology, carbon-free technology, and carbon removal technology (Lv and Qin, 2016).

replacement of existing technologies for energy production in a diverse array of sectors" (Mowery et al., 2010, p. 1013). Oftentimes, adoption barriers of different types (e.g., institutional, behavioral, social) limit the market uptake and the widespread deployment of low-carbon technologies (Gillingham and Sweeney, 2012; Iyer et al., 2015). This is also why there is notable variation in the rates of diffusion for different low-carbon technologies (Bento and Wilson, 2016; Wilson and Grübler, 2011).

The building sector exhibits a set of very particular characteristics (UNEP SBCI, 2009). First, it is a highly fragmented, local industry with multiple stakeholders (e.g., property owners, architects, engineers, investors, occupants) and low profitability, which results in restrained innovation activities and a conservative culture. Second, construction is project-based and takes place on-site, which makes each assignment unique. Third, the long lifetime of buildings locks in design (and thus performance) choices for a considerable time horizon. Due to these specific aspects, the necessity for regulatory intervention in the built environment arises. In fact, policies to control for various building-related issues (e.g., safety requirements, spatial planning) have been in place for a long time, with an increasing emphasis on technological improvement in energy efficiency over the last three decades (IEA, 2008). In general, policy support ranges from technology-driven measures, such as grants for research, development and demonstration, to more demand-based ones, such as performance standards, efficiency labels or public procurement programs. The IPCC provides a comprehensive summary of the most common policies in the building sector, along with a categorization of policy instruments (Lucon et al., 2014). The transformation of the built environment is highly complex due to the sector's special characteristics mentioned above, in particular the long lifetime of buildings, the coordination efforts among multiple stakeholders, and the interplay of various technologies. For these reasons, policy plays an essential role in ensuring adherence to and enforcement of the strategic pathways. The proximity of this industry to other sectors, such as mobility and energy, and the consequent sector convergence that has recently gained importance, calls for further regulatory guidance. Specifically, policy support seems indispensable for low-carbon innovations of an infrastructural or systemic[2] nature (e.g., energy self-sufficient buildings, district heating networks, decentralized energy systems), which may tackle lock-ins as well as path dependent and incumbent solutions.

The extent of the climate change challenge in general, and the path towards a sustainable built environment in particular, requires joint efforts. At the European level, continuous efforts have been made to reach the ambitious strategic targets of a decarbonized economy (European Commission, 2012). However, the conditions of the local market (resources, capacities, cultural context) and the characteristics of the specific technology need to be taken into account when designing policy support for technological change, especially for environmentally benign innovation in the built environment

---

[2] Systemic innovation occurs when a change in a component or subsystem requires adaptations of other parts due to its integration within the system as a whole (Gann et al., 1998).

(Boza-Kiss et al., 2013; Grübler et al., 2012a). This dissertation aims to contribute to a deeper understanding of this relationship in order to better foster the required change.

1.3 Overarching Research Question and Framework

Given the important role a sustainable built environment plays in the mitigation of climate change, the overarching objective of this dissertation is to improve the understanding of technological change within this thematic field (especially the aspects of system design and performance) and the role of policy in fostering this technological change. In particular, the guiding research question is as follows:

> *How can system design and performance contribute to a sustainable built environment and how can technological change be supported by policy?*

To better grasp technological change, this dissertation sheds light on the process of technological progress itself. To do so, it uses the notion of the Schumpeterian trichotomy by classifying technological change as occuring in three phases: invention, innovation and diffusion (Schumpeter, 1942). While the invention phase and the impact of policy on it has been widely explored, this thesis focuses predominantly on the innovation and diffusion phases. It is worth noting that the link between policy and technological change is not of an unidirectional nature. Rather, progress that is manifested within each of these phases, e.g., by patent activities, novel products or services, or market deployment, feeds back to policy makers who alter or adapt their strategies according to the required level of change.

Figure 1 depicts the simplified research framework graphically. An extended version of the research framework, along with the specific objectives, is introduced in section 4, after the theoretical foundations and the research cases of the thesis have been laid out.

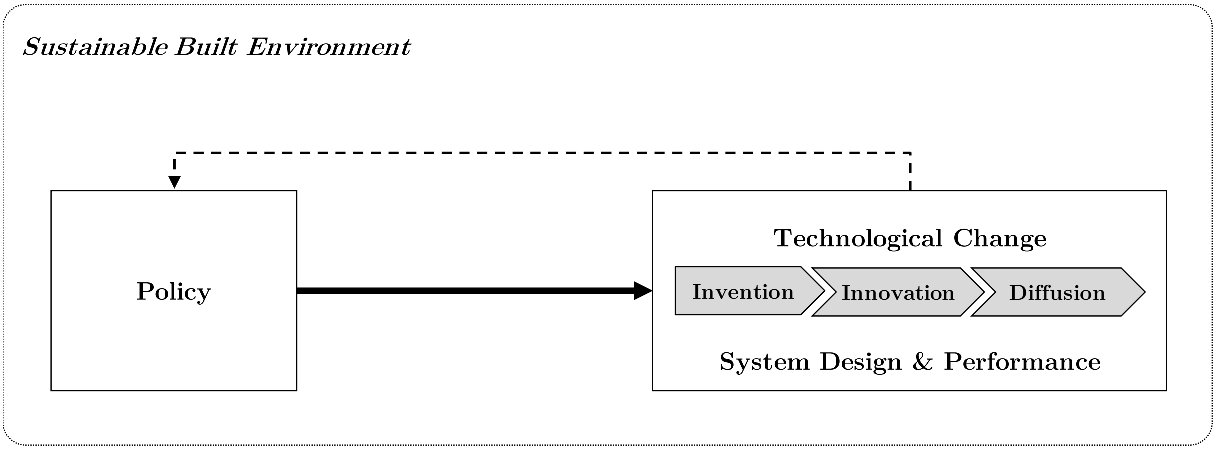


Figure 1: Overview of simplified research framework

The remainder of this dissertation is structured as follows. Section 2 provides the theoretical background on technological change (2.1) and the relation of policy to it (2.2). Subsequently, section 3 outlines the two research cases, namely decentralized energy systems (3.1) and energy-efficient building technologies (3.2), before section 4 provides the research framework and the detailed objectives of this thesis. Section 5 presents the selected methodological approaches (5.1) and the underlying data sources (5.2). The results of each of the four research articles are summarized in section 6. Lastly, section 7 concludes by discussing the main contributions (7.1), implications (7.2) and limitations (7.3) of this dissertation.

2 Theoretical Background

This section lays out the theoretical foundations of this dissertation. It starts by introducing the concept of technological change (2.1), and subsequently illuminates the role of policy as a driver for innovation and diffusion (2.2). In the end, the theory gap in literature that this thesis builds upon is deducted.

2.1 Fundamentals of Technological Change

Drawing upon history, one needs to acknowledge technological change and the progress in applying novel ideas as the ever-existing engine of huge transformations. The development of personal mobility, for instance, has undergone multiple paradigm shifts that were caused by the emergence of new technologies: from a limited radius of movement on foot, to animal domestication (e.g., horse-drawn carriages), the exploration of water transportation (e.g., boats, sailing ships), railway travel (e.g., steam engine, tram), to bicycles, automobiles, airplanes and spacecraft (Bruno, 1998). In addition to the drastic changes, the features of technological change also become evident: it unfolds in a non-linear way (i.e., simultaneous development or deployment) and is accompanied by societal transitions (Geels and Schot, 2007; Geels, 2005).

As illustrated by this exemplary historical excursus in brief, technological change in general is considered to be “one of the most important sources of economic growth” (Saviotti, 1986, p. 773). Therefore, the concept of technological change was already used by prominent scholars in their theoretical masterpieces centuries ago (e.g., Adam Smith, Karl Marx). The extant literature has captured technological change within different theory streams, where two general distinctions can be made (Nelson, 2008). First, neoclassical economic theory studies the input factors and outcomes of technological change (Solow, 1957; Swan, 1956). By disregarding the underlying transformative processes, technological change is considered to be of an exogenous nature (black box view) (Freeman, 1994; Mulder et al., 2001). To measure technological change, the quantification of exogenous change relies on the mathematical formalization of transformation and production functions (cf. Cobb-Douglas functions), where technological change is simplified as being subject to the passage of time, modeled through a certain efficiency factor (Popp et al., 2010; Solow, 1957). Second, other scholars, in contrast, endogenize technological change by opening the black box and examining the mechanisms behind the progress (Arrow, 1962; Dosi, 1982; Nelson and Winter, 1982; Romer, 1986; Rosenberg, 2008; Schumpeter, 1942). According to Schumpeter (1942), the general process of technological change can been divided into three phases: i) invention, ii) innovation, and iii) diffusion. The first phase, invention, represents the generation of novel scientific or technical ideas and their transition into new products or processes, which may be patented. The second phase, innovation, materializes the commercialization of the invention, that is, it is introduced at the market. In the third phase, diffusion, the innovation is adopted by individuals or firms, and thus spreads across its target market (Jaffe et al., 2005, 2002; Rogers, 2003; Stoneman and Diederen, 1994). In general, evolutionary economic theory provides a large pool of conceptual approaches to scrutinize the cause and effect of technological change, among them, technological learning (Arrow, 1962; Kline and Rosenberg, 1986; Wilson, 2012), technology cycle and dominant design (Anderson and Tushman, 1990; Murmann and Frenken, 2006), and path dependency and lock-in (Arthur, 1989; David, 1985). The quantification of endogenous technological change is a more complex task and differs substantially in its methodological approaches compared to exogenous change. Integrated assessment models are one approach (of many others, cf. Gillingham et al. (2008), Grübler et al. (1999), and Mulder et al. (2001)), in which, for instance, bottom-up models focus on the simulation and optimization of different technologies, and their performances (e.g., technical, economic, environmental), as well as improvement and replacement potential via learning curves (Vollebergh and Kemfert, 2005).

This dissertation follows the second theory stream and thus the notion of endogenous technological change in order to grasp the underlying mechanisms. Parts of the thesis apply bottom-up integrated assessment models to quantify the level of change for a certain technology (cf. subsection 3.1) and to evaluate its potential contribution to climate change mitigation. To complement the quantitative assessment, a qualitative understanding of endogenous technological change is also aimed for in parts of this thesis, following the remarkable body of literature that focuses on observations of technology developments from an evolutionary perspective (Bento and Wilson, 2016; Grübler et al., 2012a; Negro et al., 2007; Wilson, 2012; Wilson and Grübler, 2011). Furthermore, while all of Schumpeter's three phases (invention, innovation, diffusion) create "the cumulative economic or environmental impact of new technology" (Jaffe et al., 2002, p. 43), it is clear that technological advances in the form of invention and innovation are "of little use unless society makes use of" them (Pizer and Popp, 2008, p. 2765). However, the extant literature has prioritized the first two phases, studying invention and innovation activities (e.g., knowledge spillover, patenting) more extensively than diffusion. For these reasons, the focus of this thesis is on the last two phases (innovation and diffusion) rather than on the invention phase of technological change, in order to capture the commercialization and deployment of new technologies instead of their discovery and development.

Technological change is associated with being both the cause of and the solution to global climate change at the same time and is considered "at once the most important and least understood feature driving the future cost of climate change mitigation" (Pizer and Popp, 2008, p. 2768). In fact, the rate and direction of technological change remain uncertain (Popp et al., 2010). With regard to the rate, scholars have observed large temporal discrepancies in the innovation and diffusion phases of low-carbon technologies (Grübler et al., 1999; Iyer et al., 2015), such as wind turbines (Bento and Wilson, 2016; Wilson and Grübler, 2011), compact fluorescent lamps (CFL) (Bento and Wilson, 2016; Wilson and Grübler, 2011), or bioenergy (Höök et al., 2012). Concerning the direction, as long as the negative externalities of harming the atmosphere – due to its public goods nature – cannot be appropriately internalized, the development and diffusion of low-carbon technologies, for example, are not given priority and their desired progress remains erratic and undirected (Jaffe et al., 2005; Kemp and Soete, 1990). At this point, policy becomes relevant, as it is recognized as exerting substantial influence on both rate and direction of technological change (Clarke and Weyant, 2002; Jaffe et al., 2002; OECD, 2001; Unruh, 2002, 2000; Vollebergh and Kemfert, 2005). Although a better understanding of policy-induced technological change has been a goal of research agendas for years, there seems to be no silver bullet available for how to design policy support in an effective and efficient manner. Therefore, many important aspects of this link still need to be further explored.

2.2 The Role of Policy in Fostering Innovation and Diffusion

As stated above, this dissertation follows the notion of endogenous technological change, whose rate and direction can be induced by institutional action, such as public policy intervention. Scholars have studied policy-induced technological change from a wide range of angles (Edler and Fagerberg, 2017; Vollebergh, 2007). Empirical contributions comprise analyses of policy impact on invention and innovation activities, mostly relying on patent counts as a proxy (Brunnermeier and Cohen, 2003; Lanjouw and Mody, 1996). Popp (2002), for instance, carves out the strong effect of energy prices on the patent activity for energy-efficient technologies. Further empirical studies focus on the influence of policy for the diffusion of new technologies (Hassett and Metcalf, 1995; Kemp, 1998), often using adoption rates to measure deployment. Jaffe and Stavins (1995), for example, investigate the adoption of insulation technologies and compare the effectiveness of two specific instruments (i.e., adoption subsidies and energy taxes). In the same vein, a related body of literature emphasizes the role of market failures as barriers to the adoption of (low-carbon) technologies, which thus hinders their diffusion (Gillingham and Sweeney, 2012; Pelenur and Cruickshank, 2012). In general, according to Pizer and Popp (2008), the link between policy and diffusion has received less attention in research than the invention and innovation phases. This link, however, is of high relevance to policy makers as better understanding of diffusion would enable more targeted support.

While the influence of policy on technological change, especially for environmental benign technologies, is commonly agreed upon, the nature of policy support, including choice, design or sequence of instruments, remains a topic of controversial discussion (Edler and Fagerberg, 2017; Fischer and Newell, 2008; Höhne, 2011; Vollebergh, 2007). This is a highly complex issue for two main reasons. First, policy intervention usually consists of multiple instruments, so called policy mixes (Ossenbrink et al., 2018; Rogge and Reichardt, 2016), and the availability of data that disaggregates the individual effects is limited (Vollebergh, 2007). Second, the circumstances for comparing different instruments are dynamic and highly dependent on societal, technological and institutional conditions, which render a fair basis of comparison almost impossible (Foxon, 2011). Despite these difficulties in evaluating the potential differential impact of various policies, the literature is rich in studies that analyze policy-induced technological change, particularly in the low-carbon realm, with a specific focus, such as certain instruments or technologies (Kemp and Pontoglio, 2011; Newell, 2010; OECD, 2001).

Collectively, there is profound knowledge about the idealized approach of policy support from innovation to diffusion, that is documented in a quasi-linear process with different stages, where the technology-push concept is associated with the earlier stages, while the demand-pull concept accounts for the later ones (cf. Grubb (2004), Grubler et al. (2012), and Halsnæs et al. (2007)). Each of these stages implies the use of different policy instruments that can differ in their design (IEA, 2018).

However, scholars have pointed out that effective policy support needs to account for the specific context (e.g., local resources, capacities, cultures) and nature of the technology, and that policy therefore needs to be tailored accordingly (Boza-Kiss et al., 2013; Grübler et al., 2012a). Today, there is only a limited understanding about the link between policy support and its adaptation for individual technologies and their specific natures (del Río González, 2009; IEA, 2015; Stucki and Woerter, 2016). To address this issue, individual case studies have examined this link by reflecting the characteristics of technologies (e.g., complexity of product architecture, scale of production process) and their national contexts (Grösser et al., 2006; Huenteler et al., 2016; Kemp, 1998). While some cases emphasize the necessity of the entire range of policy support, i.e., all stages of the quasi-linear process (Kiss et al., 2013), others have shown that selective support measures can successfully kick off market diffusion (Kimura, 2013).

To understand the mechanisms behind these different forms, an analysis is needed that allows for a direct comparison between several technologies within the same policy and industry context, where the technologies' diffusion has been exposed to disparate policy support. This would enable more informed decisions by policy makers regarding the way to adapt support to the specific nature and conditions of a (low-carbon) technology. This dissertation aims to address this theory gap in order to improve understanding.

3 Research Cases

This section introduces the two research cases that build the empirical basis for the analysis of this dissertation. It starts by presenting the case of decentralized energy systems (3.1) and then describes the case of energy efficiency technologies (3.2). For both research cases, the thematic field is outlined and defined based on the relevant literature. Then the rationale behind each case selection is given. Lastly, the context of Switzerland for these cases is sketched out.

3.1 Decentralized Energy Systems

Despite the energy landscape's centralized nature during the last century, where large-scale power plants connected local consumers via transmission and distribution grids, over the past decade it is shifting increasingly towards a more decentralized renewable energy generation at the consumer level. These so-called "prosumers" (i.e., agents that both produce and consume energy (Parag and Sovacool, 2016)) are shaping a transition to local systems that fulfill their energy demands to a large extent on their own. A remarkable driver for the decentralization is the advent of techno-economically feasible renewable energy technologies, such as solar PV (Barbose and Darghouth, 2016; Vaishnav et al., 2017), and energy storage options, such as battery technologies (Crabtree et al., 2015; Nykvist and Nilsson, 2015; Schmidt et al., 2017). For instance, PV module prices decreased by about 70% between 2010 and 2014 (Feldman et al., 2014) and at the same time global cumulative installed capacity of solar PV more than quadrupled to 180 GW of installed capacity (IRENA, 2015b). This is a development that has been spurred to a large extent by massive policy support. As a substantial share of energy from RES comes from decentralized settings, storage technologies represent a perfect complement to cope with their intermittent nature and to match local production with local consumption (Battke et al., 2013).

The concept of decentralized energy systems broadens the scope from individual technologies to the integration of multiple technologies at the system level. At this level, systems can range from single buildings to groups of buildings within neighborhoods, communities or city quarters (Orehounig et al., 2015; Weber et al., 2006). As a result, decentralized energy systems provide numerous benefits. Among others, they have large synergy potential and provide high operational flexibility by combining different energy carriers (e.g., electricity, heat) and end-use services (e.g., mobility), they improve the input resource utilization (e.g., micro combined heat and power), relieve stress from the local grid, reduce transmission and distribution losses, and they could guarantee a more reliable energy supply (e.g., in islanded mode) (Alanne and Saari, 2006; IEA, 2013a; IPCC, 2007; Omu et al., 2013; Ren and Gao, 2010).

Today, there is an abundance of different terminologies and definitions to describe the concept of decentralized energy systems. Among them the most prominent notions are "multi-energy system" (Mancarella, 2014), "hybrid (renewable) energy system" (Sharafi et al., 2015), "distributed multi-generation" (Chicco and Mancarella, 2009), and "energy hub" (Geidl et al., 2007). While the concept of decentralized energy systems traces back to the 1990s (Groscurth et al., 1995), it has received substantial attention in both academia and practice within the last decade, not least because of the technological progress of relevant technologies outlined above (Bruckner et al., 2014; IPCC, 2007). However, despite the increasing interest, there is no widely agreed definition available. Therefore, the definition underlying this dissertation is based on the notions of different scholars in the field (Geidl, 2007; Hajimiragha et al., 2007; Hemmes et al., 2007; Mancarella, 2014; Manwell, 2004; Omu et al., 2013; Orehounig et al., 2015) and is worded as follows:

> *A decentralized energy system is a collection of energy production*[3]*, conversion*[4] *and storage*[5] *devices, which has an input of at least one renewable energy source, deals with multiple energy carriers*[6]*, allows for conversion from one energy carrier to another, and provides energy carriers as an output to serve local energy service demands.*

Figure 2 illustrates this concept of decentralized energy systems by displaying a selection of exemplary technologies and energy flows within the system.

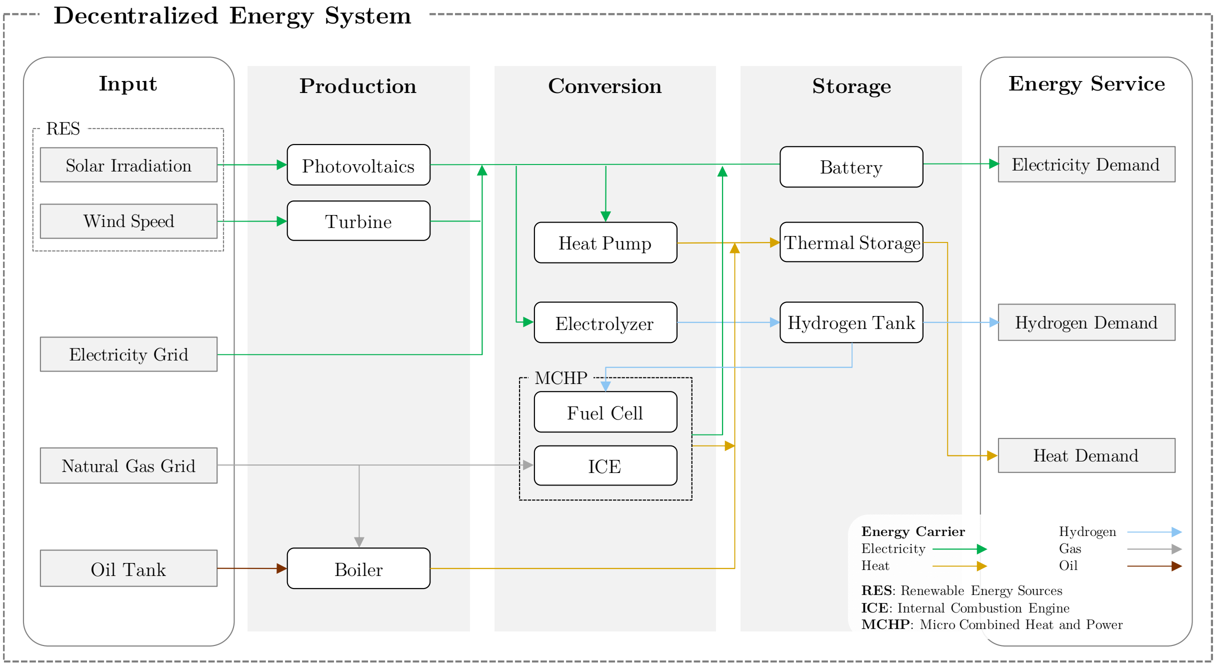


Figure 2: Illustration of the decentralized energy system concept (exemplary selection of technologies)

---

[3] Production devices convert a primary energy source into an energy carrier, e.g., solar PV, wind turbine.

[4] Conversion devices convert one energy carrier to another, e.g., electrolyzer, fuel cell, heat pump.

[5] Storage devices allow the storage of energy carriers, e.g., battery, hot water, hydrogen storage tanks.

[6] "Energy carriers include electricity and heat as well as solid, liquid and gaseous fuels, occupy intermediate steps in the energy-supply chain between primary sources and end-use applications. An energy carrier is thus a transmitter of energy", according to the IPCC (2007), p. 280.

Scholars have assessed decentralized energy systems from different perspectives, mostly focusing on specific technological aspects and test cases (Bernal-Agustín and Dufo-López, 2009; Evins et al., 2014; Fabrizio et al., 2010; Li et al., 2017; Zhang et al., 2017), methodological approaches, such as evaluation and optimization tools (Gabrielli et al., 2017; Prakash and Khatod, 2016; Sinha and Chandel, 2014), or socio-economic issues (Kaundinya et al., 2009; Nygren et al., 2015; von Wirth et al., 2017). However, the extant literature lacks three important parts. First, due to the substantial growth of this scientific domain, a comprehensive overview is missing that describes the knowledge base of the field. Second, the techno-economic performance of decentralized energy systems is controversially discussed with inconclusive results. A precise quantification in the innovation phase is needed to proceed with an eventual diffusion. Third, the potential contribution of decentralized energy systems to a sustainable built environment, today and in the future, has not yet been thoroughly evaluated. It is the aim of this thesis to augment the understanding in these regards and to address the described gaps.

In the wider context, decentralized energy systems serve as a suitable research case for this dissertation, and they have been selected for the following reasons. On the one hand, systemic solutions, such as decentralized energy systems, are reported to be the next evolutionary step towards a sustainable built environment. This development is enabled by the commercial availability of the individual technologies, the technical feasibility to connect them in a smart[7] way, and existing net zero energy concepts at the demand side (IEA, 2017b; Manfren et al., 2011; Voss and Musall, 2013). Interconnecting the various technologies and exploiting the resultant benefits is likely to be a key lever on the selected pathway. On the other hand, the need for policy intervention is considerably high, especially for systemic innovations that might overhaul the incumbent system. Therefore, policy plays an important role in spurring technological progress, i.e., nurturing systemic innovations from niche to mass markets. Lastly, decentralized energy systems represent a promising research case, as they are located in an interesting phase of technological change. Introduced in the 1990s, their invention is comparably recent and the innovation phase is consequently not fully completed. At the same time, however, it is still a very long way until their widespread diffusion. Therefore, a prospective analysis of decentralized energy systems is required to better understand the innovation phase and to eventually derive implications for (support of) the diffusion phase.

Switzerland's decision to phase out nuclear energy in the long run and to halve carbon emissions by 2030 (compared to the 1990 level) is manifested and operationalized in the Swiss Energy Strategy 2050 (Prognos AG, 2012; Swiss Federal Council, 2018). To achieve these ambitious targets, among numerous other levers, Switzerland aims at restructuring the energy system and focusing on the built environment by i) reducing the energy intensity of buildings via energy efficiency measures, ii) lowering the carbon intensity via RES, and iii) increasing renewal activities via retrofitting or

---

[7] Smart grids and meters are examples of intelligent, digital innovations that are deemed inevitable for the transformation of the electricity sector (Farhangi, 2010).

replacement (Mavromatidis et al., 2016). In fact, decentralized energy systems are promising options to address the first two of these aspects in particular. As a result, the Swiss built environment has exhibited initial deployment with several lighthouse, pilot and demonstration projects. These projects being implemented to showcase, test, and improve decentralized energy systems include, among others, the NEST ("Next Evolution in Sustainable Building Technologies") demonstrator in Dübendorf (EMPA, 2018), the energy autarkic multi-family house in Brütten (Umwelt Arena AG, 2018), and the majority of the 20 certified Swiss "2000-Watt Sites" (Heinrich Gugerli, 2017). Switzerland's pioneer role defines the Swiss built environment as an ideal context to investigate them, and thus in large part determines the spatial focus of this dissertation.

3.2 Energy Efficiency Technologies

Based on the first law of thermodynamics, energy efficiency can be defined as "the ratio of the desired (usable) energy output to the energy input", the so-called first law efficiency (Grübler et al., 2012b, p. 116). A more efficient way of harvesting, distributing and using energy reduces the amount of required primary energy and additionally lowers costs and environmental stress. While there are ample opportunities to increase energy efficiency at the various stages of the energy value chain, the focus of this dissertation rests on the downstream, that is, providing final energy services to buildings (the front-end part of the energy value chain), where the lion's share of the conversion losses accumulate (Cullen et al., 2011). Energy-efficient building technologies however still serve a wide range of applications and can be divided into three general categories: i) Heating, Ventilation and Air Conditioning (HVAC) and water heating; ii) appliances and lighting; and iii) building envelope, including windows (IEA, 2013a; Navigant Reserach, 2017; U.S. Department of Energy, 2011; Ürge-Vorsatz et al., 2012). Examples of energy-efficient building technologies in the first category are co-generation[8] devices (i.e., micro combined heat and power) or wood pellet boilers. Prominent examples in the second category include energy-efficient white goods[9] (e.g., dishwasher, refrigerator) or light-emitting diode (LED) technology as a light source. In the third category, energy-efficient innovations cover, for instance, improved insulation material (e.g., aerogel insulation), adaptive building skins or dynamic glazing[10].

During the oil crises in the 1970s public awareness of resource scarcity and environmental pollution increased and, as a result, an energy-conscious behavior arose, especially in Western Europe. This momentum led to the launching of large-scale technological developments in energy-efficient building technologies (with the initial focus mainly on heating) as well as policy efforts (e.g., building energy

---

[8] Co-generation refers to the simultaneous generation of heat and power, where heat as a by-product of the process is recovered and used to satisfy thermal demands, thus increasing overall efficiency.

[9] White goods is a stylized term to describe large electrical household appliances, such as refrigerators or washing machines, and refers to their typical color.

[10] Dynamic glazing defines glass that integrates elements to control light transmission or solar heat gains (Lollini et al., 2010).

codes) to foster their implementation (IEA, 2013b). While public policy was limited to the national level until then, beginning in the 1990s energy efficiency policies for buildings were introduced at the European level, gradually increasing in coverage and stringency (Gynther et al., 2015). Today, there is a plethora of commercially available energy-efficient building technologies in all three categories and a similarly large number of policy measures in place, from the regional to the national to the supra-national (e.g., European) level (IEA, 2013b, 2008).

Given this long history, the extant literature has explored energy-efficient building technologies in various disciplines, for instance, with a strong focus on technical aspects (e.g., material, mechanical or civil engineering), societal issues (e.g., behavioral science), economic factors (e.g., from micro to macro level), and political facets. However, while further deployment of energy efficiency technologies in the built environment is needed to reach global emission targets, there is still limited understanding of the mechanism behind effective policy support and the necessary technological change. This dissertation aims to shed light on this link. To do so, energy-efficient building technologies are deemed to be a suitable case because of i) their long and relevant history, which is properly documented, ii) their successful completion of all three phases of technological change (invention, innovation, diffusion) for today's well established energy efficiency technologies, and iii) their intertwined nature with policy intervention, which has shaped technology development (invention and innovation) and market deployment (innovation and diffusion). For these reasons, a retrospective analysis of energy efficiency technologies in the built environment is considered a promising approach to derive insights on the "policy-technology" link.

This dissertation draws upon three distinct energy-efficient building technologies: heat pump, comfort ventilation, and low-e glazing. A heat pump is a device that delivers space heating to a building by transferring heat from a low temperature source to a high temperature source using thermodynamic principles. Since the required amount of electric power is lower than the extracted heat, heat pumps bear energy reduction potentials of 50–75% compared to their fossil-fueled rival technologies (e.g., oil or gas boilers), and they allow for reducing CO_2 emissions close to zero if powered by fossil-free electricity. A comfort ventilation is a ventilation system for residential buildings or apartments that supplies fresh air while reducing heat loss by exchanging heat between intake and exhaust airflow. In doing so, the comfort ventilation technology directly complements insulation measures and allows for savings of around 30% (Nussbaumer, 2015) on heating energy and up to 70% on ventilation losses (Verein Komfortlüftung.at, 2014) compared to a regular manual exchange of room air. Low-e glazing technology is a type of insulating glass that uses low emissivity (thus "low-e") float glass coated with a layer of a specific metal to reduce the heat transfer coefficient. It improves the insulation of the building envelope by up to 50% against a standard insulating glass (Efficient Window Collaborative, 2016).

As outlined above, Switzerland's ambition for emission reduction is anchored in the Swiss Energy Strategy 2050, with one specific emphasis on curbing the energy intensity of buildings via energy efficiency technologies (Prognos AG, 2012). In total, the Swiss federal government and the cantons spent over CHF 1 billion (2010-2014) to incentivize the buildings' energy efficiency (Luterbacher, 2016; Swiss Federal Office of Energy (SFOE), 2018). Despite this more recent strategic roadmap, the Swiss history in supporting energy efficiency dates back to the 1980s with concrete suggestions and operationalization, for example, in the program “Energie2000” (1991–2000), an investment program of up to CHF 560 million to increase the acceptance of energy-efficient technologies (Grösser et al., 2006). Switzerland’s role as an engine of energy efficiency innovation has not only resulted in numerous product developments, but has also had success in terms of emission reduction. Between 2000 and 2013, Swiss residential buildings, for instance, exhibited a drop in CO_2 emissions by 17%[11] (Federal Statistical Office, 2015). Being among the forerunner countries for energy-efficient building technologies, Switzerland provides a perfect spatial context to examine them and their link to the respective policy support.

---

[11] The total of 17% already compensates for the population growth (11%) and the increase in living area per resident (2%) and is climatically adjusted.

4 Research Framework and Objectives

Based on the outlined gaps in theory and the research cases above, this dissertation sets out four distinct objectives by specifying the overarching research question (cf. section 1.3). Given the emphasis on technological change, the four articles study different phases of this change. While articles I–III focus on the innovation phase, with glances at the invention (I) and diffusion phases (I, II, III), article IV examines the diffusion phase and touches upon the preceding innovation phase. Table 1 summarizes the specific foci and research questions of the individual articles.

Table 1: Overview of the objectives of the individual articles of this dissertation

#	Focus	Title	Research Question
I	Invention, Innovation, Diffusion	Matching Decentralized Renewable Production and Local Consumption: A Review of Energy Conversion and Storage Systems	What is the current state of literature and practice for renewable decentralized energy systems with energy conversion and storage?
II	Innovation, Diffusion	How, When, and Where? Assessing Renewable Energy Self-Sufficiency at the Neighborhood Level	How, when, and where could energy self-sufficient neighborhoods become competitive?
III	Innovation, Diffusion	A Comparison of Storage Systems in Neighborhood Decentralized Energy System Applications from 2015 to 2050	What is the optimal technical design for renewable decentralized energy systems from 2015 to 2050?
IV	Innovation, Diffusion	The Role of Policy in Fostering the Diffusion of Low-Carbon Innovations	How does policy support need to be adapted to the specificities of a technology in order to accelerate the diffusion of low-carbon innovations?

Embedded in the research domain of a sustainable built environment, the articles assess different thematic fields within the scope of the research cases. Articles I–III look into the context of decentralized energy systems and aim at an improved understanding and quantifying of the level of technological change. Their objective is to shed light on the nature of innovation, namely, system design, technological setup and configuration, as well as today's performance and potential future performance along various dimensions. Article IV applies the research case of energy efficiency technologies and aims at understanding the powerful link between policy and technological change. In particular it explores the mechanisms by which policy fosters the diffusion phase of low-carbon technologies. It is important to note that while the main objective of article III is the quantification of technological change, it also gives first indications on the feedback loop back to policy. Thereby, it provides valuable insights to policy makers by mapping out whether the potential level of technological change might be sufficient to reach desired emission targets. Figure 3 illustrates the scope of the individual articles within an extended outline of the research framework.

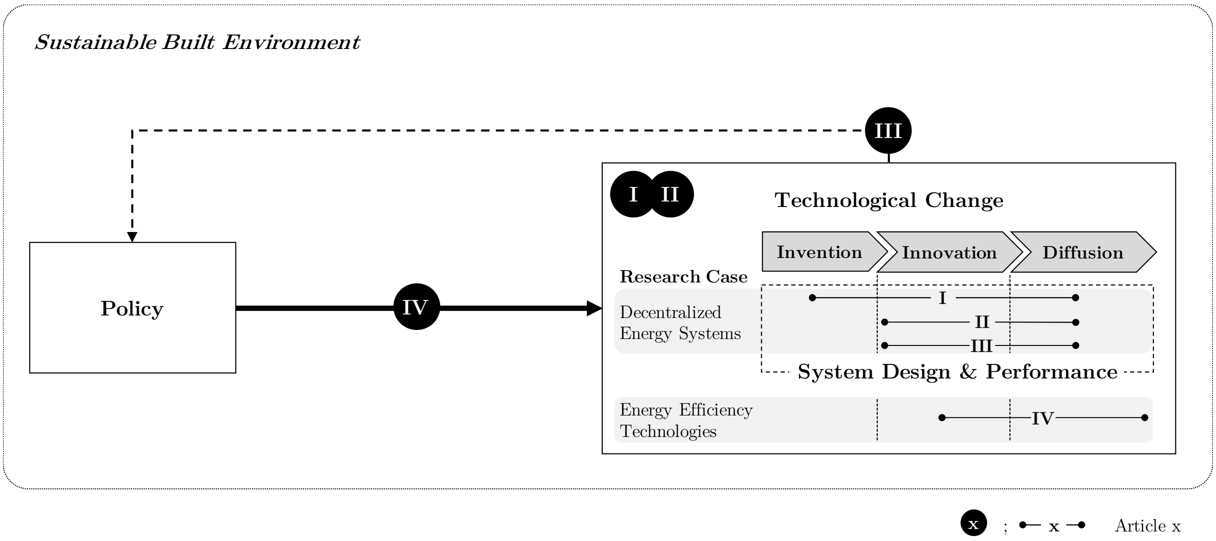


Figure 3: Extended research framework and scope of the individual articles

5 Methods and Data

To capture the different aspects of the research framework and address the outlined objectives, this dissertation applies a mix of quantitative and qualitative methods (Brannen, 1995). This section first introduces the two methodological approaches (5.1), namely techno-economic modeling and case study research, and the rationale for their selection. Then, the underlying data sources are presented (5.2), before a brief overview of methods and data for the individual articles is provided (5.3).

5.1 Methods

Techno-Economic Modeling

Techno-economic modeling provides the empirical foundation for assessing both economic and technical performance, for example, of a low-carbon innovation. It combines an engineering perspective that accounts for technical parameters, such as sizing or efficiency, with an economic point of view focusing on the costs and benefits of the object of investigation, such as positive and negative cash flows or return on investment. In doing so, they are used to conduct a performance assessment along the technical and economic dimension, but can be extended by further dimensions (e.g., environmental performance). Typical output indicators comprise levelized cost of energy (LCOE), internal rate of return (IRR) or net present value (NPV) (Padmanathan et al., 2017). Techno-economic models are always exposed to the challenging trade-off between precision and complexity (Manwell, 2004; Petruschke et al., 2014). Although they depict the real world in a simplified and concise manner, they need to capture the underlying techno-economic mechanisms (e.g., operating principle, business model, cash flows) as accurately as possible to allow disentangling and quantifying the impact of individual variables. Various assumptions need to be made to limit complexity in order to reduce, for instance, the computational effort. Since many assumptions cannot be considered as certainly known, especially due to their temporal development (e.g., market dynamics, technological learning), techno-economic models must cope with uncertainty. Scenario analysis, sensitivity analysis and Monte Carlo analysis are potential ways to deal with uncertainty and increase both robustness and operational validity of the model (Jacoboni and Reggiani, 1983).

This dissertation applies techno-economic modeling to scrutinize the performance of decentralized energy systems, which is needed to understand i) where the innovation stands (from a technical and an economic point of view) compared to baseline or reference technologies, and ii) what it can contribute to solving the climate change mitigation puzzle. For these reasons, the techno-economic modeling is extended by an environmental assessment (of direct CO_2 emissions) and an optimization to determine ideal system size. Article II focuses on self-sufficient decentralized energy systems decoupled from an existing energy infrastructure (neither electricity grid nor gas grid) and relies on genetic algorithms to identify optimal solutions. In comparison, article III uses a different modeling approach to simulate a grid-connected urban and rural test case in Switzerland and applies multi-objective optimization with mixed-integer linear programming (MILP) to generate Pareto optimal solutions (minimizing both cost and emissions). Both articles have different ways to cope with uncertainty. Article II applies sensitivity analyses to determine the key levers for system performance and includes a parametric scenario analysis to estimate potential future performance. Article III integrates a scenario analysis based on three alternative images of future developments from the baseline year 2015 to 2020, 2035 and 2050.

While techno-economic modeling employs a perspective that is based on economic rationale and thus allows for quantifying the cost and benefits of an innovation (or already in the invention phase), it falls short in detecting alternative explanations, such as bounded rationality or market failures (Gillingham and Sweeney, 2012). However, these alternative explanations are equally important to decoding the reasons for insufficient diffusion of techno-economically superior innovations. The analysis of qualitative, non-economic determinants requires a different methodological approach though, which is why the case study approach has been selected to complement the quantitative findings of the modeling.

Case Study

According to Yin (2009), a case study is “an empirical inquiry that investigates a contemporary phenomenon in depth and within its real-life context” (Yin, 2009, p. 13) and is considered a suitable research design to understand the mechanisms behind “a program, event, activity, process, or one or more individuals”, thus addressing *how* and *why* questions (Creswell, 2009, p. 13). This is why case studies have an explanatory purpose and “help to gain insight into the structure of a phenomenon” and also serve as a basis for the development of hypotheses, models and theory (inductive theory building) (Scholz and Tietje, 2002, p. 11; Yin, 2009). Typically, case studies rely on a large number of sources and data collection procedures to gather evidence for the phenomenon in scope.

Building upon a single case study, a multiple case study design allows for capturing the “similarities and differences between the cases” and therefore provides an opportunity for comparison and an eventual generalization (Baxter and Jack, 2008, p. 550). While multiple case studies increase the robustness and reliability of a study, it comes at the expense of time and effort (Baxter and Jack, 2008). Both single and multiple case studies are an important methodological approach in policy research (Jupp, 2006).

This dissertation applies a case study design to explore the causal relations between policy support and its impact on technological change, specifically on the diffusion phase, which is still poorly understood. In particular, article IV uses a multiple case study approach to increase the understanding of the effect between policy and the diffusion of energy-efficient building technologies and capitalizes on the comparative power by exploring three cases.

5.2 Data Sources

Archival Data and Techno-Economic Inputs

Archival data comprises any accessible sort of information that has been gathered at a preceding point in time by individuals or organizations for their own purpose and can stem from various sources, such as corporate annual reports, press releases, or weblogs (Fischer and Parmentier, 2010). The main advantage of working with archival data is "the opportunity to examine data from long-term longitudinal studies of individuals", thereby enabling researchers to address questions that are focused on past historical periods (Jones, 2010, p. 1011).

The collection and analysis of archival data has been vital for both the quantitative and the qualitative part of this dissertation. Due to its partly retrospective nature, this thesis relies on secondary data from multiple sources, such as public and private documents, official records and data archives. The data sources stem from various disciplines to obtain a comprehensive picture of technical, economic, environmental, societal, and political aspects, and capture a longitudinal perspective. The temporal dynamics for the retrospective analysis is covered through an extensive review of secondary data for the investigated time period, whereas the prospective analysis copes with the uncertain future by a scenario analysis. To build upon robust assumptions and to ensure validity of the input parameters, the findings from archival data were triangulated across different sources and through expert interviews.

Interview Data

In three out of the four articles (I, II, and IV), this dissertation draws on expert interviews. It does so for two reasons. First, expert interviews were used for exploration, that is, to obtain "an orientation in a new field in order to give the field of study a thematic structure […] [and] […] to collect context information complementing insights" from other sources (Flick, 2014, p. 228). Second, the opinion of subject matter experts was used to triangulate selected assumptions, input parameters, and preliminary results (mostly from the quantitative parts of this thesis).

To be precise, data from 34 formal, semi-structured interviews with experts from different fields (e.g., academia, industry, policy) was collected between 2014 and 2016. The interviews were conducted in person or via telephone by my co-authors and/or myself. The majority of the interviews were recorded, transcribed and analyzed. For the analysis (mostly for the qualitative parts of this thesis), the interview transcripts were revised and processed using an inductively based analytical strategy (Saunders et al., 2009). According to Langley's (1999) "synthetic strategy" for sensemaking, the analysis included iterations between empirical data and different theoretical concepts to better understand the main mechanisms. Once theoretical saturation was reached, data collection and analysis was stopped (Flick, 2014).

Aside from the formal interviews, assumptions and preliminary findings were regularly discussed and triangulated throughout the entire period of this dissertation, as it was embedded in two larger research projects, in which scholars from different fields (e.g., electrical and control engineers, building physicists, mechanical engineers, sociologist) were involved.

5.3 Overview

The individual articles of this dissertation apply the methods and data sources described above in different ways. Table 2 provides the corresponding overview, while details on the methodological approaches and underlying data are given in the individual articles (cf. Annex).

While the spatial scope of article I (and to some extent article II) is at the global level, articles II–IV have their focus at the Swiss level. The temporal scope of the articles is rather broad, ranging from the retrospective analysis of article IV (1970 to 2015) to the prospective analysis of article III (2015 to 2050), with articles I and II in between.

Table 2: Methods and data sources used in the individual articles

#	Title	Method	Data Sources	Scope	
I	Matching Decentralized Renewable Production and Local Consumption: A Review of Energy Conversion and Storage Systems	Review (multiple case study)	Archival data (publication and project database), expert interviews	Global	2004–2017
II	How, When, and Where? Assessing Renewable Energy Self-Sufficiency at the Neighborhood Level	Techno-economic model	Archival data, expert interviews	CH, (global)	2015
III	A Comparison of Storage Systems in Neighborhood Decentralized Energy System Applications from 2015 to 2050	Techno-economic model	Archival data	CH	2015–2050
IV	The Role of Policy in Fostering the Diffusion of Low-Carbon Innovations	Case study (multiple)	Archival data (longitudinal), expert interviews	CH	1970–2015

CH = Switzerland

6 Summary of Results

This section summarizes the main findings of the four individual articles that this dissertation comprises. Each article's summary is provided in a separate subsection and contains the most important results and implications. The respective research designs, objectives and discussions can be found in the individual articles (see Annex for details).

6.1 Article I: Matching Decentralized Renewable Energy Production and Local Consumption: A Review of Energy Conversion and Storage Systems

This article provides a comprehensive overview of the status-quo of decentralized energy systems, both in literature and practice. From a systematic, keyword-based search with the Web of Science™ database, 64 relevant publications are retrieved and analyzed side-by-side with 56 project descriptions. For this purpose, four key criteria are used: i) terminology in use, ii) scope/motivation, iii) application, and iv) technical configuration. In order to complement the knowledge gained from the review of literature and practice, a series of expert interviews (N=13) with different stakeholders (e.g., investors, technology providers, project developers and managers, integrators, academic experts) was conducted.

First, the findings reveal a lack of common terminology. With 46 different terms in use within the sample of 64 publications, the literature shows a wide variety in nomenclature. While there is no consistent detectable naming pattern, five main terminology clusters were identified: multi- (e.g., "multi-energy system"), hybrid (e.g., "hybrid energy system"), distributed or decentralized (e.g., "distributed energy system"), hub (e.g., "energy hub"), and microgrid or smartgrid (e.g., "(multi) microgrid"). The significant variation in terminology is more obvious in literature than in practice, where it is less common to designate a specific name for the type of system used other than the project or site name itself. The high terminological variation presumably stems from different academic communities or institutions, which coin and consequently promote a certain term, and the lack of conceptual delineation of the phenomenon of decentralized energy systems, their definition, and integral components.

Second, literature and practice vary in the scope of and motivation for decentralized energy systems. While the literature predominantly approaches systems with a theoretical focus and addresses front-end characteristics (e.g., optimization techniques), the practical side tends to elaborate on operational aspects, such as regulatory constraints. These different perspectives indicate the potential for technological learning. Pilot projects could help to develop best practices for operating and integrating various technical devices within an overall system. At the same time, project leaders and other stakeholders could benefit from using the ideas presented in the literature to optimize system design and performance as well as energy dispatch alongside other objectives, such as reduction of cost and/or emissions.

Third, the observations indicate a more consistent pattern regarding the use of decentralized energy systems than the terminological variety might convey. Four typical application categories for both literature and practice are determined by reviewing and analyzing cases: i) residential, ii) commercial or mixed-use, iii) island, and iv) utility. Remarkably, the distributions of cases from publications and projects are very similar, which implies that – for otherwise closely related applications – literature and practice differ only in the nature of the problems and approaches to solving them.

Fourth, technological diversity results from a large number of possible combinations for each of the individual technologies. In total, 31 different combinations of renewable energy technologies and storage technologies exist across 55 test cases (out of the 64 publications) in literature, and 30 different combinations exist across 56 pilot projects. Thus, no dominant configuration stands out as the most favorable one in either literature or practice. Solar PV and wind seem to constitute the majority of technology clusters, along with electrical energy storage and hydrogen storage, especially in grid-independent settings (cf. Figure 4). Apart from that, the technical configurations are multifaceted and are specific to geography, site, or application with no true dominant technology emerging (yet) – but this might change in the medium- to long-term because of sufficient levels of maturity for certain technologies and configurations.

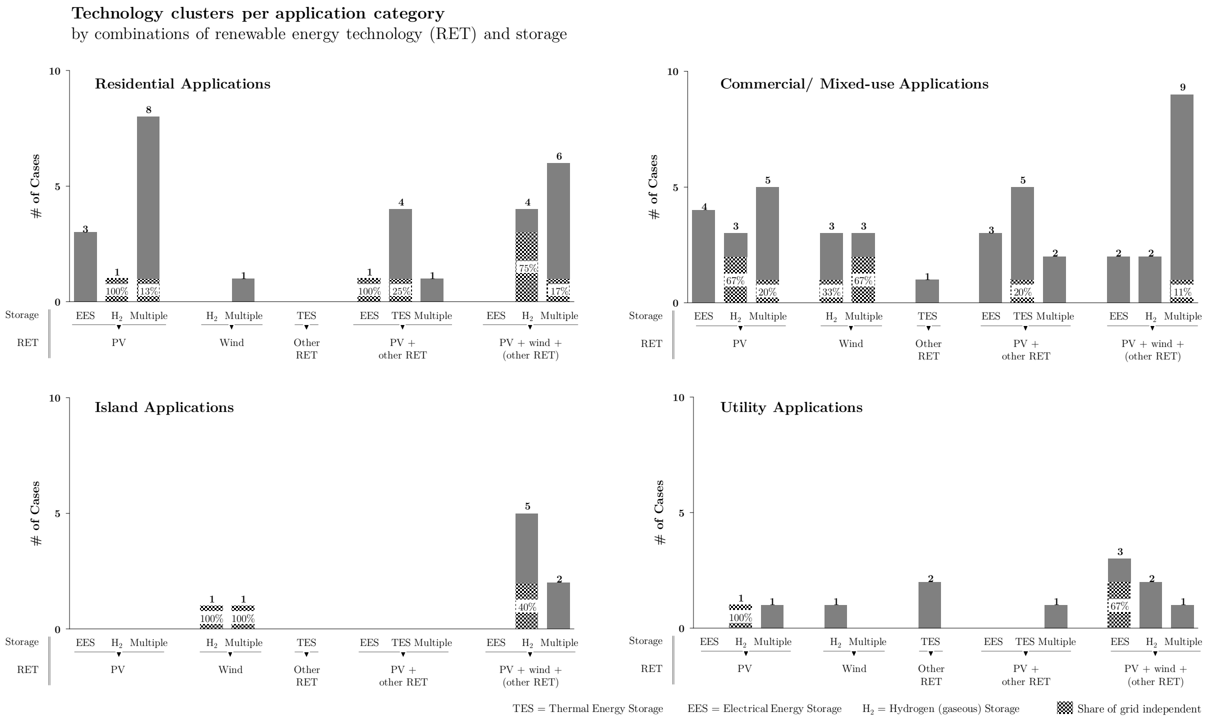


Figure 4: Distribution of cases for each application category across frequently occurring technology clusters and share of grid independent cases (number of cases include both literature and practice combined)

6.2 Article II: How, When, and Where? Assessing Renewable Energy Self-Sufficiency at the Neighborhood Level

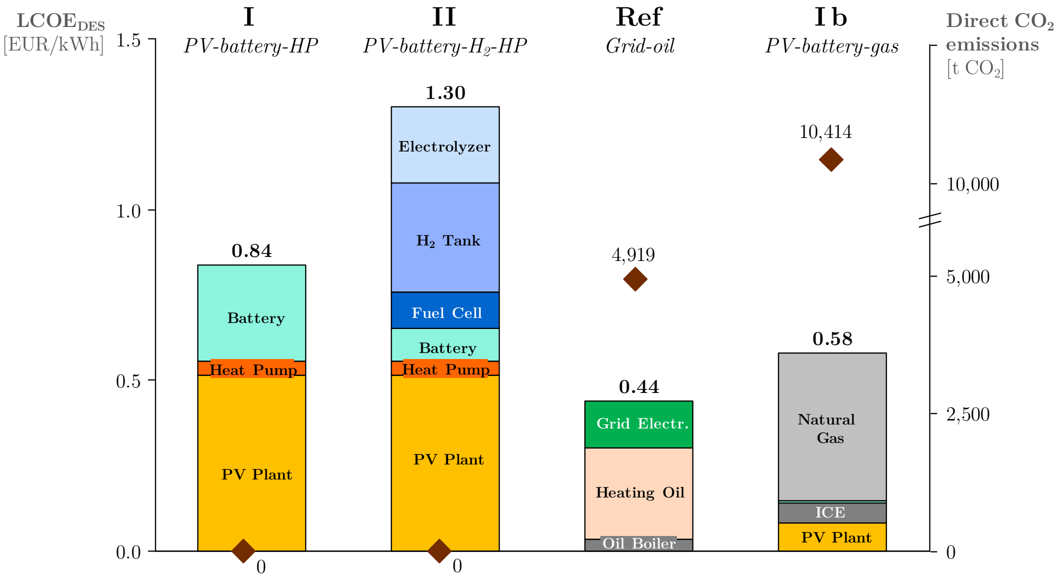
Identified as an extremely interesting application of decentralized energy systems, this article studies energy self-sufficient neighborhoods. In particular, it investigates the conditions under which the concept of energy self-sufficiency (both electricity and heat) for small-size neighborhoods could become an economically competitive alternative to the current paradigm of energy supply. To this end, a techno-economic model was developed that integrates solar PV, and different conversion and storage technologies.

First, regarding *how* to design self-sufficient neighborhoods, two technical configurations were identified and extended with another two configurations for the analysis: 1) I *PV-battery-heat pump (HP),* 2) II *PV-battery-hydrogen-HP*, 3) REF *Grid-oil*, and 4) Ib *PV-battery-gas*. Figure 5 presents the technology sizing of each technical configuration, as well as the Levelized Cost of Energy for Decentralized Energy Systems ($\mathrm{LCOE_{DES}}$) and direct CO_2 emissions. The two genuinely self-sufficient configurations (I and II) display costs more than twice as high as the reference configuration but produce zero direct CO_2 emissions.

Second, related to *if* and *when* self-sufficient systems could become cheaper than the grid-connected reference configuration, energy prices and technological learning are major influence factors. It is found that the *PV-battery-hydrogen-HP* configuration (II) is projected to outperform a fossil-fueled and grid-connected reference configuration *when* energy prices increase by 2.5% annually and cost reductions in hydrogen-related technologies by a factor of 2 are achieved. The *PV-battery-HP* configuration (I) would allow achieving parity with the reference configuration sooner, at 21% technology cost reduction and medium energy price increases of 2.5% per annum.

Third, the *where* question includes two aspects: i) neighborhood type and ii) geographic location. First, purely commercial usage (and mixed-use compositions) appears to be most suitable due to the overlap of load profiles with PV generation profiles, and allows for lower costs for storage and conversion devices. The larger the neighborhood (within the scale of a low voltage, local distribution grid), the lower the $\mathrm{LCOE_{DES}}$ due to economies of scale and leveling out of demand profiles. Second, locations with lower latitudes (equatorial areas) display only little seasonal influence, which allows the battery to close short-term power deficiencies. By contrast, in regions with higher latitudes (toward the polar circles), strong seasonal fluctuations render the *PV-battery-hydrogen-HP* configuration (II) more cost-efficient at bridging the seasonal gap than the *PV-battery-HP* configuration (I). These results indicate *where* potential early implementations of self-sufficient neighborhoods could be reasonable, that is, in larger neighborhoods in areas with lower seasonality that include commercial buildings.

Today, cost-competitive applications can be found in remote, rural, or island areas, where the cost of providing grid access exceeds the high technology investments and the space requirements for a PV plant and a respective storage technology are less rigid. In urban areas, it remains open to what extent the self-sufficient paradigm challenges the existing one (e.g., impact on infrastructure, semi- and close-to self-sufficient systems) and which pathways policy makers decide to support in the future.



Technologies	PV Plant [kW$_p$]	893	893	-	112
	HP / Boiler / ICE [kW$_{th}$]	111.5 (GS)	111.5 (GS)	111.5 (Boiler)	111.5 (ICE)
	Battery [kW]/ [kWh]	330 / 1100	111/ 370	-	9/ 30
	Electrolyzer [kW]	-	170 kW	-	-
	H$_2$ Tank [Nm^3]	-	191 Nm^3	-	-
	Fuel Cell [kW]	-	27 kW	-	-
System	Discount rate [%]	7	7	7	7
	System lifetime [years]	40	40	40	40
	SSR [%]	100	100	0	100[a]
	Mitigation cost [EUR/t CO$_2$][b]	216.21	466.12	-	-68.38

[a] Still, provision of natural gas needed, thus not considered as fully autarkic mode.
[b] Cost-effectiveness in terms of money per CO$_2$ emissions avoided compared to Ref.

Figure 5: LCOE$_{DES}$ split, direct CO$_2$ emissions, and technology sizing for the four technical configurations: I, II, Ref, and Ib. (Acronyms: LCOE$_{DES}$ = Levelized Cost of Energy for Decentralized Energy Systems, PV = Photovoltaics, HP = Heat Pump, GS = Ground-Sourced, ICE = Internal Combustion Engine, H$_2$ = Hydrogen, SSR = Self-Sufficiency Rate)

6.3 Article III: A Comparison of Storage Systems in Neighborhood Decentralized Energy System Applications from 2015 to 2050

To project a potential diffusion of decentralized energy systems and their contribution to climate change mitigation, this article extends both the methodology and the findings of article II. It investigates the potential of both long-term (power-to-hydrogen) and short-term storage systems (batteries and thermal storage) for decentralized energy systems in neighborhood applications. Hence, a model was developed that allows for evaluating the system design and performance (cost-effectiveness and carbon dioxide reduction) of storage technologies through the use of multi-objective optimization. In order to analyze the possible future developments of market and technology related parameters, a scenario approach is deployed based on the IPCC's "Special Report on Emissions Scenarios". These scenarios are evaluated for two case studies in Switzerland, one rural and one urban, for the years 2015, 2020, 2035, and 2050.

First, the findings indicate a drop in emissions from 2015 to 2050 caused by more RES being used to meet a higher fraction of the demand over time. Because of its higher renewable potential, the Zernez case study (rural case) can achieve much larger emission reductions than the Altstetten case study (urban case). In addition, costs also drop over time due to decreases in capital costs of technologies. For both case studies, the Pareto curves initially have a steep drop in emissions followed by shallow and rapid increases in costs, indicating that large emission reductions can be achieved with low cost increases (cf. Figure 6). The rapid increase in costs in the CO_2 optimal solution is mostly caused by the installation of large hydrogen storage systems. Typically, solutions at the elbows of the Pareto curves would represent the best trade-off between emissions and costs. The Swiss energy targets can be met in all three future scenarios with the 50% CO_2 objective solution in 2050 in Zernez, whereas in Altstetten all solutions would miss them.

Second, the urban case study of Altstetten is unable to meet the energy targets for two reasons: i) an old building stock and ii) a high ratio of heated and electrified area to the available area for solar installations compared to the rural case study. In order to improve the buildings' energy performance, a higher retrofit rate is necessary for the neighborhood, while at the same time renewable energy use would need to increase, for example, via additional on-site generation (e.g., building integrated PV façades) or imports.

Third, with regard to system design, solar PV and heat pumps are both cost-optimal as they are mostly installed to their full capacity. In Zernez, small-wind and hydro as RES complement the generation technologies, but these are not options in the urban context. Micro gas turbines are only installed as long as gas prices are at a low level, whereas gas boilers are the back-up heating technology in all cases in combination with thermal storage.

Fourth, feed-in tariffs disincentive storage of renewables on-site, thus they restrict the deployment of hydrogen storage systems. High feed-in tariffs with a high penetration of RES could cause many producers to sell their electricity back at the same time, resulting in centralized grid overloading issues. In Zernez, the storage systems are used to a larger extent (e.g., hydrogen storage in all three future scenarios in 2050) because of the large renewable surplus. In Altstetten, the lower renewable surplus results in the deployment of short-term storage given its higher efficiency compared to long-term storage.

The findings suggest that feed-in remuneration and the level of surplus energy (which is highly impacted by the building energy demand and the level of available renewable potential) have a high impact on the optimal system design and its performance. They provide first indications to quantify the contribution of decentralized energy systems towards a sustainable built environment. Therefore, the results are extremely informative and useful for project developers and policy makers alike. Furthermore, the developed methodology is widely applicable in both spatial scope (i.e., other locations and sizes) and temporal scope (i.e., different years and scenarios) and enables the optimization with a range of objective functions.

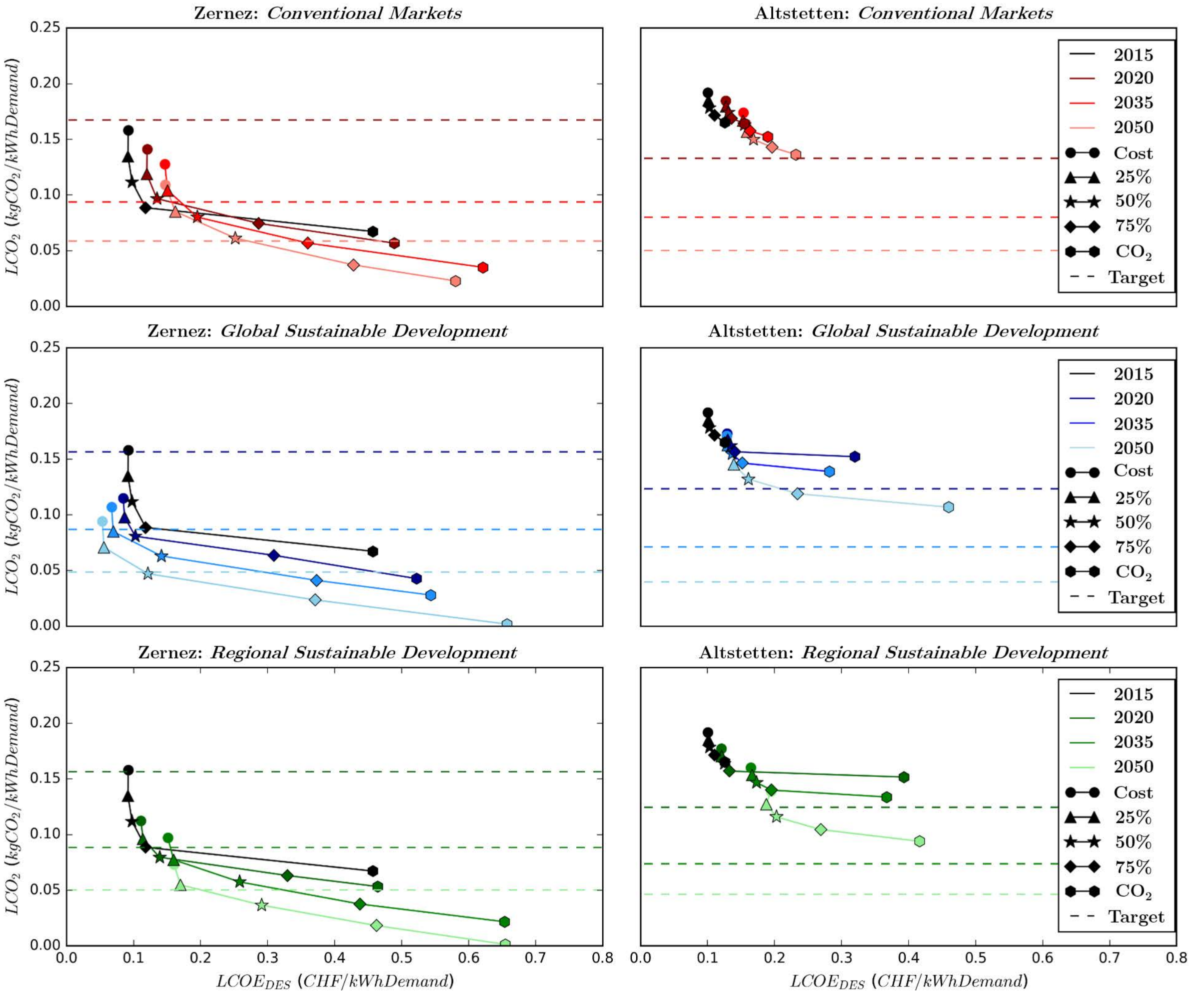


Figure 6: Pareto fronts for $LCOE_{DES}$ and Levelized CO_2 emissions (LCO_2) for each year, scenario, and case study. (Dashed lines represent the targets of the Swiss Energy Strategy 2050 and colors represent the respective year)

6.4 Article IV: The Role of Policy in Fostering the Diffusion of Low-Carbon Innovations

This article examines how policy support can accelerate the diffusion of low-carbon innovations and how it needs to be tailored to specific technologies. Therefore, it analyzes the long-term developments and the diffusion patterns of three selected technologies: heat pump, low-e glazing, and comfort ventilation technology. Switzerland and its policy context was chosen as it is the lead market for the diffusion of these technologies, and a constant political and contextual environment is needed to capture the integral mechanisms of policy support.

First, large variations of the diffusion curves in length and shape can be observed across the three case studies. While, for example, the heat pump technology required 37 years from its first commercial appearance to a market share of 80%, the low-e glazing technology (double insulation) diffused almost twice as fast within 19 years. Despite the typical S-shape curve, the diffusion pattern of the heat pump technology, for instance, displays an unusual up-and-down stage during its early market phase (1970–1996).

Second, the policies (i.e., type, timing, sequence) that were applied are markedly different, which highlights their impact on the respective diffusion patterns. In fact, policy support is observed as a response to addressing the prevailing issues that were limiting further diffusion in each market phase. It is important to point out that all of the observed technologies benefitted from several cross-cutting events and policy efforts (e.g., oil crises, CO_2 tax), which have clearly shaped Switzerland's energy-efficient built environment.

Third, the three cases reveal intriguing differences. While the case of the heat pump technology demonstrated the need for substantial RD&D support and a step-by-step application of policy along the idealized policy approach (Grübler et al., 2012a; Halsnæs et al., 2007), the cases of the comfort ventilation and the low-e glazing technology portray a different situation with less emphasis on the technology-push side. Instead, their diffusion patterns are strongly influenced by different kinds of demand-pull support: Comfort ventilation was mostly pulled into the market using the vehicle of an established label, whereas the major market pull for low-e glazing was created by technology-specific performance standards. In both cases, monetary incentives complemented the demand-pull support but did not play a primary role.

Fourth, generalizing the findings above, two dimensions can be identified as critical for tailoring technology support policies: i) technological maturity level and ii) diffusion status of an innovation. In fact, innovations of insufficient maturity, namely, of limited reliability and quality, would benefit from a technology-specific support (e.g., via R&D grants, conferences or fairs, pilot and demonstration projects), while demand-driven support (e.g., via labels, performance standards) is more effective once a certain maturity threshold is achieved. Figure 7 illustrates the suggested framework by combining the stylized diffusion (in % adoption or market share) with the level of technological maturity (indicated with low, medium, high), as well as the interplay between technology-push and demand-pull policies. This article's empirical analysis covers the three archetypes that are sketched out in the framework and the role of effective policy support for each.

The findings indicate that in order to be effective, policy support must be adjusted towards the specific nature of an innovation; thus, a thorough understanding of a technology's maturity level and diffusion status is needed before effective policy support can be designed. Even though the two dimensions, maturity and diffusion stage, are interrelated to a certain extent, it seems crucial – especially in an early phase – to identify an innovation's status prior to the design of policy intervention. Additionally, due to their dynamic nature, both dimensions require continuous re-evaluation to tailor both the amount and nature of potential policy support.

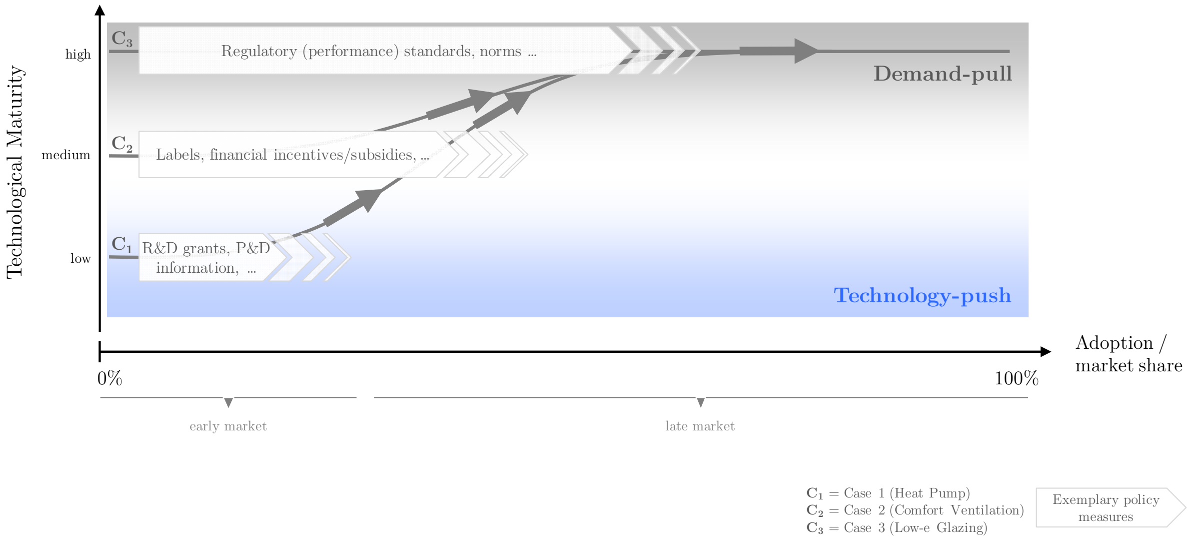


Figure 7: Framework for tailored policy support in accelerating the diffusion of low-carbon innovations

7 Conclusion

This concluding section summarizes the answers that this dissertation provides for the overarching research question of *how system design and performance can contribute to a sustainable built environment* and *how technological change can be supported by policy.* Derived from the insights of the individual articles, it starts by carving out the thesis' core contributions to the literature (7.1), continues to summarize implications for practitioners and policy makers (7.2), and ends with a reflection on its limitations and areas for further research (7.3).

7.1 Contributions to Literature

Decentralized Energy Systems

This dissertation contributes to the literature on decentralized energy systems, which embraces a wide range of different disciplines and methodological approaches. Articles I, II and III specifically augment the understanding of this broad thematic field by providing first indications on the technical, economic and environmental potential of decentralized energy systems to combat climate change, given their role as key enablers for the integration of RES. To grasp the level of technological change in this field, three major contributions for the literature on decentralized energy systems are laid out and discussed in the following.

First, this thesis – in particular, article I – introduces a synthesis of the diverse conceptual approaches in the literature that capture decentralized energy systems. By providing a comprehensive review of both publications and pilot projects, it adds clarity, especially with regard to the four key aspects of terminology, motivation/scope, application, and technical configuration. This is the first systematic overview and comparison of the status-quo for decentralized energy systems in academia and practice. Such a review is highly relevant as the development and deployment of decentralized energy systems hinges, among other things, on a consistent terminology, a set of feasible technical configurations per application, and mutual learning between literature and practice. This work is an initial attempt to address these aspects and thus contributes to a common understanding of the concept of decentralized energy systems.

Second, building upon the conceptual clarifications, articles II and III add to the existing literature by assessing the techno-economic and environmental performance of decentralized energy systems. Therefore, they provide approaches to quantify the level of technological change, which decentralized energy systems are already reaching or might be able to reach under certain future developments. In this context, various technical configurations and applications are evaluated with different emphases: article II examines self-sufficient neighborhoods, while article III studies grid-connected neighborhoods in rural and urban settings. In addition, the contribution of this dissertation is on the chosen technological foci (e.g., battery, power-to-hydrogen) as well as on the spatial (i.e., Switzerland and partially beyond) and temporal scopes (i.e., from the baseline year 2015 to 2050).

Third, this thesis extends the existing literature on decentralized energy systems in several methodological aspects. For instance, both articles II and III apply an optimization based on a full annual time horizon (instead of typical days or rolling horizon methods) in order to accurately disentangle the impact of short- and long-term storage. Furthermore, both underlying models integrate more sophisticated and realistic depictions of conversion technologies, such as fuel cells or electrolyzers, by relying on piecewise affine linear relationships (instead of constant efficiencies). At the same time, articles II and III deal with the uncertainty of input data and assumptions either by a parametric sensitivity analysis (article II) or by deploying a scenario analysis (article III) to reveal potential future developments beyond the baseline year 2015.

Policy-induced Diffusion

This dissertation advances the literature on policy-induced technological change that focuses on the diffusion phase. It draws upon diffusion theory from an evolutionary perspective and the wide literature on environmental policy. In particular, article IV scrutinizes the diffusion patterns for three energy-efficient building technologies and their link to the deployed policy types. The following key contributions to the literature are made.

First, this work is pioneering because it provides a multiple case study research design that builds on a constant national context to control for, e.g., economic, societal, governmental effects. While previous literature has mostly focused on singular case studies (e.g., a certain technology in one country), or comparative case studies between different policy contexts (e.g., multiple technologies across countries or industries), a comparison was still missing that allowed for disentangling the impact of policy types on the diffusion of different kinds of technology within similar system boundaries. To close this gap, the built environment in Switzerland represents an excellent setting for an extensive retrospective analysis of several case studies exposed to substantial policy interventions. Due to the selected research design and sampling strategy, this thesis constitutes a promising contribution to the extant literature.

Second, while the findings of this study confirm that there is no silver bullet for policy to accelerate the diffusion of low-carbon technologies, it contributes initial conceptual guidance on how policy support needs to be tailored to the specific nature of a certain technology. Diffusion status and technological maturity are distilled as the key dimensions that policy support should be adapted to in order to spur the market diffusion. Based on the three case study observations, this work adds to the wider policy literature by giving first indications on a potential tailoring of technology-specific policy support along these dimensions. Eventually, this can enable more informed decisions regarding the selection, design and sequence of policy types (including the specific instruments) and thus render policy intervention more effective and efficient.

7.2 Implications for Practitioners and Policy Makers

Decentralized energy systems provide promising options to pursue the decarbonization and transition towards a sustainable built environment. Even though they are still in their infancy, these systems can already serve various applications today, are proven in practice, and their techno-economic performance can outperform conventional, fossil-based solutions in many areas. For corporate managers, as well as public and private investors, it might be beneficial to consider the full spectrum of possible options that decentralized energy systems can already offer. In the same vein, the dynamic developments, both on the market and the technology side, require thorough investigation, especially when considering the long lifetimes in the built environment. Besides their potential benefits, the systemic nature of decentralized energy systems, which are composed of different technologies, subsystems and components (cf. Murmann and Frenken (2006)), will likely render system integrator capabilities even more important than they already are in the complex built environment with multiple stakeholders. In addition, the extreme case of self-sufficient decentralized energy systems could provoke an overhaul of the conventional method to supply buildings with energy, which will possibly undermine existing business models of energy utilities. Therefore, corporate decision makers need to carefully monitor the future pathways of decentralized energy systems and eventually adapt their businesses accordingly.

On the one hand, this work has revealed the potential contributions that decentralized energy systems can make to achieve political energy strategy targets, namely the Swiss Energy Strategy 2050. To foster their development and large-scale deployment, policy makers need to support research, development and demonstration (RD&D) both at the level of the individual technologies (e.g., fuel cells) and the system level (e.g., lighthouse projects), while at the same time lowering adoption barriers and promoting their implementation. This could include a nurturing phase to draw decentralized energy systems from niches to larger market segments, for example, by subsidizing the intensive upfront capital cost (Iyer et al., 2015). On the other hand, critical factors were identified that affect the successful contribution of decentralized energy systems to climate change mitigation. Among them are the retrofit rate, the potential of RES (especially in urban settings), the design of the electricity price and the feed-in remuneration, and many more. All these factors can and should be firmly controlled by policy makers, if the support of decentralized energy systems in certain applications or of specific technical configurations is the goal.

On a more general level, and in line with the extant literature, the findings of this dissertation stress policy makers' substantial lever for accelerating the diffusion of low-carbon innovation. The retrospective analysis of article IV points policy makers towards understanding the need for and the mechanisms behind tailoring their support measures to individual technologies. While a comprehensive set of support policies might be expedient for the diffusion of some technologies, singular support measures might be sufficient for others. This underlines the need for policy makers to adjust their support to the specific nature of an innovation, which requires them to precisely assess an innovation's maturity level and diffusion status before designing corresponding support measures. Due to the dynamic nature of both of these dimensions, a periodic re-evaluation is inevitable. More specifically, if an innovation's maturity level is low, technology-specific support (e.g., via R&D grants, conferences or fairs, pilot and demonstration projects) is required before policy makers introduce a demand-driven support (e.g., via labels, performance standards). A premature demand-pull can lead to reputational issues and declining acceptance and could jeopardize an innovation's market diffusion in the mid- and long-term.

7.3 Limitations and Further Research

In the following, the major limitations of this dissertation are laid out along with suggestions for promising future research in this domain. While each of the articles I–IV describes its specific limitations and avenues for further research in detail (cf. Annex), the overarching limitations predominantly stem from the selection of the research cases.

First, the findings of this thesis draw from two research cases, decentralized energy systems and energy efficiency technologies (cf. section 3). For the prospective analysis of the former case, admittedly the understanding and quantification of technological change would have resulted in different insights when building upon another case from the plethora of promising innovations at the intersection of energy and buildings, such as demand side management or crypto currencies. For the retrospective analysis of the latter case, this analysis might have yielded additional observations when sampling i) from different kinds of innovation, such as business model innovation or systemic innovation, in contrast to the tangible, singular building technologies, and ii) from failure cases, that is, technologies that did not get beyond the invention or innovation phase. While data availability for cases with an unsuccessful ("failed") diffusion is limited, it would have helped to avoid a pro-innovation bias that most diffusion studies suffer from (Grübler et al., 2016; Rogers, 2003). Broadening the empirical basis for the retrospective analysis by extending the selection of cases is regarded as a valuable enrichment to further advance the understanding of the outlined mechanisms. Once the qualitative aspects are sufficiently understood, collecting quantitative empirical data to disentangle the moderating effect of different technologies in policy-induced diffusion could be another relevant follow-up study.

Second, the geographical focus for the major parts of this dissertation is Switzerland. While the Swiss context is deemed to be promising for several reasons (cf. section 3), another spatial focus would likely have brought forth complementary insights, as hinted at in articles I and II. This holds true for both the quantitative analysis of decentralized energy systems (e.g., different market data, demand and supply profiles) and the qualitative study of the link between policy support and diffusion (e.g., different socio-economic, political contexts). Thus, expanding the geographical scope is considered a promising avenue for future work.

Third, there are several methodological limitations in the techno-economic models (of articles II and III) that could be addressed in further research. For example, integrating additional technologies (e.g., building integrated PV, biogas) or energy services (e.g., mobility, control reserve) would broaden the technological variety and certainly add to the data basis for the optimization. Another example would be the approach to deal with uncertainty that underlies the large set of input parameters and assumptions. Aside from the applied sensitivity and scenario analyses, a Monte Carlo analysis could provide an interesting opportunity for future work to scrutinize the impact of the stochastic input data on system design and performance. Another promising methodological extension could be the integration of comprehensive environmental impact analyses (e.g., life cycle assessment) in order to go beyond direct CO_2 emissions as a proxy for environmental performance.

8 Overview of Articles

The four articles included in the Annex are shown in Table 3, including the target journal and their current status in the publication process as of October 10, 2018.

Table 3: Overview of the articles included in the dissertation

#	Title	Authors	Contributions	Journal	Status
I	Matching decentralized renewable production and local consumption: A review of energy conversion and storage systems	Grosspietsch, D. Saenger, M. Girod, B.	DG and BG designed the analysis; MS and DG collected and analyzed the data; DG wrote the article; BG and MS contributed to the writing	*WIREs Energy and Environment*	Under review
II	How, When, and Where? Assessing Renewable Energy Self-Sufficiency at the Neighborhood Level	Grosspietsch, D. Thömmes, P. Girod, B. Hoffmann, V.H.	DG, BG and VH designed the analysis; PT (and in parts DG) developed the model; DG conducted the analysis; DG wrote the article; PT, BG and VH contributed to the writing	*Environmental Science & Technology*	Published, cf. 2018, Volume 52, Issue 4, pp. 2339–2348
III	A Comparison of Storage Systems in Neighborhood Decentralized Energy System Applications from 2015 to 2050	Murray, P. Orehounig, K. Grosspietsch, D. Carmeliet, J.	PM, KO, DG (cf. scenario analysis) and JC designed the analysis; PM developed the model; PM (and in parts DG, cf. section 2) wrote the article; KO, DG and JC contributed to the writing	*Applied Energy*	Published, cf. 2018, Volume 231, pp. 1285–1306
IV	The Role of Policy in Fostering the Diffusion of Low-Carbon Innovations	Grosspietsch, D. Girod, B. Kant, M. Kugler, M. Hoffmann, V.H.	DG, BG and VH designed the analysis; MK1 and MK2 collected the data; DG, MK1 and MK2 analyzed the data; DG wrote the article; BG and VH contributed to the writing	*Research Policy*	Working draft

References

Alanne, K., Saari, A., 2006. Distributed energy generation and sustainable development. Renewable and Sustainable Energy Reviews 10, 539–558.

Anderson, P., Tushman, M.L., 1990. Technological Discontinuities and Dominant Designs: A Cyclical Model of Technological Change. Administrative Science Quarterly 35, 604–633.

Arrow, K.J., 1962. The Economic Implications of Learning by Doing. The Review of Economic Studies 29, 155–173.

Arthur, W.B., 1989. Competing technologies, increasing returns, and lock-in by historical events. The Economic Journal 99, 116–131.

Barbose, G., Darghouth, N., 2016. Tracking the Sun IX: The Installed Price of Residential and Non-Residential Photovoltaic Systems in the United States. Lawrence Berkeley National Laboratory (LBNL), Berkeley.

Battke, B., Schmidt, T.S., Grosspietsch, D., Hoffmann, V.H., 2013. A review and probabilistic model of lifecycle costs of stationary batteries in multiple applications. Renewable and Sustainable Energy Reviews 25, 240–250.

Baxter, P., Jack, S., 2008. The Qualitative Report Qualitative Case Study Methodology: Study Design and Implementation for Novice Researchers. The Qualitative Report 13, 544–559.

Bento, N., Wilson, C., 2016. Environmental Innovation and Societal Transitions Measuring the duration of formative phases for energy technologies. Environmental Innovation and Societal Transitions 21, 95–112.

Bernal-Agustín, J.L., Dufo-López, R., 2009. Simulation and optimization of stand-alone hybrid renewable energy systems. Renewable and Sustainable Energy Reviews 13, 2111–2118.

Boza-Kiss, B., Moles-Grueso, S., Urge-Vorsatz, D., 2013. Evaluating policy instruments to foster energy efficiency for the sustainable transformation of buildings. Current Opinion in Environmental Sustainability 5, 163–176.

Brannen, J., 1995. Mixing Methods: Qualitative and Quantitative Research. Routledge, London.

Bruckner, T., Bashmakov, I.A., Mulugetta, Y., Chum, H., de la Vega Navarro, A., Edmonds, J., Faaij, A., Fungtammasan, B., Garg, A., Hertwich, E., Honnery, D., Infield, D., Kainuma, M., Khennas, S., Kim, S., Nimir, H.B., Riahi, K., Strachan, N., Wiser, R., Zhang, X., 2014. Energy Systems, in: Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 527–532.

Brunnermeier, S.B., Cohen, M.A., 2003. Determinants of environmental innovation in US manufacturing industries. Journal of Environmental Economics and Management 45, 278–293.

Bruno, L.C., 1998. On the Move: A Chronology of Advances in Transportation. Gale Research, Detroit.

Chicco, G., Mancarella, P., 2009. Distributed multi-generation: A comprehensive view. Renewable and Sustainable Energy Reviews 13, 535–551.

Clarke, L.E., Weyant, J.P., 2002. Modeling induced technological change: An overview. Technological change and the environment 320–363.

Cole, R.J., Fedoruk, L., 2015. Shifting from net-zero to net-positive energy buildings. Building Research and Information 43, 111–120.

Crabtree, G., Kócs, E., Trahey, L., 2015. The energy-storage frontier: Lithium-ion batteries and beyond. MRS Bulletin 40, 1067–1078.

Creswell, J.W., 2009. Research design: Qualitative, quantitative, and mixed methods approaches. Sage Publications, Thousand Oaks, California.

Cullen, J.M., Allwood, J.M., Borgstein, E.H., 2011. Reducing energy demand: What are the practical limits? Environmental Science and Technology 45, 1711–1718.

David, P.A., 1985. Clio and the Economics of QWERTY. American Economic Review 75, 332–337.

del Río González, P., 2009. The empirical analysis of the determinants for environmental technological change: A research agenda. Ecological Economics 68, 861–878.

Dosi, G., 1982. Technological paradigms and technological trajectories. Research Policy 11, 147–162.

Edler, J., Fagerberg, J., 2017. Innovation policy: What, why, and how. Oxford Review of Economic Policy 33, 2–23.

Efficient Window Collaborative, 2016. Window Technologies: Low-E Coatings [WWW Document]. URL http://www.efficientwindows.org/lowe.php (accessed 29 July, 2016).

EMPA, 2018. NEST − Exploring the Future of Buildings [WWW Document]. empa.ch. URL https://www.empa.ch/web/nest/overview (accessed 13 June, 2018).

European Commission, 2012. 2050 low-carbon economy [WWW Document]. Climate strategies & targets. URL https://ec.europa.eu/clima/policies/strategies/2050_en (accessed 13 June, 2018).

European Patent Office, 2018. Building the future: Four innovation trends that are shaping green construction [WWW Document]. News & issues. URL https://www.epo.org/news-issues/technology/sustainable-technologies/green-construction.html (accessed 11 April, 2018).

Evins, R., Orehounig, K., Dorer, V., Carmeliet, J., 2014. New formulations of the "energy hub" model to address operational constraints. Energy 73, 387–398.

Fabrizio, E., Corrado, V., Filippi, M., 2010. A model to design and optimize multi-energy systems in buildings at the design concept stage. Renewable Energy 35, 644–655.

Farhangi, H., 2010. The path of the smart grid. IEEE Power and Energy Magazine 8, 18–28.

Federal Statistical Office, 2015. Decomposition of Switzerland's fossil CO2 emissions [WWW Document]. Air emissions accounts. URL https://www.bfs.admin.ch/bfs/en/home/statistics/catalogues-databases/publications.assetdetail.350072.html (accessed 30 April, 2018).

Feldman, D., Barbose, G., James, T., Weaver, S., Fu, R., Davidson, C., 2014. Photovoltaic System Pricing Trends Historical, Recent, and Near-Term Projections - 2014 Edition. U.S. Department of Energy, Oak Ridge.

Figenbaum, E., 2017. Perspectives on Norway's supercharged electric vehicle policy. Environmental Innovation and Societal Transitions 25, 14–34.

Fischer, C., Newell, R.G., 2008. Environmental and technology policies for climate mitigation. Journal of Environmental Economics and Management 55, 142–162.

Fischer, E., Parmentier, M.-A., 2010. Doing Qualitative Research With Archival Data: Making Secondary Data a Primary Resource. Advances in Consumer Research 37, 798–799.

Flick, U., 2014. An Introduction to Qualitative Research. Sage Publications, Thousand Oaks; London; New Delhi.

Foxon, T.J., 2011. A coevolutionary framework for analysing a transition to a sustainable low carbon economy. Ecological Economics 70, 2258–2267.

Freeman, C., 1994. The economics of technical change: Critical survey. The Cambridge Journal of Economics 18, 463–514.

Gabrielli, P., Gazzani, M., Martelli, E., Mazzotti, M., 2017. Optimal design of multi-energy systems with seasonal storage. Applied Energy 219, 408–424.

Gann, D.M., Wang, Y., Hawkins, R., 1998. Do regulations encourage innovation? - The case of energy efficiency in housing. Building Research and Information 26, 280–296.

Geels, F.W., Schot, J., 2007. Typology of sociotechnical transition pathways. Research Policy 36, 399–417.

Geels, I.F.W., 2005. The dynamics of transitions in socio-technical systems: A multi-level analysis of the transition pathway from horse-drawn carriages to automobiles (1860-1930). Technology Analysis and Strategic Management 17, 445–476.

Geidl, M., 2007. Integrated Modeling and Optimization of Multi-Carrier Energy Systems. ETH Zurich.

Geidl, M., Koeppel, G., Favre-Perrod, P., 2007. The Energy Hub–A powerful concept for future energy systems. Third Annual Carnegie Mellon Conference on the Electricity Industry 1–10.

Gillingham, K., Newell, R.G., Pizer, W.A., 2008. Modeling endogenous technological change for climate policy analysis. Energy Economics 30, 2734–2753.

Gillingham, K., Sweeney, J., 2012. Barriers To Implementing Low-Carbon Technologies. Climate Change Economics 03, 1250019-1–21.

Groscurth, H.-M., Bruckner, T., Kümmel, R., 1995. Modeling of energy-services supply systems. Energy 20, 941–958.

Grösser, S.N., Ulli-Beer, S., Mojtahedzadeh, M.T., 2006. Diffusion dynamics of energy efficient innovations in the residential building environment: a conceptual model. Proceedings of the 24th International Conference of System Dynamics Society 1–27.

Grubb, M., 2004. Title Technology Innovation and Climate Change Policy : An Overview of Issues and Options. Keio Economic Studies 41, 103–132.

Grübler, A., Aguayo, F., Gallagher, K., Hekkert, M., Jiang, K., Mytelka, L., Neij, L., Nemet, G., Wilson, C., 2012a. Policies for the Energy Technology Innovation System (ETIS), in: T.B. Johansson, N. Nakicenovic, A. Patwardhan, L.G.-E. (Ed.), Global Energy Assessment - Toward a Sustainable Future. Cambridge University Press, Cambridge, pp. 1665–1744.

Grübler, A., Johansson, T.B., Mundaca, L., Nakicenovic, N., Pachauri, S., Riahi, K., Rogner, H.-H., Strupeit, L., 2012b. Chapter 1 - Energy Primer, in: Global Energy Assessment - Toward a Sustainable Future. Cambridge University Press, Cambridge, UK and New York, NY, USA and the International Institute for Applied Systems Analysis, Laxenburg, Austria, pp. 99–150.

Grübler, A., Nakicenovic, N., Victor, D.G., 1999. Dynamics of energy technologies and global change. Energy Policy 27, 247–280.

Grübler, A., Wilson, C., Nemet, G., 2016. Apples, oranges, and consistent comparisons of the temporal dynamics of energy transitions. Energy Research and Social Science 22, 18–25.

Guen, M. Le, Mosca, L., Perera, A.T.D., Coccolo, S., Mohajeri, N., Scartezzini, J.L., 2018. Improving the energy sustainability of a Swiss village through building renovation and renewable energy integration. Energy and Buildings 158, 906–923.

Gynther, L., Lappillone, B., Pollier, K., 2015. Energy efficiency trends and policies in the household and tertiary sectors. An analysis based on the ODYSSEE and MURE databases.

Hajimiragha, H., Canizares, C., Fowler, M., Geidl, M., Andersson, G., 2007. Optimal Energy Flow of Integrated Energy Systems with Hydrogen Economy Considerations. Bulk Power System Dynamics and Control – VII 1–11.

Halsnæs, K., Shukla, P., Ahuja, D., Akumu, G., Beale, R., Edmonds, J., Gollier, C., Grübler, A., Duong, M.H., Markandya, A., McFarland, M., Nikitina, E., Sugiyama, T., Villavicencio, A., Zou, J., 2007. Framing issues, in: Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK and New York, NY, USA.

Hassett, K.A., Metcalf, G.E., 1995. Energy tax credits and residential conservation investment: Evidence from panel data. Journal of Public Economics 57, 201–217.

Heinrich Gugerli, 2017. Zertifizierte 2000-Watt-Areale [WWW Document]. Fachstelle 2000-Watt-Gesellschaft. URL http://www.2000watt.ch/fuer-areale/zertifizierte-2000-watt-areale/ (accessed 5 February, 2017).

Hemmes, K., Zachariah-Wolf, J.L., Geidl, M., Andersson, G., 2007. Towards multi-source multi-product energy systems. International Journal of Hydrogen Energy 32, 1332–1338.

Höhne, N., 2011. Changing the rules. Nature Climate Change 1, 31–33.

Höök, M., Li, J., Johansson, K., Snowden, S., 2012. Growth Rates of Global Energy Systems and Future Outlooks. Natural Resources Research 21, 23–41.

Hoppmann, J., Huenteler, J., Girod, B., 2014. Compulsive policy-making—The evolution of the German feed-in tariff system for solar photovoltaic power. Research Policy 43, 1422–1441.

Hoppmann, J., Peters, M., Schneider, M., Hoffmann, V.H., 2013. The two faces of market support- How deployment policies affect technological exploration and exploitation in the solar photovoltaic industry. Research Policy 42, 989–1003.

Huenteler, J., Schmidt, T.S., Ossenbrink, J., Hoffmann, V.H., 2016. Technology life-cycles in the energy sector - Technological characteristics and the role of deployment for innovation. Technological Forecasting and Social Change 104, 102–121.

IEA, 2018. Policies and Measures Databases [WWW Document]. International Energy Agency (IEA). URL https://www.iea.org/policiesandmeasures/ (accessed 12 April, 2018).

IEA, 2017a. CO2 Emissions from Fuel Combustion 2017 - Highlights, International Energy Agency (IEA). Paris.

IEA, 2017b. Digitalization & Energy. Paris.

IEA, 2015. Energy Technology Perspectives 2015 - Mobilising Innovation to Accelerate Climate Action. Paris.

IEA, 2013a. Transition to Sustainable Buildings - Strategies and opportunities to 2050. Paris.

IEA, 2013b. Modernising Building Energy Codes to secure our Global Energy Future.

IEA, 2010. Energy Technology Perspectives: Scenarios & Strategies To 2050, International Energy Agency (IEA) Publications.

IEA, 2008. Energy Efficiency Requirements in Building Codes, Energy Efficiency Policies for New Buildings.

IPCC, 2018. Publications and Data [WWW Document]. Intergovernmental Panel on Climate Change (IPCC). URL http://www.ipcc.ch/publications_and_data/publications_and_data.shtml (accessed 7 June, 2018).

IPCC, 2014. Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Working Group III Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

IPCC, 2007. Mitigation of climate change: Contribution of working group III to the fourth assessment report of the Intergovernmental Panel on Climate Change, Intergovernmental Panel on Climate Change.

IRENA, 2015a. Rethinking Energy: Renewable Energy and Climate Change. Bonn.

IRENA, 2015b. Renewable Power Generation Costs in 2014. Bonn.

Iyer, G., Hultman, N., Eom, J., McJeon, H., Patel, P., Clarke, L., 2015. Diffusion of low-carbon technologies and the feasibility of long-term climate targets. Technological Forecasting and Social Change 90, 103–118.

Jacoboni, C., Reggiani, L., 1983. The Monte Carlo Method for the Solution of Charge Transport in Semiconductors with Applications to Covalent Materials. Reviews of Modern Physics 55, 645–705.

Jaffe, A.B., Newell, R., Stavins, R., 2005. A tale of two market failures: Technology and environmental policy. Ecological Economics 54, 164–174.

Jaffe, A.B., Newell, R.G., Stavins, R.N., 2002. Environmental policy and technological change. Environmental and Resource Economics 22, 41–69.

Jaffe, A.B., Stavins, R.N., 1995. Dynamic incentives of environmental regulations: The effects of alternative policy instruments on technology diffusion. Journal of Environmental Economics and Management 29, S43–S63.

Jones, C., 2010. Archival data: Advantages and disadvantages for research in psychology. Social and Personality Psychology Compass 4, 1008–1017.

Jupp, V., 2006. The SAGE Dictionary of Social Reserach Methods. Sage Publications, Thousand Oaks; London; New Delhi.

Kaundinya, D.P., Balachandra, P., Ravindranath, N.H., 2009. Grid-connected versus stand-alone energy systems for decentralized power-A review of literature. Renewable and Sustainable Energy Reviews 13, 2041–2050.

Kemp, R., 1998. The diffusion of biological waste-water treatment plants in the Dutch food and beverage industry. Environmental & Resource Economics 12, 113–136.

Kemp, R., Pontoglio, S., 2011. The innovation effects of environmental policy instruments—A typical case of the blind men and the elephant? Ecological Economics 72, 28–36.

Kemp, R., Soete, L., 1990. Inside the “green box”: on the economics of technological change and the environment, in: Freeman, C., Soete, L. (Eds.), New Explorations in the Economics of Technological Change. Pinter, London, pp. 244–257.

Kimura, O., 2013. The role of standards: The Japanese Top Runner Program for end-use efficiency. Historical case studies of enegy technology innovation, in: Energy Technology Innovation: Learning from Historical Successes and Failures. Cambridge University Press, pp. 231–243.

Kiss, B., Neij, L., Jakob, M., 2013. Heat pumps: A comparative assessment of innovation and diffusion policies in Sweden and Switzerland, in: Energy Technology Innovation: Learning from Historical Successes and Failures. Cambridge University Press, pp. 118–132.

Kline, S.J., Rosenberg, N., 1986. An Overview of Innovation, in: Landau, R., Rosenberg, N. (Ed.), The Positive Sum Strategy: Harnessing Technology for Economic Growth. National Academic Press, Washington, pp. 275–305.

Kulatunga, K.J., Amaratunga, R.D.G., Haigh, R., 2006. Construction innovation: a literature review on current research, in: Conference in the Built and Human Environment. Delft, pp. 654–662.

Langley, A.N.N., 1999. Strategies for Theorizing From Process Data. Academy of Management Review 24, 691–710.

Lanjouw, J.O., Mody, A., 1996. Innovation and the international diffusion of environmentally responisve technology. Research Policy 25, 549–571.

Le Quéré, C., Andrew, R.M., Canadell, J.G., Sitch, S., Ivar Korsbakken, J., Peters, G.P., Manning, A.C., Boden, T.A., Tans, P.P., Houghton, R.A., Keeling, R.F., Alin, S., Andrews, O.D., Anthoni, P., Barbero, L., Bopp, L., Chevallier, F., Chini, L.P., Ciais, P., Currie, K., Delire, C., Doney, S.C., Friedlingstein, P., Gkritzalis, T., Harris, I., Hauck, J., Haverd, V., Hoppema, M., Klein Goldewijk, K., Jain, A.K., Kato, E., Körtzinger, A., Landschützer, P., Lefèvre, N., Lenton, A., Lienert, S., Lombardozzi, D., Melton, J.R., Metzl, N., Millero, F., Monteiro, P.M.S., Munro, D.R., Nabel, J.E.M.S., Nakaoka, S.I., O'Brien, K., Olsen, A., Omar, A.M., Ono, T., Pierrot, D., Poulter, B., Rödenbeck, C., Salisbury, J., Schuster, U., Schwinger, J., Séférian, R., Skjelvan, I., Stocker, B.D., Sutton, A.J., Takahashi, T., Tian, H., Tilbrook, B., Van Der Laan-Luijkx, I.T., Van Der Werf, G.R., Viovy, N., Walker, A.P., Wiltshire, A.J., Zaehle, S., 2016. Global Carbon Budget 2016. Earth System Science Data 8, 605–649.

Li, B., Roche, R., Paire, D., Miraoui, A., 2017. Sizing of a stand-alone microgrid considering electric power, cooling/heating, hydrogen loads and hydrogen storage degradation. Applied Energy 205, 1244–1259.

Lollini, R., Danza, L., Meroni, I., 2010. Energy efficiency of a dynamic glazing system. Solar Energy 84, 526–537.

Lucon, O., Ürge-Vorsatz, D., Zain Ahmed, A., Akbari, H., Bertoldi, P., Cabeza, L.F., Eyre, N., Gadgil, A., Harvey, L.D.D., Jiang, Y., Liphoto, E., Mirasgedis, S., Murakami, S., Parikh, J., Pyke, C., Vilariño, M.V., 2014. Buildings, in: Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 671–738.

Luterbacher, C., 2016. The Swiss houses making energy go a long way [WWW Document]. swissinfo.ch. URL https://www.swissinfo.ch/eng/business/falling-emissions_the-swiss-houses-making-energy-go-a-long-way/41977836 (accessed 30 April, 2018).

Lv, J., Qin, S., 2016. On Low-Carbon Technology. Low Carbon Economy 07, 107–115.

Mancarella, P., 2014. MES (multi-energy systems): An overview of concepts and evaluation models. Energy 65, 1–17.

Manfren, M., Caputo, P., Costa, G., 2011. Paradigm shift in urban energy systems through distributed generation: Methods and models. Applied Energy 88, 1032–1048.

Manwell, J.F., 2004. Hybrid Energy Systems. Encyclopedia of Energy 3, 215–229.

Mavromatidis, G., Orehounig, K., Richner, P., Carmeliet, J., 2016. A strategy for reducing CO2 emissions from buildings with the Kaya identity - A Swiss energy system analysis and a case study. Energy Policy 88, 343–354.

Mazzucato, M., 2013. The Entrepreneurial State: debunking public vs. private sector myths. Anthem Press, London.

Mowery, D.C., Nelson, R.R., Martin, B.R., 2010. Technology policy and global warming: Why new policy models are needed (or why putting new wine in old bottles won't work). Research Policy 39, 1011–1023.

Mulder, P., De Groot, H.L.F., Hofkes, M.W., 2001. Economic growth and technological change: A comparison of insights from a neo-classical and an evolutionary perspective. Technological Forecasting and Social Change 68, 151–171.

Murmann, J.P., Frenken, K., 2006. Toward a systematic framework for research on dominant designs, technological innovations, and industrial change. Research Policy 35, 925–952.

Navigant Reserach, 2017. Energy Efficient Buildings Global Outlook. Chicago.

Negro, S.O., Hekkert, M.P., Smits, R.E., 2007. Explaining the failure of the Dutch innovation system for biomass digestion-A functional analysis. Energy Policy 35, 925–938.

Nelson, R.R., 2008. Economic Development from the Perspective of Evolutionary Economic Theory. Oxford Development Studies 36, 9–21.

Nelson, R.R., Winter, S.G., 1982. An evolutionary theory of economic change, Belknap Press Series. Belknap Press of Harvard University Press.

Nemet, G.F., 2009. Demand-pull, technology-push, and government-led incentives for non-incremental technical change. Research Policy 38, 700–709.

Newell, R.G., 2010. The role of markets and policies in delivering innovation for climate change mitigation. Oxford Review of Economic Policy 26, 253–269.

Nussbaumer, B., 2015. Komfortlüftungen in der Schweiz; Markt- und Technologieentwicklung, Kompetenzen, Potentiale. Bern.

Nygren, N.A., Kontio, P., Lyytimaki, J., Varho, V., Tapio, P., 2015. Early adopters boosting the diffusion of sustainable small-scale energy solutions. Renewable and Sustainable Energy Reviews 46, 79–87.

Nykvist, B., Nilsson, M., 2015. Rapidly falling costs of battery packs for electric vehicles. Nature Climate Change 5, 329--332.

OECD, 2015. Climate Change Mitigation: Policies and Progress. Paris.

OECD, 2001. Policies to Enhance Sustainable Development. Paris.

Omu, A., Choudhary, R., Boies, A., 2013. Distributed energy resource system optimisation using mixed integer linear programming. Energy Policy 61, 249–266.

Orehounig, K., Evins, R., Dorer, V., 2015. Integration of decentralized energy systems in neighbourhoods using the energy hub approach. Applied Energy 154, 277–289.

Ossenbrink, J., Finnsson, S., Bening, C.R., Hoffmann, V.H., 2018. Delineating policy mixes – contrasting the top down and bottom up approach along the case of energy storage in California. Research Policy in press.

Padmanathan, K., Govindarajan, U., Ramachandaramurthy, V.K., Selvi T., S.O., 2017. Multiple Criteria Decision Making (MCDM) Based Economic Analysis of Solar PV System with Respect to Performance Investigation for Indian Market. Sustainability 9, 820.

Parag, Y., Sovacool, B.K., 2016. Electricity market design for the prosumer era. Nature Energy 1, 16032.

Pelenur, M.J., Cruickshank, H.J., 2012. Closing the Energy Efficiency Gap : A study linking demographics with barriers to adopting energy efficiency measures in the home. Energy 47, 348–357.

Petruschke, P., Gasparovic, G., Voll, P., Krajačić, G., Duić, N., Bardow, A., 2014. A hybrid approach for the efficient synthesis of renewable energy systems. Applied Energy 135, 625–633.

Pizer, W.A., Popp, D., 2008. Endogenizing technological change: Matching empirical evidence to modeling needs. Energy Economics 30, 2754–2770.

Popp, D., 2002. Induced Innovation and Energy Prices Induced Innovation and Energy Prices. American Economic Review 92, 160–180.

Popp, D., Newell, R.G., Jaffe, A.B., 2010. Energy, the Environment, and Technological Change, in: Handbook of the Economics of Innovation- Vol-II. Elsevier B.V., Burlington, pp. 873–938.

Prakash, P., Khatod, D.K., 2016. Optimal sizing and siting techniques for distributed generation in distribution systems: A review. Renewable and Sustainable Energy Reviews 57, 111–130.

Prognos AG, 2012. Die Energieperspektiven für die Schweiz bis 2050 - Energienachfrage und Elektrizitätsangebot in der Schweiz 2000 – 2050. Bern.

Ren, H., Gao, W., 2010. A MILP model for integrated plan and evaluation of distributed energy systems. Applied Energy 87, 1001–1014.

Rockström, J., Gaffney, O., Rogelj, J., Meinshausen, M., Nakicenovic, N., Schellnhuber, H.J., 2017. A Roadmap for Rapid Decarbonization. Science 355, 1269–1271.

Rogers, E.M., 2003. Diffusion of innovations, 5th ed, Diffusion of Innovation. Free Press, New York.

Rogge, K.S., Reichardt, K., 2016. Policy mixes for sustainability transitions: An extended concept and framework for analysis. Research Policy 45, 1620–1635.

Romer, P.M., 1986. Increasing Returns and Long-Run Growth. Journal of Political Economy 94, 1002–1037.

Rosenberg, N., 2008. Inside the Black Box: Technology and Economics. Cambridge University Press, Cambridge.

Saunders, M., Lewis, P., Thornhill, A., 2009. Research Methods for Business Students, 5th ed. Pearson Education, Essex.

Saviotti, P.P., 1986. Systems theory and technological change. Futures 18, 773–786.

Schmidt, O., Hawkes, A., Gambhir, A., 2017. The future cost of electrical energy storage based on experience rates. Nature Energy 2, 1–8.

Scholz, R.W., Tietje, O., 2002. Embedded Case Study Methods - integrating quantitative and qualitative knowledge. Sage Publications, Thousand Oaks; London; New Delhi.

Schumpeter, J., 1942. Capitalism, socialism and democracy. Harper, New York.

Seaden, G., Manseau, A., 2001. Public policy and construction innovation. Building Research and Information 29, 182–196.

Sharafi, M., ElMekkawy, T.Y., Bibeau, E.L., 2015. Optimal design of hybrid renewable energy systems in buildings with low to high renewable energy ratio. Renewable Energy 83, 1026–1042.

Sinha, S., Chandel, S.S., 2014. Review of software tools for hybrid renewable energy systems. Renewable and Sustainable Energy Reviews 32, 192–205.

Solow, R., 1957. Technical change and the aggregate production function. Review of Economic Statistics 39, 312–320.

Stoneman, P., Diederen, P., 1994. Technology Diffusion and Public Policy. The Economic Journal 104, 918–930.

Stucki, T., Woerter, M., 2016. Intra-firm diffusion of green energy technologies and the choice of policy instruments. Journal of Cleaner Production 131, 545–560.

Swan, T.W., 1956. Economic Growth and Capital Accumulation. Economic Record 32, 334–361.

Swiss Federal Council, 2018. Energiegesetz (EnG). Switzerland.

Swiss Federal Office of Energy (SFOE), 2018. Energy Strategy 2050 [WWW Document]. URL http://www.bfe.admin.ch/energiestrategie2050/index.html?lang=en (accessed 30 April, 2018).

U.S. Department of Energy, 2011. Buildings R&D Breakthroughs: Technologies and Products Supported by the Building Technologies Program. Washington.

Umwelt Arena AG, 2018. Erstes Energieautarkes Mehrfamilienhaus in Brütten [WWW Document]. umweltarena.ch. URL http://www.umweltarena.ch/uber-uns/energieautarkes-mfh-brutten/ (accessed 26 April, 2018).

UN, 2017. World Population Prospects: The 2017 Revision, Methodology of the United Nations Population Estimates and Projections. New York.

UNEP SBCI, 2009. Buildings and climate change: a summary for decision-makers, United Nations Environmental Programme, Sustainable Buildings and Climate Initiative, Paris.

UNFCCC, 2015. Paris Agreement. United Nations Framework Convention on Climate Change, Paris.

Unruh, G.C., 2002. Escaping carbon lock-in. Energy Policy 30, 317–325.

Unruh, G.C., 2000. Understanding carbon lock-in. Energy Policy 28.

Ürge-Vorsatz, D., Eyre, N., Graham, P., Harvey, D., Hertwich, E., Jiang, Y., Kornevall, C., Majumdar, M., McMahon, J.E., Mirasgedis, S., Murakami, S., Novikova, A., Janda, K., Masera, O., McNeil, M., Petrichenko, K., Herrero, S.T., Jochem, E., 2012. Energy End-Use: Buildings, in: Global Energy Assessment (GEA). Cambridge University Press, Cambridge, UK and New York, NY, USA and the International Institute for Applied Systems Analysis, Laxenburg, Austria, pp. 649–760.

Vaishnav, P., Horner, N., Azevedo, I.L., 2017. Was it worthwhile? Where have the benefits of rooftop solar photovoltaic generation exceeded the cost? Environmental Research Letters 12, 1–46.

Verein Komfortlüftung.at, 2014. Energieeffizienz Komfortlüftung [WWW Document]. URL http://www.komfortlüftung.at/energieeffizienz/ (accessed 29 July, 2016).

Vieira, F.M., Moura, P.S., de Almeida, A.T., 2017. Energy storage system for self-consumption of photovoltaic energy in residential zero energy buildings. Renewable Energy 103, 308–320.

Vollebergh, H.R.J., 2007. Differential Impact of Environmental Policy Instruments on Technological Change: A Review of the Empirical Literature (No. TI 2007-042/3), Tinbergen Institute Discussion Paper TI. Rotterdam.

Vollebergh, H.R.J., Kemfert, C., 2005. The role of technological change for a sustainable development. Ecological Economics 54, 133–147.

von Wirth, T., Gislason, L., Seidl, R., 2017. Distributed energy systems on a neighborhood scale: Reviewing drivers of and barriers to social acceptance. Renewable and Sustainable Energy Reviews 1–12.

Voss, K., Musall, E., 2013. Net Zero Energy Buildings - International Projects of Carbon Neutrality in Buildings. Detail Green Books, Munich.

Weber, C., Koyama, M., Kraines, S., 2006. CO2-emissions reduction potential and costs of a decentralized energy system for providing electricity, cooling and heating in an office-building in Tokyo. Energy 31, 2705–2725.

Wilson, C., 2012. Up-scaling, formative phases, and learning in the historical diffusion of energy technologies. Energy Policy 50, 81–94.

Wilson, C., Grübler, A., 2011. Lessons from the History of Technology and Global Change for the Emerging Clean Technology Cluster. Laxenburg.

Yin, R.K., 2009. Case Study Research: Design and Methods, 3rd ed, Applied Social Research Methods Series. Sage Publications, Thousand Oaks; London; New Delhi.

Zhang, Y., Campana, P.E., Lundblad, A., Yan, J., 2017. Comparative study of hydrogen storage and battery storage in grid connected photovoltaic system: Storage sizing and rule-based operation. Applied Energy 201, 397–411.

Annex: Articles

Article I

Under Review at *WIREs Energy and Environment,* since July 24th 2018

Matching Decentralized Renewable Energy Production and Local Consumption: A Review of Energy Conversion and Storage Systems

David Grosspietsch* [1], Marissa Saenger [2], and Bastien Girod [1]

[1] ETH Zurich
Department of Management, Technology, and Economics
Weinbergstrasse 56/58, 8092 Zurich, Switzerland

[2] Harvard University
Harvard John A. Paulson School of Engineering and Applied Sciences
29 Oxford Street, Cambridge, MA 02138, USA

* Corresponding author
Phone: +41-44 633 88 91
Email: dgrosspietsch@ethz.ch

Abstract

The increasing share of decentralized intermittent renewable energy reinforces the necessity of balancing local production and consumption. Decentralized energy systems, powered by renewable energy technologies and incorporating storage and conversion technologies, are promising options to cope with this challenge. Many studies have evaluated their potential contributions, but an overview of the status-quo in both academia and practice is missing. Literature lacks a comprehensive review of scientific knowledge, partially attributed to the lack of common terminology. Besides, it remains unclear what kind of systems are already implemented today as they have not yet been thoroughly analyzed and described. However, pilot projects provide valuable insights into future applications and operational aspects. To fill these gaps, this study conducts an extensive review of the current state of literature and practice. To do so, it analyzes 64 publications and 56 projects and provides an overview using four criteria: terminology, scope/motivation, application, and technical configuration. These criteria facilitate the understanding of decentralized energy systems needed to spur their development and diffusion. Further advancements of research and practice are discussed. For example, technological learning hinges on a common terminology and on an identification of optimal technical configurations per application. There are both avenues for future research.

Keywords

Decentralized energy system, renewable energy technologies, energy storage, energy conversion, pilot projects

Highlights

- Provides a review of decentralized energy systems in literature and practice.
- Identifies, analyzes and compares 64 publications and 56 pilot projects.
- Assesses different concepts along terminology, application and technical configuration.
- Finds solar PV with electrical/thermal storage dominant in residential applications.

1 Introduction

Efforts toward climate change mitigation, energy independence, and nuclear phase-out have led to an increase in the deployment of renewable energy technologies for power generation. Global power-generation capacity by renewable energy technologies has nearly doubled within the last decade, reaching 2,011 GW by the end of 2016 (IRENA, 2017). Solar photovoltaics (PV) and wind are emerging as the most popular renewable energy technologies, with solar PV used predominantly in decentralized settings located close to consumers. This creates a shift in the energy sector toward decentralized (or distributed) generation with smaller production units (Alanne and Saari, 2006). The primary challenge of using renewable energy technologies, such as wind and solar PV, is their highly intermittent and weather-dependent power output. Therefore, to match generation with load, additional measures for flexibility and balance are required. Such improvements can be provided by decentralized systems[1], which employ multiple energy carriers[2] in combination with conversion and storage technologies. These combinations allow surplus renewable energy to be stored and converted between different carriers, which can help balance load with demand and thus offer additional flexibility in energy management.

Systems of this type have been explored under a broad range of names in various publications in the literature, which focus on different theoretical and societal concepts (Chicco and Mancarella, 2009; Mancarella, 2014; von Wirth et al., 2017), evaluation and optimization methods (Gabrielli et al., 2017; Prakash and Khatod, 2016; Sinha and Chandel, 2014a), or specific technical aspects (Bernal-Agustín and Dufo-López, 2010; Li et al., 2017; Zhang et al., 2017). And while several publications include a case study example to apply their introduced methodology or illustrate the analysis (Evins et al., 2014; Fabrizio et al., 2010; Maroufmashat et al., 2014), numerous implementations of such systems already exist and can be observed in practice. After reviewing these energy systems, we have found the gap in the research to be twofold. On the one hand, the extant literature lacks a comprehensive overview of the current state of research on decentralized energy systems with renewable energy technologies as well as both conversion and storage technologies. The absence of a systematic literature review can also be attributed partially to the lack of common terminology. On the other hand, it remains unclear what kind of systems are implemented today because current project developments have not yet been thoroughly analyzed and described. Pilot projects provide valuable insights into potential future applications as well as practical experiences and challenges. Therefore,

---

[1] We follow the notion of Alanne and Saari where "decentralized" (or "distributed") refers to conversion units that are located close to energy consumers (Alanne and Saari, 2006), with ratings of generation units below 100 MW and specific characteristics regarding purpose, location, power scale and delivery, technology, environmental impact, mode of operation, ownership, and penetration (Ackermann et al., 2001).

[2] According to IPCC (IPCC, 2007), energy carriers include electricity, heat, and fuels (solid, liquid, gaseous).

this study aims to fill these gaps by providing an extensive review of the current state of literature and practice for RES-based decentralized energy systems with energy conversion and storage.

This work is the first to analyze both literature and practice side-by-side, and to review a broad sample of publications and pilot projects. Our systematic overview of the academic literature is complemented by a database of pilot projects, which includes projects in operation as well as those in the planning stage. We compare literature and projects according to relevant thematic fields to determine general trends and patterns across fields. This study reviews decentralized energy systems across a wide range of application (residential, commercial, island, utility) and scale (tens of kW to MW). Although the extant literature is multifaceted, three required characteristics limit the technological scope of this study to systems that provide: (1) at least one renewable energy technology, (2) conversion device(s), and therefore multiple energy carriers, and (3) energy storage device(s).

The paper is structured as follows: Section 2 describes materials and methods used herein. The obtained results are presented and discussed in section 3. Section 4 concludes with a summary of the main contributions.

2 Material and Methods

This section starts by introducing the main categories used to review and analyze both literature and practice (2.1). We then describe the strategies for collection, sampling, and analysis of data for the literature review (2.2) and the project database (2.3).

2.1 Review Criteria

The review of the extensive collection of relevant publications and pilot projects is structured across four main categories: i.) terminology in use, ii.) scope/motivation[3], iii.) application, and iv.) technical configuration. First, the terminology used around an elusive phenomenon is an essential initial step for a larger community to grasp the phenomenon, create consensus, and to avoid misinterpretation (Strehlow, 1988). Second, before delving into the details of each publication or project, it seems necessary to understand the general scope of each scientific article (e.g., methodological contribution, theoretical proof of concept) and capture the motivation or rationale for the implementation of such systems. Third, while stationary electricity storage can be classified as a multi-purpose technology serving several distinct applications (Battke and Schmidt, 2015), decentralized systems that incorporate storage technologies are similarly capable of providing different sorts of services, thus serving multiple applications. Fourth and last, the technical configuration is a key element of a system as it is characterized by the multiple technical options for each of the above-named criteria (renewable energy technologies, conversion and storage devices) and gives a system an individual note. In summary, these four categories were distilled as key characteristics during the analysis to both describe literature and compare it to practice, and to address relevant questions (i.e., what, why, where, how) concerning decentralized energy systems.

2.2 Literature Review

A structured review of academic literature was conducted using a sample sourced from two different approaches: a systematic, bottom-up search query in the Web of Science^{TM} database, and an explorative, top-down complementary analysis for relevant articles not captured in the database search. Figure 1A depicts the process, with the number of articles in-/excluded and remaining after each step. The bottom-up search query was formulated based on the system definition established in this paper and adapted through an iterative process to minimize the appearance of false positives (i.e., articles not meeting the definition but resulting from the search) and maximize breadth of inclusion (see Appendix A for details on the search string). The final version originally yielded 402 results from Web of Science^{TM}, (see Figure 1A, step 1), which were subsequently filtered by number

---

[3] For literature, this category refers to a publication's focus or method, whereas for projects it refers to the primary goal(s) of or the rationale for implementation.

of times cited[4] and journal title, and then manually coded to refine the quantity, relevance, and legitimacy of the sample.

The criteria for number of times cited was established with consideration for how old an article is, to account for the possibility that more recently published articles may not have been frequently cited. Thus, one filter was set to exclude all articles that had been cited fewer than ten times if they were published in 2014 or earlier (see step 2 in Figure 1A). A second filter was set to exclude all articles that had been cited fewer than five times if they were published in 2015 (see step 3)[5]. In a next step, 19 articles were filtered out of the final results as their journal titles were deemed unrelated to the topic (step 4), such as *Neural Computing and Applications*.

The above criteria narrowed the bottom-up sample to 281 publications, which were further sorted manually by evaluating the title and abstract for relevance to our study's purpose (step 5). Most articles were excluded in this step, as it was clear in each abstract that either the system(s) evaluated did not meet the definition established for this overview (i.e., at least one of each type: renewable energy technology, conversion technology, and storage technology), or that the article did not focus on decentralized energy systems but rather on a separate topic or only on a particular part of the energy system (e.g., voltage or frequency control, battery lifetime, converter topology). The abstract was not always specific enough to make sure that an article met the definition. Hence, for the remaining 106 articles, the full paper was evaluated for further detail and on this basis 56 additional articles were excluded (step 6). Thus, 50 publications remained in the final bottom-up search sample.

The explorative, top-down approach incorporated articles previously acquired and deemed relevant to the topic as they fulfill the study's definition, but which were not captured by the database search due to a missing keyword in the title or abstract. This sample comprised 14 articles, which were confirmed to meet our standards of definition and scope (step 7). The final literature sample was comprised of the combined total of 64 publications, which were then analyzed across the four categories listed above. The full literature sample can be found in Table B1 in the appendix.

2.3 Project Database

To better understand implemented systems, we used a variety of sources to create a database containing both planned and operational pilot projects. Figure 1B illustrates the process by which projects were added to the database. Project sources came from the following categories[6]: 1.) peer-

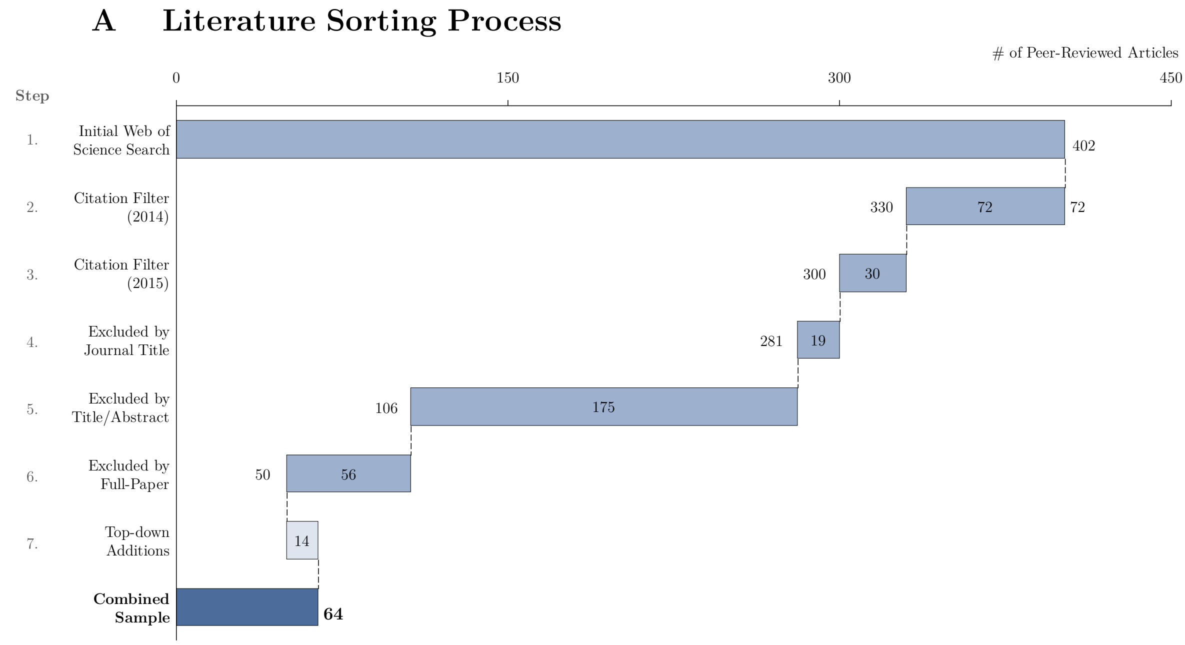
---

[4] As indicated in the Web of Science™ database as of June 2017.

[5] No filter was set for citation number for articles published in 2016 or later, as this may have been an inaccurate measure of legitimacy for more recently published articles.

[6] Certain projects were found in more than one source. For these cases, the source from which each project was initially detected has been designated its primary source. Thus, overlaps exist but are not shown in Figure 1B.

reviewed journal articles (Gahleitner, 2013; Hossain et al., 2014; Neves et al., 2014; Soshinskaya et al., 2014), 2.) online databases (Energiewendebauen, 2015; Gangale, 2017; International Energy Agency (IEA), 2015; Rydin, 2010; Sandia National Laboratories, 2015), 3.) industry talks and conferences (e.g., firm presentations, project descriptions/releases, academic conferences), 4.) suggestions by experts in the field, and 5.) internet keyword searches.



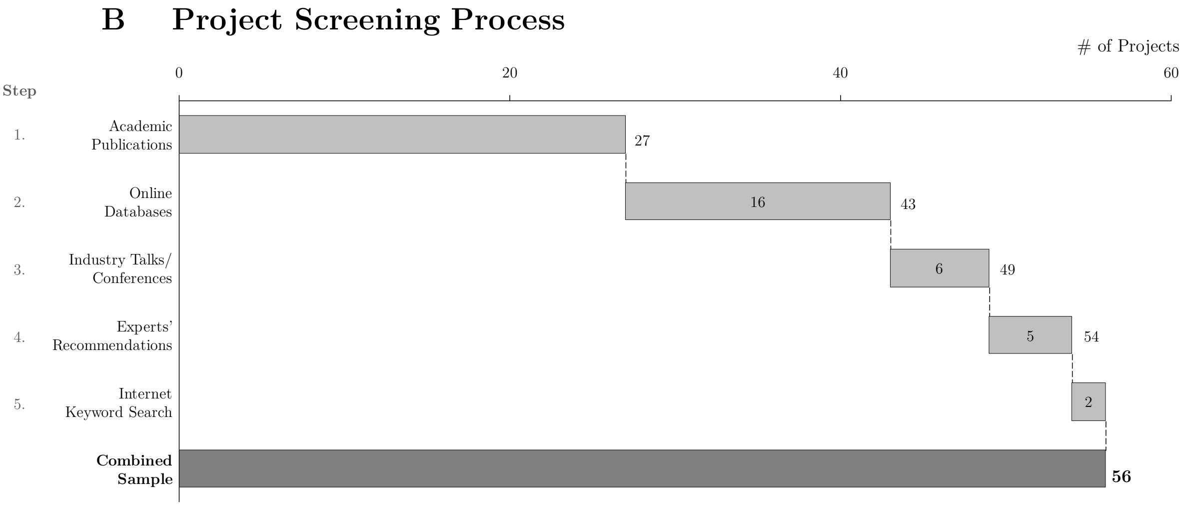


Figure 1: (A) Process of collecting and sorting relevant publications for the literature review [number of peer-reviewed journal articles]. (B) Process of identifying and screening relevant projects for the practice overview [number of projects]

A total of 56 implemented or planned projects were ultimately considered (see Table B2 in the appendix for a full summary of projects in the database). As the search was not constrained to a specific geographical area, it represents a global spread of projects.

The project database has been maintained and updated through July 2017 with available data, the majority of which was found through the analysis of archival data, publications, press releases, and reports collected on each specific project via a targeted web search. In addition to location and operation status, projects were analyzed across the same four main categories we used for the review of academic literature.

To complement the knowledge gained from our review of literature and practice, we conducted a series of expert interviews to validate project information and enrich our knowledge of operational aspects as well as project and technology specifics. We chose our sample of interview partners based on their project involvement as well as their industry experience, and the sample comprised different stakeholders of renewable-based decentralized systems with energy conversion and storage (e.g., investors, technology providers, project developers/managers, integrators, academic experts). A total of 13 people were interviewed between April 2015 and August 2016[7]. Table 1 provides a summary of the expert interviews along with additional details about the interviewees.

Table 1: Overview of conducted expert interviews

#	Interviewee's role	Interviewee's details
1	Capital provider	CEO of a real estate developer investing in distributed concepts on residential scale
2	Project developer	Project leader for a real estate company in a concept for self-sufficiency on residential scale
3	Academic expert	Senior researcher in a P2G pilot project including a mobility application
4	Project developer	Head of R&D for an integrator company focusing on self-sufficient residential systems
5	Technology provider	CTO of a conversion technology (e.g., fuel cell, electrolyzer) manufacturer
6	Technology provider	Head of Sales for a fuel cell manufacturer
7	Project developer	Department head for spatial planning/public building authority involved in approval process
8	Project developer	Project manager for a distribution system operator of an island project
9	Project developer	Project engineer for a government energy research organization working on P2G
10	Project developer	Project manager for an organization working on development of P2G projects
11	Project developer	Project developer for P2G projects
12	Project developer	Project & innovation manager for a municipality for a pilot project of a decentralized energy system
13	Project developer	Project manager for a local municipality working on the planning/implementation of a pilot project

---

[7] The semi-structured interviews were run by two interviewers in person or via telephone, lasted between 30–90 minutes, and were prepared and adapted for the individual interviewees.

3 Results and Discussions

The resulting overview of the status of decentralized systems with renewable energy technologies as well as conversion and storage technologies is presented and discussed here in five parts. We present our findings from literature and projects side-by-side across the four main categories introduced above: terminology in use (section 3.1), scope and motivation (3.2), application (3.3), and technical configuration (3.4). We close this section with a discussion of limitations and recommendations for future research (3.5).

3.1 Terminology in Use

With 46 different terms in use within our sample of 64 publications, the literature reveals a wide variety in nomenclature[8]. While there is no consistent naming pattern detectable, we identified five main categories: multi-, hybrid, distributed/decentralized, hub, and microgrid/ smartgrid. Again, each category includes many different, specific terms[9]. Table 2 shows an excerpt of the most popular terms from the categories above, along with the number of publications and citations. It is worth noting that several outliers did not fit the five categories, but include names such as “integrated energy system” (Ahmadi et al., 2014; Pelet et al., 2005) and “energy-services supply system” (Groscurth et al., 1995). Although a broad range of terms was already in use in 2013 (also in each of the categories above), we have observed an even more diversified terminology in 2017, which we see as the result of the increasing number of publications from 2014 to 2017.

In contrast to the academic literature, implementations in practice tend not to use generalized names for the systems other than that of the specific project (often determined by geographical site, application, purpose, owner, or end-user). Still, the most widely used categories of terms to refer to a project were “microgrid”, “smartgrid”, and “multi”. Additionally, a few outlier terms appeared, including “virtual power plant” and “energy park”. Table 3 provides an overview of terms that are used in practice to describe related projects.

Overall, there continues to be significant variation in terminology, which is more obvious in literature than in practice as it is less common to designate a specific name for the type of system used other than the project or site name itself. This high variation presumably stems from i.) different academic communities/institutions that coined and consequently promote a certain term, and ii.) the lack of conceptual delineation of the phenomenon of decentralized energy systems, their definition, and integral components.

---

[8] Some publications use more than one term to describe their system (unit of analysis).

[9] A few terms exists that overlap between the categories (e.g., “hybrid distributed energy system” (Shah et al., 2015), “multi-energy hub” (Maroufmashat et al., 2016)).

Table 2: Overview of terminologies used in literature

Category	Term	# of Publications	# of Citations	Exemplary Reference
Multi	*Multigeneration system*	4	89	(Ahmadi et al., 2014)
	Multi-energy system (MES)	3	146	(Mancarella, 2014)
	Multi-source multi-product	2	57	(Xu et al., 2015)
Hybrid	*Hybrid renewable energy system (HRES)*	9	325	(Fathima and Palanisamy, 2015)
	Hybrid energy system (HES)	8	193	(Hacatoglu et al., 2015)
	Hybrid system	4	78	(Bailera et al., 2016)
Distributed/ Decentralized	*Distributed energy system*	5	28	(Akbari et al., 2016)
	Distributed generation (system)	3	72	(Soheyli et al., 2017)
	Distributed multi-generation	2	503	(Mancarella, 2014)
Microgrid/ Smartgrid	*Microgrid*	9	387	(Wouters et al., 2017)
	Multi microgrid	2	67	(Zhang et al., 2014)
	Smartgrid	2	16	(Li et al., 2016)
Hub	*Energy hub*	7	127	(Geidl et al., 2007)
	Multi energy hub	1	2	(Maroufmashat et al., 2016)

Table 3: Overview of terminologies used in practice. (The project number in the last column refers to the project number that is provided in Table B2 of the appendix.)

Category	Term	Project Name	# of Appearances	Project Number
Microgrid		*Fort Collins Microgrid*	10	3
		Sendai Microgrid		52
		University of California San Diego Microgrid		54
Smartgrid		*Linear-Smartgrid demonstration*	6	27
		Irvine Smart Grid demonstration		41
		SmartGrid Gotland		45
Multi	Multi-Energy-System	*Reka Holiday Village Blatten-Belalp*	4	10
	Multi-Purpose Hybrid System	*Wind/hydrogen demonstration system Utsira*		14
	Multi-Source Renewable Energy System	*HARI project – West Beacon Farm*		28
Other	Virtual Power Plant	*San Agustin del Guadalix*	2	12
	Hybrid Powerplant	*Hybrid PowerPlant Enertrag*	1	35
	Green Hydrogen Hub	*H2Ber New Berlin Brandenburg Airport*	1	39
	Energiepark	*Energiepark Clausthal*	1	13

3.2 Scope and Motivation

The majority of the literature falls into four main categories: i.) general overview, ii.) model and optimization, iii.) energy management, and iv.) system analysis or case study. First, the general overview focus ranges from system definition and characteristics (Mancarella, 2014), to technology components (Manwell, 2004), optimization techniques (Allison, 2017; Maroufmashat et al., 2016), and software tools used for system modeling (Sinha and Chandel, 2014b). Second, in the model and optimization category, the most common optimization objectives are minimization of both cost and emissions in a multi-objective analysis. Conflicting objectives are demonstrated by a Pareto curve (Pelet et al., 2005; Sharafi et al., 2015; Sharafi and ELMekkawy, 2014), while particle swarm optimization (García-Triviño et al., 2016; Li et al., 2016; Safari et al., 2013; Sharafi et al., 2015; Sharafi and ELMekkawy, 2014; Stoppato et al., 2016), mixed integer linear programming (MILP) optimization (Evins et al., 2014; Harb et al., 2014; Majidi et al., 2017; Pantaleo et al., 2014; Scheubel et al., 2017; Wouters et al., 2017, 2015), fuzzy logic controller (Athari and Ardehali, 2016; Majidi et al., 2017; Safari et al., 2013), and evolutionary algorithm (Ahmadi et al., 2014; Pelet et al., 2005) appear as the main optimization methods in use. Some publications propose a novel approach for optimization or modeling/simulation of a system to better account for dynamic system complexities (Maleki et al., 2016; Pelet et al., 2005; Petruschke et al., 2014; Sharafi and ELMekkawy, 2014; Yang et al., 2016). Third, regarding energy management, publications discuss or propose specific detailed methods for balancing load and demand (Choudar et al., 2015; García et al., 2016; Tan et al., 2013; Torreglosa et al., 2014; Xu et al., 2015; Zhang et al., 2014). Fourth, concerning system analysis or case study, the articles in this category most commonly discuss energy/exergy efficiency (Bailera et al., 2016; Ezzat and Dincer, 2016; Islam and Dincer, 2017; Türkay and Telli, 2011), scheduling/control strategies (Garcia et al., 2013), or study a specific site or sites[10].

Figure 2A shows the distribution of literature across these four scope categories. It is worth mentioning that the share of category 2 (model/optimization) has increased considerably since 2013, when categories 1, 2, and 4 were almost evenly distributed.

---

[10] These cases are not included in the project database, as the database concerns pilot projects and is intended to provide a separate sample from the (sometimes theoretical or stylized) cases discussed in literature.

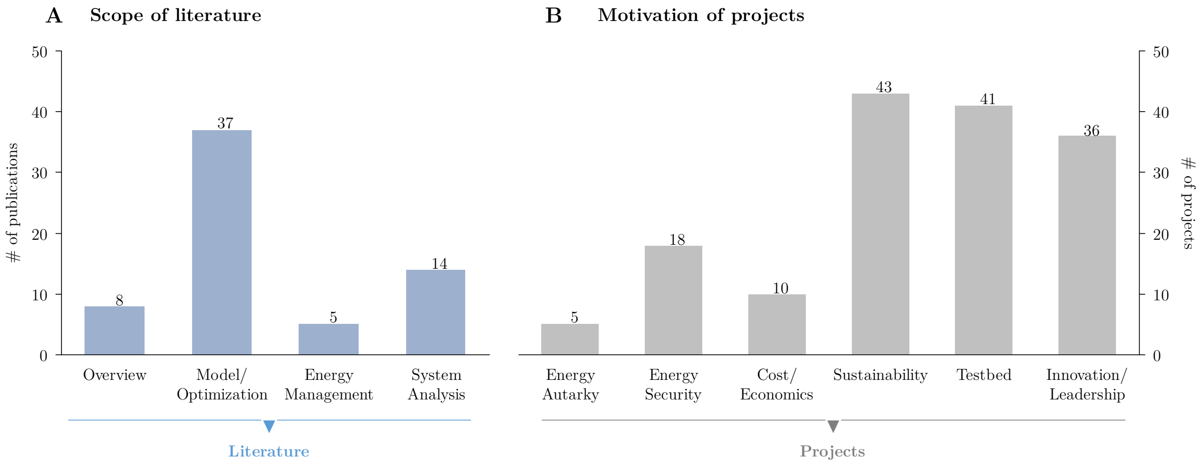


Figure 2: (A) Distribution of literature according to scope, i.e., publication category. (B) Distribution of projects according to motivation, i.e., rationale(s) for implementing. (Projects which include more than one category are counted in each category, thus the total sum exceeds the number of publications of our sample.)

Figure 2B depicts the distribution of projects across the main motivation categories. The stated rationale or motivation for implementing most projects falls within three major categories with the following objectives: i.) learning, e.g., demonstration, test bed, ii.) sustainability, e.g., reduction of emissions or increased renewable portfolio, or iii.) innovation and leadership, e.g., pioneer role. For example, one of the projects we analyzed has the following objectives, and is therefore considered in all three categories:

> *“The main goals are to develop and demonstrate a coordinated and integrated system of mixed distributed resources [...], reduce peak loads by 20%-30% [...], increase the penetration of renewables, and deliver improved efficiency and reliability to the grid [...] [T]he project is considered to be very innovative for a small municipally-owned utility and will offer interesting lessons [...].”*

The other goals that we observed were cost savings, energy independence, and improved energy security or reliability, but these goals were significantly less common than learning, sustainability, or innovation/ leadership. The fact that the major objective is demonstrating innovative concepts rather than cost efficiency is likely a function of the database being composed of pilot projects.

We found that the expert interviews that we conducted yielded further insights. While the literature predominantly approaches systems with a theoretical focus and addresses front-end characteristics (e.g., optimization techniques, energy efficiency), the practical side tends to elaborate on operational aspects, such as the interaction between certain components or regulatory constraints. These latter aspects remain mostly unexplored in the literature where the majority of test cases described overlook operational aspects of various technologies involved, for instance the interplay of a PV panel with an electrolyzer or differing communication protocols for various smart devices. This gap highlights the potential opportunity for technological learning through the pilot projects, which could help develop best practices for operating and integrating various technical devices within an overall system.

Similarly, project leaders and other stakeholders could benefit from using the ideas presented in literature to optimize system design/performance and energy dispatch alongside other objectives, such as reduction of cost and/or emissions.

3.3 Case and Application

We determined four typical applications for both literature and practice by reviewing and analyzing cases in the following categories: i.) residential, ii.) commercial or mixed-use, iii.) island, and iv.) utility. Figure 3 below shows the distribution of test cases for both literature and pilot projects in each of these application categories[11]. The residential category includes a size range from multi-family houses to neighborhood or village districts. For the purposes of this study, mixed-use is defined as an application consisting of both residential and commercial end-users (e.g., an urban area with both apartments and retail buildings) or applications that are neither specifically residential nor commercial, such as a hospital, school, jail, or resort. The island category consists of systems used to power entire geographical islands, either as a supplement to the power consumption from the main grid or as the only source of energy in a self-sufficient system. Utility applications comprise systems that serve as the central energy source for a region or plant. We have included a separate "unspecified" category in Figure 3 to address test cases in the literature where the applications were generic rather than specified.

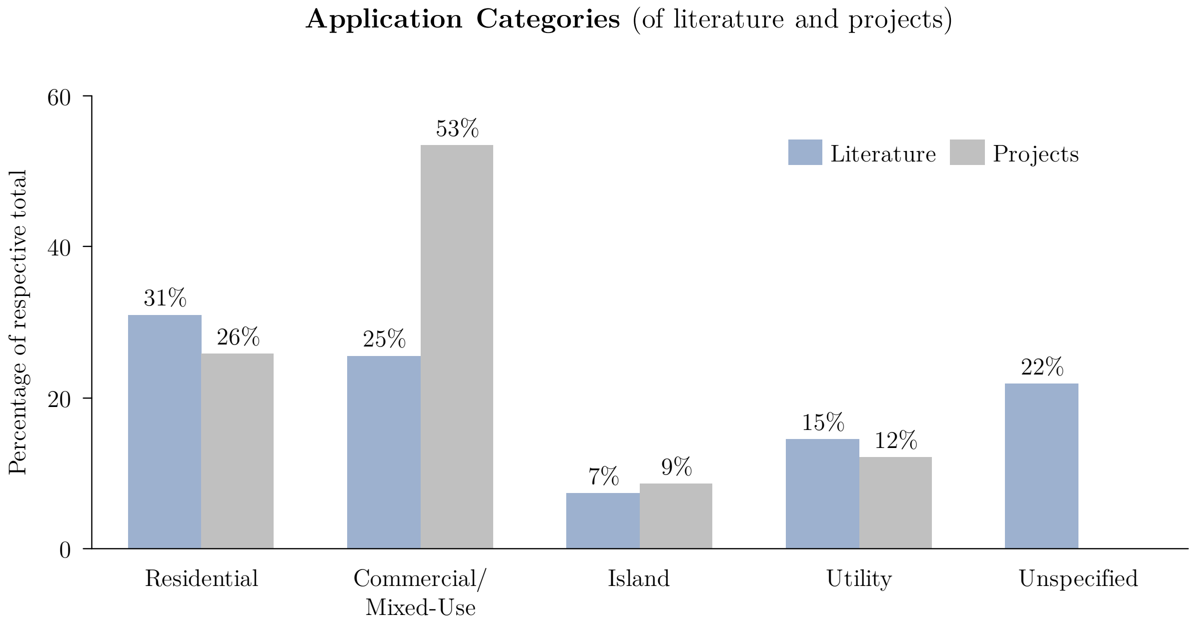


Figure 3: Distribution of test cases, both from literature and pilot projects, in each application category

---

[11] Each case is counted in only one application category (thus no overlaps or double-counts exist in this portion of the analysis).

Overall, we observe that the distributions for cases from publications and projects are very similar, which implies that – for otherwise closely related applications – literature and practice differ only in the nature of problems and approaches to solve them. The fact that the commercial and mixed-use category applications is more prominent in practice might be due to a stronger economic prioritization by stakeholders (e.g., owner, operator) in this category over residential end-use, or that these applications are considered economically more feasible (e.g., by aggregating different load patterns). While residential and utility applications were predominant in earlier publications (until 2013), the share of commercial and mixed-use applications has increased in recent literature, mirroring the high percentage observed in the projects.

3.4 Technical Configuration

In total, 31 different combinations of renewable energy technologies and storage technologies exist across 55 test cases in the literature, and 30 different combinations exist across 56 pilot projects. Thus, no dominant configuration stands out as the most favorable for any category.

Figure 4 shows the distribution of combined literature and project cases across the most frequently occurring technology clusters, along with the share of grid independent cases within each cluster. Technology shows a tendency toward PV and/or wind-based systems, but combinations of PV and/or wind with other renewable energy technologies, conversion and storage technologies vary significantly. In earlier publications (until 2013), PV and wind are already the technologies of choice, and the percentage of cases concerning PV and wind has increased further in more recent literature despite numerous alternative renewable energy technologies, such as bioenergy, solar thermal, hydro, or geothermal. These alternatives were much less prominent in the cases we observed, and no specific combination of conversion and storage technologies has emerged as profoundly dominant. Instead, we noticed that specificity of site, system size, and regional resources or policies are likely to be more influential factors than any specific technology's benefits or drawbacks, as different technologies may be suitable depending on the set of conditions at hand. In general, literature tends to favor solar PV, with a higher percentage of cases in the literature containing solar PV than cases observed in the projects.

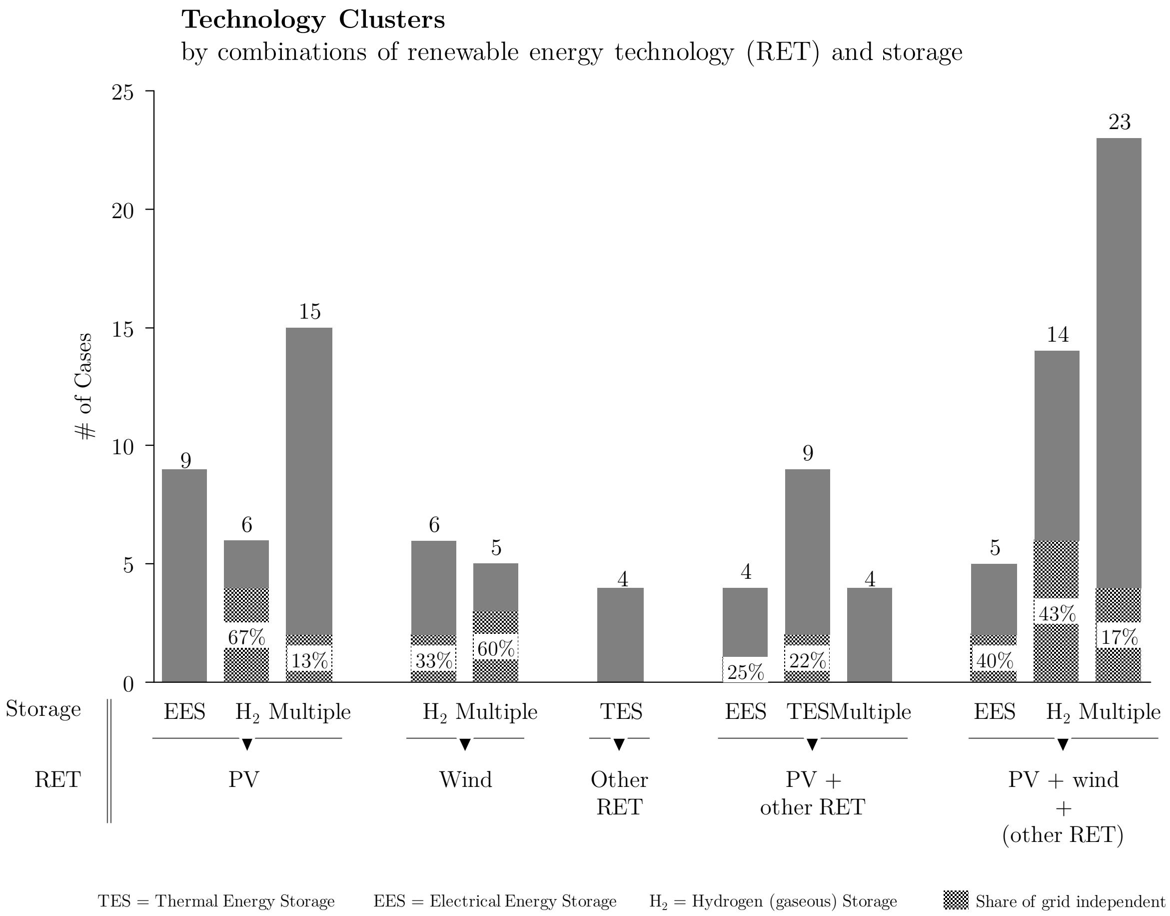


Figure 4: Distribution of cases (literature and practice combined) across frequently occurring technology clusters and share of grid independent cases. (Clusters with two or fewer cases are omitted.)

While there exists a large variety of combinations for the integration of different technologies within a system (i.e., technical configuration) and no configuration is completely dominant, in the following we discuss further the technologies included across applications. Turning towards the application level, the findings reveal more specificity. Figure 5 displays the distribution of the major technology clusters for each of the four applications.

In both literature and practice, solar PV is the dominant renewable energy technology for residential applications, present in over 90% of cases. We see that solar PV in residential settings is usually combined either exclusively with electrical energy storage or with additional thermal energy storage (the latter combination being the most prominent residential configuration). Conversion technologies are almost equally distributed between the following options: electrolyzer, fuel cell, (micro) combined heat and power, boiler/furnace, heat pump, and electrical heater/chiller or heat exchanger. The share of conversion technologies remains similar for all applications, except for island systems, where electrolyzer and fuel cell become dominant due to a higher percentage of hydrogen-based solutions.

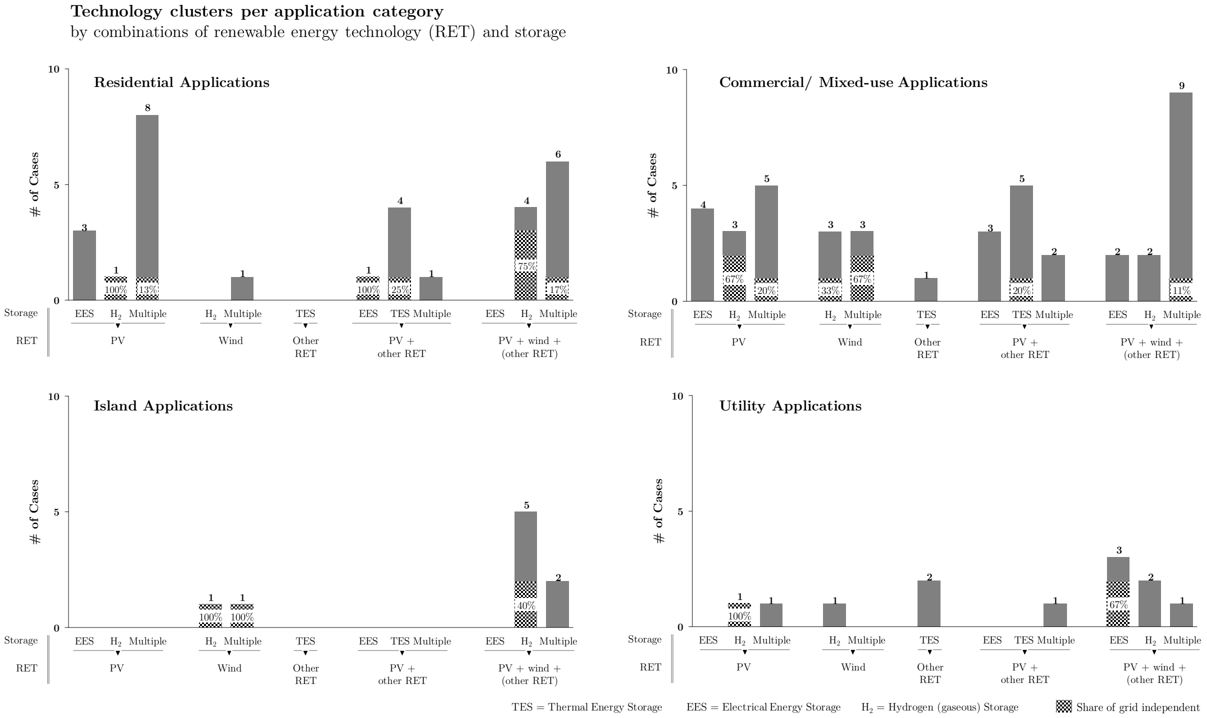


Figure 5: Distribution of cases (both literature and practice combined) for each application category across frequently occurring technology clusters and share of grid independent cases

Solar PV remains the primary renewable energy technology in commercial and mixed-use applications – although it is less common than in the residential category – and the share of wind (oftentimes in combination with solar PV) increases, along with hydrogen and thermal storage. It is worth noting that the commercial and mixed-use application category exhibits the highest variety of technical configurations. Wind turbines are used in 100% of cases for the island application, both for literature and practice, and frequently in combination with solar PV. In these settings, hydrogen is the predominant storage option, occasionally complemented with electric storage. For the utility application, solar PV is less dominant than in the other categories, presumably due to the more decentralized nature of solar PV and because of larger system sizes that favor renewable energy technologies with larger capacities, such as wind or bioenergy. We also observe a higher share of combinations with multiple renewable energy technologies in utility applications.

While the share of grid independent cases remains between 15% and 29% for residential, commercial/mixed-use, and utility applications in literature and in practice[12], in island applications it is much higher. 50% of literature island cases and one-third of island projects operate independently from the mainland electricity grid. It is notable that the majority of cases operating without grid connection utilize hydrogen storage as well as fuel cells and electrolyzers.

---

[12] The remainder utilizes a combination of electrical, district heat, and/or natural gas grid access with electrical as the most common form of grid access.

Overall, we do not observe striking discrepancies between each application category in terms of technical configuration or of contrast between literature and practice. The technology share of each application shows expected variations, and has a tendency toward higher-capacity renewable energy technologies as scale increases. Nevertheless, it seems conceivable that the variety of technical configurations will converge in the medium term and that dominant configurations per application and/or location will emerge. This is due to the fact that certain technologies, such as solar PV or stationary battery storage, are maturing rapidly and are likely to be established in specific settings. The potential role of hydrogen, along with the cost and maturity level of its related technologies (e.g., fuel cell, electrolyzer), in complementing short-term storage in order to bridge seasonal fluctuations remains a pivotal issue (Dodds et al., 2015; Zhang et al., 2017).

3.5 Limitations and Further Research

Both reviews yielded a wide variety of relevant articles and projects, which allowed us to recognize relevant properties of this emerging phenomenon as well as identify differences between literature and practice. Nevertheless, we acknowledge that both the literature and project review approaches might not yield an exhaustive list of publications due to possible limitations in the search scope or the databases used. First, data availability for projects may have shown a bias toward OECD countries or toward the authors' academic affiliations and backgrounds. Second, the literature review comprised only academic peer-reviewed journal articles, which may represent only a portion of the full literature collection available worldwide on this article's topic. Web of Science^{TM} was the only database used for the literature bottom-up search, raising the possibility that certain relevant reports were not discovered.

We have identified several promising avenues for further research based on our overview. Technological learning is required for these systems to be further developed and diffused. First, to facilitate communication within research, and between research and practice, it is important that a consistent terminology be established. This would create uniformity and consolidate research on this topic. Our study has identified an even more diversified terminology in 2017 than in 2013, due to an increase in publications, which highlights the need for consistent terminology. Second, bidirectional knowledge and feedback between scholars in this field and practitioners responsible for project implementation would enhance the scope of understanding on both sides and accelerate the learning required for system improvement and implementation. Third, the clarification of optimal technical configurations for different applications under certain conditions or constraints would be a valuable insight, as we currently see large variety in renewable energy technologies as well as in conversion, and storage technologies, even within a specific application. This calls for more research on optimal technical configurations and system performance.

4 Conclusions

This article provides a comprehensive review of decentralized energy systems that are based on renewable energy technologies including energy conversion and storage. We examined these systems from two perspectives – academic literature and implementations in practice – and considered a breadth of publications and pilot projects to provide an integrated overview of the status-quo for both. We show that a large variety of terminologies are being used, especially in the academic arena. The scope of publications lies, for the most part, on optimization/modeling or system analysis, whereas the projects' rationale is predominantly of three kinds: sustainability, testbed, and innovation/leadership. We distilled four applications that were found in a similar distribution throughout literature and practice, but which also exhibit differences regarding their technical configurations, i.e., the types of renewable energy technologies, conversion and storage technologies that are included within a system. Solar PV and wind seem to constitute the majority of technology clusters, along with electrical energy storage and hydrogen storage, especially in grid-independent settings. Apart from that, the technical configurations are multifaceted and are specific to geography, site, or application with no true dominant technology designs emerging (yet) – but these are likely to be established in the medium term because of sufficient levels of maturity for certain technologies. In order to accelerate academic research and implementation of these systems in practice, a consistent terminology is needed, mutual learning/feedback between literature and practice should be encouraged for the very constructive results, and optimal technical configurations per application should be further evaluated and clarified.

This work contributes to the diverse literature on the phenomenon of decentralized energy systems and also supports practitioners involved in the planning and operation of such systems. We aim to illuminate the current state from both perspectives to enable future research and pathways in practice.

Acknowledgements

This research has been financially supported by Innosuisse within the SCCER FEEB&D (Grant No. 1155000149) and by the Swiss National Science Foundation (SNF) under the National Research Program Energy Turnaround (NRP70), Grant No. 407040-153781. We thank Shreyas Gaur, Christof Knoeri and Volker Hoffmann for their valuable contributions and constructive comments on earlier versions of this manuscript.

Appendix

(A) Search string Web of Science^{TM} database, (B) full sample publications (Table B1) and implementations / pilot projects (Table B2).

References

Ackermann, T., Andersson, G., Söder, L., 2001. Distributed generation: A definition. Electric Power Systems Research 57, 195–204.

Ahmadi, P., Dincer, I., Rosen, M. a., 2014. Thermoeconomic multi-objective optimization of a novel biomass-based integrated energy system. Energy 68, 958–970.

Akbari, K., Jolai, F., Ghaderi, S.F., 2016. Optimal design of distributed energy system in a neighborhood under uncertainty. Energy 116, 567–582.

Alanne, K., Saari, A., 2006. Distributed energy generation and sustainable development. Renewable and Sustainable Energy Reviews 10, 539–558.

Allison, J., 2017. Robust multi-objective control of hybrid renewable microgeneration systems with energy storage. Applied Thermal Engineering 114, 1498–1506.

Athari, M.H., Ardehali, M.M., 2016. Operational performance of energy storage as function of electricity prices for on-grid hybrid renewable energy system by optimized fuzzy logic controller. Renewable Energy 85, 890–902.

Bailera, M., Lisbona, P., Romeo, L.M., Espatolero, S., 2016. Power to Gas-biomass oxycombustion hybrid system: Energy integration and potential applications. Applied Energy 167, 221–229.

Battke, B., Schmidt, T.S., 2015. Cost-efficient demand-pull policies for multi-purpose technologies - The case of stationary electricity storage. Applied Energy 155, 334–348.

Bernal-Agustín, J.L., Dufo-López, R., 2010. Techno-economical optimization of the production of hydrogen from PV-Wind systems connected to the electrical grid. Renewable Energy 35, 747–758.

Chicco, G., Mancarella, P., 2009. Distributed multi-generation: A comprehensive view. Renewable and Sustainable Energy Reviews 13, 535–551.

Choudar, A., Boukhetala, D., Barkat, S., Brucker, J.-M., 2015. A local energy management of a hybrid PV-storage based distributed generation for microgrids. Energy Conversion and Management 90, 21–33.

Dodds, P.E., Staffell, I., Hawkes, A.D., Li, F., Grünewald, P., McDowall, W., Ekins, P., 2015. Hydrogen and fuel cell technologies for heating: A review. International Journal of Hydrogen Energy 40, 2065–2083.

Energiewendebauen, 2015. Forschung für energieoptimierte Gebäude und Quartiere [WWW Document]. URL https://projektinfos.energiewendebauen.de/projekte/ (accessed 10 May, 2017).

Evins, R., Orehounig, K., Dorer, V., Carmeliet, J., 2014. New formulations of the “energy hub” model to address operational constraints. Energy 73, 387–398.

Ezzat, M.F., Dincer, I., 2016. Energy and exergy analyses of a new geothermal-solar energy based system. Solar Energy 134, 95–106.

Fabrizio, E., Corrado, V., Filippi, M., 2010. A model to design and optimize multi-energy systems in buildings at the design concept stage. Renewable Energy 35, 644–655.

Fathima, a. H., Palanisamy, K., 2015. Optimization in microgrids with hybrid energy systems – A review. Renewable and Sustainable Energy Reviews 45, 431–446.

Gabrielli, P., Gazzani, M., Martelli, E., Mazzotti, M., 2017. Optimal design of multi-energy systems with seasonal storage. Applied Energy 219, 408–424.

Gahleitner, G., 2013. Hydrogen from renewable electricity: An international review of power-to-gas pilot plants for stationary applications. International Journal of Hydrogen Energy 38, 2039–2061.

Gangale, F., 2017. Smart Grid Projects Outlook 2017 [WWW Document]. URL http://ses.jrc.ec.europa.eu/smart-grids-observatory (accessed 10 May, 2017).

García-Triviño, P., Fernández-Ramírez, L.M., Gil-Mena, A.J., Llorens-Iborra, F., García-Vázquez, C.A., Jurado, F., 2016. Optimized operation combining costs, efficiency and lifetime of a hybrid renewable energy system with energy storage by battery and hydrogen in grid-connected applications. International Journal of Hydrogen Energy 41, 23132–23144.

Garcia, H.E., Mohanty, A., Lin, W.-C., Cherry, R.S., 2013. Dynamic analysis of hybrid energy systems under flexible operation and variable renewable generation – Part I: Dynamic performance analysis. Energy 52, 1–16.

García, P., Torreglosa, J.P., Fernández, L.M., Jurado, F., Langella, R., Testa, A., 2016. Energy management system based on techno-economic optimization for microgrids. Electric Power Systems Research 131, 49–59.

Geidl, M., Koeppel, G., Favre-Perrod, P., 2007. The Energy Hub–A powerful concept for future energy systems. Third Annual Carnegie Mellon Conference on the Electricity Industry.

Groscurth, H.-M., Bruckner, T., Kümmel, R., 1995. Modeling of energy-services supply systems. Energy 20, 941–958.

Hacatoglu, K., Dincer, I., Rosen, M.A., 2015. Sustainability assessment of a hybrid energy system with hydrogen-based storage. International Journal of Hydrogen Energy 40, 1559–1568.

Harb, H., Matthes, P., Wolisz, H., Streblow, R., Müller, D., 2014. Management of electricity and heating demand to match sustainable energy supply. REHVA European HVAC Journal 34–39.

Hossain, E., Kabalci, E., Bayindir, R., Perez, R., 2014. Microgrid testbeds around the world: State of art. Energy Conversion and Management 86, 132–153.

International Energy Agency (IEA), 2015. Implementing Agreement for a Co-operative Programme on Smart Grids (ISGAN): Smart Grid Case Studies [WWW Document]. URL http://www.iea-isgan.org (accessed 10 May, 2017).

IPCC, 2007. Mitigation of climate change: Contribution of working group III to the fourth assessment report of the Intergovernmental Panel on Climate Change, Intergovernmental Panel on Climate Change.

IRENA, 2017. Renewable Energy Statistics 2017. Bonn.

Islam, S., Dincer, I., 2017. Development, analysis and performance assessment of a combined solar and geothermal energy-based integrated system for multigeneration. Solar Energy 147, 328–343.

Li, B., Roche, R., Paire, D., Miraoui, A., 2017. Sizing of a stand-alone microgrid considering electric power, cooling/heating, hydrogen loads and hydrogen storage degradation. Applied Energy 205, 1244–1259.

Li, X., Wen, J., Malkawi, A., 2016. An operation optimization and decision framework for a building cluster with distributed energy systems. Applied Energy 178, 98–109.

Majidi, M., Nojavan, S., Nourani Esfetanaj, N., Najafi-Ghalelou, A., Zare, K., 2017. A multi-objective model for optimal operation of a battery/PV/fuel cell/grid hybrid energy system using weighted sum technique and fuzzy satisfying approach considering responsible load management. Solar Energy 144, 79–89.

Maleki, A., Pourfayaz, F., Rosen, M.A., 2016. A novel framework for optimal design of hybrid renewable energy-based autonomous energy systems: A case study for Namin, Iran. Energy 98, 168–180.

Mancarella, P., 2014. MES (multi-energy systems): An overview of concepts and evaluation models. Energy 65, 1–17.

Manwell, J.F., 2004. Hybrid Energy Systems. Encyclopedia of Energy 3, 215–229.

Maroufmashat, A., Khavas, S.S., Bakhteeyar, H., 2014. Design and Operation of a Multicarrier Energy System Based On Multi Objective Optimization Approach. International Journal of Environmental, Ecological, Geological and Mining Engineering 8, 582–587.

Maroufmashat, A., Sattari, S., Roshandel, R., Fowler, M., Elkamel, A., 2016. Multi-objective Optimization for Design and Operation of Distributed Energy Systems through the Multi-energy Hub Network Approach. Industrial & Engineering Chemistry Research 55, 8950–8966.

Neves, D., Silva, C.A., Connors, S., 2014. Design and implementation of hybrid renewable energy systems on micro-communities: A review on case studies. Renewable and Sustainable Energy Reviews 31, 935–946.

Pantaleo, A.M., Giarola, S., Bauen, A., Shah, N., 2014. Integration of biomass into urban energy systems for heat and power. Part I: An MILP based spatial optimization methodology. Energy Conversion and Management 83, 347–361.

Pelet, X., Favrat, D., Leyland, G., 2005. Multiobjective optimisation of integrated energy systems for remote communities considering economics and CO2 emissions. International Journal of Thermal Sciences 44, 1180–1189.

Petruschke, P., Gasparovic, G., Voll, P., Krajačić, G., Duić, N., Bardow, A., 2014. A hybrid approach for the efficient synthesis of renewable energy systems. Applied Energy 135, 625–633.

Prakash, P., Khatod, D.K., 2016. Optimal sizing and siting techniques for distributed generation in distribution systems: A review. Renewable and Sustainable Energy Reviews 57, 111–130.

Rydin, Y., 2010. Challenging Lock-in through Urban Energy System (CLUES) [WWW Document]. URL http://www.ucl.ac.uk/clues/outputs/project_reports (accessed 10 May, 2017).

Safari, S., Ardehali, M.M., Sirizi, M.J., 2013. Particle swarm optimization based fuzzy logic controller for autonomous green power energy system with hydrogen storage. Energy Conversion and Management 65, 41–49.

Sandia National Laboratories, 2015. DOE Global Energy Storage Database [WWW Document]. URL http://www.energystorageexchange.org/ (accessed 22 November, 2017).

Scheubel, C., Zipperle, T., Tzscheutschler, P., 2017. Modeling of industrial-scale hybrid renewable energy systems (HRES) - The profitability of decentralized supply for industry. Renewable Energy 108, 52–63.

Shah, K.K., Mundada, A.S., Pearce, J.M., 2015. Performance of U.S. hybrid distributed energy systems: Solar photovoltaic, battery and combined heat and power. Energy Conversion and Management 105, 71–80.

Sharafi, M., ELMekkawy, T.Y., 2014. Multi-objective optimal design of hybrid renewable energy systems using PSO-simulation based approach. Renewable Energy 68, 67–79.

Sharafi, M., ElMekkawy, T.Y., Bibeau, E.L., 2015. Optimal design of hybrid renewable energy systems in buildings with low to high renewable energy ratio. Renewable Energy 83, 1026–1042.

Sinha, S., Chandel, S.S., 2014a. Review of software tools for hybrid renewable energy systems. Renewable and Sustainable Energy Reviews 32, 192–205.

Sinha, S., Chandel, S.S., 2014b. Review of software tools for hybrid renewable energy systems. Renewable and Sustainable Energy Reviews 32, 192–205.

Soheyli, S., Mehrjoo, M., Shafiei Mayam, M.H., 2017. Modeling and optimal resources allocation of a novel tri-distributed generation system based on sustainable energy resources. Energy Conversion and Management 143, 1–22.

Soshinskaya, M., Graus, W.H.J., Guerrero, J.M., Vasquez, J.C., 2014. Microgrids: experiences, barriers and success factors. Renewable and Sustainable Energy Reviews 40, 659–672.

Stoppato, A., Benato, A., Destro, N., Mirandola, A., 2016. A model for the optimal design and management of a cogeneration system with energy storage. Energy and Buildings 124, 241–247.

Strehlow, R.A., 1988. Standardization of Technical Terminology: Principles and Practices, 2nd editio. ed.

Tan, K.T., So, P.L., Chu, Y.C., Chen, M.Z.Q., 2013. Coordinated Control and Energy Management of Distributed Generation Inverters in a Microgrid. IEEE Transactions on Power Delivery 28, 704–713.

Torreglosa, J.P., García, P., Fernández, L.M., Jurado, F., 2014. Hierarchical energy management system for stand-alone hybrid system based on generation costs and cascade control. Energy Conversion and Management 77, 514–526.

Türkay, B.E., Telli, A.Y., 2011. Economic analysis of standalone and grid connected hybrid energy systems. Renewable Energy 36, 1931–1943.

von Wirth, T., Gislason, L., Seidl, R., 2017. Distributed energy systems on a neighborhood scale: Reviewing drivers of and barriers to social acceptance. Renewable and Sustainable Energy Reviews 1–12.

Wouters, C., Fraga, E.S., James, A.M., 2017. A multi-objective framework for cost-unavailability optimisation of residential distributed energy system design. Sustainable Energy, Grids and Networks 9, 104–117.

Wouters, C., Fraga, E.S., James, A.M., 2015. An energy integrated, multi-microgrid, MILP (mixed-integer linear programming) approach for residential distributed energy system planning - A South Australian case-study. Energy 85, 30–44.

Xu, X., Jia, H., Wang, D., Yu, D.C., Chiang, H.D., 2015. Hierarchical energy management system for multi-source multi-product microgrids. Renewable Energy 78, 621–630.

Yang, H., Xiong, T., Qiu, J., Qiu, D., Dong, Z.Y., 2016. Optimal operation of DES/CCHP based regional multi-energy prosumer with demand response. Applied Energy 167, 353–365.

Zhang, L., Gari, N., Hmurcik, L. V., 2014. Energy management in a microgrid with distributed energy resources. Energy Conversion and Management 78, 297–305.

Zhang, Y., Campana, P.E., Lundblad, A., Yan, J., 2017. Comparative study of hydrogen storage and battery storage in grid connected photovoltaic system: Storage sizing and rule-based operation. Applied Energy 201, 397–411.

Appendix

Appendix A: Search String

The search string used to extract the literature sample from the Web of Science^{TM} database was as follows:

TS= ((((embedded OR distributed OR decentrali* OR hybrid) NEAR/5 (generation OR power OR energy OR electric*)) OR (multi*generation OR multi*energy OR multi*hub OR multi*source OR multi*product OR multi*carrier OR conver*)) AND (Renewabl* OR “RES” OR solar OR PV OR photovoltaic OR wind OR biomass OR biofuel OR biogas OR geothermal) AND (Storage NEAR (heat OR battery OR energy)) NOT "storage system") AND TI= (((multi*) NEAR/3 (energy)) OR (energy NEAR/2 system) OR ((distributed OR decentrali* OR local) NEAR/3 (energy OR generat*)) NOT "storage system")

The search was also filtered to include only peer-reviewed journal articles written in English and published within the last 10 years (2008–2017).

Appendix B: Full Sample Publications and Projects

Table B1: Full sample of publications considered for the literature review

#	Title	Author(s)	Year	Citations
1	MES (multi-energy systems): An overview of concepts and evaluation models	Mancarella P	2013	136
2	Distributed multi-generation: A Comprehensive Review	Chicco G, Mancarella P	2009	367
3	Optimization in microgrids with hybrid energy systems - A review	Fathima a. H	2015	78
4	Thermoeconomic multi-objective optimization of a novel biomass-based integrated energy system	Ahmadi, Pouria; Dincer, Ibrahim; Rosen, Marc A.	2014	68
5	Modeling of energy-services supply-systems	Groscurth, Hm; Bruckner, T; Kummel, R	1995	40
6	New formulations of the 'energy hub' model to address operational constraints	Evins, Ralph; Orehounig, Kristina; Dorer, Viktor; Carmeliet, Jan	2014	16
7	Hierarchical energy management system for multi-source multi-product microgrids	Xu, Xiandong; Jia, Hongjie; Wang, Dan; Yu, David C.; Chiang, Hsiao-Dong	2015	9
8	Multiobjective optimisation of integrated energy systems for remote communities considering economics and CO2 emissions	Pelet, X; Favrat, D; Leyland, G	2005	47
9	Hybrid Energy Systems	Manwell JF	2004	17
10	The Energy Hub - a Powerful concept for future energy systems	Geidl et al	2007	29
11	Management of electricity and heating demand to match sustainable energy supply	Harb H, Matthes P	2014	3
12	Towards multi-source multi-product energy systems	Hemmes, K.; Zachariah-Wolff, J. L.; Geidl, M.; Andersson, G.	2007	48
13	A hybrid approach for the efficient synthesis of renewable energy systems	Petruschke, Philipp; Gasparovic, Goran; Voll, Philip; Krajacic, Goran; Duic, Neven; Bardow, Andre	2014	15
14	Review of software tools for hybrid renewable energy systems	Sinha S	2014	132
15	A model for the optimal design and management of a cogeneration system with energy storage	Stoppato, Anna; Benato, Alberto; Destro, Nicola; Mirandola, Alberto	2016	0
16	Integration of decentralized energy systems in neighbourhoods using the energy hub approach	Orehounig, Kristina; Evins, Ralph; Dorer, Viktor	2015	36
17	The role of decentralized generation and storage technologies in future energy systems planning for a rural agglomeration in Switzerland	Yazdanie, Mashael; Densing, Martin; Wokaun, Alexander	2016	0
18	Multi-objective Optimization for Design and Operation of Distributed Energy Systems through the Multi-energy Hub Network Approach	Maroufmashat, Azadeh; Sattari, Sourena; Roshandel, Ramin; Fowler, Michael; Elkamel, Ali	2016	2
19	A multi-objective framework for cost-unavailability optimisation of residential distributed energy system design	Wouters, Carmen; Fraga, Eric S.; James, Adrian M.	2017	0
20	An energy integrated, multi-microgrid, MILP (mixed-integer linear programming) approach for residential distributed energy system planning - A South Australian case-study	Wouters, Carmen; Fraga, Eric S.; James, Adrian M.	2015	14

21	A general methodology for optimal load management with distributed renewable energy generation and storage in residential housing	Georges, E.; Braun, J. E.; Lemort, V.	2017	0
22	Energy and exergy analyses of a new geothermal-solar energy based system	Ezzat, M. F.; Dincer, I.	2016	7
23	Efficient simulation of Hybrid Renewable Energy Systems	Migoni, G.; Rullo, P.; Bergero, F.; Kofman, E.	2016	2
24	Modeling of industrial-scale hybrid renewable energy systems (HRES) - The profitability of decentralized supply for industry	Scheubel, Christopher; Zipperle, Thomas; Tzscheutschler, Peter	2017	0
25	Operational performance of energy storage as function of electricity prices for on-grid hybrid renewable energy system by optimized fuzzy logic controller	Athari, M. H.; Ardehali, M. M.	2016	7
26	Optimal design of hybrid renewable energy systems in buildings with low to high renewable energy ratio	Sharafi, Masoud; ElMekkawy, Tarek Y.; Bibeau, Eric L.	2015	12
27	Optimized operation combining costs, efficiency and lifetime of a hybrid renewable energy system with energy storage by battery and hydrogen in grid-connected applications	Garcia-Trivino, Pablo; Fernandez-Ramirez, Luis M.; Gil-Mena, Antonio J.; Llorens-Iborra, Francisco; Andres Garcia-Vazquez, Carlos; Jurado, Francisco	2016	3
28	Techno-economic analysis of a stand-alone hybrid renewable energy system with hydrogen production and storage options	Kalinci, Yildiz; Hepbasli, Arif; Dincer, Ibrahim	2015	29
29	Performance of US hybrid distributed energy systems: Solar photovoltaic, battery and combined heat and power	Shah, Kunal K.; Mundada, Aishwarya S.; Pearce, J. M.	2015	13
30	A local energy management of a hybrid PV-storage based distributed generation for microgrids	Choudar, Adel; Boukhetala, Djamel; Barkat, Said; Brucker, Jean-Michel	2015	20
31	Performance Analysis of a Variable-speed Wind and Fuel Cell-based Hybrid Distributed Generation System in Grid-connected Mode of Operation	Ayyappa, Santhosha Kumar; Gaonkar, Dattatreya Narayan	2016	0
32	Synergy of smart grids and hybrid distributed generation on the value of energy storage	Del Granado, Pedro Crespo; Pang, Zhan; Wallace, Stein W.	2016	6
33	A multi-objective model for optimal operation of a battery/PV/fuel cell/grid hybrid energy system using weighted sum technique and fuzzy satisfying approach considering responsible load management	Majidi, Majid; Nojavan, Sayyad; Esfetanaj, Naser Nourani; Najafi-Ghalelou, Afshin; Zare, Kazem	2017	0
34	Heuristic-based power management of a grid-connected hybrid energy system combined with hydrogen storage	Rouholamini, Mehdi; Mohammadian, Mohsen	2016	0
35	Sustainability assessment of a hybrid energy system with hydrogen-based storage	Hacatoglu, Kevork; Dincer, Ibrahim; Rosen, Marc A.	2015	5
36	Energy Management of an Off-Grid Hybrid Power Plant with Multiple Energy Storage Systems	Tribioli, Laura; Cozzolino, Raffaello; Evangelisti, Luca; Bella, Gino	2016	1
37	A novel framework for optimal design of hybrid renewable energy-based autonomous energy systems: A case study for Namin, Iran	Maleki, Akbar; Pourfayaz, Fathollah; Rosen, Marc A.	2016	13

38	Robust multi-objective control of hybrid renewable microgeneration systems with energy storage	Allison, John	2017	0
39	Power to Gas-biomass oxycombustion hybrid system: Energy integration and potential applications	Bailera, Manuel; Lisbona, Pilar; Romeo, Luis M.; Espatolero, Sergio	2016	1
40	Development, analysis and performance assessment of a combined solar and geothermal energy-based integrated system for multigeneration	Islam, Shahid; Dincer, Ibrahim	2017	0
41	Modeling and optimal resources allocation of a novel tri-distributed generation system based on sustainable energy resources	Soheyli, Saman; Mehrjoo, Mehri; Mayam, Mohamad Hossein Shafiei	2017	0
42	A Dynamic Decision Model for the Real-Time Control of Hybrid Renewable Energy Production Systems	Dagdougui, Hanane; Minciardi, Riccardo; Ouammi, Ahmed; Robba, Michela; Sacile, Roberto	2010	35
43	Coordinated Control and Energy Management of Distributed Generation Inverters in a Microgrid	Tan, K. T.; So, P. L.; Chu, Y. C.; Chen, M. Z. Q.	2013	50
44	Domestic distributed power generation: Effect of sizing and energy management strategy on the environmental efficiency of a photovoltaic-battery-fuel cell system	Bruni, G.; Cordiner, S.; Mulone, V.	2014	22
45	Dynamic analysis of hybrid energy systems under flexible operation and variable renewable generation - Part I: Dynamic performance analysis	Garcia, Humberto E.; Mohanty, Amit; Lin, Wen-Chiao; Cherry, Robert S.	2013	25
46	Economic analysis of standalone and grid connected hybrid energy systems	Turkay, Belgin Emre; Telli, Ali Yasin	2011	52
47	Energy management in a microgrid with distributed energy resources	Zhang, Linfeng; Gari, Nicolae; Hmurcik, Lawrence V.	2014	53
48	Hierarchical energy management system for stand-alone hybrid system based on generation costs and cascade control	Torreglosa, J. P.; Garcia, P.; Fernandez, L. M.; Jurado, F.	2014	39
49	Multi-objective optimal design of hybrid renewable energy systems using PSO-simulation based approach	Sharafi, Masoud; ELMekkawy, Tarek Y.	2014	62
50	On Decisive Storage Parameters for Minimizing Energy Supply Costs in Multicarrier Energy Systems	Adamek, Franziska; Arnold, Michele; Andersson, Goeran	2014	14
51	Particle swarm optimization based fuzzy logic controller for autonomous green power energy system with hydrogen storage	Safari, S.; Ardehali, M. M.; Sirizi, M. J.	2013	28
52	Potential improvement to a citric wastewater treatment plant using bio-hydrogen and a hybrid energy system	Zhi, Xiaohua; Yang, Haijun; Berthold, Sascha; Doetsch, Christian; Shen, Jianquan	2010	16
53	Sustainable energy planning based on a stand-alone hybrid renewable energy/hydrogen power system: Application in Karpathos island, Greece	Giatrakos, G. P.; Tsoutsos, T. D.; Mouchtaropoulos, P. G.; Naxakis, G. D.; Stavrakakis, G.	2009	36
54	Optimal design of distributed energy system in a neighborhood under uncertainty	Akbari, Kaveh; Jolai, Fariborz; Ghaderi, Seyed Farid	2016	2
55	An operation optimization and decision framework for a building cluster with distributed energy systems	Li, Xiwang; Wen, Jin; Malkawi, Ali	2016	10
56	A linear programming approach to the optimization of residential energy systems	Lauinger, D.; Caliandro, P.; Van Herle, J.; Kuhn, D.	2016	2

57	Optimal operation of DES/CCHP based regional multi-energy prosumer with demand response	Yang, Hongming; Xiong, Tonglin; Qiu, Jing; Qiu, Duo; Dong, Zhao Yang	2016	7
58	City Energy Analyst (CEA): Integrated framework for analysis and optimization of building energy systems in neighborhoods and city districts	Fonseca, Jimeno A.; Thuy-An Nguyen; Schlueter, Arno; Marechal, Francois	2016	4
59	H2RES, Energy planning tool for island energy systems - The case of the Island of Mljet	Krajacic, Goran; Duic, Neven; Carvalho, Maria da Graca	2009	45
60	Integration of biomass into urban energy systems for heat and power. Part I: An MILP based spatial optimization methodology	Pantaleo, Antonio M.; Giarola, Sara; Bauen, Ausilio; Shah, Nilay	2014	15
61	Towards an energy sustainable community: An energy system analysis for a village in Switzerland	Orehounig, Kristina; Mavromatidis, Georgios; Evins, Ralph; Dorer, Viktor; Carmeliet, Jan	2014	16
62	Experimental results for hybrid energy storage systems coupled to photovoltaic generation in residential applications	Maclay, James D.; Brouwer, Jacob; Samuelsen, G. Scott	2011	16
63	Energy management system based on techno-economic optimization for microgrids	Garcia, Pablo; Torreglosa, Juan P.; Fernandez, Luis M.; Jurado, Francisco; Langella, Roberto; Testa, Alfredo	2016	3
64	The effectiveness of storage and relocation options in renewable energy systems	Blarke, M. B.; Lund, H.	2008	89

Table B2: Full sample of implementations / pilot projects considered in the project database

#	Name	Location
1	Aspern Seestadt	Austria
2	Project SWIVT Darmstadt	Germany
3	Fort Collins Microgrid	Colorado, USA
4	Greencity Zurich	Wollishofen, Switzerland
5	LEXU II	Saarland University, Germany
6	Monitoring Willibald-Gluck-Gymnasium	Neumarkt, Germany
7	St. Franziskus Grundschule	Germany
8	Klimaneutraler Campus Leuphana University of Lüneburg - Scharnhorststraße / Bockelsberg	Hansestadt Lüneburg, Germany
9	Oberfeld	Bern, Switzerland
10	Reka Holiday Village Blatten-Belalp	Belalp, Switzerland
11	“Am Steinweg“ estate	Stutensee, Germany
12	San Agustín del Guadalix	Spain
13	Energiepark Clausthal	Germany
14	Wind/hydrogen demonstration system at Utsira Norway	Utsira, Norway
15	STORIES project	Corvo Island, Portugal
16	Porto Santo	Portugal
17	Karpathos Island	Greece
18	Mawson Hydrogen Demonstration Project	Antarctica
19	PHOEBUS Demonstration Plant	Jülich, Germany
20	SHEPL	Misurata, Libya
21	Hawaii Hydrogen Power Park	Hawaii, USA
22	CESI RICERCA DER Test Facility	Milan, Italy
23	Energieautarkes MFH Brutten	Brutten, Switzerland
24	Energieautarker Ortsteil Feldheim	Feldheim, Germany
25	PowerMatchingCity - phase 2	Groningen, Netherlands
26	Creative Homes Nottingham	Nottingham, England
27	Linear-Smartgrid demonstration	Flanders, BEL
28	HARI project - West Beacon Farm	Leicestershire, UK
29	DTE Energy Hydrogen Technology Park	Michigan, USA
30	PURE Project	Unst, UK
31	Wind2H2 Project	Boulder, Colorado, USA
32	Hydrogen Community Lolland-Phase 3 in Vestenskov	Lolland, Denmark
33	Hydrogen energy research and demonstration centre at Baglan Energy Park	Swansea, UK
34	HARP system - Bella Coola	British Columbia, Canada
35	Hybrid PowerPlant Enertrag	Prenzlau, Germany
36	Hydrogen Mini Grid System Environmental Energy Technology Centre	Yorkshire, UK

37	H2Herten	North Rhine-Westphalia, Germany
38	RH2 WKA	Grapzow/Mecklenburg-Vorpommern, Germany
39	H2Ber - New Berlin Brandenburg Airport	Brandenburg, Germany
40	INGRID Hydrogen Demonstration Project	Puglia, Italy
41	Irvine Smart Grid Demonstration- Residential units	California, USA
42	Aichi-Central Japan Airport City	Aichi, Japan
43	Smart Region Pellworm	Pellworm, Germany
44	Encinitas Civic Center	California, USA
45	SmartGrid Gotland	Gotland, Sweden
46	Rosa Zukunft (SmartCity Salzburg)	Salzburg, Austria
47	Kitakyushu Smart Community Project	Kitakyushu, Japan
48	Marstal-District Heating Network SUNSTOR4	Marstal, Denmark
49	Low Carbon Networks Fund submission from Western Power Distribution - BRISTOL	Bristol, UK
50	MVV - StromBank	Mannheim-Rheinau, Germany
51	Hydrogen Project Office-Bright Green Hydrogen	Methil, Scotland
52	Sendai Microgrid	Sendai, Japan
53	Santa Rita Jail-Microgrid	California, USA
54	University of Californa San Diego Microgrid	California, USA
55	Solar-Wasserstoff-Bayern GmbH (SWB)	Neunburg vorm Wald, Germany
56	Aperture Center Mesa Del Sol	New Mexico, USA

Article II

Published in *Environmental Science & Technology* **2018** *52* (4), 2339-2348
DOI: 10.1021/acs.est.7b02686

How, When, and Where? Assessing Renewable Energy Self-Sufficiency at the Neighborhood Level

David Grosspietsch*, Philippe Thömmes, Bastien Girod, and Volker H. Hoffmann

ETH Zurich
Department of Management, Technology, and Economics
Weinbergstrasse 56/58, 8092 Zurich, Switzerland

* Corresponding author
Phone: +41-44 633 88 91
Email: dgrosspietsch@ethz.ch

Copyrights and Permissions

Abstract

Self-sufficient decentralized systems challenge the centralized energy paradigm. Although scholars have assessed specific locations and technological aspects, it remains unclear *how*, *when*, and *where* energy self-sufficiency could become competitive. To address this gap, we develop a techno-economic model for energy self-sufficient neighborhoods that integrates solar photovoltaics (PV), conversion, and storage technologies. We assess the cost of 100% self-sufficiency for both electricity and heat, comparing different technical configurations for a stylized neighborhood in Switzerland and juxtaposing these findings with projections on market and technology development. We then broaden the scope and vary the neighborhood's composition (residential share) and geographic position (along different latitudes). Regarding *how* to design self-sufficient neighborhoods, we find two promising technical configurations. The "PV-battery-hydrogen" configuration is projected to outperform a fossil-fueled and grid-connected reference configuration *when* energy prices increase by 2.5% annually and cost reductions in hydrogen-related technologies by a factor of 2 are achieved. The "PV-battery" configuration would allow achieving parity with the reference configuration sooner, at 21% cost reduction. Additionally, more cost-efficient deployment is found in neighborhoods *where* the end-use is small commercial or mixed and in regions *where* seasonal fluctuations are low and thus allow for reducing storage requirements.

Keywords

Decentralized energy system, renewable energy, storage technologies, techno-economic modeling, energy self-sufficiency, energy autarky

Highlights

- Cost of solar-powered self-sufficient energy supply to a neighborhood is assessed.
- *PV-battery-heat pump (HP)* and *PV-battery-*H_2*-HP* are feasible configurations.
- *PV-battery-HP* turns profitable at medium energy price increases and 21% techn. cost reductions.
- Locations with low seasonality and a high share of commercial usage lower costs.

1 Introduction

The energy sector has experienced a major shakeup in recent years because of the sharp decline in the cost of renewable generation technologies, in particular wind and solar photovoltaics (PV). The low variable costs and intermittent nature of renewable energy sources (RES) along with their deployment in decentralized settings by prosumers (i.e., agents that both produce and consume energy (Parag and Sovacool, 2016)), could pose significant challenges to the energy sector in general, and to the power sector in particular (Kassakian and Schmalensee, 2011; von Meier, 2014), potentially undermining today's business models for utilities (Alanne and Saari, 2006; Burger and Weinmann, 2013; Richter, 2013). Decentralized production by RES disables the unidirectional grid flow and lowers the energy amount delivered by utilities, thus rendering many of their existing assets and capabilities obsolete, and requiring them to change their way of producing, distributing, and selling energy (Burger and Weinmann, 2013; Richter, 2013, 2012).

The industry's shakeup could escalate to another level if prosumers at various levels—from building to neighborhood to district/region—are disconnected from a superordinate grid and operate fully self-sufficient units with RES (Bronski et al., 2014; Schleicher-Tappeser, 2012). Self-sufficiency brings a new value proposition to the market by satisfying the need for reliability/resilience, cleaner energy, and better economics, and by overcoming utility/grid frustration and regulatory changes (Bronski et al., 2014). Fully decoupled from the prevalent infrastructure, self-sufficient units could disrupt the current business logic of utilities and grid operators alike (Agnew and Dargusch, 2015; Burger and Weinmann, 2013; PricewaterhouseCoopers (pwc), 2013). With partial self-sufficiency and the necessary grid connection, utilities retain their power to demand higher charges for grid access. With full self-sufficiency, however, the utilities' claim on grid access and power supply charges would lose its functional justification. As a result, infrastructure costs would need to be allocated to fewer customers, which would increase the grid costs per kilowatt hour delivered, an effect that would be reinforced as more and more units in the system became fully self-sufficient.

The essential technologies required for self-sufficiency in decentralized settings, i.e., RES and storage technologies, have experienced significant cost declines over the past decade. For instance, PV module prices decreased by about 70% between 2010 and 2014 and are soon likely to render solar PV profitable without subsidies (Barbose and Darghouth, 2016; Feldman et al., 2014; Vaishnav et al., 2017). These massive price declines, in turn, induce further deployment. Technological learning, that is, technology cost decreases with cumulative produced or installed capacity, can be observed for solar PV and is projected for battery storage in a similar vein (Crabtree et al., 2015; Nykvist and Nilsson, 2015).

Few studies have investigated the conditions under which the concept of energy self-sufficiency could become a competitive alternative to the current paradigm of energy supply. Scholars have discussed the general concept of energy self-sufficiency (or *energy autarky*, *energy independence*, or *energy autonomy*) from various disciplines and perspectives (Mueller et al., 2011; Rae and Bradley, 2012). The more specific idea of self-sufficient systems has been studied using different spatial perspectives (e.g., buildings to regions) and with varying technological or methodological scope (Mancarella, 2014; McKenna et al., 2017). At the same time, the economic performance of self-sufficient systems remains controversial (Giatrakos et al., 2009; Krajacic et al., 2011), especially as most studies analyze a particular site or case, i.e., a certain scale and location, or a given technological focus. A variety of pilot projects and initiatives for self-sufficient systems have already been implemented (Mueller et al., 2011; Rae and Bradley, 2012), but they are oftentimes characterized by rationales other than purely economic and environmental ones (Patel et al., 2016; Rae and Bradley, 2012). However, there has not yet been a systematic study that examines how to equip these systems, at what point they would become economically feasible, and where to best apply them.

Our article addresses this gap in the literature on a more abstract level. We first evaluate *how* self-sufficient systems can be composed in a cost-efficient way and which technologies to employ. Second, we assess if and *when* these systems could become a viable alternative to a grid-connected reference. Third, we investigate *where* their deployment could be more cost-efficient due to different end-use and geographic factors, such as solar irradiation.

We evaluate a system in the context of small-size neighborhoods (i.e., residential and small office buildings) and undertake three types of analysis: (1) On the basis of a review of the literature and existing pilot projects, we conduct expert interviews to identify feasible technical configurations that are close to market introduction. We build on this to develop a techno-economic model to conduct a simulation for a stylized neighborhood in Switzerland. We assess its economic performance from an investor perspective for different technical configurations, including the selection of technologies and their optimal sizing. (2) We complement these findings by analyzing the effect of projected increases in energy prices and potential reductions in technology costs. In this way, we scrutinize their impact on the competitiveness of a self-sufficient neighborhood compared to an on-grid reference configuration. (3) In order to account for temperature- and irradiation-induced seasonality, we broaden the geographical scope by assessing the performance of the stylized neighborhood along varying latitudes. Furthermore, we adjust the composition of the neighborhood to cope with different forms of end-use, from residential to small commercial consumers.

The remainder of this article is structured as follows: Section 2 describes our methodology. We then present and discuss our results in section 3.

2 Materials and Methods

2.1 Model Design and Logic

The challenge posed by seasonal and diurnal mismatches of local energy supply by RES to its consumption calls for flexibility measures, such as demand-side management or storage. In particular, storage technologies can cope with these mismatches by bridging the temporal gap and shifting energy from times of generation to times of actual use (Battke et al., 2013). Moreover, the conversion of different energy carriers and their storage is considered promising (Mancarella, 2014). In this way, a surplus from one energy carrier (e.g., electricity, gas) can compensate for a shortage from another by converting to the type of energy that is demanded at a particular time.

To determine the economic performance of different technical configurations, we developed a Matlab-based, techno-economic model that simulates an energy self-sufficient neighborhood, including the required capital investment and future cash flows. The model extends an existing PV self-consumption model by Lang et al. (Lang et al., 2015a, 2016), and can be structured into (1) input data, (2) simulation logic, and (3) output data, as shown in Figure 1.

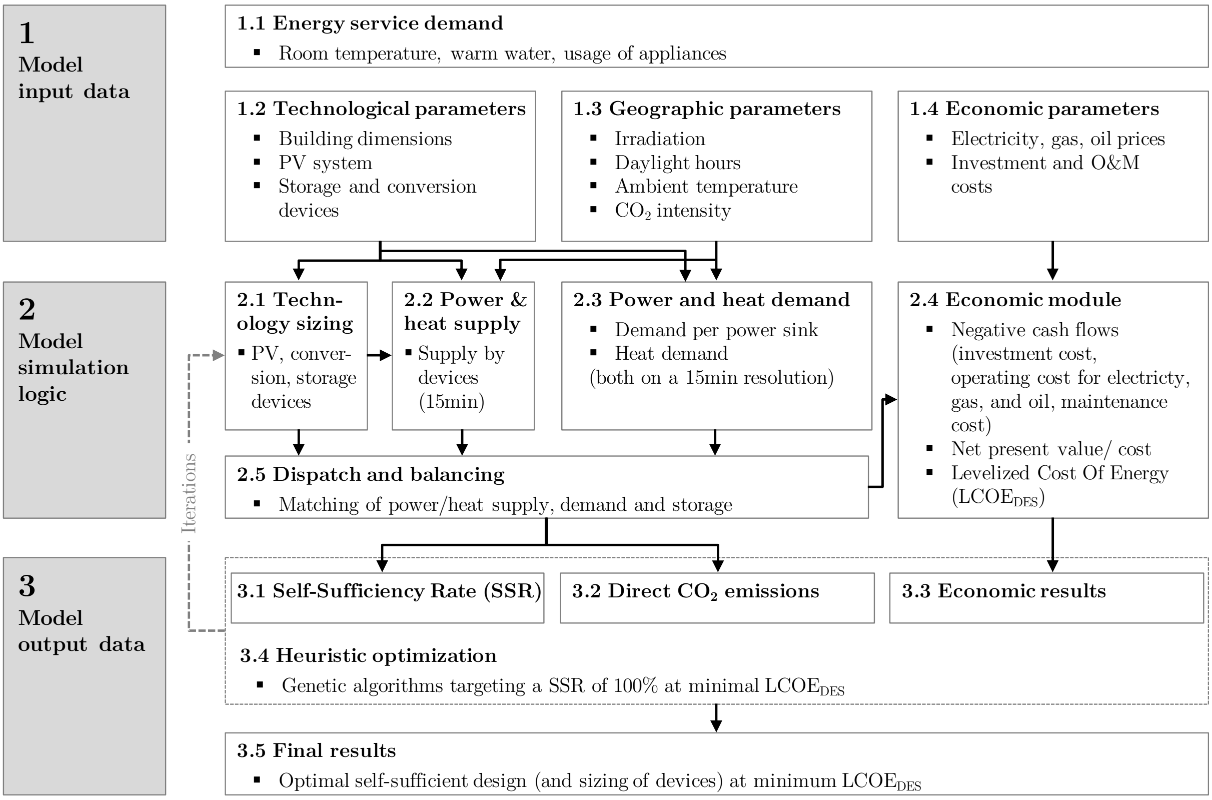


Figure 1: Structural overview of the techno-economic model. (Numbers refer to the subsections of the Supporting Information (SI) 'techno-economic model' (A))

On the input side, regarding the demand, the focus is on the neighborhood level. We consider mixed end-usage, i.e., a combination of residential and small commercial units, since they exhibit different demand patterns. Regarding technologies, we restrict our analysis to solar PV as RES technology because it can be easily deployed in buildings and decentralized settings and is considered the most cost competitive with further projected cost decreases (de La Tour et al., 2013). Besides solar PV, building-related aspects and both storage and conversion devices complete the technological parameters. Geographic parameters (e.g., irradiation data, temperature) and economic parameters (e.g., energy prices, investment cost) complement the input side of the model.

Fed by all input parameters, the simulation of the model is initialized by the sizing of technologies (PV, conversion, storage) which then determines power and heat supply for every 15 min throughout a full year. In parallel, the neighborhood's temporal profiles for power and heat demand are simulated with the same timely resolution. Consequently, during the dispatch energy supply and demand are balanced on a 15 min basis throughout the year, where PV power is used to meet demand whenever available. The residual power, remaining demand or PV excess, is then provided or absorbed by the storage options. Following the dispatch, the economic module employs the concept of Levelized Costs of Energy (LCOE) (Darling et al., 2011) to compute the economic performance in an adapted approach of "Levelized Costs of Energy for Decentralized Energy Systems" ($LCOE_{DES}$). $LCOE_{DES}$ are defined as the total discounted costs of a decentralized energy system divided by its discounted energy demand. The $LCOE_{DES}$ comprise initial investment costs and cash flows (e.g., operations and maintenance (O&M), replacement costs) for generation, storage, and conversion technologies discounted over the investment period.

On the basis of a single full year simulation, the model derives three output indicators: Self-Sufficiency Rate (SSR), direct CO_2 emissions, and the costs of energy provision (in $LCOE_{DES}$). With the objective function of minimizing $LCOE_{DES}$ subject to a SSR of 100%, the model uses genetic algorithms to iteratively adapt the technology sizing, thus exploring an optimal solution. Genetic algorithms are applied because they qualify as a metaheuristic approach to coping with the complex problem of a nonlinear and highly multimodal objective function (see Supporting Information (SI) A3.4) (Ahmadi et al., 2014; Li et al., 2006). The optimal technology sizing and $LCOE_{DES}$ of the self-sufficient neighborhood are then displayed in the final results.

2.2 Context and Parametrization

The starting point for our evaluation is the techno-economic performance of a stylized neighborhood at the selected location of Bern, Switzerland. We chose the Swiss context due to its central location in Europe. In addition, the economic and political environment seems to favor innovative decentralized solutions, and a variety of pilot and lighthouse projects already exist in Switzerland. Later in the analysis, we broaden the geographical scope to examine the influence of seasonal fluctuation—in solar irradiation and ambient temperature—that shapes energy demand and power production.

We start our analysis by defining a stylized neighborhood that aggregates multiple buildings of three generic types, i.e., single-family houses (SFH), multifamily houses (MFH), and small office buildings

(SOB) (Lang et al., 2015a, 2016). In order to define a suitable composition, that is, mix of building types and end-use within the neighborhood, we evaluated a set of 56 global decentralized energy systems and analyzed the 20 certified Swiss "2000-Watt Sites" (Heinrich Gugerli, 2017). Within the typical range of our project observations, our neighborhood is composed of three SFHs, three MFHs, and one SOB, with accumulated load profiles for each building type. The annual energy demand of this neighborhood, located in Bern, Switzerland, sums up to 115.5 MWh_{el} of electricity demand and 388.9 MWh_{th} of heat demand. Later in our analysis, we provide an additional step to begin widening the scope from this specific setup to explore the influence of the neighborhood's composition on the economic performance more generally by varying its ratio of residential to small office buildings (*where* question), an important factor as each type is differently suited to match local PV production (Lang et al., 2016).

Each of the considered building types is mainly characterized by building-specific features, electric appliances and their usage patterns, room temperature, as well as the corresponding heat flows, which influence the calculation of electricity and heat demand. The model simulates synthetic load curves for electricity and heat for each building type on a 15 min resolution throughout a full year. The temporal demand profiles are based on the simulation of the building demands of the so-called "Household Model for Intelligent Energy supply and use (HoMIE)" (Lang et al., 2016, 2015b; Ossenbrink, 2017). Technology data incorporates all operational parameters, such as efficiency or cycle lifetime, that are important to characterize the considered technologies. Economic data includes market prices for energy as well as the investment period and the discount rate (7%). The development of future energy prices is based on projections by the U.S. Department of Energy's Annual Energy Outlook 2015 (U.S. Energy Information Administration (EIA), 2015). Economic assumptions for the technologies encompass upfront investment costs and O&M costs, as well as replacement costs for specific technologies with a shorter lifetime than the whole system's lifetime. Planning and installation expenses are excluded due to their site specificity. Table 1 provides an overview of selected model-related parameters and assumptions regarding building, technology, and economic information. The comprehensive set of assumptions is given in the SI (A 1.1–1.4).

Table 1: Selection of model-related parameters and assumptions to provide an overview of building, technology, and economic information. (The data below is only an excerpt of the full range of information, which can be found in the SI.)

Building

	Parameter	Unit	SFH	MFH	SOB
Characteristics	L x W x H	m	10 x 7 x 6	20 x 9 x 14	22 x 15 x 10
	Number of stories	-	2	5	3
	Total floor area	m^2	150	900	1000
	Window share	%	30	30	60
	Roof area	m^2	80	180	330
	Number of people	-	4	20	90
Energy service demands	Power demand p.a.	MWh_{el}	3.0	19.1	49.4
	Heat demand p.a.	MWh_{th}	19.6	79.2	92.5
	Room temperature	°C	23		
	Hot water	liter	50-70 (at 60°C/person/day)		5-7
	Daily lighting	-	1223 Wh / day		76 Wh/m^2
	Fridge/freezer	-	274 / 329 Wh/day/party		274 Wh/day
	ICT		1223 Wh /day		69.3 Wh/m^2
	... .. .				

Technology

	Parameter	Unit	Value
PV (cryst. silicon)	Angle Correction Factor	-	1.15
	Performance Ratio	%	20
	Module Efficiency	-	0.85
	Lifetime	a	10
Battery (Lithium-ion)	Capacity	kWh	10
	Power	kW	3.3
	Efficiency	%	92
	DoD	-	0.8
	Lifetime	a	10
	Cycle Lifetime	-	10,250
Fuel Cell (PEM)	Therm. Effic.	%	42
	Electr. Effic.	%	50
	Lifetime	a	15
	Cycle Lifetime	-	40,000
	... .. .		

Economic

			Unit	Value
Market parameters		Electricity Price	EUR/kWh	0.17
		Gas Price	EUR/kWh	0.07
		Oil Price	EUR/kWh	0.09
		Investment horizon	years	40
		Discount rate	%	7.0
Technology parameters	**PV** (cryst. silicon)	Investm. Cost	EUR/kW	451.57
		BOS	EUR/kW	901.89
		O&M Cost	%	1.5
	Battery (Li-ion)	Investm. Cost	EUR/kW	322.48
		BOS	EUR/kW	141.76
		O&M Cost	EUR/kW	20.66
	Fuel Cell (PEM)	Investm. Cost	EUR/kW	$= 6{,}506 \cdot P_{inst.}^{-0.18}$
		BOS	%	20
		O&M Cost	%	10
		... .. .		

On the supply side, local solar irradiation data are sourced from NASA for every quarter of an hour over a full year (National Aeronautics and Space Administration (NASA), 2012), and subsequently used for the computation of available electricity yield by the solar PV plant. To account for a reference configuration, we include the option to source electricity from the local grid and to draw heating oil from a tank. As we aim to assess the general impact of seasonality (in the *where* question), we alter latitude-dependent environmental data, that is, irradiation (National Aeronautics and Space Administration (NASA), 2012), temperature and daylight hours (U.S. Department of Energy, 2013).

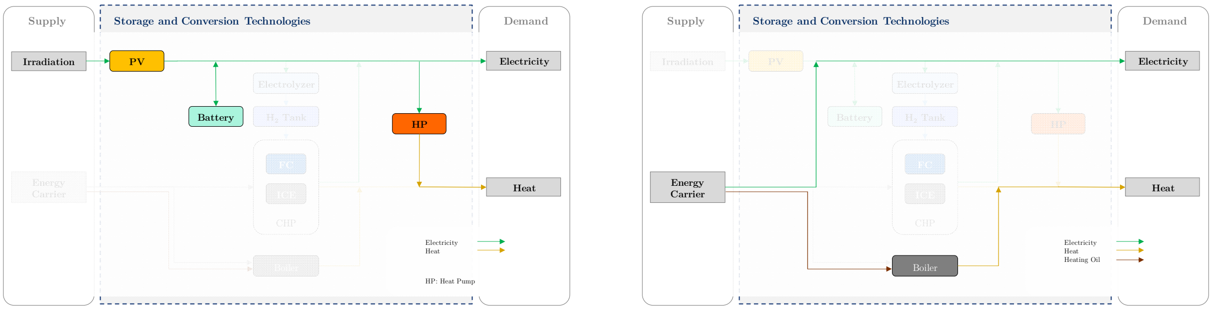
In addition to a literature-based approach for the parametrization of the model, we conducted 13 interviews with experts from academia and industry to (i) triangulate and validate specific assumptions, input parameters, and preliminary results, and (ii) distill interesting technical configurations for the analysis, i.e., addressing the *how* question (see SI "experts interviews" (B)). Apart from interviews, our modeling benefitted from close interaction and iterative development with academic experts on some of the individual technologies and their integration who partook in the research project.

3 Results

We report and discuss *how* (3.1), *when* (3.2), and *where* (3.3) renewable energy self-sufficiency at the neighborhood level can become economically feasible and what alternative pathways are (3.4).

3.1 *How*: Examining Technical Configurations

On the basis of the existing literature and expert interviews, four technical configurations evolved for our analysis. Figure 2 displays these configurations, along with their technical devices and energy flows.


I «PV-battery-HP» **Ref** «Grid-oil»

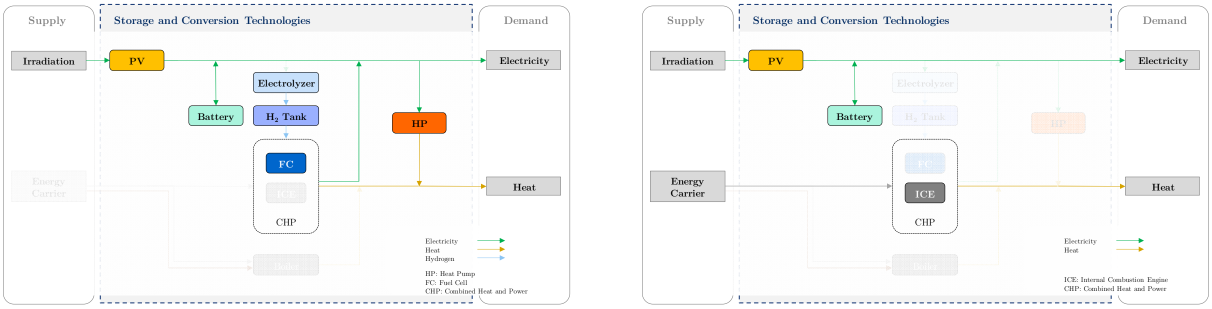
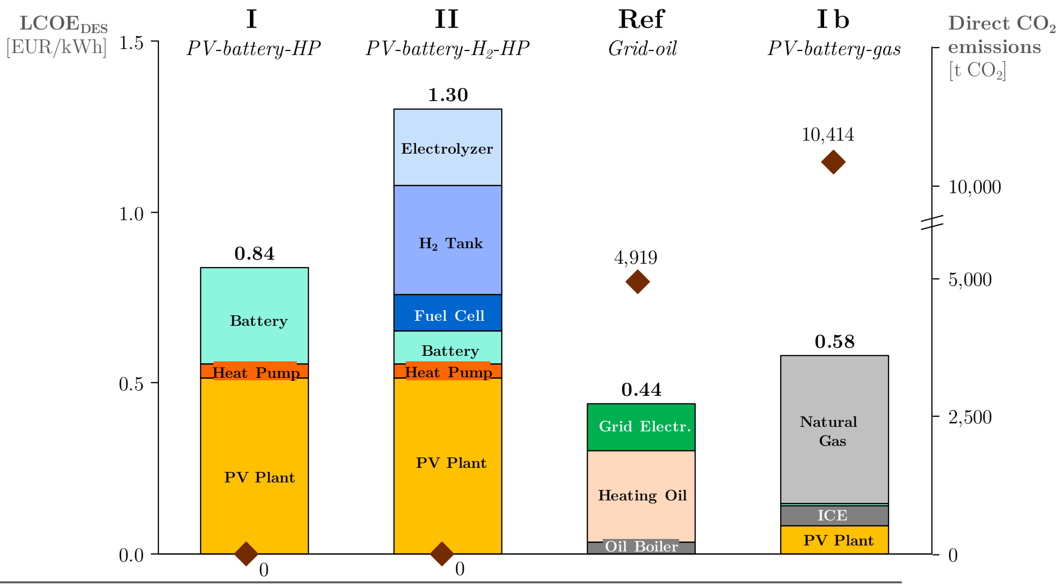

II «PV-battery-H_2-HP» **Ib** «PV-battery-gas»

Figure 2: Overview of technical configurations (I, II, Ref, Ib), their technical devices (i.e., storage and conversion technologies), and energy flows. (Acronyms: PV = Photovoltaics, HP = Heat Pump, H_2 = Hydrogen, FC = Fuel Cell, ICE = Internal Combustion Engine)

We identify two dominant configurations for achieving a fully independent, renewable self-sufficient energy supply at the neighborhood level. The first configuration (“PV-battery-HP”) relies solely on batteries for storage technology and supplies the heat by means of a heat pump (HP). The second configuration (“PV-battery-H_2-HP”) adds hydrogen (H_2) storage to complement the battery storage. The latter is a promising configuration that is observed in pilot projects and discussed in the literature (Abdin et al., 2015; Bernal-Agustín and Dufo-López, 2010; Castañeda et al., 2013; Dufo-López and Bernal-Agustín, 2008; Gahleitner, 2013), and it splits storage requirements technically into diurnal and seasonal components. The *PV-battery-H_2-HP* configuration requires further technical devices, such as an electrolyzer to convert power to hydrogen, hydrogen storage tanks, and a fuel cell to reconvert hydrogen to electricity with heat as a byproduct. We compare the self-sufficient configurations to a conventional, grid-connected configuration, the reference one (ref “Grid-oil”). This configuration sources electricity from the grid and uses an oil-fired heating boiler, the predominant configuration in the existing Swiss building stock.

An alteration to the first configuration is Ib (“PV-battery-gas”), which has been discussed in the literature and practice in recent years (Perez et al., 2016). It relies on a natural gas-based combined heat and power (CHP) solution that uses an internal combustion engine (ICE) to cosupply heat and electricity, and additionally benefits from a small battery to compensate for demand peaks. This configuration relies on the provision of natural gas, either by making use of an existing gas grid infrastructure, on-site production (e.g., biogas), or through its storage (e.g., tanks, caverns). Given its gas dependence, *PV-battery-gas* cannot be considered a fully autarkic configuration in the strict sense, which is why we report its results in this section but disregard it in the subsequent result sections.

Figure 3 presents the technology sizing of each technical configuration, as well as the $LCOE_{DES}$. It reveals that configurations I and II require both a high electricity supply by the PV plant and large storage capacities to cope with the typical Swiss seasonality of energy demand. Specifically, the large PV installation of 893 kW peak power, which exceeds the available rooftop area, is due to fulfilling the demand peaks during winter daylight hours from the PV plant. However, rising module efficiencies resulting in higher yields, combined with facades that contribute to solar gains via building-integrated PV and higher efficiency standards to lower the buildings’ or neighborhood’s overall energy demand, can alleviate this situation in the future. In configuration I, the battery system needs to be sized extensively to bridge the seasonal gap, thus accounting for about one-third of the total cost. Comparing $LCOE_{DES}$ of the two genuinely self-sufficient configurations (I and II) using commercially available technologies shows that both are more than twice as expensive as the reference configuration but produce zero direct CO_2 emissions (compared to ref and Ib). Moreover, the cost of *PV-battery-HP* is 35% lower than the hydrogen-based configuration. The PV power plant itself accounts for an important share of the total cost, with 61% (I) and 39% (II) respectively. In the hydrogen-based configuration, the storage and conversion technologies have higher costs than the PV plant and comprise the three main components of the hydrogen system: Hydrogen tank (25%), electrolyzer (17%), and fuel cell (8%).



Technologies	PV Plant [kW$_p$]	893	893	-	112
	HP / Boiler / ICE [kW$_{th}$]	111.5 (GS)	111.5 (GS)	111.5 (Boiler)	111.5 (ICE)
	Battery [kW]/ [kWh]	330 / 1100	111/ 370	-	9/ 30
	Electrolyzer [kW]	-	170 kW	-	-
	H$_2$ Tank [Nm^3]	-	191 Nm^3	-	-
	Fuel Cell [kW]	-	27 kW	-	-
System	Discount rate [%]	7	7	7	7
	System lifetime [years]	40	40	40	40
	SSR [%]	100	100	0	100[a]
	Mitigation cost [EUR/t CO$_2$][b]	216.21	466.12	-	-68.38

[a] Still, provision of natural gas needed, thus not considered as fully autarkic mode.
[b] Cost-effectiveness in terms of money per CO$_2$ emissions avoided compared to Ref.

Figure 3: LCOE$_{DES}$ split, direct CO$_2$ emissions, and technology sizing for the four technical configurations: I, II, Ref, and Ib. (Acronyms: LCOE$_{DES}$ = Levelized Cost of Energy for Decentralized Energy Systems, PV = Photovoltaics, HP = Heat Pump, GS = Ground-Sourced, ICE = Internal Combustion Engine, H$_2$ = Hydrogen, SSR = Self-Sufficiency Rate)

From an economic perspective, the discount rate is an important factor with a strong impact on the overall performance. For the presented results, we chose a conservatively high discount rate (7%), which favors the reference configuration with its constant negative cash flows for energy purchase, both electricity and heating oil. A drop in the discount rate by two percentage points, for instance, improves the economic performance of configurations I and II compared to the reference configuration (factor 1.49, instead of 1.91, higher costs for configuration I than the reference configuration, and factor 2.36, instead of 2.97, for configuration II compared to the reference configuration). The most sensitive technology-related parameter is the investment cost, which has the highest impact on the economic performance. With a weaker overall effect, the technology lifetime is the second most sensitive technical parameter (see SI "sensitivity analysis" (C)).

Since the *PV-battery-HP* system exhibits lower costs than the *PV-battery-H$_2$-HP* system, cost-optimal sizing by the genetic algorithm results in zero component sizes for the hydrogen devices. Therefore, in configuration II, we assume a PV plant size identical to configuration I, and we limit the battery size to a capacity large enough to cope with diurnal fluctuations.

3.2 *When*: Investigating Technology and Market Development

Energy prices and technological learning are major factors that influence the point at which self-sufficient systems will become cheaper than the grid-connected reference configuration. On the one hand, energy prices strongly determine the cost of the reference configuration. These costs are prone to variation and could increase in the future because of rising electricity and fossil fuel prices or because of policy measures, such as environmental taxes or regulations. On the other hand, technological learning strongly affects the technology-intense configurations *PV-battery-HP* and *PV-battery-*H_2*-HP*, as solar PV, battery, and hydrogen technologies are the largest contributors to total costs for these configurations. Costs for all these technologies are expected to decline because of further technological learning (both learning by doing and learning by researching) (Crabtree et al., 2015; Feldman et al., 2014; Körner, 2015; Nykvist and Nilsson, 2015; Rubin et al., 2015; Schoots et al., 2008; Tsuchiya, 2004).

Figure 4 illustrates how costs for the three configurations under consideration (I, II, and ref) depend on these two factors. Specifically, the indifference curve for both self-sufficient configurations I and II represents LCOE_{DES} equality to the reference configuration.

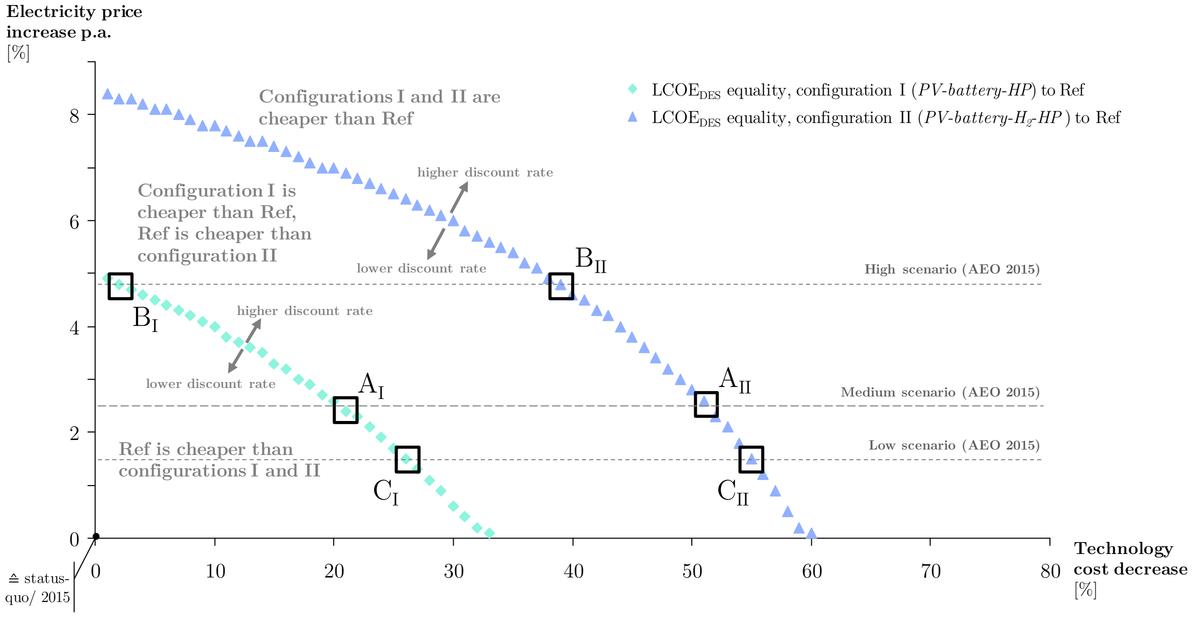


Figure 4: Indifference curve of Ref to configuration I and Ref to configuration II (LCOE_{DES} equality) with development of technology costs (aggregated over all technical components) and electricity price. The oil price increase is set to AEO's medium scenario of 2.52% per annum. The underlying discount rate is set to 7%

We find that self-sufficient configurations would become competitive under a medium energy price scenario (both for electricity and heating oil) of the Annual Energy Outlook (AEO) (U.S. Energy Information Administration (EIA), 2015) and a decrease in technology costs by 21% for *PV-battery-HP* (see A_{I}) and 51% for *PV-battery-*H_2*-HP* (A_{II}) from 2015 cost levels. AEO's high electricity price scenario would render these two configurations competitive at even lower technology cost reductions of 2% for *PV-battery-HP* (B_{I}) and 39% for *PV-battery-*H_2*-HP* (B_{II}), whereas the AEO's low electricity price scenario would require technology cost reductions of 26% for *PV-battery-HP* (C_I) and 65% for *PV-battery-H₂-HP* (C_{II}), respectively. In general, such cost reductions are possible, as we briefly illustrate for AEO's medium scenario.

On the basis of projections from the scientific literature on annual learning rates—PV cost decreases of 5.5% per annum according to IRENA (International Renewable Energy Agency) (IRENA, 2016) and 7% for the lithium-ion battery (Nykvist and Nilsson, 2015)—configuration I could achieve the required 21% in cost reduction (A_I in Figure 4) to draw level with the reference configuration within four years from start of operation. As hydrogen technologies are in an earlier phase of development, these cost projections are more challenging to make (Decourt et al., 2014). Still, cost parity with the reference configuration (51% cost reduction, see A_{II}) could be reached if technological learning during production combined with the use of the technologies translates into sufficient cost reductions. On the basis of estimated technological learning coefficients of 20% for the alkaline electrolyzer and the proton exchange membrane fuel cell, as well as 10% for the pressurized storage tanks, this would require an increase in cumulative deployed capacity by 2 orders of magnitude. Such a development seems plausible based on observations from technologies at similar maturity levels and might render hydrogen-based solutions cheaper than the *PV-battery-HP* configuration in the long run (Danish Energy Agency, 2016; Decourt et al., 2014; Grübler et al., 1999; Körner, 2015). In addition to energy prices and technology costs, the discount rate also influences the indifference curve. As presented in Figure 4, the competitiveness of self-sufficiency systems is accelerated with lower discount rates and delayed with higher discount rates.

Figure 4 allows us to estimate the impact on the competitiveness of various other scenarios for increasing energy prices or decreasing technology costs. Among them, policy measures can promote or hinder the development of self-sufficient systems directly (e.g., technology push or demand pull measures (Nemet, 2009)) or indirectly (e.g., increase in electricity price) by worsening the reference configuration. It is worth mentioning that the reference configuration might also enhance its own economic performance, e.g., via the sailing ship effect (efficiency gains in established boiler technology), through hybrid solutions (grid-connected PV prosumers), or by upgrading from fossil-based to state-of-the-art heating (heat pumps).

3.3 *Where*: Exploring End-Use Composition and Seasonality

We examine the *where* question by changing (1) the neighborhood type and (2) the geographic location. First, we discuss the neighborhood type with respect to composition and size. We find purely commercial usage–in our case, small office-buildings–as the most suitable, as their load profiles exhibit higher overlap to PV generation profiles than a purely residential composition. This allows a reduction in peak capacity, and therefore lower costs for storage and conversion devices. Accordingly, mixed-use compositions exhibit lower costs than residential-only compositions. Size is another element of neighborhood type that has an economic impact. The larger the neighborhood size (within the scale of a low voltage, local distribution grid), the lower the $LCOE_{DES}$. This is due to two factors: (1) economies of scale in the procurement and maintenance of technology, and (2) leveling out of demand profiles for individual users. The latter is in line with previous studies that demonstrate the considerable impact demand profiles have on overall performance as a result of their effect on technical configuration and sizing (Söderman and Pettersson, 2006; Ulleberg et al., 2010).

Second, the seasonal fluctuation exhibits a strong impact on the selection and sizing of technologies. We find that in locations with lower latitudes (equatorial areas) the seasonal influence is not prominent, which allows the battery to close short-term power deficiencies. By contrast, in regions with higher latitudes (toward the polar circles), strong seasonal fluctuations render the configuration of battery complemented by hydrogen storage (II) more cost-efficient at bridging the seasonal gap than the battery only configuration (I).

To account for both of these aspects, we calculated LCOE_{DES} for the reference configuration *Grid-oil* and the two self-sufficient ones, *PV-battery-HP* and *PV-battery-H_2-HP*, at selected compositions [residential share in %] and latitudes [Northern latitude in °]. The results shown in Figure 5 point to a composition- and location-specific fit for each technical configuration, e.g., revealing small office and mixed-use as economically superior to solely residential applications (Figure 5A), and rendering *PV-battery-H_2* economically more attractive than *PV-battery* at latitudes with high seasonality, here 64.5° (Figure 5B). Beyond that, higher seasonality generally results in higher costs for running a neighborhood self-sufficiently.

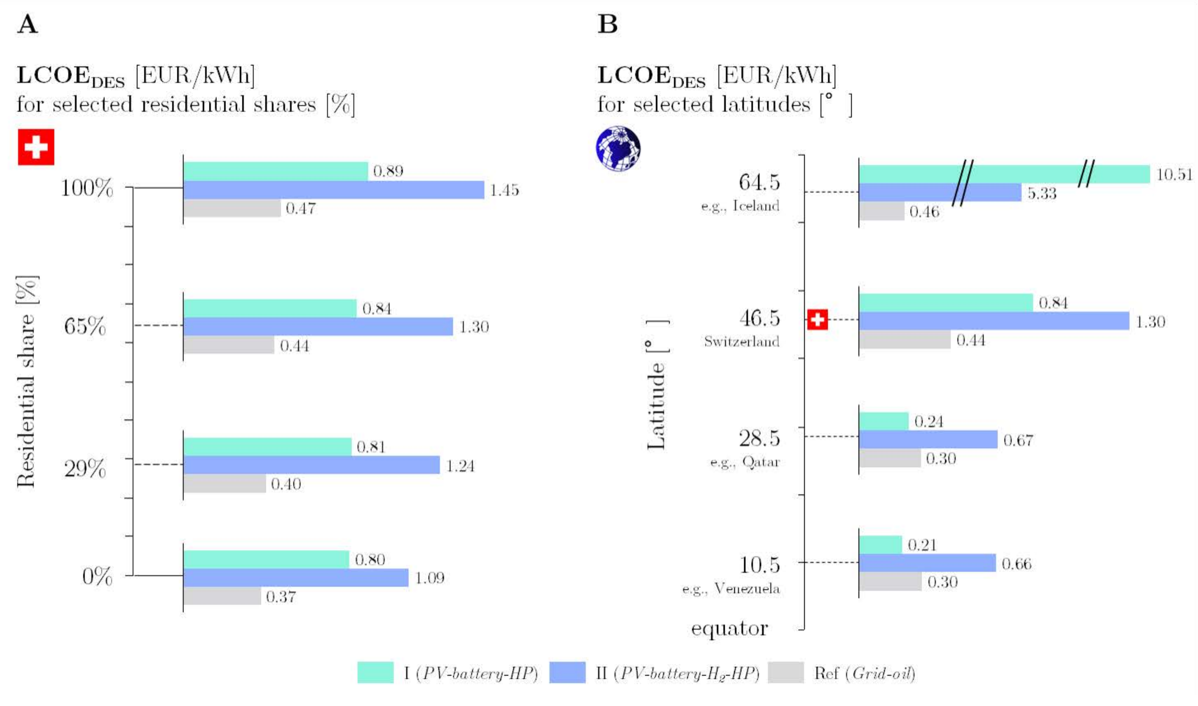


Figure 5: (A) Comparison of LCOE_{DES} for configurations I, II, and Ref at selected residential shares, by aggregating the three building types (SFH, MFH, SOB) to different combinations (100% = 7 SFHs + 4 MFHs, 65% = 3 SFHs+ 3 MFHs + 1 SOB, 29% = 3 SFHs + 1 MFH + 2 SOBs, 0% = 3 SOBs) at the location of Bern, Switzerland. (B) Comparison of LCOE_{DES} for configurations I, II, and Ref at selected latitudes in the Northern hemisphere (64.5° = Reykjavik, Iceland, 46.5° = Bern, Switzerland, 28.5° = Doha, Qatar, 10.5° = Caracas, Venezuela) for the stylized neighborhood of 3 SFHs, 3 MFHs, and 1 SOB

The geographical application of this study is limited because economic parameters are not adjusted to a specific location (e.g., energy prices, regulations), which is why the relative trend of the results in Figure 5 is more meaningful and indicative than the absolute values for locations other than Switzerland. At the same time, while both generation and demand profiles are subject to seasonal variation of weather-related parameters (outside air temperature, solar irradiation, and daylight hours), the demand side is limited to the synthetic load profiles from the three generic building types. Future work would benefit from a more diverse portfolio on the demand side, scrutinizing different types of end-usage, especially for small commercial buildings other than office buildings, and taking measured load data instead of simulated loads into account due to their potential discrepancies (Glasgo et al., 2017). Nevertheless, the results indicate where potential early implementations of these neighborhoods could be reasonable. Specifically, the road to self-sufficient systems—at least when the economic rationale is primary—will not be paved with single, purely residential buildings, but rather with larger neighborhoods in areas with lower seasonality that include commercial buildings.

3.4 Alternative Developments

In this section, we discuss potential alternative developments for the evaluated pathway. We have explored *how*, *when*, and *where* self-sufficient neighborhoods might disrupt the market by becoming cost-competitive with current baseline technology. Table 2 summarizes the main findings for these questions.

Table 2: Summary of main findings to how, when, and where questions

How			***When***	***Where***	
	Carrier	**Technology**	**(under medium energy price scenario)**	**Location**	**Composition**
I	Electricity, Heat	PV, Battery, HP	Cost competitive if and when technology costs decrease by 21%	Competitive in areas with little seasonality (low latitudes)	More cost-efficient with lower residential share and larger neighborhood size
II	Electricity, Heat, H_2	PV, Battery, HP, Electrolyzer, H_2 storage, Fuel Cell	Cost competitive if and when technology costs decrease by 51%	More competitive than I in areas with high seasonality (very high latitudes)	
Ref	Electricity, Heat, Oil	Boiler, Grid	Cost competitive at 2015 energy prices and technology costs	Cost competitive in areas with medium to high seasonality (medium to very high latitudes)	

Battery and hydrogen storage-based configurations can be feasible and cost-effective self-sufficiency solutions. With technological learning and increasing energy prices, these solutions can become cost-competitive. This could occur even sooner for applications in areas with low seasonality (favoring the *PV-battery-HP* configuration) and small commercial to mixed end-usage.

However, potential alternative developments for the evaluated pathway also need to be discussed. At least in the short term, development of self-sufficient energy solutions will differ from the outlined pathways because niche markets follow different rules. Given today's technology and energy costs, the pursuit of self-sufficient neighborhoods still comes at a high price. Total costs exceed reference costs by a factor of 2 to 3, depending on the technical configuration. Today, therefore, cost-competitive applications can be found in remote, rural, or island areas, where the high technology investments compensate for the cost of providing grid access and the space requirements for the PV plant and the respective storage technology are less rigid (Bilich et al., 2017; Neves et al., 2014). Additionally, on the adopter side, decision-making is not based exclusively on a purely economic rationale, but involves other motivations, such as overarching goals including environmental leadership, energy independence, or power reliability. Accordingly, we observed pilot projects in areas where cost-effectiveness does not hold but adopter preferences for a lighthouse project are high (Nygren et al., 2015; Voss and Musall, 2013).

While we evaluated fully self-sufficient solutions in this study, moving from negligible niches to a wider deployment of self-sufficient systems (buildings, neighborhoods, districts/regions) can be a multifaceted journey. Reaching fully autarkic, grid-disconnected solutions means progressing through various increments of self-sufficiency along the way. Today, there is a broad range of hybrid solutions in manifold combinations of diverse technologies, where prosumers can meet their energy supply demands for the most part autonomously and rely on the fallback power provision by the centralized grid only in rare cases (McKenna et al., 2017). This will be accelerated by the looming phase-out of feed-in tariffs and the resulting incentive to increase self-sufficiency rates. While regulatory issues may still restrict a community-based “self-supply” approach in some places, it is likely to gain momentum in the future because of entrepreneurial activities or progressive policy-making in other places (e.g., “self-consumption regulation” in Switzerland (Verband Schweizerischer Elektrizitätsunternehmen VSE, 2016)). Moreover, the sectoral convergence (e.g., energy, transport, building) will affect future technology trajectories on the one hand, and overall system design on the other (Mancarella, 2014; von Delft, 2013). The extent to which these semi- and close-to self-sufficient systems challenge the existing paradigm of a centralized infrastructure remains to be determined, as does the question of whether fully autarkic, off-grid systems pose a more severe threat to this infrastructure. An important unknown is the potential reallocation of grid charges, which could push self-sufficiency on prosumers’ agendas as a logical next step toward an independent energy supply.

It is also conceivable that, despite their radical characteristics, self-sufficient systems will not cause major disruption to the overall energy system if the industry and its main actors adapt and transform accordingly. Not least because of the high deployment rates and the technological trajectories of distributed RES (wind, PV), incumbent actors are starting to change their business models to cope with these developments. Among these innovations, new pricing schemes (e.g., charging a premium for providing back-up capacity) and the buildup of system integrator capabilities (i.e., mastering the integration of different energy services, technologies, and adjacent markets) are likely to play a role. Assuming a gradual shift over time, self-sufficient systems may not cause a major upheaval in the energy landscape and industry.

Interesting avenues for further research can be identified for both the competitiveness and disruptive potential of self-sufficient solutions. In terms of cost-competitiveness, quantifying and determining the relative profitability of various increments of self-sufficiency–below the full autarkic, off-grid 100% self-sufficiency rate—and the model expansion by further technologies (RES, storage) are of high interest for future work. Beyond that, potential additional benefits of these technologies, such as higher reliability of supply, reduced environmental impact and increases in the connected buildings' property value, need further evaluation.

Additionally, overall implications for the existing infrastructure, as well as societal effects triggered by a higher diffusion of truly self-sufficient systems, need to be thoroughly assessed to give business and policy makers a basis for deciding on the *if* and the *how* of their potential support.

Acknowledgements

This research has been financially supported by Innosuisse within the SCCER FEEB&D (Grant No. 1155000149) and by the Swiss National Science Foundation (SNF) under the National Research Program Energy Turnaround (NRP70), Grant No. 407040-153781. The authors are grateful to (in alphabetical order) Paolo Gabrielli, Jan Ossenbrink, and Mark Pfeiffer for their valuable contributions and constructive comments on earlier versions of this manuscript.

Supporting Information

(A) Techno-economic model (1. model input data, 2. model simulation logic, and 3. model output data), (B) expert interviews, (C) sensitivity analysis.

References

Abdin, Z., Webb, C.J., Gray, E.M., 2015. Solar hydrogen hybrid energy systems for off-grid electricity supply: A critical review. Renewable and Sustainable Energy Reviews 52, 1791–1808.

Agnew, S., Dargusch, P., 2015. Effect of residential solar and storage on centralized electricity supply systems. Nature Climate Change 5, 315–318.

Ahmadi, P., Dincer, I., Rosen, M. a., 2014. Thermoeconomic multi-objective optimization of a novel biomass-based integrated energy system. Energy 68, 958–970.

Alanne, K., Saari, A., 2006. Distributed energy generation and sustainable development. Renewable and Sustainable Energy Reviews 10, 539–558.

Ammermann, H., Hoff, P., Atanasiu, M., Ayllor, J., Kaufmann, M., Tisler, O., 2015. Advancing Europe's energy systems: Stationary fuel cells in distributed generation. Fuel Cells and Hydrogen Joint Undertaking (FCH JU), Luxemburg.

Barbose, G., Darghouth, N.R., 2016. Tracking the Sun IX: The Installed Price of Residential and Non-Residential Photovoltaic Systems in the United States. Lawrence Berkeley National Laboratory (LBNL) | U.S. Department of Energy, Berkeley.

Battke, B., Schmidt, T.S., Grosspietsch, D., Hoffmann, V.H., 2013. A review and probabilistic model of lifecycle costs of stationary batteries in multiple applications. Renewable and Sustainable Energy Reviews 25, 240–250.

Beccali, M., Brunone, S., Finocchiaro, P., Galletto, J.M., 2013. Method for size optimisation of large wind-hydrogen systems with high penetration on power grids. Applied Energy 102, 534–544.

Bernal-Agustín, J.L., Dufo-López, R., 2010. Techno-economical optimization of the production of hydrogen from PV-Wind systems connected to the electrical grid. Renewable Energy 35, 747–758.

Bilich, A., Langham, K., Geyer, R., Goyal, L., Hansen, J., Krishnan, A., Bergesen, J., Sinha, P., 2017. Life Cycle Assessment of Solar Photovoltaic Microgrid Systems in Off-Grid Communities. Environmental Science & Technology 51, 1043−1052.

Brealey, R.A., Myers, S.C., 2002. Brealey & Myers on Corporate Finance: Capital Investment and Valuation, 1st ed. ed. McGraw-Hill, New York City.

Bronski, P., Creyts, J., Guccione, L., Madrazo, M., Mandel, J., Rader, B., Seif, D., Lilienthal, P., Glassmire, J., Abromowitz, J., Crowdis, M., Richardson, J., Schmitt, E., Tocco, H., 2014. The Economics of Grid Defection: When and where distributed solar generation plus storage competes with traditional utility service. Rocky Mountain Institute | HOMER Energy | Cohnreznick Think Energy, Boulder.

Bundesamt für Energie (BFE), 2011. Der Energieverbrauch der Privaten Haushalte 2000 - 2010. Basel, Switzerland.

Bundesamt für Statistik (BFS), 2017. Landesindex der Konsumentenpreise – Indikatoren Durchschnittspreise [WWW Document]. URL http://www.bfs.admin.ch/bfs/portal/de/index/themen/05/02/blank/key/durchschnittspreise.html (accessed 5 February, 2017).

Burger, C., Weinmann, J., 2013. The Decentralized Energy Revolution: Business Strategies for a New Paradigm, 1st ed. ed. Palgrave Macmillan, Hampshire.

Bush, E., Nipkow, J., 2002. Revision SIA 380/4 Elektrische Energie im Hochbau - Betriebseinrichtungen: Vorgehensvorschlag. Zürich, Schweiz.

Castañeda, M., Cano, A., Jurado, F., Sánchez, H., Fernández, L.M., 2013. Sizing optimization, dynamic modeling and energy management strategies of a stand-alone PV/hydrogen/battery-based hybrid system. International Journal of Hydrogen Energy 38, 3830–3845.

Crabtree, G., Kócs, E., Trahey, L., 2015. The energy-storage frontier: Lithium-ion batteries and beyond. MRS Bulletin 40, 1067–1078.

Danish Energy Agency, 2016. Technology data for energy plants - Generation of Electricity and District Heating, Energy Storage and Energy Carrier Generation and Conversion. Copenhagen.

Darling, S.B., You, F., Velosa, A., 2011. Environmental Science Assumptions and the levelized cost of energy for photovoltaics. Energy & Environmental Science 4, 3133–3139.

Darrow, K., Tidball, R., Wang, J., Hampson, A., 2015. Catolog of CHP Technologies. Washington.

de La Tour, A., Glachant, M., Ménière, Y., 2013. Predicting the costs of photovoltaic solar modules in 2020 using experience curve models. Energy 62, 341–348.

Decourt, B., Lajoie, B., Debarre, R., Soupa, O., 2014. Hydrogen-Based Energy Conversion - More than storage: system flexibility. SBC Energy Institute, Gravenhage.

Dodds, P.E., Staffell, I., Hawkes, A.D., Li, F., Grünewald, P., McDowall, W., Ekins, P., 2015. Hydrogen and fuel cell technologies for heating: A review. International Journal of Hydrogen Energy 40, 2065–2083.

Dufo-López, R., Bernal-Agustín, J.L., 2008. Multi-objective design of PV-wind-diesel-hydrogen-battery systems. Renewable Energy 33, 2559–2572.

Energie-Bewusstsein.de, 2013. Energierechner [WWW Document]. URL http://www.energie-bewusstsein.de/index.php?page=thema_energie&p2=geraete_leistungen (accessed 17 October, 2017).

Energiewirtschaft, F. für, 2010. Basisdaten zur Bereitstellung elektrischer Energie [WWW Document]. URL https://www.ffe.de/download/wissen/186_Basisdaten_Energietraeger/Basisdaten_von_Energietraegern_2010.pdf (accessed 17 October, 2017).

Eurostat, 2017. Gaspreise nach Art des Benutzers [WWW Document]. URL http://ec.europa.eu/eurostat/tgm/table.do?tab=table&init=1&plugin=1&language=de&pcode=ten00118 (accessed 5 February, 2017).

Feldman, D., Barbose, G., James, T., Weaver, S., Fu, R., Davidson, C., 2014. Photovoltaic System Pricing Trends Historical, Recent, and Near-Term Projections - 2014 Edition. U.S. Department of Energy, Oak Ridge.

Gahleitner, G., 2013. Hydrogen from renewable electricity: An international review of power-to-gas pilot plants for stationary applications. International Journal of Hydrogen Energy 38, 2039–2061.

Gassel, A., 1996. Beiträge zur Berechnung solarthermischer und energieeffizienter Energiesysteme. Fraunhofer-IRB-Verl., Dresden.

Geidl, M., Koeppel, G., Favre-Perrod, P., Klöckl, B., Andersson, G., Fröhlich, K., 2007. The Energy Hub – A powerful concept for future energy systems. Third Annual Carnegie Mellon Conference on the Electricity Industry 1–10.

Geschäftsstelle MINERGIE, 2014a. Reglement zur Nutzung der Qualitätsmarke MINERGIE ®. Verein MINERGIE®, Bern.

Geschäftsstelle MINERGIE, 2014b. Minergie - Modul Fenster [WWW Document]. URL https://www.minergie.ch/de/verstehen/module/fenster/ (accessed 17 October, 2017).

Giatrakos, G.P., Tsoutsos, T.D., Mouchtaropoulos, P.G., Naxakis, G.D., Stavrakakis, G., 2009. Sustainable energy planning based on a stand-alone hybrid renewable energy/hydrogen power system: Application in Karpathos island, Greece. Renewable Energy 34, 2562–2570.

Gierga, M., 2009. EnEV 2009. Energie-Einsparverordung, Energie-Einsparverordnung, Leitfaden für Wohngebäude, Bonn. Arbeitsgemeinschaft Mauerziegel im Bundesverband der Deutschen Ziegelindustrie e.V., Bonn, Germany.

Glasgo, B., Hendrickson, C., Azevedo, I.L., 2017. Assessing the value of information in residential building simulation: Comparing simulated and actual building loads at the circuit level. Applied Energy 203, 348–363.

Gloor, R., 2015. Heizungsvergleich [WWW Document]. energie.ch. URL http://www.energie.ch/heizungsvergleich (accessed 5 February, 2017).

Grosspietsch, D., Thömmes, P., Girod, B., Hoffmann, V.H., 2018. How, When, and Where? Assessing Renewable Energy Self-Sufficiency at the Neighborhood Level. Environmental Science and Technology 52.

Grübler, A., Nakicenovic, N., Victor, D.G., 1999. Dynamics of energy technologies and global change. Energy Policy 27, 247–280.

Heatpumpcenter.org, 2013. Heat pump performance [WWW Document]. URL http://www.heatpumpcentre.org/en/aboutheatpumps/heatpumpperformance/Sidor/default.aspx (accessed 18 June, 2013).

Heinrich Gugerli, 2017. Zertifizierte 2000-Watt-Areale [WWW Document]. Fachstelle 2000-Watt-Gesellschaft. URL http://www.2000watt.ch/fuer-areale/zertifizierte-2000-watt-areale/ (accessed 5 February, 2017).

Henel, M., Köppel, W., Mlaker, H., Dr. Sterner, M., Dr. Höcher, T., 2013. Entwicklung von modularen Konzepten zur Erzeugung , Speicherung und Einspeisung von Wasserstoff und Methan ins Erdgasnetz, DVGW Forschung. Bonn.

Hoppmann, J., Volland, J., Schmidt, T.S., Hoffmann, V.H., 2014. The economic viability of battery storage for residential solar photovoltaic systems - A review and a simulation model. Renewable and Sustainable Energy Reviews 39, 1101–1118.

International Energy Agency, 2011. Technology Roadmap - Energy efficient buildings: Heating and Cooling Equipment. Paris.

IRENA, 2016. The Power To Change: Solar and Wind Cost Reduction Potential to 2025. International Renewable Energy Agency (IRENA), Bonn.

IRENA, 2015. Renewable Power Generation Costs in 2014. Bonn.

Jordan, U., Vajen, K., 2001. Realistische Trinkwarmwasser-Profile für bis zu 100 Wohneinheiten, in: Symposium Thermische Solarenergie, Staffelstein, Germany. pp. 384–389.

Kasper, T., 2013. The energy efficiency potential of intelligent heating control approaches in the residential sector. ETH Zurich, Zurich, Switzerland.

Kassakian, J.G., Schmalensee, R., 2011. The Future of the Electric Grid: An Interdisciplinary MIT Study. Massachusetts Institute of Technology (MIT), Cambridge.

Kaut.de, 2013. Klimapedia: COP und EER [WWW Document]. URL http://www.kaut.de/hitachi/klimapedia.php (accessed 17 October, 2017).

Klebanoff, L., 2012. Hydrogen Storage Technology: Materials and Applications, 1st ed. ed. CRC Press, Boca Raton.

Körner, A., 2015. Technology Roadmap: Hydrogen and Fuel Cells. International Energy Agency (IEA), Paris.

Krajacic, G., Duic, N., Zmijarevic, Z., Mathiesen, B.V., Vucinic, A.A., Da Graa Carvalho, M., 2011. Planning for a 100% independent energy system based on smart energy storage for integration of renewables and CO2 emissions reduction. Applied Thermal Engineering 31, 2073–2083.

Lang, T., Ammann, D., Girod, B., 2016. Profitability in absence of subsidies: A techno-economic analysis of rooftop photovoltaic self-consumption in residential and commercial buildings. Renewable Energy 87, 77–87.

Lang, T., Gloerfeld, E., Girod, B., 2015a. Don't just follow the sun - A global assessment of economic performance for residential building photovoltaic. Renewable and Sustainable Energy Reviews. 42, 932–951.

Lang, T., Gloerfeld, E., Girod, B., 2015b. Don't just follow the sun - A global assessment of economic performance for residential building photovoltaic. Renewable and Sustainable Energy Reviews 42, 932–951.

Lang, T., Gloerfeld, E., Girod, B., 2013. Model Description of the HOMIE model (Household Model for intelligent energy supply and use) [WWW Document]. URL http://www.sustec.ethz.ch/content/dam/ethz/special-interest/mtec/sustainability-and-technology/PDFs/HOMIE_documentation.pdf (accessed 17 October, 2017).

Lehmann, B., Wirth, K., Dorer, V., Frank, T., Gwerder, M., 2010. Control problem and experimental set-up, in: Gyalistras, D., Gwerder, M. (Eds.), Use of Weather and Occupancy Forecasts For Optimal Building Climate Control (OptiControl): Two Years Progress Report. Terrestrial Systems Ecology ETH Zurich, Switzerland and Building Technologies Division, Siemens Switzerland Ltd., Zug, pp. 15–28.

Levene, J., Kroposki, B., Sverdrup, G., 2006. Wind Energy and Production of Hydrogen and Electricity — Opportunities for Renewable Hydrogen, in: 2006 POWER-GEN Renewable Energy and Fuels Technical Conference. National Renewable Energy Laboratory (NREL), Golden.

Li, H., Nalim, R., Haldi, P. a., 2006. Thermal-economic optimization of a distributed multi-generation energy system - A case study of Beijing. Applied Thermal Engineering 26, 709–719.

Luo, X., Wang, J., Dooner, M., Clarke, J., 2015. Overview of current development in electrical energy storage technologies and the application potential in power system operation. Applied Energy 137, 511–536.

Lutz, J.D., Hopkins, A., Letschert, V., Franco, V.H., Sturges, A., 2011. Using national survey data to estimate lifetimes of residential appliances 17, 726–736.

Mancarella, P., 2014. MES (multi-energy systems): An overview of concepts and evaluation models. Energy 65, 1–17.

Marangio, F., Santarelli, M., Calì, M., 2009. Theoretical model and experimental analysis of a high pressure PEM water electrolyser for hydrogen production. International Journal of Hydrogen Energy 34, 1143–1158.

Märtel, C., 2013. Dachneigung Photovoltaik Anlage - Auswirkungen auf den Ertrag [WWW Document]. photovoltaik-web.de. URL https://www.photovoltaik-web.de/photovoltaik/dacheignung/dachneigung (accessed 17 October, 2017).

MathWorks, 2017. Genetic Algorithm [WWW Document]. URL https://ch.mathworks.com/help/gads/genetic-algorithm.html (accessed 17 October, 2017).

McKenna, R., Merkel, E., Fichtner, W., 2017. Energy autonomy in residential buildings: A techno-economic model-based analysis of the scale effects. Applied Energy 189, 800–815.

Messmer, A., Frischknecht, R., 2016. Umweltbilanz Strommix Schweiz 2014. Bundesamt für Umwelt (BAFU), Uster.

Mueller, M.O., Stömpfli, A., Dold, U., Hammer, T., 2011. Energy autarky: A conceptual framework for sustainable regional development. Energy Policy 39, 5800–5810.

Münzenberg, U., Weithaas, T., Thumulla, J., 2003. Luftwechsel im Gebäudebestand - Natürlicher Luftwechsel, Fensterlüftung und die Notwendigkeit von Lüftungskonzepten, in: Tagungsbände Pilztagungen Des VDB - 7. Pilztagung 2003. Berufsverband Deutscher Baubiologen e.V., Jesteburg, Germany, pp. 1–14.

National Aeronautics and Space Administration (NASA), 2012. Surface meteorology and Solar Energy - A renewable energy resource web site (release 6.0) [WWW Document]. URL https://eosweb.larc.nasa.gov/cgi-bin/sse/sse.cgi?rets@nrcan.gc.ca (accessed 8 December, 2015).

Nemet, G.F., 2009. Demand-pull, technology-push, and government-led incentives for non-incremental technical change. Research Policy 38, 700–709.

Neves, D., Silva, C.A., Connors, S., 2014. Design and implementation of hybrid renewable energy systems on micro-communities: A review on case studies. Renewable and Sustainable Energy Reviews 31, 935–946.

Nipkow, J., 2005. Elektrizitätsverbrauch und Einspar-Potenziale bei Aufzügen. Bulletin SEV/VSE 9/06, Zurich, Switzerland.

Northwest Power and Conservation Council, 2010. Sixth Northwest Conservation and Electric Power Plan - Appendix N: Financial Assumptions and Discount Rate. Northwest Power and Conservation Council, Portland.

Nygren, N.A., Kontio, P., Lyytimaki, J., Varho, V., Tapio, P., 2015. Early adopters boosting the diffusion of sustainable small-scale energy solutions. Renewable and Sustainable Energy Reviews 46, 79–87.

Nykvist, B., Nilsson, M., 2015. Rapidly falling costs of battery packs for electric vehicles. Nature Climate Change 5, 329--332.

Orehounig, K., Evins, R., Dorer, V., 2015. Integration of decentralized energy systems in neighbourhoods using the energy hub approach. Applied Energy 154, 277–289.

Ossenbrink, J., 2017. How feed-in remuneration design shapes residential PV prosumer paradigms. Energy Policy 108, 239–255.

Parag, Y., Sovacool, B.K., 2016. Electricity market design for the prosumer era. Nature Energy 1, 16032.

Patel, R., Paleari, W., Selva, D., 2016. Architecture study of an energy microgrid. Proceedings of the IEEE Systems of Systems Conference (SoSE) 1–8.

Perez, K.X., Baldea, M., Edgar, T.F., Hoogsteen, G., Van Leeuwen, R.P., Van Der Klauw, T., Homan, B., Fink, J., Smit, G.J.M., 2016. Soft-islanding a group of houses through scheduling of CHP, PV and storage, in: 2016 IEEE International Energy Conference (ENERGYCON).

PricewaterhouseCoopers (pwc), 2013. Energy transformation - The impact on the power sector business model.

Prior, D., 1997. Nachbildung der Energiebedarfsstruktur der privaten Haushalte: Werkzeug zur Bewertung von Energieeinsparmaßnahmen. VDI Verlag, Düsseldorf, Germany.

Rae, C., Bradley, F., 2012. Energy autonomy in sustainable communities - A review of key issues. Renewable and Sustainable Energy Reviews 16, 6497–6506.

Richter, M., 2013. Business model innovation for sustainable energy: German utilities and renewable energy. Energy Policy 62, 1226–1237.

Richter, M., 2012. Utilities' business models for renewable energy: A review. Renewable and Sustainable Energy Reviews 16, 2483–2493.

Rubin, E.S., Azevedo, I.M.L., Jaramillo, P., Yeh, S., 2015. A review of learning rates for electricity supply technologies. Energy Policy 86, 198–218.

Schleicher-Tappeser, R., 2012. How renewables will change electricity markets in the next five years. Energy Policy 48, 64–75.

Schoots, K., Ferioli, F., Kramer, G.J., van der Zwaan, B.C.C., 2008. Learning curves for hydrogen production technology: An assessment of observed cost reductions. International Journal of Hydrogen Energy 33, 2630–2645.

SIA, 2006. Standard-Nutzungsbedingungen für die Energie- und Gebäudetechnik, Zürich: Swiss Society of Engineers and Architects. Schweizerischer Ingenieur- und Architektenverein (SIA), Zurich, Switzerland.

Smolinka, T., Günther, M., Garche, J., 2011. Stand und Entwicklungspotenzial der Wasserelektrolyse zur Herstellung von Wasserstoff aus regenerativen Energien, NOW-Studie. Fraunhofer ISE, Freiburg.

Söderman, J., Pettersson, F., 2006. Structural and operational optimisation of distributed energy systems. Applied Thermal Engineering 26, 1400–1408.

Sterner, M., 2009. Bioenergy and renewable power methane in integrated 100% renewable energy systems - Limiting global warming by transforming energy systems. kassel university press, Kassel.

Stromverbrauchinfo.de, 2013. Stromverbrauch von Waschmaschinen [WWW Document]. URL http://www.stromverbrauchinfo.de/stromverbrauch-waschmaschinen.php (accessed 17 October, 2017).

Swiss Federal Electricity Commission ElCom, 2017. Electricity price - overview [WWW Document]. URL https://www.elcom.admin.ch/elcom/en/home.html (accessed 5 February, 2017).

Tesla, I., 2017. Tesla Powerwall [WWW Document]. URL https://www.tesla.com/powerwall (accessed 5 February, 2017).

Testberichte.de, 2013. Technische Daten: Trockner Blomberg TKF 7451 W50 [WWW Document]. URL http://www.testberichte.de/p/blomberg-tests/tkf-7451-w50-testbericht.html (accessed 17 October, 2017).

TopTest GmbH, 2013. TopTen Gefrierschränke und Kühlschränke [WWW Document]. URL http://www.topten.ch/private/products/refrigerators (accessed 17 October, 2017).

Tsuchiya, H., 2004. Mass production cost of PEM fuel cell by learning curve. International Journal of Hydrogen Energy 29, 985–990.

U.S. Department of Energy, 2013. EnergyPlus Energy Simulation Software - Weather Data [WWW Document]. URL https://energyplus.net/weather (accessed 17 October, 2017).

U.S. Energy Information Administration (EIA), 2015. Annual Energy Outlook 2015 with projections to 2040. U.S. Department of Energy (DOE), Washington.

Ulleberg, Ø., Nakken, T., Eté, A., 2010. The wind/hydrogen demonstration system at Utsira in Norway: Evaluation of system performance using operational data and updated hydrogen energy system modeling tools. International Journal of Hydrogen Energy 35, 1841–1852.

Vaishnav, P., Horner, N., Azevedo, I.L., 2017. Was it worthwhile? Where have the benefits of rooftop solar photovoltaic generation exceeded the cost? Environmental Research Letters 12, 1–46.

Verband Schweizerischer Elektrizitätsunternehmen VSE, 2016. Handbuch Eigenverbrauchsregelung (HER). Aarau.

von Delft, S., 2013. Inter-industry innovations in terms of electric mobility: Should firms take a look outside their industry? Journal of Business Chemistry 10, 67–87.

von Meier, A., 2014. Challenges To the Integration of Renewable Resources At High System Penetration. California Energy Commission, Berkeley.

Voss, K., Musall, E., 2013. Net Zero Energy Buildings - International Projects of Carbon Neutrality in Buildings. Detail Green Books, Munich.

Supporting Information

Supporting Information A: Techno-economic Model

This part provides the details for the techno-economic model, which has been introduced and described in brief in section 2 (‘materials and methods’) of the manuscript. In the following, the structure is organized according to Figure 1 of the manuscript and comprises three sections (including several sub-sections): 1. model input data, 2. model simulation logic, and 3. model output data. Some parts of the model (e.g., the building simulation) are based on an existing techno-economic model, called ‘Household Model for Intelligent Energy supply and use (HoMIE)’, which is described in previous publications (Lang et al., 2016, 2015b; Ossenbrink, 2017).

1 Model Input Data

This section comprises all input data and relevant assumptions of the model regarding energy service demand (1.1), technological parameters (1.2), geographic parameters (1.3), and economic parameters (1.4).

1.1 Energy Service Demand

The energy service demand is modeled according to common usage patterns. Demand data used for the parametrization including data sources is given in Table S3 for both the residential (single-family house (SFH) and multi-family house (MFH)) and the small commercial (small office building (SOB)) building type. The actual time of day for appliance use is randomized across the year between 12 am and 3 pm for cooking and between 8 am and 9 pm for all others. Power demand per use is calculated from specifications of state-of-the-art technology. Of all energy service demands, only lighting is region-dependent (due to local daylight hours). However, the service demands for heat demand (room temperature and warm water) translate into region-specific power demands because of differences in the local outside temperature.

Table S3: Overview of energy service demands per appliance and building type (adapted from Lang, T.; Ammann, D.; Girod, B. Profitability in absence of subsidies: A techno-economic analysis of rooftop photovoltaic self-consumption in residential and commercial buildings. Renewable Energy 2016, 87, 77–87 with permission (Lang et al., 2016). Copyright 2016 Elsevier.)

Energy Service	Residential (SFH, MFH)	Reference	Small Commercial (SOB)	Reference
Room temperature	23°C constant	expert interview	23°C constant	expert interview
Hot water	50l-70l at 60°C /person and day, depending on the time of year	(Gassel, 1996; Jordan and Vajen, 2001)	5-7l at 60°C per person and day, depending on the time of year	(SIA, 2006)
Daily lighting	Base value: 1223 Wh/day Load pattern /day (Mon-Fri, Sat, Sun; summer, winter)	(Bundesamt für Energie (BFE), 2011) (Prior, 1997)	Base value: 76 Wh/m^2 (90% on Fridays and 10% on weekends) Load pattern /day (Mon-Thu, Fri, Sat-Sun, summer winter)	(Bush and Nipkow, 2002; SIA, 2006) (Lehmann et al., 2010)
Information & Communication Technology (ICT)	1223 Wh/day	(Bundesamt für Energie (BFE), 2011)	69.3 Wh/m^2 (90% on Fridays and 10% on weekends)	(Bush and Nipkow, 2002; SIA, 2006) (Lehmann et al., 2010)
Fridge/freezer	274 Wh/day / 329 Wh/day and occupant party	Parameters for state-of-the-art technology (TopTest GmbH, 2013)	274 Wh/day and floor, no freezer	Parameters for state-of-the-art technology (TopTest GmbH, 2013)
Dishwasher	1200 Wh/day and party	(Energie-Bewusstsein.de, 2013)	1200 Wh/day and floor	(Energie-Bewusstsein.de, 2013)
Washing machine	500 Wh/day and party	(Stromverbrauchinfo.de, 2013)	-	-
Dryer	1500 Wh/day and party	(Testberichte.de, 2013)	-	-
Cooking	1200 Wh/day and party	Parameters for state-of-the-art technology (TopTest GmbH, 2013)	-	-
Ventilation	-	-	0.34 Wh/(m^3/h) 50 (m^3/h)/person	(Lehmann et al., 2010) expert interview
Elevator	-	-	20 Wh/trip	(Nipkow, 2005)

1.2 Technological Parameters

We modeled three different building types, SFH, MFH, and SOB, which are defined by their key parameters shown in Table S4. All assumptions are based on Lang et al. (2016) who built their study on recent publications and expert interviews (from industry), e.g. to represent typical buildings of the corresponding type. The technological set-up, and thus the parameters used, is kept identical for all geographic locations to allow for a comparison of the design drivers and the economic impact based on consistent assumptions.

Table S4: General characteristics of building types (adapted from Lang, T.; Ammann, D.; Girod, B. Profitability in absence of subsidies: A techno-economic analysis of rooftop photovoltaic self-consumption in residential and commercial buildings. Renewable Energy 2016, 87, 77–87 with permission (Lang et al., 2016). Copyright 2016 Elsevier.)

Category	Parameter	Unit	Single Family House (SFH)	Multi-Family House (MFH)	Small Office Building (SOB)
Geometry	L x W x H	m	10 x 7 x 6	20 x9 x14	22 x 15 x 10
	Number of stories	-	2	5	3
	Total floor area	m^2	150	900	1000
	Window share	%	30	30	60
	Roof area	m^2	80	180	330
Other	Number of people	-	4	20	90
Demand	Electricity demand p.a.	MWh_{el}	3.0	19.1	49.4
	Heat demand p.a.	MWh_{th}	19.6	79.2	92.5

Technological parameters describe the basic building set-up and are kept identical for all building types. Table S5 presents the technological parametrization of this building set-up.

Table S5: Basic technological building parametrization (adapted from Lang, T.; Ammann, D.; Girod, B. Profitability in absence of subsidies: A techno-economic analysis of rooftop photovoltaic self-consumption in residential and commercial buildings. Renewable Energy 2016, 87, 77–87 with permission (Lang et al., 2016). Copyright 2016 Elsevier.)

Component	Parameter	Value/modeling rationale	Reference
Building hull	U-value, walls	0.15 W/m^2K (constant)	(Geschäftsstelle MINERGIE, 2014a)
	Heat capacity walls	380 Wh/m^3K	(Kasper, 2013)
Windows	U-value, windows	1 W/m^2K (constant)	(Geschäftsstelle MINERGIE, 2014a)
	Transmission factor	0.15	(Geschäftsstelle MINERGIE, 2014b)
	Angle correction	0.85	(Märtel, 2013)

Building	Heat capacity interior	50 Wh/m³K	(Gierga, 2009)
	Air exchange rate	0.3/h for residential	(Münzenberg et al., 2003)
Heating, Ventilation and Air Conditioning (HVAC)	Coefficient of performance heat pump	(1/2) * ideal Coefficient of Performance (COP)	(Heatpumpcenter.org, 2013)
	Coefficient of performance Air Conditioning (AC)	4	(Kaut.de, 2013)
Water tanks	Temperature	Heating water tank: 35°C; warm water tank: 60°C	(Lang et al., 2015a)
	Heat losses	0	(Lang et al., 2015a)
	Heat capacity water	1.16 kWh/m³K	(Lang et al., 2015a)

Besides the building-specific parameters, there are in general various levels of detail for the simulation of technologies in the literature. These range from models with constant system efficiency or a basic operating principle (Geidl et al., 2007; Orehounig et al., 2015) to more sophisticated simulations, where the dynamics of various external factors, such as temperature or pressure, is incorporated (Marangio et al., 2009). Since this study assesses techno-economic performance on a system level, we limit the model complexity per technology to a level that does not sacrifice precision. Nevertheless, the model disregards electrochemical processes, such as current densities or internal resistances. Table S6 displays our technology-related parameters and assumptions.

Table S6: Technology-related parameters

Technology	**Parameter**	**Unit**	**Value**	**Reference**
PV (crystalline silicon)	Angle Correction Factor	-	1.15	(Lang et al., 2016)
	Performance Ratio	%	20	(IRENA, 2015)
	Module Efficiency	%	85	(Lang et al., 2016)
	Lifetime	a	10	(Hoppmann et al., 2014)
Heat Pump (ground-sourced)	Coefficient of Performance (COP)	-	$\mathrm{COP} = \frac{T_{Tank}}{T_{Tank} - T_{Air}}$	(Henel et al., 2013)
	Lifetime	a	16	(International Energy Agency, 2011)
Oil Boiler	Efficiency	%	95	(Gloor, 2015)
	Lifetime	a	25	(Lutz et al., 2011)
ICE	Thermal Efficiency	%	70	manufacturer data
	Electric Efficiency	%	16	manufacturer data
	Lifetime	a	25	(Darrow et al., 2015)

	Operating Hours	h	40,000	manufacturer data
Electrolyzer (alkaline)	Efficiency	kWh/scm (standard cubic meter)	$e_i^{specific} = 0.13 \cdot P_{rel,i}^3 - 0.40 \cdot P_{rel,i}^2 + 0.72 \cdot P_{rel,i} + 3.85$	manufacturer data
	Standby Power	%	1.5	(Sterner, 2009)
	Operating Temperature	°C	70	manufacturer data
	Operating Pressure	bar	15	manufacturer data
	Lifetime	a	16	expert interview
	Operating Hours	h	60,000	expert interview
Fuel Cell (polymer electrolyte membrane (PEM))	Thermal Efficiency	%	42	(Dodds et al., 2015)
	Electrical Efficiency	%	50	(Dodds et al., 2015)
	Lifetime	a	15	(Ammermann et al., 2015)
	Cycle Lifetime	-	40,000	(Ammermann et al., 2015; Dodds et al., 2015)
Battery (Lithium-ion)	Capacity	kWh	10	(Tesla, 2017)
	Power	kW	3.3	(Tesla, 2017)
	Efficiency	%	92	(Tesla, 2017)
	Depth of Discharge	%	80	(Tesla, 2017)
	Lifetime	a	10	(Tesla, 2017)
	Cycle Lifetime	-	10,250	(Battke et al., 2013)
H_2 Storage incl. Compressor	Pressure	bar	90	manufacturer data
	Hydrogen Compression	kWh/scm	0.3	(Smolinka et al., 2011)
	Lifetime (Compressor)	a	30	expert interview
	Lifetime (H_2 Storage)	a	30	(Klebanoff, 2012)

1.3 Geographic Parameters

Weather-related parameters in the model cover outside air temperature, solar irradiation, and daylight hours. Data for outside temperature and daylight hours is sourced from the U.S. Department of Energy (U.S. Department of Energy, 2013). Local irradiation data is sourced from NASA (National Aeronautics and Space Administration (NASA), 2012) for every quarter of an hour over a full year and subsequently used for the computation of available electricity yield by the solar PV plant.

The model also includes CO_2 emission factors measuring the amount of CO_2 released per kWh of electricity produced when fuels are burned, or for grid electricity, the underlying technology mix employed to generate the electricity. Owing to the high share of hydropower plants in the Swiss energy mix, we assume a CO_2 footprint of 169.0 g CO_2/kWh in Switzerland (including electricity imports from neighboring countries) (Messmer and Frischknecht, 2016), and specific values for natural gas and heating oil of 202 g CO_2/kWh and 266 g CO_2/kWh, respectively (Energiewirtschaft, 2010).

1.4 Economic Parameters

Economic parameters include market prices for energy, such as grid electricity, heating oil, and natural gas. The development of future market prices for energy is based on the projections by the Annual Energy Outlook 2015 (U.S. Energy Information Administration (EIA), 2015). An investment horizon of 40 years and a discount rate of 7.0% are assumed. Table S7 displays the market-related economic parameters.

Table S7: Overview of economic parameters

Parameter	Unit	Value	Reference
Electricity Price[a]	EUR/kWh	0.17	(Swiss Federal Electricity Commission ElCom, 2017)
Gas Price	EUR/kWh	0.07	(Eurostat, 2017)
Oil Price	EUR/kWh	0.09	(Bundesamt für Statistik (BFS), 2017)
Investment horizon	years	40	expert interview
Discount rate[b]	%	7.0	expert interview

a Only one retail price for buying electricity from the grid is examined, even though our stylized neighborhood examines both residential and commercial units.

b Discount rates can be differentiated between residential (3-5%) and business consumers (7-9%) (Northwest Power and Conservation Council, 2010).

Economic parameters also include capital and operational costs (all inflation-adjusted to 2014 EUR) for the different technologies. Table S8 provides the cost-related parameters per technology. While for some of the covered technologies, we include system costs that account for all supplementary costs, where available (i.e., solar PV, electrolyzer, ICE, fuel cell, battery), we provide more detailed Balance Of System (BOS) costs which are, for instance, in the case of solar PV, all costs aside from the module costs, such as costs for transformer, wiring, or racking. In general, the technologies need to be replaced during the overall lifetime (i.e., investment horizon of 40 years) according to their individual lifetimes (calendrical and/or cyclical). We assume that both the costs for module/stack and the BOS costs accrue according to the technology's replacement cycle. Apart from that, a seamless operation across overall lifetime is accounted for with the Operation & Maintenance (O&M) costs.

Table S8: Technology cost-related parameters

Technology	Investment Cost[a]	Reference	BOS	Reference	O&M Cost	Reference
PV (1-3 kW_p)	451.57 €/kW_p	manufacturer data	2364.91 €/kW_p	(IRENA, 2015; Lang et al., 2016)	1.5%	(Hoppmann et al., 2014)
PV (3-20 kW_p)			1753.04 €/kW_p			
PV (20-200 kW_p)			1197.84 €/kW_p			
PV (200-1000 kW_p)			901.89 €/kW_p			
Heat Pump (ground-sourced)	746.43 €/kW	(International Energy Agency, 2011)	-	-	1.5%	(International Energy Agency, 2011)
Oil Boiler (1-28 kW)	23,056.65 €	expert interview	-	-	3.0%	(Gloor, 2015)
Oil Boiler (29-90 kW)	37,055.33 €					
Oil Boiler (91-320 kW)	57,641.64 €					
Internal Combustion Engine	$2{,}310.8 \cdot P_{inst.}^{-0.419}$ €/kW	manufacturer data	43% of initial costs	expert interview	4.0%	(Darrow et al., 2015)
Electrolyzer (alkaline)	$16{,}624.1 \cdot P_{inst.}^{-0.406}$ €/kW	(Henel et al., 2013)	30% of initial costs	(Levene et al., 2006)	5.0%	expert interview
Fuel Cell (PEM)	$6{,}506.6 \cdot P_{inst.}^{-0.177}$ €/kW	expert interview	30% of initial costs	expert interview	10.0%	expert interview
Battery (Lithium-ion)	322.48 €/kW	(Tesla, 2017)	141.76 €/kW	(Hoppmann et al., 2014)	20.66 €/kW	(Battke et al., 2013)
H_2 Storage	$378.3 \cdot M_{inst.}^{-0.090}$ €/kg	(Beccali et al., 2013)	-	-	3.0%	expert interview
Compressor	$24{,}567 \cdot P_{inst.}^{-0.414}$ €/kW	(Beccali et al., 2013)	-	-	4.0%	expert interview

We hold investment, BOS and O&M costs constant across different latitudes (geographies).

[a] All costs are inflation-adjusted to 2014 EUR.

2 Model Simulation Logic

This section describes all the steps of the model simulation including technology sizing (2.1), power and heat supply (2.2), power and heat demand (2.3), economic module (2.4), and dispatch and balancing (2.5).

2.1 Technology Sizing

While the model allows us to initialize the sizing of the technologies, for example, to consider potential constraints or to calculate the output parameters for a given system design, the technology sizing is iteratively determined to optimize the overall system according to a given objective. In this study, the sizing of the technical devices is iteratively adapted in order to meet the particular constraint of a 100% self-sufficiency and to minimize the overall cost of energy.

2.2 Power and Heat Supply

Power supply is available from the solar PV plant, for which a fixed roof mount installation with a 20° tilt is assumed. We furthermore assume that a constant azimuth of 180° (southward orientation) is applied as the focal locations of this study are in the Northern hemisphere. The quarter-hourly yield of the PV system is defined as follows:

$$P_{PV}(i) = Q_i^{Irr} * \eta_{el,i} * PR * A * \beta \tag{S1}$$

where Q_i^{Irr} denotes the specific horizontal irradiation in every time step i of the year measured in Watt per square meter, $\eta_{el,i}$ represents the electric module efficiency that depends on outside air temperature, PR is the performance ratio of the complete system (e.g. conversion/inverter losses, external factors), A is the total panel area of the PV system, and β is the tilt angle correction factor compared to a horizontal panel.

Heat can be supplied by an oil boiler (in reference configuration, Ref), by an internal combustion engine (ICE) that co-produces heat and power using a heat-driven operating strategy and fueled by natural gas (configuration Ib), by a ground-sourced heat pump (configurations I and II) and by a fuel cell co-producing heat and power with a power-driven operating strategy (configuration II).

2.3 Power and Heat Demand

Each of the considered building types is characterized by building-specific features, such as floor space, physical properties, and number of occupants, which influence the calculation of electricity and heat demand. To simulate their electricity demand, it is assumed that every building type contains certain electrical appliances (see Table S4). The actual use of these appliances during a specific time of day is based on discrete distribution patterns. These usage patterns display the activities and needs of the building occupants during a specific time of the year. The nominal power of these appliances multiplied by their discrete daily usage pattern for each time step (15 min) ultimately determines the daily electricity demand of the building type. The heat demand of a building is composed of two elements: Room heating and warm water use. The former builds on a thermal model that entails heat flows caused by outside air temperature and room temperature, which is set to 23°C and kept constant. Building properties, such as heat capacities and heat transfer coefficients (U-values) of windows and walls, are accounted for in order to simulate the heat flows and correspond to values of state of the art building standards. For warm water use, as with the use of electric appliances, predefined patterns are applied. Consequently, daily warm water usage changes with the considered building type, season, and time of the week, with hot or fresh water being added to a thermal tank. A comprehensive and detailed description of the modeling logic for electricity and heat demand is available online (Lang et al., 2015b, 2013).

Figure S6 displays the temporal profiles of both the heat and electricity demand on a daily and an annual scale (for a SFH in Bern, Switzerland).

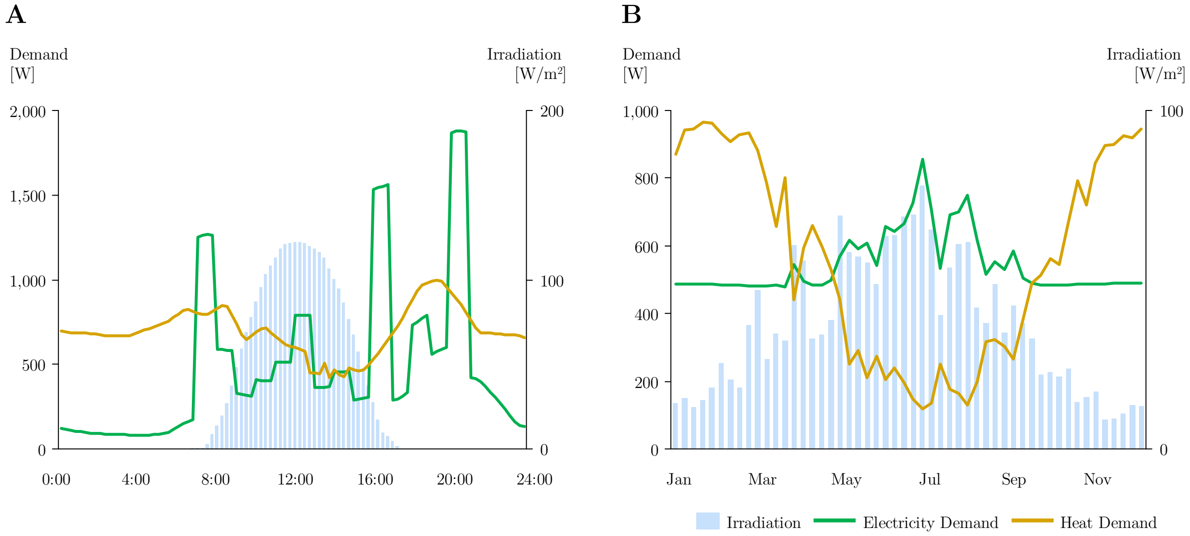


Figure S6: (A) Diurnal irradiation data, heat and electricity demand for a single-family house at the location of Bern, Switzerland (15 min-based average) for a weekday in November. (B) Annual irradiation data, heat and electricity demand for a single-family house at the location of Bern, Switzerland (weekly-based average)

2.4 Economic Module

We assess economic attractiveness from an investor perspective, which is why we initially apply the Net Present Value (NPV) method to calculate total costs over lifetime (Brealey and Myers, 2002). It is calculated using the following equation:

$$NPV = -I_o + \sum_{i=1}^{T} \frac{CF_i}{(1+r)^i} \tag{S2}$$

where I_o denotes the initial investment, T is the total investment horizon of the system, CF_i are the cash flows in year i>0 and r is the underlying discount rate. Figure S7 shows a schematic breakdown of the determining factors of the NPV. However, with the scope of this study resting on off-grid systems, there are either no positive cash flows (e.g., grid-related activities, hydrogen reimbursement) or they are assumed to be equal across all configurations (e.g. energy savings). Therefore, positive cash flows are excluded from the analysis.

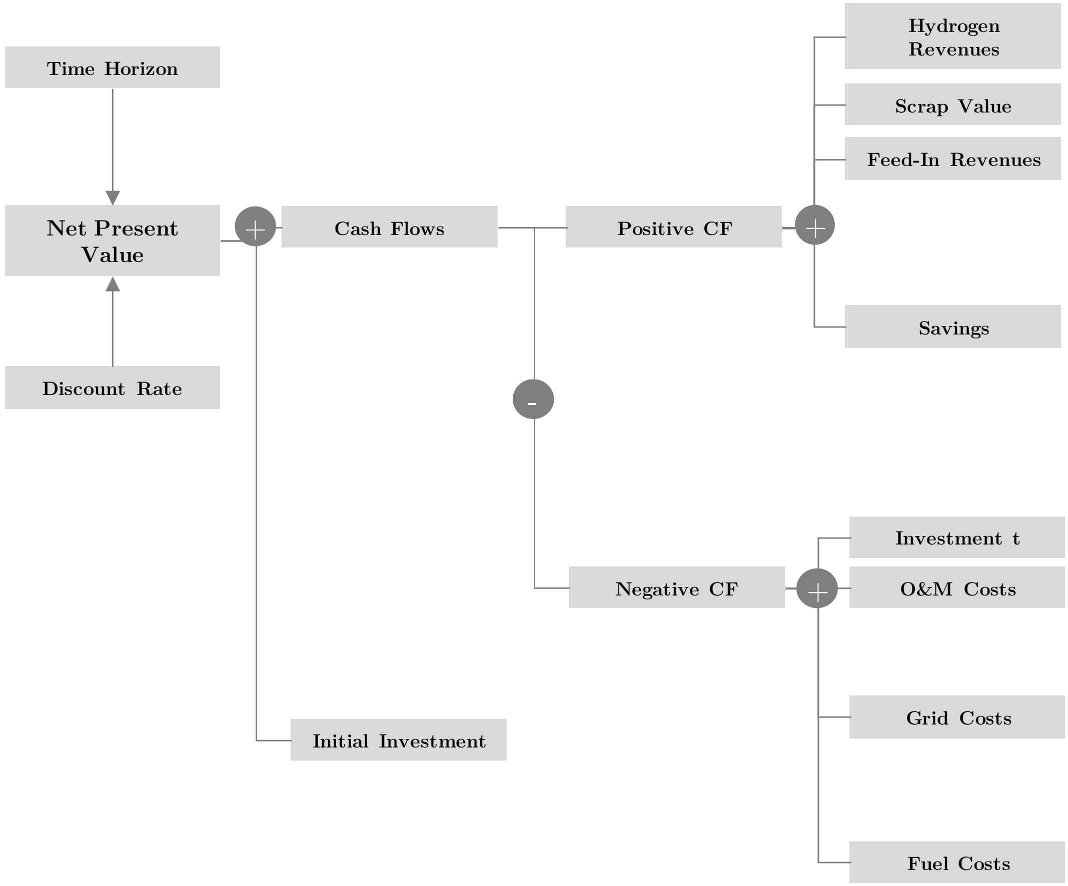


Figure S7: Schematic breakdown of net present value and its determining factors

In order to evaluate the economic impact of different neighborhood types (size, composition), a normalization of the net present cost is needed. Therefore, we define the "Levelized Cost of Energy for Decentralized Energy Systems" (LCOE$_{\mathrm{DES}}$) as follows:

$$LCOE_{DES} = \frac{\sum_{i=0}^{T} \frac{CAPEX + OPEX}{(1+r)^i}}{\sum_{i=0}^{T} \frac{E_D}{(1+r)^i}} \tag{S3}$$

where CAPEX are the investment costs, OPEX the operation and maintenance costs, and E_D the energy demand, both for electricity and heat of the decentralized system (to normalize, the thermal demand is converted to electrical demand using the heat pump's coefficient of performance). The approach of the LCOE$_{\mathrm{DES}}$ adapts the LCOE concept (Darling et al., 2011) to decentralized systems. The LCOE$_{\mathrm{DES}}$ is defined as the total annualized costs of the energy supply system (including storage and conversion) divided by the discounted energy demand of the system.

2.5 Dispatch and Balancing

Energy supply (both power and heat) and demand are matched for every quarter of an hour of the year. Whenever available, PV power is used to meet demand. The residual power, remaining demand or PV excess, is then provided or absorbed by storage options, such as battery or hydrogen storage, and priority is given to short- over long-term storage. In line with the literature (Luo et al., 2015), this study considers hydrogen as a medium- to long-term storage option and batteries (lithium-ion) as a short- to medium-term option. In the technical configuration where both storage options are applied (II), during the energy dispatch/balancing in each time step the battery is the primary storage device for either sourcing or storing energy. In case the battery is fully charged or completely empty, hydrogen as the secondary storage device assists by either absorbing the excess power (via electrolyzer) or providing the required power (via fuel cell). Figure S8 outlines the logical flow of dispatching with the two storage devices.

PV power supply, heat and power demand fluctuate on different temporal levels (hourly, weekly, seasonally), causing a mismatch between supply and demand. In order to compensate for this temporal gap, the following formula has to be satisfied for every considered time step i:

$$P_{PV,i} - Electricity\ Demand_i - Heat\ Demand_i + Storage\ Devices_i + Residual_i = 0 \tag{S4}$$

where $P_{PV,i}$ is the power supply by the solar PV system in the time step i (see 2.2), $Electricity\ Demand_i$ and $Heat\ Demand_i$ are the power and heat demands in i (see 2.3), $Storage\ Devices_i$ is positive when the battery or hydrogen storage has the capacity to provide power (i.e., discharge mode) and negative when either of both absorbs excess PV power (i.e., charge mode). $Residual_i$ denotes the remaining power demand or excess in time step i that needs to be greater than (or equal to) zero in order to reach a 100% self-sufficient energy supply.

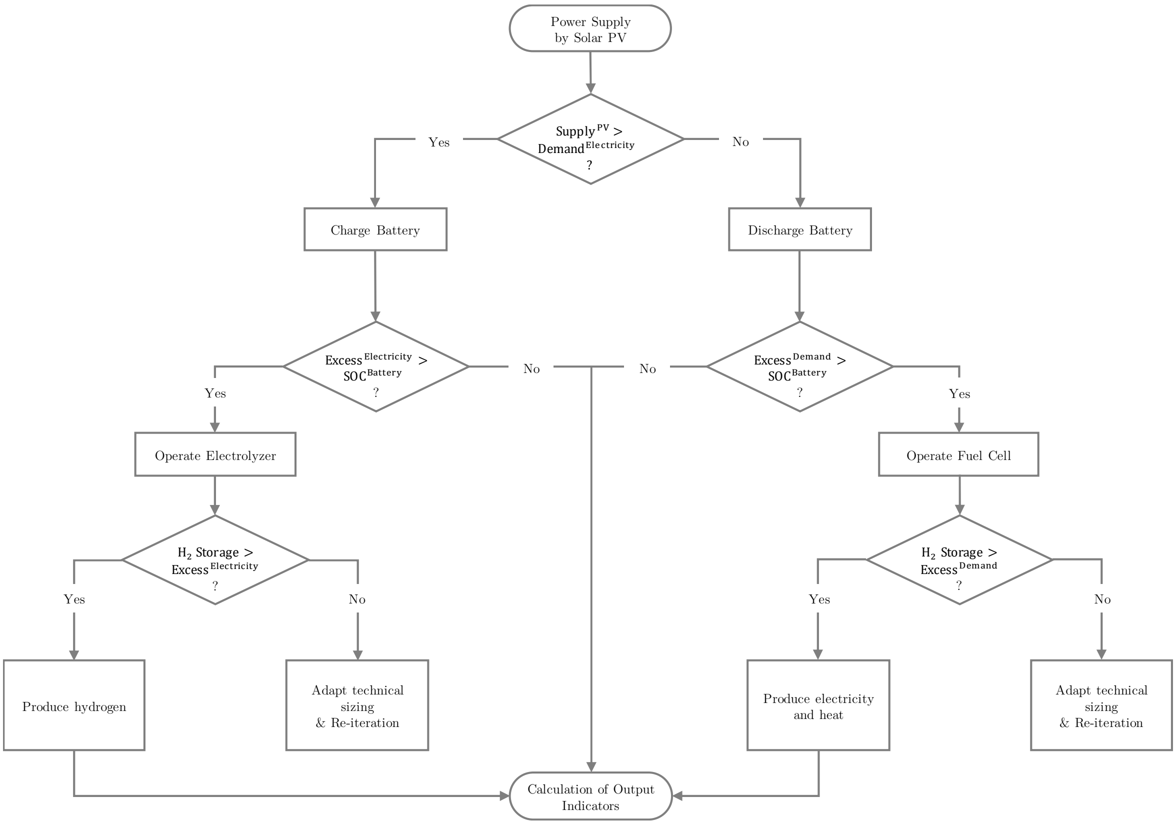


Figure S8: Logical flow of balancing approach with priority of short- (battery) over long-term (hydrogen) storage

3 Model Output Data

The following section introduces the output data, i.e., self-sufficiency rate (3.1), direct CO_2 emissions (3.2), and economic results (3.3), and describes how the heuristic optimization (3.4) allows the final results to be derived (3.5).

3.1 Self-Sufficiency Rate (SSR)

The level of energy autarky is indicated by the energy self-sufficiency rate SSR_{Energy} which describes the ratio between energy covered by the PV plant and the total energy consumption in a given year:

$$SSR_{Energy} = \frac{E_D^{PV}}{E_D^{total}} \tag{S5}$$

where E_D^{PV} denotes the energy demand covered by the PV module, and E_D^{total} represents the overall energy demand in a year (and also includes the energy provided by different storage devices). Hence, the SSR focuses on the demand side indicating how much of the total demand can be fulfilled by local generation, here solar PV. A SSR of 100% implies that no electricity or fuel (oil/gas) is needed externally, e.g., from the grid.

3.2 Direct CO_2 Emissions

Besides energy independence or an economic rationale, a decentralized system might also be beneficial environmentally. We account for direct CO_2 emissions caused by the consumption of fuel (i.e., heating oil, natural gas) or by using the grid (and its underlying generation mix). CO_2 mitigation costs describe costs that are incurred in reducing an amount of CO_2 compared to a reference case. To do so, we assess CO_2 mitigation cost as follows:

$$Cost_{Mitigation}^{CO_2} = \frac{NPC_{Config.} - NPC_{Ref}}{CO_{2,Ref} - CO_{2,Config.}} \tag{S6}$$

where mitigation costs are given in EUR per ton CO_2. Here, $NPC_{Config.}$ and NPC_{Ref} describe the net present costs for the considered technical configuration and the reference configuration, respectively. $CO_{2,Config.}$ and $CO_{2,Ref}$ are the direct CO_2 emissions for the considered configuration and the reference one without discounting over the entire system lifetime.

3.3 Economic Results

The economic performance is evaluated following the Net Present Value (NPV) approach described above (see sub-section 2.4). In order to allow a comparison of the results for different neighborhood types (size, composition), we normalize the overall costs following the $LCOE_{DES}$ concept and thus display our results as $LCOE_{DES}$ in the manuscript.

3.4 Heuristic Optimization

Our model is developed to optimize the design of a decentralized system (i.e., building or district) with the above-mentioned three outcomes or objectives (3.1.-3.3). In this study, the objective function is the minimization of net present cost (or normalized to $LCOE_{DES}$). Since the SSR – here constrained to be 100% – is an outcome of the model and requires a full simulation cycle for one year (for each 15min time step, which sums up to a total of 35,040 time steps), the optimization problem is considerably complex. In addition to the characteristic of this soft constraint being subject to a simulation cycle of the model, which is implemented through a slack variable penalty term in case the 100% SSR is not reached, the non-linear and highly multi-modal nature of the objective function given the covered technologies (namely heat pump, MCHP, electrolyzer, fuel cell, H_2 storage), and the continuous nature of all variables increase the overall complexity significantly. Genetic Algorithms (GA), as a metaheuristic approach, have proven to be a promising option to deal with these types of complex problems because their evolutionary aspect of iterative mutation and crossover (i.e., via generations) allows the generation of optimal solutions in reasonable optimization time. Matlab provides a library for genetic algorithms in its global optimization toolbox (MathWorks, 2017). As the objective function, the system's $LCOES_{DES}$ is minimized. Because of the different optimization variables and the soft constraint of an SSR of 100%, the optimization iteratively adapts the technology sizing distilling search directions to explore an optimal design.

The following are a few additional remarks on the application of GA in our model. Changing the distribution within the initial population (same number of candidate solutions) had no influence on either the quality of the solution or on the simulation time. The lower bound was set to zero, while the upper bound was limitless for the optimization variables. The population size was set to 150 and the maximum number of generations was set to 100.

3.5 Final Results

Once the genetic algorithm finds an optimal system design, the model iterations stop and we report the final results according to the formulation of the problem, that is, $LCOE_{DES}$, direct CO_2 emissions (and CO_2 mitigation cost), and the sizing of the considered technologies at an SSR of 100%.

Supporting Information B: Expert Interviews

Subject matter experts from academia and industry were interviewed to triangulate selected assumptions, input parameters, and preliminary results, such as building dimensions, specific demands for appliances, or operating modes of technical devices. The usual procedure was as follows: First, we conducted a literature review on a certain technology and its characteristics (e.g., technical/economic assumptions), developed a simplified model or produced initial results. Then, during the semi-structured interviews, we discussed to what extent these assumptions, modeling approaches, and initial results depict reality. For instance, the CTO of an electrolyzer and fuel cell manufacturer helped us to refine our input parameters and modeling approach for these two conversion devices to depict them in a simplified but robust way. Since the interviewees were from different fields of expertise, the interview guideline comprised a brief project introduction (i.e., objective, researchers) which was identical for all inquiries and then a tailored questionnaire depending on the technical field. In total, we conducted 13 interviews both in person and via telephone, between May 2015 and March 2016. Table S9 provides an overview of the interviewees including their role and position at the time of the interview.

Table S9: Overview of expert interviews

#	Category	Position
1	Project developer	CEO of a real estate developer investing in distributed concepts on residential-scale
2	Project developer	Project leader for a real estate company in a concept for residential self-sufficiency
3	Academia	Senior researcher in a P2G pilot project including a mobility application
4	Technology provider	Head of R&D at an integrator company focusing on self-sufficient residential systems
5	Technology provider	CTO of a conversion technology (e.g., fuel cell, electrolyzer) manufacturer
6	Technology provider	Head of sales at a fuel cell manufacturer
7	Project developer	Department head for spatial planning / public building authority
8	Project developer	Project manager of a pilot project for a decentralized energy system
9	Academia / project developer	Senior researcher at a national research laboratory working on several pilot projects
10	Project developer	Technical manager of a pilot project for a decentralized energy system
11	Academia / project developer	Senior researcher and project developer for a pilot project
12	Project developer	Project & innovation manager of a municipality for a pilot project
13	Project developer	Business development of a local municipality, project manager of a pilot project

Sample interview guideline / questionnaire

Below we reproduce example questions from an interview guide that has been used for a semi-structured interview with the CTO of a conversion technology manufacturer (#5 in Table S9).

Technology specifics

- Is a larger dimensioning (e.g., multiple family house, neighborhood level) of a fuel cell technically feasible?
- Are there operational obstacles with regard to operating fuel cells in self-sufficient cases?
- How high is the utilization rate of fuel cells in a self-sufficient energy case [in %]? Are such systems generally lead by heat or electricity?
- What is the ratio between the size of the fuel cell and that of the electrolyzer?
- How maintenance-prone are the PEM fuel cell systems? What is their lifetime [in years]?
- How does the operation of PEM fuel cells change with the type of energy carrier (H_2 vs. gas)?

Model assumptions (for triangulation, based on literature review)

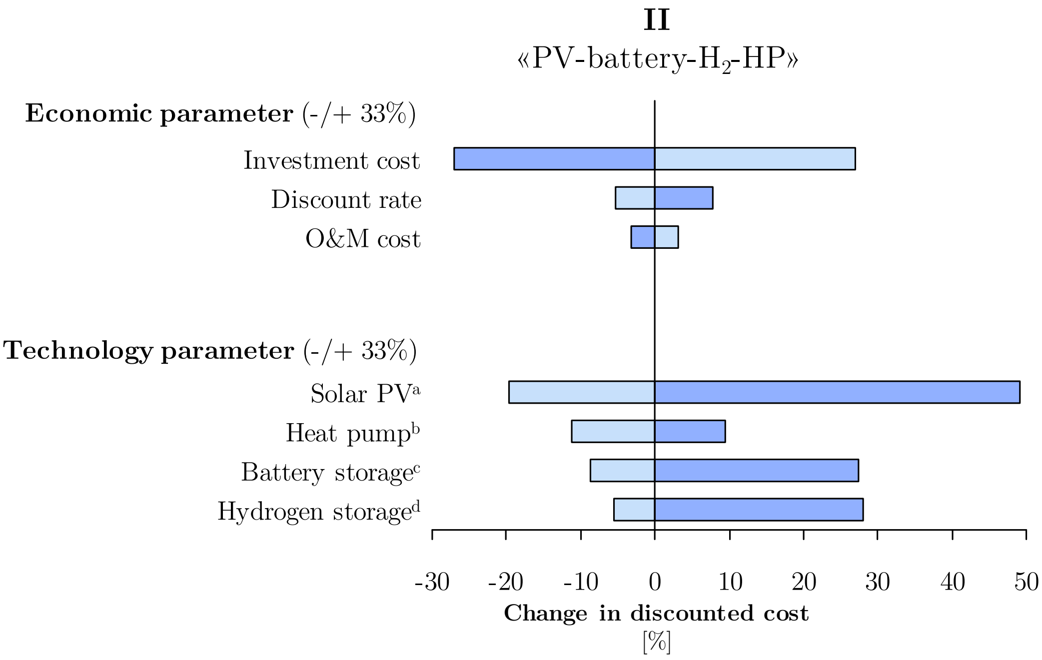
- Feedback to model assumptions and parameters (triangulation/validation)
  - Fuel Cell (PEM)
    - CAPEX approx. 6,500€/kW_{el} (5 kW_{el}) resp. approx. 1,900€/ kW_{el} (250 kW_{el})
    - Balance-of-Plant Costs approx. 60% of the CAPEX
    - Maintenance Costs 5% of the CAPEX per year
    - η_{el}=30% resp. η_{total}=90%; Operating Hours 60,000h
  - Electrolyzer (Alkaline)
    - CAPEX 3,065€/kW (10Nm^3/h) or 1,600€/kW (100Nm^3/h)
    - Efficiency approx. 5kWh/Nm^3 (depending on load profile, temperature)
    - Operating Hours 90,000h
  - Hydrogen Tank
    - CAPEX 700€/kg H_2 (100kg H_2 Storage)

General aspects

- What is the most costly aspect of the fuel cell technology?
- What are the main drivers/barriers in the development and rollout of the fuel cell technology?
- What are the future concepts of fuel cells? In which areas are they best optimized?
- What learning curves are to be expected with fuel cells in the next 20 years?
- Why do some countries (e.g., Japan, South Korea) have a technical lead compared to Europe?

Supporting Information C: Sensitivity Analysis

As we report in the manuscript, the most sensitive economic parameter is the investment cost for the covered technologies, followed by the discount rate and the O&M cost. Regarding the influence of the technologies, we see solar PV as having the highest impact on the overall discounted cost, followed by the battery and hydrogen storage technologies, and the heat pump. Notably, within each of the modeled technologies, lifetime appears to be the most sensitive parameter. Figure S9 presents the sensitivity of the model to changes in economic and technology parameters for our stylized neighborhood (here, as an example for configuration II). Remarkably, a reduction in the performance characteristics of the technologies exerts a stronger impact on the overall discounted costs than a performance increase by the same proportion. This is due the impact on the overall system design, which in the case of technology performance decreases forces the system toward less cost-efficient designs compared to technology performance increases because of constraints, such as PV area or ratio of short- to long-term storage.



a includes performance ratio, module efficiency, lifetime, angle correction factor

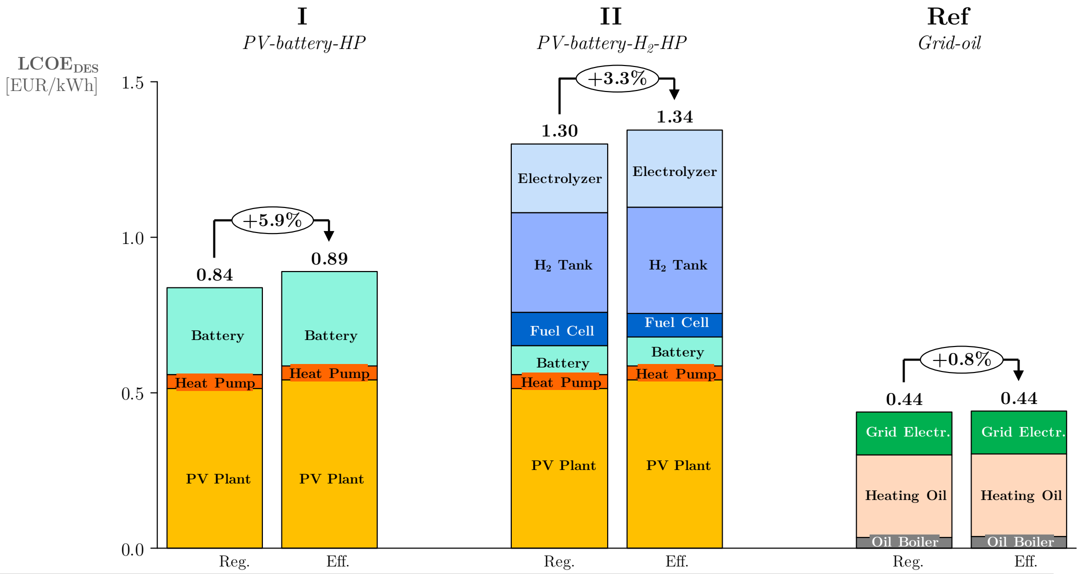
b includes coefficient of performance

c includes efficiency, depth of discharge, lifetime

d includes electrolyzer (standby power, efficiency, operating temperature/pressure, lifetime), storage (pressure, compression rate), fuel cell (thermal/electrical efficiency, lifetime)

Figure S9: Impact of altering economic and technology parameters on the discounted cost for configuration II of the case neighborhood in Bern, Switzerland

In order to assess the sensitivity of our model to end-use efficiency, we include an analysis which assumes improvements to end-use efficiency (e.g., by more efficient appliances, building insulation) of 10%. Thus, for every time-step throughout the full year, we reduced the electricity and heat demand of our stylized neighborhood in Bern, Switzerland by one tenth. While the overall discounted cost of the three configurations is reduced, along with their technology sizing being adapted to the lowered demand profiles, the impact on the LCOE$_{\mathrm{DES}}$ remains considerably small with increases of 0.8% (Ref), 5.9% (I), and 3.3% (II). Figure S10 displays the comparison of LCOE$_{\mathrm{DES}}$ split and technology sizing between the 'regular demand scenario' (cf. Figure 3 of the manuscript) and the 'efficiency scenario' with a 10% reduction in demand.



		I Reg.	I Eff.	II Reg.	II Eff.	Ref Reg.	Ref Eff.
Technologies	PV Plant [kW$_p$]	893	850	893	850	-	
	HP / Boiler / ICE [kW$_{th}$]	111.5 (GS)	100.3 (GS)	111.5 (GS)	100.3 (GS)	111.5 (Boiler)	100.3 (Boiler)
	Battery [kW]/ [kWh]	330 / 1100	318 / 1060	111/ 370	99/ 330	-	-
	Electrolyzer [kW]	-	-	170 kW	169 kW	-	-
	H_2 Tank [Nm^3]	-	-	191 Nm^3	183 Nm^3	-	-
	Fuel Cell [kW]	-	-	27 kW	16 kW	-	-
System	Discount rate [%]	7					
	System lifetime [years]	40					
	SSR [%]	100				0	

Reg. Regular demands (heat and power)
Eff. Efficiency gains by 10% on both heat and power

Figure S10: Comparison of LCOE$_{\mathrm{DES}}$ split and technology sizing for a demand (both heat and power) reduction of 10%, e.g. via efficiency measures (stylized neighborhood in Bern, Switzerland for technical configurations I, II, Ref)

Article III

Published in *Applied Energy* 231 (2018) 1285–1306
https://doi.org/10.1016/j.apenergy.2018.08.106

A Comparison of Storage Systems in Neighborhood Decentralized Energy System Applications from 2015 to 2050

Portia Murray* [1,2], Kristina Orehounig [1,2], David Grosspietsch [3], and Jan Carmeliet [1]

[1] ETH Zurich
Department of Mechanical and Process Engineering, Chair of Building Physics
HIB E13, ETH Hönggerberg, Stefano-Franscini-Platz 1, 8093 Zurich, Switzerland

[2] EMPA
Urban Energy Systems Laboratory, Swiss Federal Laboratories for Materials Science and Technology
313, Überlandstrasse 129, 8600 Dübendorf, Switzerland

[3] ETH Zurich
Department of Management, Technology, and Economics
Weinbergstrasse 56/58, 8092 Zurich, Switzerland

* Corresponding author
Phone: +41 58 765 4889
Email: portia.murray@empa.ch

Abstract

The potential of both long-term (hydrogen storage) and short-term (batteries and thermal) storage systems in decentralized neighborhoods are assessed using a multi-objective optimization approach that minimizes both costs and CO_2 emissions. A method is developed, which evaluates the performance of long and short-term storage systems in the future based on multi-objective optimization. More specifically, hydrogen storage is investigated for its future potential to be used as a long-term storage in a decentralized context and it is compared with short-term storage systems such as batteries and thermal storage. In order to analyze potential future developments, a scenario approach is deployed based on the Intergovernmental Panel of Climate Change's "Special Report on Emissions Scenarios". Three future scenarios are defined and simulated for the years of 2015, 2020, 2035, and 2050 for both a rural and an urban neighborhood in Switzerland. Based on the scenarios, the energy demand and renewable potential projections until 2050 are simulated including retrofitted buildings and renewable potential in the neighborhoods. The Pareto front of solutions is then benchmarked against national carbon and energy targets from 2020 until 2050. In addition, a range of parameter assumptions (e.g., for economic variables, policy changes, environmental conditions) are used in each scenario to incorporate uncertainty into the analysis. The long-term storage potential of hydrogen, in particular, is evaluated for its capability to shift renewable surpluses in summer towards demand later in the year. From the results, it is predicted that neighborhoods with high renewable surpluses (i.e., in rural settings) should consider the advantages of a hydrogen storage system from 2035 to 2050. For neighborhoods with low surpluses, short-term battery and thermal storage systems are predicted to be sufficient for load shifting. It is also observed that a high feed-in remuneration undermines on-site consumption, thus resulting in lower levels of storage deployment due the selling of production back to the centralized electricity grid. Lastly, it is concluded that both an increase in renewable technology deployment and in the retrofit rate of buildings will both be required to meet energy targets for the two case studies. As the renewable potential in urban contexts is limited, it is particularly important for older building stock to be retrofitted at a high rate (more than 2% of buildings per year) in order to reduce the end energy demand of the buildings. The approach used in this article is widely applicable both in spatial scope (e.g., other decentralized energy systems, geographies) and temporal scope (e.g., different years, scenarios) and allows for an optimization with a range of objective functions, thus making it an effective approach to identify the renewable and storage technologies that can contribute to most of the decarbonization of the building stock in the future.

Keywords

Decentralized energy systems, power-to-hydrogen, multi-objective optimization, renewable energy sources, storage technologies

Highlights

- Long-term (hydrogen) and short-term (batteries and thermal) storage are evaluated.
- Multi-objective optimization platform minimizes both costs and CO_2 emissions.
- Optimal solutions for neighborhoods are compared against national CO_2 targets.
- Three future scenarios between 2015 and 2050 are developed to predict future outcomes.
- Two test decentralized neighborhoods (one urban and one rural) are compared.

1 Introduction

In order to support energy self-reliance within countries, decrease greenhouse gas emissions, and reduce dependence of a declining fossil fuel supply, renewable energy sources (RES) are planned to replace a large percentage of fossil fuel electricity generation by 2050. With the replacement of centralized plants with decentralized solar photovoltaics (PV) or wind turbines, the energy future may rely on partial shifts from centralized energy generation to distributed energy generation that is based around neighborhoods of prosumers in decentralized energy systems (DES) (Parag and Sovacool, 2016).

The major drawback of RES is that they are non-dispatchable, thus their output generation fluctuates stochastically over time with associated weather conditions (i.e., solar radiation or wind velocities), resulting in a temporal mismatch of supply and demand. Currently, this temporal mismatch is managed by exporting excess renewable production to the grid or curtailing renewable production and then importing electricity from the grid when demand is not met by renewable energy supply. However, as the fraction of renewables in our electricity grid increases, this temporal mismatch will become more severe.

1.1 Motivation

In order to allow shifting of non-dispatchable loads, energy storage is required (Battke et al., 2013). Energy storage comes in many different forms, with the most prominent technologies being batteries, pumped-hydro storage, and thermal energy storage. A technological split into short and long-term storage represents a common solution (Beaudin et al., 2010). Shifting demand over longer periods of time is important, as there is often not only a day-tonight mismatch of renewable energy and demand but also a seasonal mismatch as RES are more plentiful in summer and energy demand of buildings is higher in the winter in heating dominated climates.

A promising long-term storage option is hydrogen storage or power-to-hydrogen (P2H). P2H refers to the use of an electrical current, in this case from surplus renewable electricity production, to split water via electrolysis into hydrogen and oxygen. The hydrogen can be stored in compressed tanks or metal hydride storage, used to run fuel cells, can be directly injected into the natural gas grid up to certain concentration limitations, or converted to methane via methanation and used as a substitute for natural gas (Götz et al., 2016). This technology can be installed in both a centralized or decentralized context and is not ideally considered to have time dependent losses (IEA, 2015).

There are two major disadvantages currently associated with P2H: the technology is expensive and it typically has low round-trip efficiencies. Current research into hydrogen technologies, such as fuel cells, hydrogen storage, and electrolysis, are constantly improving both equipment costs and efficiencies. In addition, the need for energy storage should increase with the predicted phase-out of feed-in tariffs and increasing implementation of RES. (SwissSolar, 2018). In order to assess the changes in these model parameters over time, a scenario based approach, looking at a time horizon from 2015 to 2050, is developed to assess the optimal technology combination over time to investigate if P2H is predicted to become more cost effective on the decentralized level in the future.

In order to predict future parameters (e.g., technology costs, fuel prices, feed-in tariffs, efficiencies, etc.) that are required in an energy optimization model, there are a large amount of assumptions and uncertainty that goes into parameter selection. In order to deal with uncertainty, a scenario based approach for potential future development is used. These future scenarios are based on a report from the Intergovernmental Panel on Climate Change's "Special Report on Emission Scenarios" (Nakicenovic and Swart, 2000). This report contains descriptions of several possible energy futures including projections and storylines on which model assumptions can be based. They provide a framework for the development of scenarios covering assumptions on the uncertain parameters.

1.2 Literature Review

There is a wide array of literature dedicated to the design and analysis of DES using optimization. First, due to the large number of publications on DES optimization, papers that have a focus on the hydrogen economy and have applications for stationary building and mobility demands are considered. Second, papers that include future scenarios or optimization horizons for long-term energy planning are presented. Finally, the research gap is derived and the focus of this study is outlined. Several of the publications on DES are based on optimization and the Energy Hub concept that was defined by Geidl and Andersson (2006). In this definition paper, Energy Hubs are described as a "system, where multiple energy carriers can be converted, conditioned, and stored to satisfy a set of demands". Technologies are defined as energy converters that can transfer energy from one carrier to another at a certain efficiency. In Geidl and Andersson (2006), hydrogen is included as an energy carrier in optimal power flow of DES.

This method was then expanded by Hajimiragha et al. (2007). The authors further developed an optimal power flow model with additional hydrogen energy considerations, such as fuel cell vehicle charging infrastructure. Their optimization model used hydrogen converters as well as district heat, natural gas, hydrogen, and electricity. Building energy demand and fuel cell vehicle demand, in the form of hydrogen, were included in the model.

A similar method using Energy Hubs was also used by Maroufmashat et al. (2016a). The authors created a mixed integer linear program (MILP) model for four pre-defined urban districts over a year of operation. The optimization included the design of hydrogen charging facilities within four urban districts.

Several other papers reviewed the design and optimization of hydrogen storage systems for applications of on-site renewable facilities, such as wind farms or large solar installations in rural areas. Zhang et al. (2017) used a genetic algorithm to design a PV-Battery-Hydrogen system using a multi-objective analysis that minimized costs and maximized self-sufficiency. It was found that under pessimistic costs, batteries were a cheaper option, however under optimistic costs, hydrogen storage was competitive with batteries and performed better when accounting for grid power fluctuations. The heating energy carrier was not addressed in this system. Bernal-Agustín and Dufo-López (2010) created a techno-economical optimization of PV-Wind systems with a grid connection. The model focused on power feed-into the grid and selling of hydrogen. It was found that the selling price of hydrogen would have to be high in order to recover the capital costs for the system in 10 years.

Similarly, Korpås and Holen (2006) developed an operation planning model for a wind-hydrogen model participating in power markets. When wind electricity production was in excess, hydrogen was produced via an electrolyzer and stored. Electricity was then later produced via hydrogen in fuel cell and was then sold back to the electricity grid on the spot market. Alternatively, hydrogen was also used directly for fuel cell vehicle charging. They used linear optimization to determine the operational set points of an electrolyzer and fuel cell using a receding horizon control strategy and participated in arbitrage to maximize profits. It was found that electricity prices must have a large variability for the fuel cell to be used, since the overall efficiency of the system is relatively low for electricity production. The authors recommended combining the scheduling model with an investment cost model and a long time horizon to estimate cost reductions and efficiency improvements over time in different power systems.

Petruschke et al. (2014) used a combination of a heuristic and linear optimization structure to separate the optimizations for system configuration, technology sizing, and operation for a PV-Wind-Hydrogen system on an island. This paper states that it was able to reduce simulation time due to the separation of the sizing and operations optimization which represents a multi-layer simulation approach. The paper investigated different percentages of renewable shares for the electric grid (heat demand was not considered) and found that the size of the hydrogen system was increased as the renewable share increased. Batteries and thermal storage were not considered in the model.

Li et al. (2017) used a bi-level optimization for a stand-alone microgrid capable of providing electric power, cooling, heating, and hydrogen demands. This bi-level strategy applies a MILP to simulate the operation and a genetic algorithm to size the component decision variables. Uncertainties were taken into account using a Minimax robust optimization approach. They also considered degradation of the storage technologies in the model and found that fuel cells, batteries, and electrolyzers were sized larger when degradation was accounted for. The uncertainty analysis found that higher levels of uncertainty resulted in larger sizes of storage to buffer the uncertainty in the demand and in the renewable forecasts. Lastly, Dufo-López and Bernal-Agustín (2008) performed a triple-objective optimization for the design of a PV-wind-diesel-hydrogen-battery system in Spain using a genetic algorithm. The three optimizations represented minimization of costs, minimization of emissions, and minimization of unmet demand in kWh/year. The authors found that “Due to the high costs of the hydrogen components, energy storage in most solutions is done only using batteries”.

Yang et al. (2016) investigated the optimal operation of residential, commercial, and industrial prosumers in a DES and found that the active participation of the prosumers played an important role in better response to time of use electricity prices and that peak shaving could be better managed for the community as a whole. Electricity, cooling, plug-in hybrid vehicle, and heating demands were all considered in this model, however only the dispatch was optimized, as opposed to the full design and operation of the system. In addition, only short-term storage with batteries and thermal storage were considered.

A major shortcoming of the assessed literature, with the exception of Dufo-López and Bernal-Agustín (2008) and Zhang et al. (2017), is the storage duration considered. One of the main benefits of P2H storage is its long storage cycle durations over many months, thus it is able to store seasonal variations without time dependent losses. Many of the papers discussed use the typical days method (Fazlollahi, 2014), or a rolling horizon method (Li et al., 2017), to reduce the time horizon of the simulation from 365 days into a shorter horizons to reduce the computational complexity of the optimization. The typical days method does not allow for storage continuity across days as simulated days are non-consecutive thus it cannot be used to accurately assess storage durations longer than the length of the time-slices. The rolling horizon method can be used to allow for storage continuity over longer periods, as was done in Marquant et al. (2015). Marquant et al. (2015) recommended that the rolling horizon approach should be aggregated in order to consider long-term storage horizons and that it must be coupled with a genetic algorithm in order to consider simultaneous design and operation. The receding horizon method is very similar to the rolling horizon method as it uses a moving time horizon, however it is typically used for model predictive control (MPC) optimization (as shown in Korpås and Holen (2006)) rather than for design and planning optimization models. However the shortening of time horizon using these techniques does not sufficiently allow for accurate analysis of long-term storage design and operation and thus is limited in assessing the long-term potential of P2H. This is particularly true for case studies with large renewable potentials and high seasonal fluctuations. The most accurate method to consider long-term storage is still to use a full horizon.

Multiple studies exist that have used optimization in the context of future energy systems to identify and assess strategies for reducing emissions. In Lunz et al. (2016), a methodological approach using Germany in 2050 was used with multi-objective optimization for 29 scenarios selected from previous studies. This work focused on analysis at the national level (i.e., Germany) instead of DES at the neighborhood or district scale.

In assessing future feasibility of P2H systems, the JRC-EU TIMES model (Simoes et al., 2013), which used linear optimization to model future energy scenarios from a policy perspective, was applied to hydrogen technologies and power-to-gas in Sgobbi et al. (2016). In this study, the model was run for two pre-defined policy scenarios for the years of 2020, 2030, 2040, and 2050 for the EU. The results showed that hydrogen technologies were relevant for meeting long-term emission reduction targets and indicated that they might become economically feasible by 2040, particularly in the industrial sector.

In Han et al. (2017), a DES was designed for the island of Jeju in South Korea. The authors used optimization and scenarios framed as conventional energy, transitional energy, and 100% renewable energy scenarios to meet thermal, electrical, and vehicle demands on the island. Although the study is framed in scenarios, the evolution of the energy system over time is not considered. In Ren and Gao (2010), a MILP model was used for the integration and evaluation of DES for a campus in Japan. The model used cost minimization to decide which technologies would be the lowest cost for the campus to meet electricity and heating demand. The sensitivity study showed that the results were the most sensitive to energy demand, energy prices, and the carbon tax rate. Although batteries and thermal storage were considered, longer term storage was neglected and it was determined that installation of DER was not cost optimal but could be optimal if a higher carbon tax was established.

Yazdanie et al. (2017) optimized the system design using the TIMES (Integrated MARKAL-EFOM System) framework for the DES of Basel in Switzerland for the years of 2010–2050. The technology focus was on boilers, heat pumps, solar thermal, PV, micro combined heat and power (CHP), batteries, and thermal storage. A cost optimization using emission target constraints was performed. Four scenarios were used representing a business as usual scenario, a new energy policy scenario, and a gas variant that allowed for either restricted or unrestricted national imports of natural gas. It was found that building renovations were the most cost optimal measure that could significantly decrease energy demand. In addition, carbon taxes were found to strongly promote low-emission technologies such as heat pumps, rooftop PV, small gas CHPs, and batteries.

Lastly, McKenna et al. (2017) created a techno-economic model based on an energy autonomous network in residential buildings for DES. This paper tested various degrees of decentralization with the lowest level being systems within single-family homes to the largest scale of 1000 single family households. The authors developed a MILP model to maximize electrical self-sustainability in the community by selecting the optimal configuration, sizing and operation of micro CHPs, photovoltaics, thermal and electrical storage, and boilers. It was found that cases with larger numbers of prosumers were able to be more electrically self-sufficient and less expensive than single family homes operating as stand-alone systems supplying. Single-family homes operating as stand-alone systems could meet 30% of their electricity needs but districts with more than 560 single family homes met almost 100% of the district's electricity demand. In this work, the heating demand was not considered in the calculation for self-sustainability and long-term storage options were neglected.

Drawing upon the reviewed publications including future scenarios, the existing studies generally focus on larger energy systems with the smallest being on the scale of a large city (Yazdanie et al., 2017) and the largest being on the national scale (Lunz et al., 2016). Many of these large case studies are overly simplified and are not suited to assess the potential of distributed resources and storage, thus it is also important to investigate these scenarios on the decentralized neighborhood or district level. In addition, many of the publications also lack a comparison of optimal solutions to emissions targets, either on a local or national scale.

1.3 Focus of the Study

There is a gap of research in which the future evolution and planning of long-term and short-term storage systems is not yet assessed in a decentralized context. This is summarized by Dodds et al.

(2015): “There is a need to include hydrogen and fuel cell heating technologies in future scenario analyses, and for policymakers to take into account the full value of the potential contribution of hydrogen and fuel cells to low-carbon energy systems”.

Rather than analyzing whether implementation of these technologies in DES is feasible today, this study assesses the future predicted potential of storage technologies in DES from 2015 to 2050 using a multi-objective optimization model and then benchmarks the optimal solutions against national carbon dioxide emissions targets for 2020-2050. We investigate the optimal storage configurations using multi-objective optimization to minimize both costs and CO_2 emissions. A particular emphasis is placed on the investigation of long-term hydrogen storage. Today, this technology is quite expensive and is associated with low round-trip efficiencies but is uniquely capable of providing long-term storage while being used in decentralized contexts. In addition, it is predicted to decrease in cost and improve in efficiency over time (Körner, 2015). The long-term with short-term storage performance is compared for two sample case studies (one rural and one urban) within municipalities in Switzerland including on-site renewable production and local energy demand to demonstrate the ability of the model to evaluate different neighborhoods. In order to consider the underlying uncertainty of the model inputs from 2015 to 2050, three scenarios and narratives are used that are developed based on the IPCC climate change scenarios (Nakicenovic and Swart, 2000).

With this goal, the paper is structured as follows. First, the future scenarios are defined and future parameters set in section 2. Second, the modeling methodology is described in a three-step process that accounts for building energy demands, local renewable potentials, and system modeling in section 3. Third, the two case studies used for analysis are described in section 4. Fourth, the results of the optimization are presented and discussed in section 5. Lastly, conclusions are discussed in section 6.

2 Future Scenario Setting

This section introduces the underlying scenarios that are analyzed in this study to depict the potential future developments of input parameters and model assumptions. It starts by presenting rationale and background of the scenarios (2.1) and continues with the description of the developed scenarios (2.2), which entails a sketch of the narrative storylines, before the setting of the parameters values for each scenario is outlined (2.3).

2.1 Introduction and Development of Scenarios

Parameters and assumptions in future energy systems underlie uncertainty regarding their future development, e.g., technology trajectories (learning) and market trends (price volatility). To cope with this uncertainty (i.e., the numerous projections for individual parameters with a broad spectrum of low, medium or high values), scenarios provide a better understanding in order to reach decisions that are robust under a wide range of possible futures (Moss et al., 2010). Thus, scenarios are an appropriate tool to assess the alternative images of complex systems by using a consistent set of assumptions within so-called storylines or narratives used to describe the economic, global, and environmental conditions of a scenario (Nakicenovic and Swart, 2000).

In 2000, the IPCC published the "Special Report on Emissions Scenarios" (SRES) (Nakicenovic and Swart, 2000), which contains both quantified projections and narratives (storylines) for the future and which has been extensively used as the reference for subsequent research and for the political and societal discourse on climate change (Girod et al., 2009). In the SRES, the IPCC scenarios are based on four narrative storylines that can be categorized along two major dimensions: globalization (from more regional to more global), and sustainability (from more economic to more environmental). These dimensions, along with the resulting storylines, seem to reappear as key archetypical scenarios in a large number of recent international assessments (van Vuuren et al., 2012). Figure 1 shows these scenarios from the original IPCC publication (Nakicenovic and Swart, 2000).

This study builds upon the IPCC classification and defines three scenarios that are deemed relevant for the investigation of potential future developments from the baseline year 2015 to 2020, 2035, and 2050: (1) Conventional Markets, (2) Global Sustainable Development, and (3) Regional Sustainable Development. These three scenarios, shown in Figure 1, are considered to cover a wide range of possible futures, but certainly not all (e.g., hazardous events, disasters). Thus, they allow using consistent combinations of assumptions composed of the various projections in literature for each parameter (see subsection 2.3, Table 1). For this analysis, the A2 scenario was omitted, as in this context it corresponds to transition to more decentralized solutions without a focus on sustainability. This scenario is both unlikely in the Swiss context and would result in neither cheaper nor lower emission solutions in this analysis.

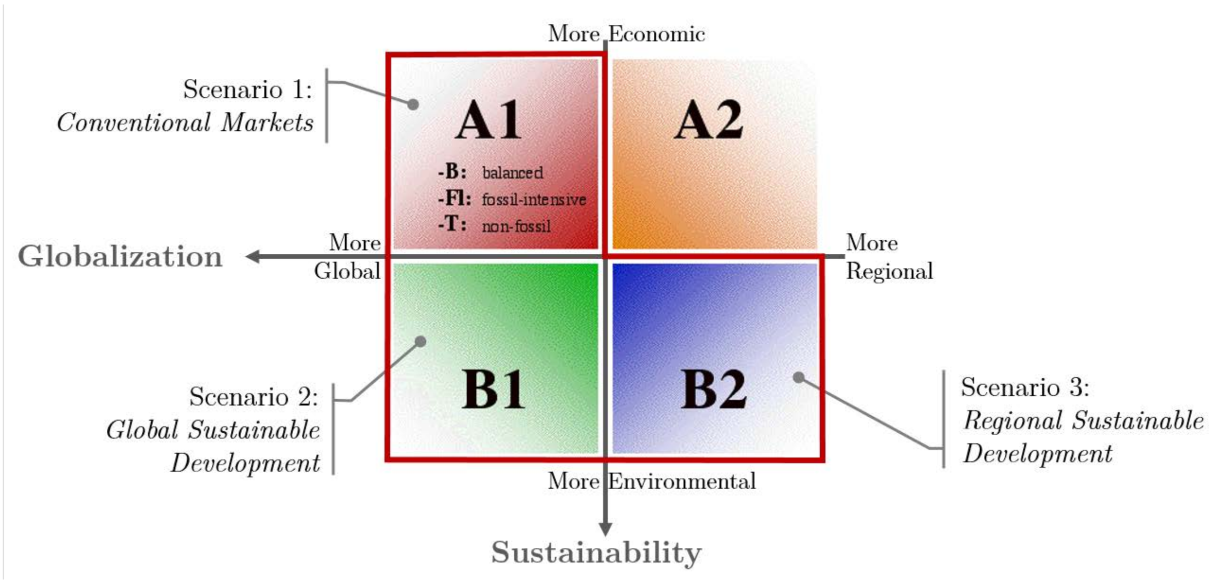


Figure 1: IPCC Special Report on Emission Scenarios (2000). The red line outlines the three scenarios adapted for this paper (Nakicenovic and Swart, 2000). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

2.2 Description of Scenarios

Conventional Markets

The *Conventional Markets* scenario (CM) is based on IPCC's scenario A1 and assumes a world of global, well connected markets with a strong economic focus. Since the emphasis rests on fossil-based generation, the deployment of RES remains on a low, business-as-usual level, and consequently the climate is changing more rapidly.

In the Conventional Markets scenario, the energy prices (electricity, gas, oil) are considered to increase only moderately due to high global flow rates and low trade barriers. Because of the economic focus, the feed-in remuneration is phased-out in the short-term, and both the CO_2 tax and the retrofit rate (i.e., pace of efficiency improvements in the building stock) are kept at a rather low, as-is level. As a consequence, technology costs are assumed to be at a high level for RES technologies (e.g., solar PV, wind), at a low level for fossil-based technologies (e.g., oil/gas boiler) and at a medium level for other storage or conversion technologies. For the technology performance, such as efficiencies or lifetime, the relations are inverted. For the building retrofits rate, the current retrofit rate in Switzerland is used, which is defined by the "Business as Usual" scenario in the Swiss Energy Strategy 2050 to be, on average (actual rates are specific to the age of buildings), 1% of buildings per year (Prognos AG, 2012).

Global Sustainable Development

The *Global Sustainable Development* (GSD) scenario, resting on IPCC's B1 scenario, pictures a future based on global cooperation, well connected markets but also a strong focus on environmental consciousness and protection. Global regulation puts the fossil phase-out into practice and fosters the deployment of RES, internationally coordinated and mostly in centralized settings, which is why the global temperature increase is more limited than the other scenarios.

In the GSD scenario, the sustainability focus leads to a high tax for emitting CO_2 and a high retrofit rate. The reimbursement for feeding electricity into the grid remains high in the GSD scenario due to strong grid infrastructure for transmission and distribution for power ex- and imports. Energy prices are expected to increase with a medium rate, as the usage and thus the flow rates for fossil fuels is limited. Since this sustainable scenario relies on the deployment of renewable energy, the cost for RES technologies are assumed to be low, while for fossil-based technologies they remain rather high, and vice versa for their technology performances. In addition, this sustainable scenario includes an increased rate in retrofits defined by the "New Energy Policy" scenario in the Swiss Energy Strategy 2050 of 2% of buildings, on average, per year (Prognos AG, 2012).

Regional Sustainable Development

The *Regional Sustainable Development* (RSD) scenario is derived from IPCC's scenario B2 and assumes a shift towards local and decentralized solutions to cope with environmental issues. Similar to the Global Sustainable Development scenario, fossil fuels are phased out, while RES are deployed to a large extent, especially in decentralized settings.

In the RSD scenario, there is also a sustainability focus which leads to a high tax for emitting CO_2 and a high retrofit rate. As opposed to the GSD scenario, in the RSD scenario feed-in rates are slowly phased out as the focus shifts towards self-consumption. Energy prices are expected to increase at a high rate, as the usage and thus the flow rates for fossil fuels is limited, especially in this scenario where additional restrictions (e.g., high import tariffs) hamper both their demand and supply. Since this scenario also relies on the deployment of renewable energy, the technology costs and performances are the same as with the GSD scenario. In addition, the retrofit rate are also be the same as the GSD scenario.

2.3 Setting of Future Parameters

In order to set the model parameters according to the underlying logic of the above described scenarios, this study relies on projections from literature. If available, projected values were directly sourced from publications, such as the Annual Energy Outlook (U.S. Energy Information Administration (EIA), 2015), or are based on ranges (i.e., lower or upper projected limits) given in different sources and referring to the nature (cf. low, medium, high) of each scenarios parameters.

Table 1 provides an overview of the three scenarios and selected model-related parameters. Due to the large number of RES, conversion, and storage technologies, the comprehensive set of parameters including references is given in Appendix A.

Table 1: Overview of the three scenarios and selected model-related parameters and assumptions, both on the economic/market and the technology side. (The data below is only an excerpt of the full range of input parameters, which can be found in the appendix.)

			0	**1**			**2**			**3**		
			Baseline	*«Conventional Markets»*			*«Global Sustainable Development»*			*«Regional Sustainable Development»*		
			2015	**2020**	**2035**	**2050**	**2020**	**2035**	**2050**	**2020**	**2035**	**2050**
	Parameter	**Unit** [a]										
Economic / Market	Electricity price	CHF/kWh	0.198	0.206	0.235	0.231	0.212	0.251	0.262	0.212	0.251	0.262
	Heating oil price	CHF/kWh	0.067	0.037	0.052	0.061	0.095	0.129	0.148	0.193	0.270	0.305
	Natural gas price	CHF/kWh	0.064	0.094	0.121	0.133	0.109	0.123	0.141	0.096	0.154	0.202
	Feed-in tariff	CHF/kWh	0.176	0.087	0.000	0.000	0.176	0.176	0.176	0.087	0.011	0.001
	Grid CO_2 intensity	g CO_2/kWh	124	150	150	150	100	89	74	0	0	0
	CO_2 tax	CHF/t CO_2	84	84	84	84	120	240	240	120	240	240
	Discount rate	%	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0
	Retrofit rate	%	1.0	1.0	1.0	1.0	2.0	2.0	2.0	2.0	2.0	2.0
Technology	**Solar PV**											
	Investment cost	CHF/kW	2669	2669	2669	2669	1285	1087	989	1285	1087	989
	O&M cost	CHF/kWh	0.034	0.025	0.019	0.013	0.025	0.019	0.013	0.025	0.019	0.013
	Lifetime	years	25	25	25	25	25	25	25	25	25	25
	Efficiency	%	17.0	17.0	17.0	17.0	17.0	17.0	17.0	17.0	17.0	17.0
	Hydro											
	Investment cost	CHF/kW	3478	3478	3478	3478	3478	3478	3478	3478	3478	3478
	O&M cost	% of inst. kW p.a.	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
	Lifetime	years	40	40	40	40	40	40	40	40	40	40
	Wind											
	...	...	...		...			...			...	
	..	..	..		..			..			..	
	.	.	.		.			.			.	

[a] all costs are inflation-adjusted to 2015 CHF (Swiss Francs)

3 Modeling Methodology

The model developed in this work represents a DES with four energy carriers: electricity, heating, gas, and hydrogen. The model optimizes for the configuration and sizing of a selection of storage technologies, conversion technologies, and RES. A schematic representation of the technologies and energy grid included in the model are shown in Figure 2. Three grids are included in the model: a natural gas grid, a heating grid, and an electricity grid. The RES technologies include small-wind turbines, small-hydro, and solar PV. Conversion technologies include heat pumps, electrolyzers, fuel cells, gas turbines, and gas boilers. The storage technologies include battery storage, thermal storage, and hydrogen storage. From the hydrogen storage, a limited portion of hydrogen can be injected directly into the natural gas grid up to a volume concentration of 2%. There is a single set of these conversion and storage technologies that are installed in a centralized location that are connected to the three networks. The output production of these technologies is fed into the networks and is then used to meet the heating and electric demand of the neighborhoods. The costs, efficiencies, and lifetimes of the technologies are found in Tables A.2 and A.3 of the Appendix A.

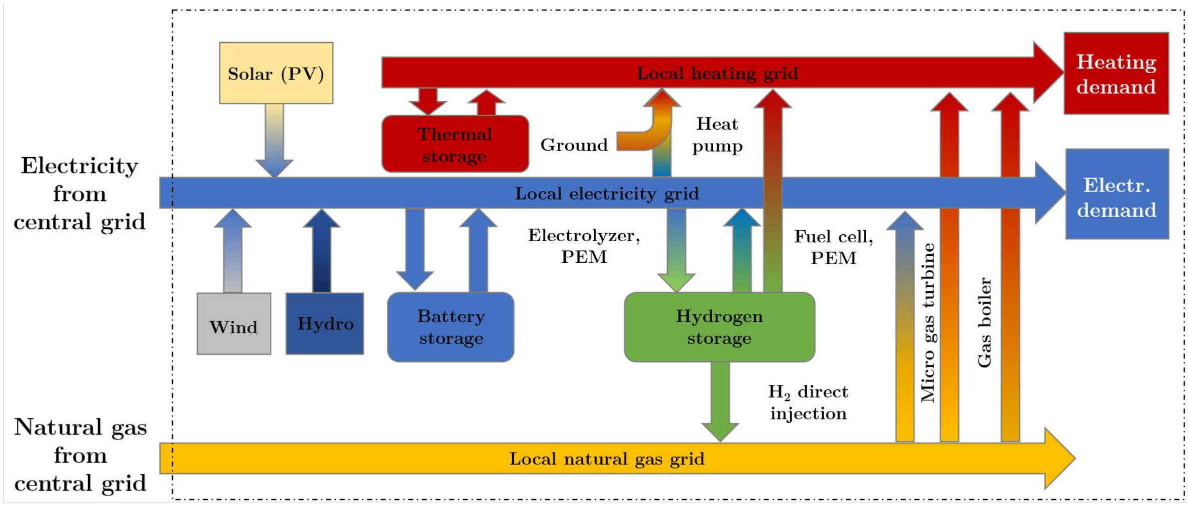


Figure 2: A Schematic representation of the P2H model with grid interactions

The modeling of the DES can be split into three separate categories. First, the buildings demand is simulated for two case studies using a dynamic building model. Second, the renewable energy supply is modeled. Lastly, a multi-objective optimization model that minimizes both costs and CO_2 emissions is run for a full year with an hourly resolution for the baseline year 2015 and the future years 2020, 2035 and 2050 based on the scenarios. According to the objective, the optimal system configuration, sizing, and operation are selected as model outputs. These models are used in the work flow described in Figure 3.

In this work flow, the process begins through selection of the future scenario and year of consideration. From the selected scenario and year, a weather file is chosen and the building geographic and statistical data are chosen. Based on this weather data (described in section 4) and the building geography, the demands of the buildings are simulated. In parallel, the renewable potentials pertaining to PV, wind, and hydro are also simulated using weather and geographic data (subsection 3.2). The outputs of these two models are the building demands and renewable energy potential profiles for the case studies over a one year period for the present and future years. These profiles are then combined with the set of economic, technical, and environmental parameters (see Table A.1) that are determined based on the year and future scenario and are used as inputs into the optimization modeling (subsection 3.3). Finally, the Pareto front for the optimization is shown in subsection 5.1 and the Pareto optimal solutions are benchmarked against national energy and emissions building targets described in subsection 3.3 and shown in subsection 5.2.

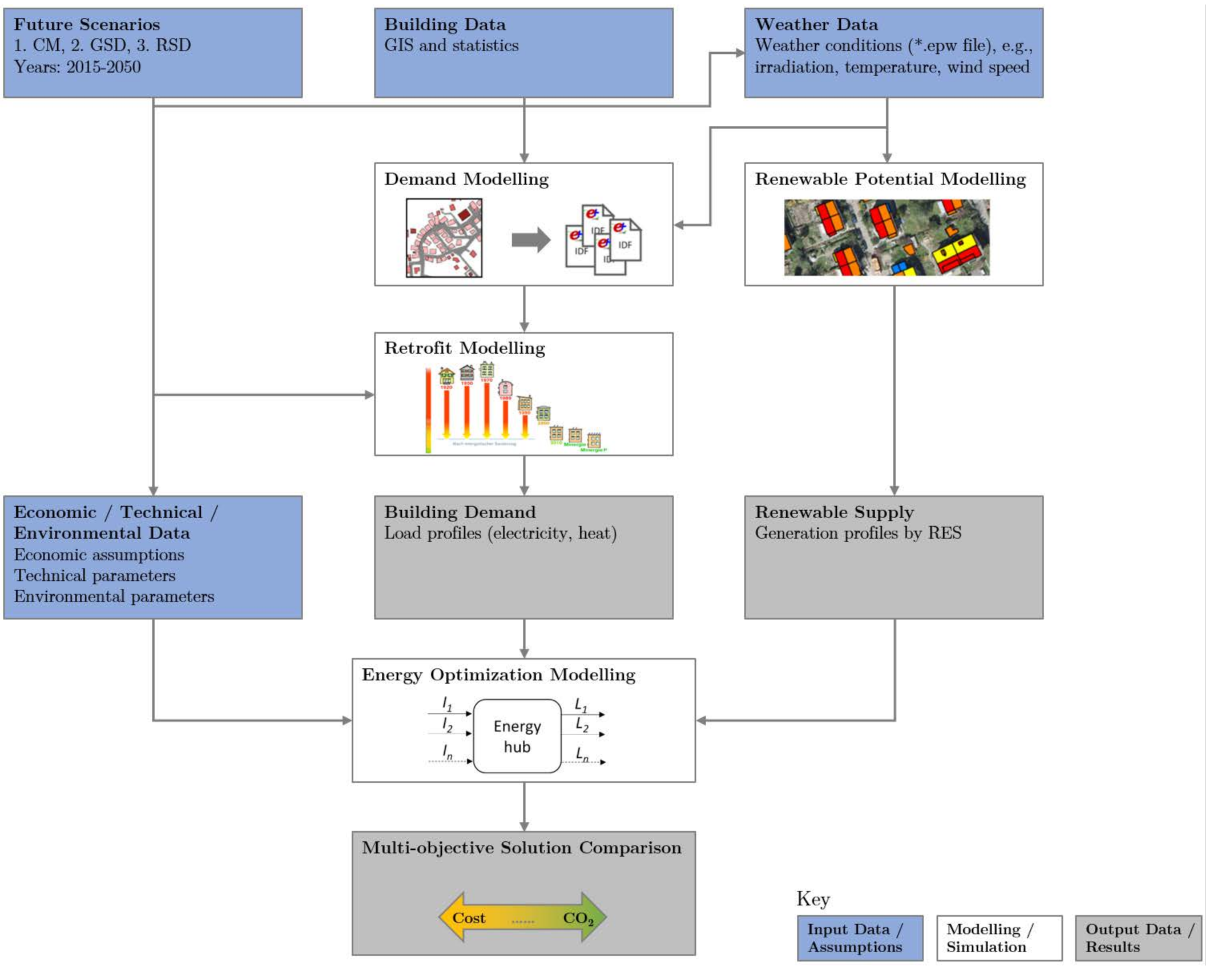


Figure 3: Modeling work flow and analysis

3.1 Building Energy Demand

Demand Model

In order to calculate the electricity and heating demand in the buildings, the dynamic building model developed in Wang et al. (2018) was used. The CESAR tool utilizes EnergyPlus as a simulation engine to model hourly electricity, space heating, and domestic hot water demand for all buildings considered in the case studies. Using the building 2D geometry available in ArcGIS and the building height, 2.5D building geometry is constructed.

In addition, statistics on building type, building age, and number of occupants is used to estimate both electrical and heating demand at hourly intervals for a year of operation. This data was taken from the Building and Apartment Registry ("Gebäude und Wohnungsregister") data from the Bundesamt für Statistik (Federal Statistical Office, 2018). It assigns building construction, glazing ratio, and infiltration values based on building age and type. This information is combined into individual EnergyPlus building files for each building, taking neighboring buildings as shading objects into account. The EnergyPlus files are combined with a weather file and simulated over a one year period at hourly intervals to compute the 2015 base demand for the case studies.

Retrofit Modeling

The current retrofit rate for residential buildings lies roughly between 1 and 2% of the building stock. The Swiss Energy Strategy 2050 has outlined retrofit rates based on building type (single or multi-family houses) and building age for the "Weiter wie Bisher" scenario (equivalent to "Business as Usual") and the "Neue Energiepolitik" scenario (equivalent to "New Energy Policy") (Prognos AG, 2012). Based on these retrofit rates, buildings within the case studies are selected to be retrofitted and their constructions are updated. The future demand is then calculated for the years of 2020, 2035, and 2050 using updated EnergyPlus files.

3.2 Renewable Potential Modeling

For both case studies, the renewable potentials within the DES boundaries are examined. As the case studies include both rural and urban settings, geographical information system (GIS) data was used to assess the amount of land on the building parcels and the natural resources in the immediate area. Light detection and ranging (LiDaR) data for both terrain and building elevation were acquired from Federal Office of Topography (2014) for both case studies to evaluate the rooftop geometry for available solar installations, as well as the shading from the terrain in the area. As decentralized renewables were the focus, wind or PV farms were not included, but rather rooftop PV and small-wind potential that is suitable for installation in more populated areas.

Rooftop Photovoltaics

A GIS approach based on the method developed in Mavromatidis et al. (2015) is used to derive the hourly solar radiation on the rooftops, as well as to calculate the available area for solar installations. Using LiDaR data for the building elevation and digital terrain raster data from Federal Office of Topography (2014), the rooftop slopes, aspects, area, and solar incidence on rooftop surfaces are calculated at a 2m×2m resolution in ArcGIS for all non-protected buildings in the two case studies. The efficiency of the PV panels is then calculated at each time interval using efficiency correlations based on the temperature of the panels. For more details, please refer to Mavromatidis et al. (2015).

Small-Wind

Due to the low average wind speeds in the case studies, a low speed wind turbine is proposed. The selected model was the Aventa LoWind Turbine (Aventa Ltd., 2016). At a hub height of 18 m, the corrected wind speed was calculated with equations (1) and (2).

$$u = u_r \left(\frac{z}{z_r}\right)^{\alpha} \tag{1}$$

$$\alpha = \frac{\ln(u_2) - \ln(u_1)}{\ln(z_2) - \ln(z_1)} \tag{2}$$

Here, u represents the corrected wind speed, u_r represents the reference wind speed at a certain height, z is the height of the wind turbine, z_r is the height at which the reference wind speed is taken, and α is a coefficient that represents the rate of wind speed increase as a function of height that can be solved with equation (2). The power curve for the selected wind turbine was then used to correlate hourly power production depending on the corrected wind speed.

Small-Hydro

The potential of a micro hydro plant is assessed for a river in one of the case studies. Flow rates are provided for a potential site in the nearby river that is currently not utilized for hydropower. These measured volumetric flow rates are aggregated into hourly intervals to calculate the available energy potential over the year using equation (3).

$$P = \eta g Q H \tag{3}$$

In equation (3), P is the generated hydropower in kWh, η is the turbine efficiency, g is the acceleration due to gravity, Q is the volumetric flow rate in m^3/s, and H is the effective pressure head of water across the turbine in meters. In this case, the turbine efficiency is assumed to be 80%, as it is a smaller turbine in a micro-hydro plant (Paish, 2002).

3.3 Energy Optimization Modeling

For the DES model, multi-objective optimization with mixed-integer linear programming (MILP) was applied. This type of modeling is based on the energy hub concept (Geidl and Andersson, 2006). In this model, multiple energy carriers (electricity, heat, hydrogen, and natural gas) are balanced from primary energy input to end energy demand according to a series of constraints that represent conversion technologies, storage technologies, distribution grids, and other factors. In this type of optimization, the decision variables represent the selection of the technology configuration, technology sizes, and operation of the technologies for hourly time steps over a one year period (8760 h). The model optimizes the sizes of the technology units, unit performance, network performance, and operation of the system.

Rather than using the typical days or rolling horizon methods for this optimization, a full horizon (8760 hourly time steps) is used to accurately assess the long-term storage system potential in the model. The model was programmed using the Python API for IBM ILOG CPLEX Optimization Studio and was solved using a CPLEX solver on a cluster computing machine.

Dispatchable Conversion Technologies

Dispatchable conversion technologies include heat pumps (HP), gas boilers (GB), micro-gas turbines (MGT), polymer electrolyte membrane fuel cells (PEMFC), and polymer electrolyte membrane electrolyzers (PEMEC). The operation parameters of each technology are based on the sizing of the technology in kW. All dispatchable conversion technologies contain maximum and minimum capacity constraints that are described in equations (4) and (5).

$$P_{t,out}^{c} \leq Cap^{c} \ \forall \ t = 1, \ldots, 8760, C \tag{4}$$

$$P_{t,out}^{c} \geq Cap^{c} * PLR_{min}^{c} \ \forall \ t = 1, \ldots, 8760, C \tag{5}$$

Here, $P_{t,out}^{c}$ is the power output for each of the dispatchable conversion technologies in set C, Cap^{c} is the maximum power of the conversion technology (PEMEC, PEMFC, MGT, GB, and HP) which is determined by its sizing, and PLR_{min}^{c} is the minimum part load of the technology.

Electrolyzers

Electrolyzers are the first component in the P2H storage configuration. Although technically a conversion technology, electrolyzers consume electricity and produce hydrogen that can be stored. Polymer electrolyte membrane electrolyzers (PEMEC) were chosen for this model due to their quick responsiveness, flexibility, ability to withstand higher degrees of cycling than alkaline electrolyzers, and ability to produce pressurized H_2 (Götz et al., 2016). In this paper, the PEMEC is assumed to produce hydrogen at a pressure of 10 bar. The model for PEMECs was not developed in this work but in a joint project that aimed to produce reduced order models for electrolyzers and fuel cells for optimization. The model for PEMECs is found in Gabrielli et al. (2016) and uses a piecewise affine (PWA) linear relationship based on four linear segments to represent the part-load efficiency curve or the produced hydrogen in Nm^2/kWh. The PWA assumption is modeled using one binary segment for each section, and only one of these binaries can be one at any given time step.

Fuel Cells

Fuel cells are the second technology included in the P2H configuration. They are considered a CHP technology that runs on hydrogen. Unlike most CHP technologies, PEMFCs have a higher electrical efficiency than a thermal efficiency. PEMFCs were chosen due to their increased flexibility and responsiveness as opposed to solid-oxide fuel cells (Götz et al., 2016). Solid-oxide fuel cells have higher electric efficiencies, however their high temperature operation (700–1000 °C) results in a slow response to changes in load. Due to the complex performance curve of PEMFCs, PWA linear relationship also from Gabrielli et al. (2016) was used to simulate the part-load electrical efficiency curve. To estimate the heat production, the total efficiency of the fuel cell was fixed at 95%, and the difference between total and electrical was approximated as the heat production efficiency. Although not directly a storage technology, in this model the running of the PEMFC indicates discharging of the hydrogen storage to produce electricity and heat.

Micro-Gas Turbines

Micro-gas turbines are micro CHP devices that run on natural gas. They are modeled based on Capstone MGT which provides their efficiency curves for both electricity and heat for all of their MGT sizes on their website (Capstone Turbine Corporation, 2018). A linear approximation of this curve is then used for both electricity and heat.

Gas Boilers

Gas boilers were modeled using a linear efficiency curve with a nominal efficiency of 90% and a minimum part-load restriction of 5%.

Heat Pumps

Ground-source heat pumps were considered over air source heat pumps due to the low temperatures of the case studies in winter. A linear correlation between COP and the heat source temperature from Sanner (2003) was used to model the heat pumps. This relationship is dependent on the heat source temperature and the delivered heat temperature which was assumed to be 70 °C. The number of heat pumps installed in each case study is limited by the number of boreholes available for placement. A GIS analysis for each case study was performed on the parcel area that the buildings are situated on. Boreholes are then placed with a minimum radius of 10 m apart from each other and from buildings. For more details on the GIS borehole placement, please refer to Miglani et al (2016).

Non-Dispatchable Renewables

Photovoltaic panels, small-wind turbines, and small-hydro are non-dispatchable technologies. The modeling of the PV, small-wind turbines, and small-hydro have been described in subsection 3.2. This modeling represents the yearly maximum output potential profile calculated and is imported into the model. PV and wind sizing is performed using integer decision variables with 1 PV unit representing 1 m^2 of panel area and one wind unit representing one 6.5 kW turbine. As the size of the 2.3MW small-hydro station is fixed, it is modeled with a single binary decision variable. The actual output produced in each hour from each non-dispatchable technology is scaled for each technology relative to the fraction of actual installed potential over the maximum potential.

Storage Technologies

Three storage systems are modeled in this work: hydrogen storage, batteries, and thermal storage. Although both long-term and short-term storage systems are considered in this work, it should be noted that the exact length of the charge and discharge cycle for each storage technology is selected by the optimizer and that long-term and short-term storage systems are not considered separately or are modeled differently. Any three of the storage systems can be chosen for either long-term or short-term storage. Hydrogen storage tends to be optimal for long-term storage as it does not have time dependent losses. In contrast, batteries and thermal storage both have significant time dependent losses (0.1 and 1% of stored energy hourly respectively) resulting in a significant decay of energy when used over longer time horizons. Over short time horizons, batteries and thermal storage tend to be optimal as they have higher round-trip efficiencies (for the electric and heating energy carriers respectfully), although hydrogen storage can occasionally be used over short-time horizons.

Hydrogen Storage

The hydrogen produced from the electrolyzer is stored in compressed gaseous cylinders up to 90 bars of pressure. The compression energy is calculated with equations (6) and (7).

$$W_{ideal} = \bar{Z}\, R\, T_1\, \frac{\gamma}{\gamma - 1}\left[(\frac{P_2}{P_1})^{\frac{\gamma-1}{\gamma}} - 1\right] \tag{6}$$

$$P_{comp} = \dot{n}\, \frac{W_{ideal}}{\eta_{isentropic} * \eta_{motor}} \tag{7}$$

In equation (6), $\bar{Z}$ is the compressibility factor of hydrogen at a certain temperature and pressure, R is the ideal gas constant in kJ/kmol-K, T_1 is the inlet temperature in Kelvin, P_1 and P_2 are the inlet and outlet pressures respectfully, and γ is the specific heat ratio of the gas (C_p/C_v). This computes the work of isentropic compression as a function of the final pressure per unit mass. The electricity of compression is calculated with equation (7), where $\dot{n}$ is the molar flow rate of hydrogen production, $\eta_{isentropic}$is the isentropic efficiency of the compressor, which is assumed to be 80% (Maroufmashat et al., 2016) and η_{motor} is the mechanical efficiency of the electric motor, which is assumed to be 90%. The sizing of hydrogen compressors is performed based on required electricity to compress the maximum hourly hydrogen production flow rate in the year. The state of charge of the hydrogen tank is calculated at each hourly time step with equation (8).

$$M_{t,H2} = M_{t-1,H2} + \dot{m}_{PEMEC}\Delta T - \dot{m}_{PEMFC_{fuel}}\Delta T - \dot{m}_{DI}\Delta T \tag{8}$$

$$M_{t,H2} \leq Cap^{H2} \tag{9}$$

In this equation, it is assumed that the decay of the storage in the tank is zero (i.e., has no leaks) and that the system has an efficiency of 99% on discharge. In addition, direct injection of natural gas into the grid is assumed to not require additional compression power as it is being injected into the low pressure part of the gas grid which is typically less than 70 bars in European gas grids compared to the 90 bars stored in the hydrogen tanks. The hydrogen storage maximum capacity is sized in kg of hydrogen. In addition, the seasonal storage component of the simulation must be included to initialize the first time step of the year to be of the same state of charge of the last time step, as is shown in equation (10).

$$M_{t=1,H2} = M_{t=8760,H2} \tag{10}$$

Batteries and Thermal Storage

Simplified battery and thermal storage models are assumed for this work. The models are described in equations (11) – (13), with equation (11) describing the energy balance in both storages, equation (12) restricting the state of charge below the capacity, and equation (13) limiting the maximum discharge and charge rates.

$$E_t^S = E_{t-1}^S * Decay^S + \eta_{Charge}^S\, \dot{P}_{Charge}^S \Delta T - \frac{1}{\eta_{Discharge}^S} \dot{P}_{Discharge}^S \Delta T \;\; \forall\, S \tag{11}$$

$$E_t^S \leq Cap^S \;\; \forall\, S \tag{12}$$

$$P_{Charge/Discharge}^S \leq Cap^S \delta_{Charge/Discharge}^S \;\; \forall\, S \tag{13}$$

Here, S is the set of non-hydrogen storage technologies (batteries and thermal storage). E_t^S is the storage level in the battery or the thermal storage, $P_{Charge/Discharge}$ are the charge and discharge powers in kW, η_{Charge} represents the charging and discharging efficiencies, and $Decay^S$ is the rate at which the stored energy decays in an hour. For this model, the efficiency of lithium-ion batteries were assumed, thus the charging and discharging efficiencies are both equal to 92% and the decay is set to 0.1% per hour. For the thermal storage, the charging efficiency, discharging efficiency, and decay are set based on the work of Stadler (2008) to 90%, 100%, and 1% per hour. $\delta_{Charge/Discharge}$ describes the limit on the discharge and charging rates as percent of maximum capacity that can be charged or discharged within an hour. For batteries, based on a C-rate of 0.5C, this is assumed to be to 50%. For thermal storage, this is set again by Stadler (2008) to be 25%. Similar to the hydrogen storage, there is also a constraint ensuring that the stored energy level at the beginning and end of the year are equal to each other. This is shown in equation (14).

$$E_{t=1}^s = E_{t=8760}^s \;\; \forall\, S \tag{14}$$

Energy Grid Modeling

In the model, network grids for electricity, heating, and natural gas were included. A transformer efficiency to the low-voltage grid of 98% was assumed. The heating network is approximated with a minimum spanning tree network from the energy center in the middle of the neighborhood to the building centroids. A heating loss rate of 4.3% per km of heating pipe is assumed (Keirstead et al., 2012). Electric pumping power is taken to be 8.5% of the total heating demand in each time step (Weber and Shah, 2011). Direct injection of hydrogen into the natural gas grid is also allowed for up to a 2% limitation by volume (the recommended value for networks with turbines (Altfeld and Pinchbeck, 2013)). This condition is enforced by equation (15).

$$V_t^{DI,H2} \leq \left(V_{in,t}^{MGT,NG} + V_{in,t}^{Boiler}\right) * 0.02 \;\; \forall t \tag{15}$$

Here, $V_t^{DI,H2}$ is the amount of hydrogen injected into the natural gas grid, $V_{in,t}^{MGT,NG}$ is the natural gas consumed by the MGT, and $V_{in,t}^{Boiler}$ is the natural gas consumed by the boiler. The energy content of both gases can be converted using their heating values, which are approximately 39.4 and 14.5 kWh/kg for hydrogen and natural gas respectively.

In the model, the three grids are assumed and are simultaneously balanced with constraints to ensure that supply meets demand. The balance for electricity, heating, and natural gas in the network are shown in equations (16) – (18) respectively.

$$\frac{P_{grid,t}^{Pur}}{\eta_{trans}} + P_{out,t}^{PV} + P_{out,t}^{Wind} + P_{out,t}^{Hydro} + P_{out,t}^{MGT} + P_{out,t}^{FC} + Pdischarge_{t,s}^{Bat} == Demand_t^{elec} + Pcharge_t^{Bat} + P_{in,t}^{HP} + P_{in,t}^{EC} + P_{in,t}^{Comp} + P_{aux,t}^{pump} + P_{grid,t}^{sell} + P_{grid,t}^{sellFIT} \quad \forall t \tag{16}$$

$$P_t^{Boiler} + P_t^{FC} + P_t^{MGT} + P_t^{HP} + Pdischarge_{t,s}^{TES} == \frac{Demand_t^{Heat}}{\eta^{losses}} + P_t^{dump} + Pcharge_t^{TES} \quad \forall t \tag{17}$$

$$P_{grid,t}^{NG} + P_t^{DI,H2} == P_{in,t}^{MGT} + P_{in,t}^{Boiler} \quad \forall t \tag{18}$$

Since the model can install several technologies at once, multiple devices can be simultaneously run to provide either electricity or heating demand in any given time step. There is no set utilization priority, but rather the technology utilization is an outcome of the model that decides during each time step which devices are the most optimal in order to meet the energy demands based on the respective objective function of the optimization.

Multi-Objective Optimization

Multi-objective optimization is used to minimize both system costs and carbon emissions. The system costs are calculated using equations (19) – (25).

$$Cost_{total} = Cost_{inv} + Cost_{OMF} + Cost_{OMV} + Cost_{elec} + Cost_{fuel} \tag{19}$$

Here, $Cost_{total}$ is the cost objective to be minimized, $Cost_{inv}$ is the equivalent annual investment cost of the technologies, $Cost_{OMF}$ is the fixed operation and maintenance costs, $Cost_{OMV}$ is the variable operations and maintenance costs, $Cost_{elec}$ is the electricity cost, and $Cost_{fuel}$ represents the fuel costs. The investment costs are calculated with equation (20).

$$Cost_{inv} = \sum_{c=1}^{C}(Cost_c * Cap_c * CRF_c) + \sum_{s=1}^{S}(Cost_s * Cap_s * CRF_s) \tag{20}$$

In equation (20), C represents the set of conversion and S represents the set of storage technologies, $Cost$ represents the capital cost of the technologies per unit of capacity installed, and Cap is the capacity of each technology installed in kW. Capital recovery factor (CRF), or equivalent annual cost factor is calculated for each technology based on its rated lifetime in years. To calculate the CRF factor, equation (21) is used (Knopf, 2011).

$$CRF_{c,s} = \frac{r}{[1 - \frac{1}{(1+r)^{Lifetime_{c,s}}}]} \quad \forall c,s \tag{21}$$

Here, r is the discount rate, and $Lifetime$ is the expected age of the technology in years. The operations and maintenance costs are then calculated with equations (22) and (23).

$$Cost_{OMF} = \sum_{c=1}^{C}(OMF_c * Cap_c) + \sum_{s=1}^{S}(OMF_s * Cap_s) \tag{22}$$

$$Cost_{OMV} = \sum_{c=1}^{C}\left(OMV_c * \sum_{t=1}^{8760} P_{c,t}^{out}\right) + \sum_{s=1}^{S}\left(OMV_s * \sum_{t=1}^{8760} Discharge_{s,t}\right) \tag{23}$$

Fixed operations costs (OMF) are calculated based on the technology sizes (Cap) and variable operations costs (OMV) are calculated based on the operational output of the technologies over the one year period. For conversion technologies, this is defined by the output energy in kWh over the year ($P_{c,t}^{out}$). For storage technologies, this is defined by the discharge energy in kWh over the one year period ($Discharge_{s,t}$). The last two costs are fuel and electricity costs, as shown in equations (24) and (25).

$$Cost_{fuel} = \sum_{t=1}^{8760}\left(P_{grid,t}^{NG} * \ Price^{NG}\right) \tag{24}$$

$$Cost_{elec} = \sum_{t=1}^{8760}\left(P_{grid,t}^{Pur} * Price_t^{Retail}\right) - \sum_{t=1}^{8760}\left(P_{grid,t}^{Sell} * Price_t^{MP}\right) - \sum_{t=1}^{8760}\left(P_{grid,t}^{SellR} * Price_t^{FIT}\right) \tag{25}$$

In equation (24), $P_{grid,t}^{NG}$ represents the natural gas purchased from the grid in each time step and $Price^{NG}$ is the fuel price.

Electricity cost represents the cost and profit from interactions of the decentralized network with the central electricity grid. Electricity from the grid ($P_{grid,t}^{Pur}$) is purchased at the retail price of electricity in CHF/kWh. Retail price represents the price of electricity that is purchased from an electric utility. This price is typically constant or uses a two-tiered high and low tariff pricing scheme for peak hours and off-peak hours of use in Switzerland. In this case, a constant rate is used. Electricity sold back to the grid is split into two categories for renewable electricity and for non-renewable electricity. Electricity sold from RES technologies ($P_{grid,t}^{SellR}$) like PV, hydro, and wind, can be sold at the feed-in tariff rate. The feed-in tariff is an incentive for renewable production such as PV, small-hydro, and wind. Electricity sold from all other devices ($P_{grid,t}^{Sell}$) is sold back at the market price (MP) of electricity. The market price represents the real price of electricity for either buying or selling (in this case selling), which fluctuates due to supply and demand on the national grid level. Its prices are typically two to three times lower than the retail price. Although battery storage or fuel cell output can indirectly come from renewable energy, in this model the electricity discharged from storage devices cannot be sold to the grid at the feed-in tariff rate. To incentive local use of renewable energy, there is a constraint to ensure that only surplus electricity from renewable devices during each time step can be sold back at the feed-in tariff price. This constraint is shown in equation (26).

$$P_t^{SellR} \leq \left(P_{out,t}^{PV} + P_{out,t}^{Hydro} + P_{out,t}^{Wind} - Demand_t^{elec}\right) * \delta_t^{surplus} \quad \forall t, t = 1, \ldots, 8760 \tag{26}$$

Here, $\delta_t^{surplus}$ is a binary variable that is 1 if $P_{out,t}^{PV} + P_{out,t}^{Hydro} + P_{out,t}^{Wind} > Demand_t^{elec}$ (i.e., a surplus) and 0 if $P_{out,t}^{PV} + P_{out,t}^{Hydro} + P_{out,t}^{Wind} \leq Demand_t^{elec}$ (i.e., a deficit). This constraint ensures that electricity can only be sold back at the feed-in tariff rate if the production of renewables is greater than the electricity demand. In addition, the amount of energy that can be sold at the feed-in tariff rate is limited by the difference between the renewable production (hydro, PV, and wind) and the electric demand.

The annual CO_2 emissions, in kg CO_2/kWh are calculated with equation (27).

$$CO2_{total} = \sum_{t=1}^{8760} \left(P_{grid,t}^{NG} * CF^{NG} + P_{grid,t}^{Pur} * CF^{elec}\right) \tag{27}$$

Here, CF is the carbon factor in kg CO_2/kWh for natural gas and the electricity intensity in the grid.

With both the objective functions defined, multi-objective optimization is then performed with the epsilon-constraint method (Laumanns et al., 2005). In this method, the optimization is first solved with only a cost objective and the CO_2 emissions are calculated consequently. Secondly, the problem is solved with a CO_2 minimization objective. To solve for multi-objective cases, the epsilon value is calculated at even intervals between the maximum (cost optimal) and minimum (CO_2 optimal) emissions, and then the total emissions are constrained below these epsilon values while optimizing for minimum costs, resulting in multiple intermediate optimal solutions. In this study, five Pareto optimal solutions are chosen to give a variety of solutions for each set of parameters. For the purpose of this study, the 5 Pareto optimal solutions will be referred to as the *cost minimization*, *25% CO_2 objective minimization*, *50% CO_2 objective minimization*, *75% CO_2 objective minimization*, and *CO_2 minimization* solutions. The percent referred to is not a reduction of the total emissions but rather the percent reduced relative to the difference between the cost minimization and CO_2 emission minimization objectives.

In order to compare the results across the two case studies on a fair basis, the *Levelized Cost of Energy* (LCOE) and *Levelized CO_2 Emissions* (LCO_2) for DES will be used. The $LCOE_{DES}$ is defined as the total annual costs of the energy system (defined in equation (19)) divided by the sum of the total annual electricity and heating demand. The $LCO_{2,DES}$ is defined as the total annual emissions (defined in equation (27)) divided by the sum of the total annual electricity and heating demand.

The calculation of $LCOE_{DES}$ and $LCO_{2,DES}$ are shown in equations (28) and (29) respectively. These terms will be used in section 5.

$$LCOE_{DES} = \frac{Cost_{total}}{\sum_{t=1}^{8760}(Demand_t^{elec} + Demand_t^{heat})} \tag{28}$$

$$LCO_{2,DES} = \frac{CO2_{total}}{\sum_{t=1}^{8760}(Demand_t^{elec} + Demand_t^{heat})} \tag{29}$$

The terms $Demand_t^{elec}$ and $Demand_t^{heat}$ in equations (28) and (29) refer to the hourly demand of all buildings simulated in subsection 3.1.

Energy Strategy Targets

In order to benchmark solutions against the targets of the Swiss Energy Strategy, the Kaya Identity is used. The emissions targets are not included in the optimization but used in section 5 to benchmark the solutions for the years of 2020, 2035, and 2050. The calculation of these energy targets for buildings is defined in (Mavromatidis et al., 2016) in reference with the Swiss Energy Strategy 2050 (Prognos AG, 2012). This paper uses the Kaya identity to calculate the emissions targets based on equation (30).

$$C = \frac{C}{E}\frac{E}{A}A \tag{30}$$

Here, C refers to the total Swiss CO_2 emissions targets from buildings (in this case in kg CO_2), E refers to the total energy consumption in buildings (in kWh), and A refers to the total floor area in buildings (in m^2) at 2020, 2035, and 2050 defined in the strategy. Both the floor area for all buildings and the CO_2 targets are defined in the strategy at the years of 2020, 2035, and 2050. As the total emissions for all buildings and the floor area of all buildings are fixed in the energy strategy at each year, the $\frac{C}{E}$ and $\frac{E}{A}$ can both be adjusted to meet the targets. The term $\frac{C}{E}$ refers to the CO_2 intensity per kWh of energy produced in buildings. The value of $\frac{C}{E}$ decreases with an increasing percentage of RES being used to meet energy demand and increases when the percentage using fossil fuels increases. The term $\frac{E}{A}$ refers to the energy density of buildings per unit area, which represents the energy efficiency of the building envelope. The more inefficient the buildings are (i.e., older building stock), the higher the energy density is. When buildings are retrofitted, their kWh/m^2 decreases, thus this value decreases from 2015 to 2050 based on increasing number of retrofitted buildings. The model optimization chooses the level of renewables on the system side, thus optimizing the $\frac{C}{E}$. The resulting optimization solutions can be compared against the official targets according to the energy strategy, which are shown in dashed lines in Figure 7 and Figure 8.

4 Case Study Descriptions

There are two case studies used in this paper representing a rural and urban neighborhood respectfully. These two types of neighborhoods represent two typical examples of neighborhoods within Switzerland. The comparison of these two highlights the differences in system design depending on RES and energy density in design locations. The total area of heated and electrified space in the buildings is defined in the building energy demand models (subsection 3.1) and this can be used to compare the energy density in the buildings (in kWh/m^2) and the LCO$_2$, which are key performance indicators in relation to the Swiss Energy Strategy 2050 and its targets for decarbonization in the Swiss building stock. This allows the two case studies to be benchmarked against each other and to the Swiss emission targets.

4.1 Zernez

Zernez is a rural alpine village in the Swiss Alps with approximately 1150 people inhabiting 308 buildings. The building stock consists of mostly of single-family homes, multi-family homes, shops, hotels, restaurants, and agricultural buildings. It is located at an altitude of 1475 m resulting in a cold climate with an average temperature of 4.7 °C. A small river that passes by the village is planned for a small 2.3 MW run-of-the-river small hydro plant. It is approximated from a GIS analysis that 60 small-wind turbines at a hub high of 18 meters could be placed in the vicinity of the village. In addition, there is 25,200 m^2 of rooftop area available for PV installation excluding protected buildings. More data on this case study can be found in Orehounig et al. (2014).

4.2 Altstetten

Altstetten is a populated and primarily residential quarter in the city of Zurich in Switzerland. A section of 77 buildings in Altstetten was chosen as it was scaled to nearly the same total annual demand as Zernez. These buildings consist of primarily multi-family homes and shops with a population of 1784 inhabitants. Statistics on the buildings is available from the Swiss Buildings and Apartments Registry (GWR) (Federal Statistical Office, 2018). As a result, it has a higher population density than Zernez. As it lies in a city, small wind and hydro are not available as renewable resources and 12,080 m^2 is available for rooftop PV area. The incident radiation of the rooftops calculated in the two case studies is shown in Figure 4.

4.3 Future Demand Data for Case Studies

In order to predict future demand for buildings, two factors are considered: retrofits and climatic weather changes. Based on the 2015 baseline year, the demand model (cf. subsection 3.1) was used to calculate individual demand for all buildings in Zernez and Altstetten. The baseline year is simulated with a typical meteorological weather file from both locations specifically. Future demand for the years of 2020, 2035, and 2050 are calculated with the retrofitting model (cf. subsection 3.1).

Figure 4: Solar radiation potentials of the cases with Zernez (left) and Altstetten (right)

Using this model, retrofits are applied and building constructions are updated at future years of consideration. In addition, weather files considering climate change in the future were obtained from Meteonorm based on the work published in Remund et al. (2010). The weather files in this work are based on the IPCC A1B and B1 scenarios. For the future demand, the CM scenario was chosen to use the "Business as Usual" scenario retrofit rates and the A1B weather files, the GSD scenario was chosen to use the "New Energy Policy" scenario retrofit rates and the B1 weather files, and the RSD scenario was chosen to use the "New Energy Policy" retrofit rates and the A1B weather files. Since the B2 weather files are not yet available for these locations, the A1B is used in its place as the warming predicted in the B2 scenario on average globally falls in the range predicted by the A1B scenario. A summary table of the temperatures in the weather file are shown Table 2.

Table 2: Weather file average temperature for the future scenarios, years, and locations

Region	Parameter	2015	2020		2035		2050	
		Baseline	A1B	B1	A1B	B1	A1B	B1
Global	Mean temp vs. 1980-1999 (Δ °C)	+0.4	+0.7	+0.5	+1.2	+1.0	+1.7	+1.3
Zernez	Max temp (°C)	25.1	24.3	24.7	27.6	26.3	27.7	26.3
	Mean temp (°C)	4.4	4.9	4.9	5.5	5.2	6.1	5.5
	Min temp (°C)	-20.0	-16.3	-15.9	-15.9	-16.6	-16.0	-16.1
Altstetten	Max temp (°C)	29.9	32.3	33.0	33.0	33.8	32.9	33.3
	Mean temp (°C)	8.7	10.4	10.4	11.0	10.7	11.5	11.0
	Min temp (°C)	-10.4	-8.6	-8.2	-8.1	-9.0	-7.6	-8.1

The results of the aggregated demand for these case studies are shown Figure 5. In this figure, three scenarios (which are Conventional Markets, Global Sustainable Development, and Regional Sustainable Development) are shown from 2015 to 2050. The heating demand decreases over time due to more buildings being retrofitted each year in both neighborhoods. When these buildings are retrofitted, windows, facade, floor, and roof insulation are all added to reduce the heating demand.

In addition, the electrical appliances and lighting are updated to increase their efficiency and decrease the electrical energy demand in the buildings. The GSD and RSD scenarios have an average retrofit rate 2% of buildings per year compared to the CM rate of 1%, thus they are able to retrofit twice the number of buildings, resulting in a lower demand. In addition, the buildings are simulated with the relevant weather files, with the A1B (used by CM and RSD scenarios) scenario having higher warming than the B1 (GSD) scenario. As a result, the RSD has a lower heating demand over time compared to the GSD scenario despite having the same retrofit rate, as the RSD has a warmer average temperature and thus less heating demand than the GSD scenario.

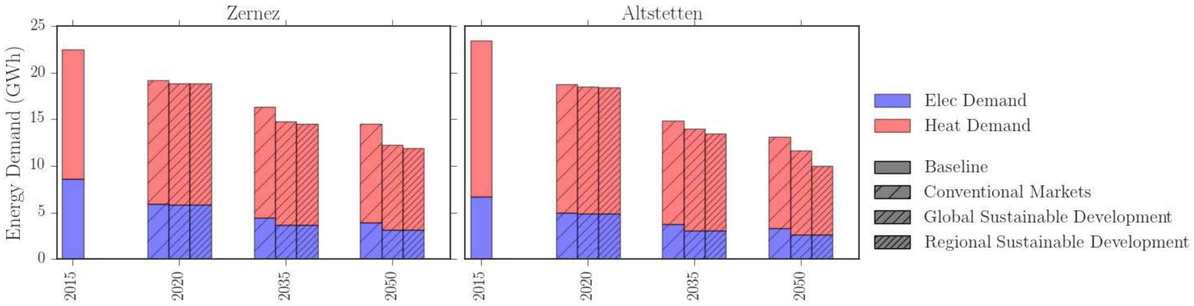


Figure 5: Future building energy demand of Zernez (left) and Altstetten (right)

4.4 Future Renewable Potential vs. Demand

In addition to the electricity and heating demand for the buildings, the renewable potentials are also calculated in the model. As the change in wind speeds and solar potential are not considered and updated in future weather files, these renewable potentials are assumed to remain the same over time. It is predicted that the demand decreases due to retrofits as the renewable potential remains constant. This is represented Figure 6. In this figure, the surplus or deficit is calculated by subtracting the total energy demand in each hour from the total renewable production in each hour and then summing up the monthly totals.

It can be observed that the surplus for both case studies grows over time due to the lower demand in 2050 compared to 2015. In addition, Zernez has a much higher amount of renewables, resulting in a greater surplus. In Figure 6, the level of surplus renewables (i.e., times of higher renewable potential than demand) increases over time, especially in the Zernez case. With extra surplus energy, the optimization may decide to install less renewables, to install the renewables but sell production to the grid, or to use storage technology to shift the energy surplus to later energy deficit.

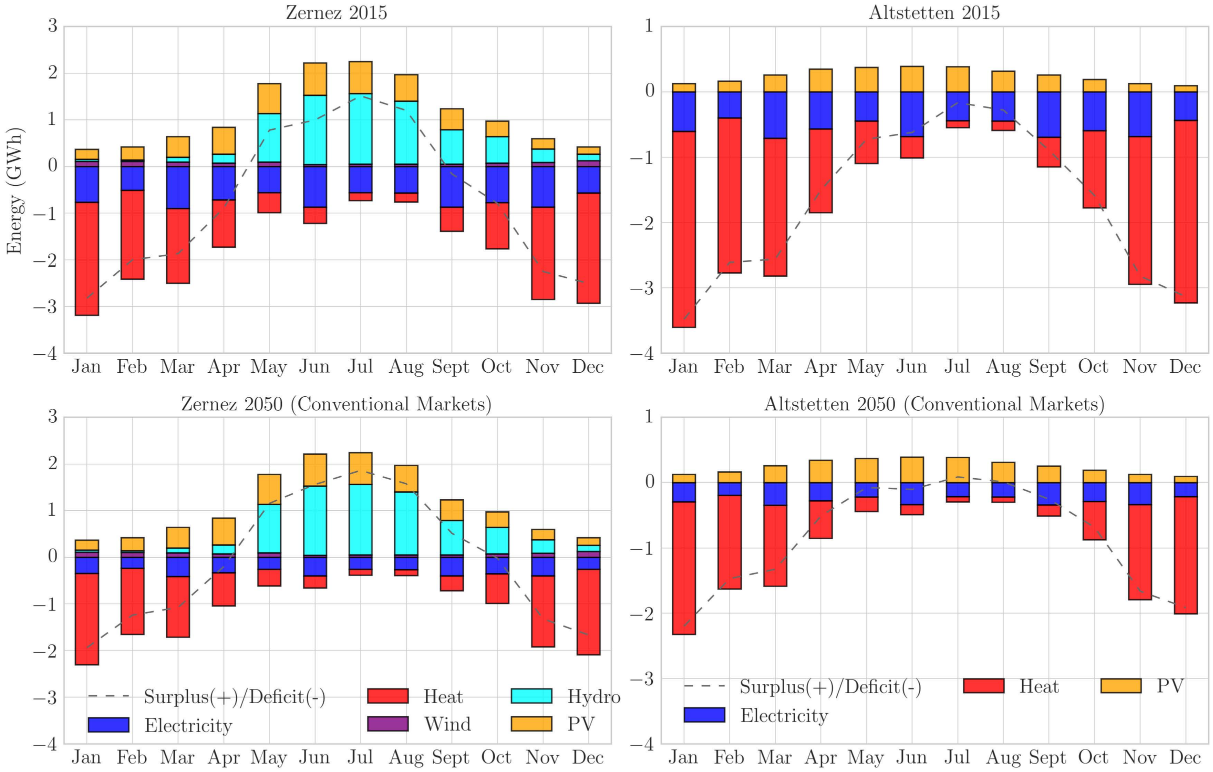


Figure 6: Renewable potential (positive) and demand (negative) for Zernez (left) and Altstetten (right) in the 2015 baseline year and the Conventional Markets scenario in 2050

5 Results and Discussion

Based on the scenarios formulated in section 2, a series of simulations were conducted to evaluate the scenarios using the multi-objective method to find a set of Pareto optimal solutions.

5.1 Pareto Fronts

Figure 7 shows the Pareto fronts for all of scenarios, years, and objectives simulated with the $LCOE_{DES}$ on the x-axis and LCO_2 on the y-axis. In multi-objective optimization, the solutions show the set of Pareto optimal solutions according to the two objectives. The energy strategy targets are included in dashed lines. Please note that the targets differ from the CM scenario to the GSD and RSD scenario due to the difference in the assumed CO_2 intensity of the electricity grid (please see Table A.1 in the Appendix A for details).

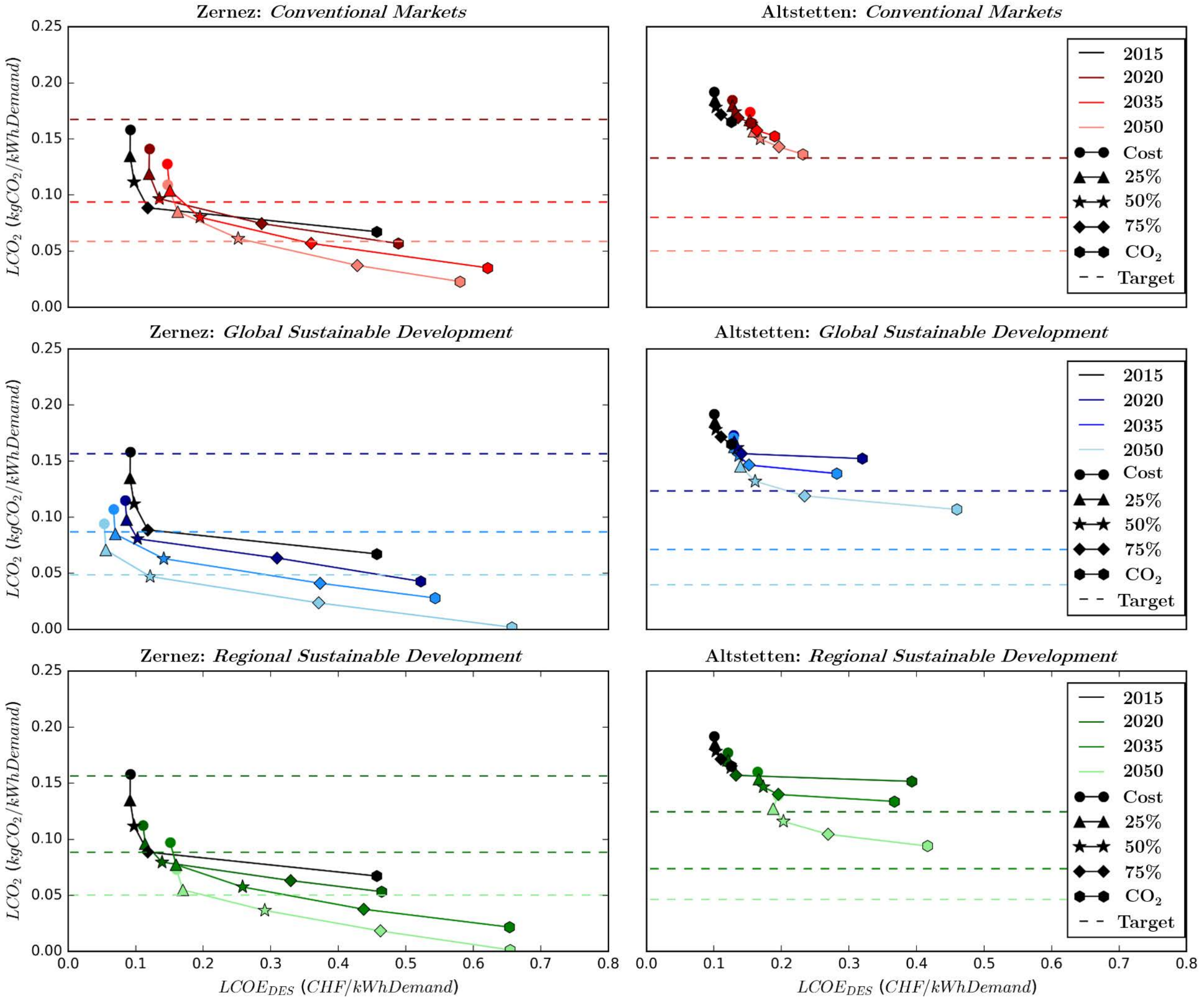


Figure 7: Pareto fronts for each year and scenario. (Dashed lines represent energy targets and colors represent the year)

The Pareto curves, moving from upper-left and cost optimal to lower-right and CO_2 optimal, show five different solutions that are all on the spectrum from fully cost optimal to fully CO_2 optimal.

From 2015 to 2050, the subsequent years' emissions drop lower, indicating that more renewable sources are being used to meet a higher fraction of the demand over time. In addition, many of these solutions are also dropping in cost over time as the capital costs of technologies decrease. For the Zernez case study, much larger emission reductions can be achieved due to the higher renewable potential. Emission reduction in the Altstetten case study is more restricted due to the lower renewable potential available.

For both case studies, the Pareto curves initially have a steep drop in emissions followed by shallow and rapid increase in costs. This indicates that a large portion emissions reduction can be met without a high increase in the costs, however the costs rapidly increase above the 75% CO_2 minimization solution. A full breakdown of costs by type is shown in Figure B.1 in the Appendix B. As seen in this figure, the rapid increase in costs in the CO_2 optimal solution is mostly caused by installation of a large hydrogen storage systems and the capital required to build them. It should be noted that the sizes of these large hydrogen storage systems in the CO_2 optimal solutions are most likely infeasible as it would require too much space for hydrogen storage tanks, however these solutions provide us with reference point to the minimum possible feasible emissions that can be theoretically obtained. Typically solutions at the elbows of these curves would represent the best trade-off of emissions and cost, although ultimately it would be up to a decision maker to decide where along the curve the ideal solution would lie. If the intention is to meet the energy targets, all three future scenarios are projected to be able to meet the energy targets with the 50% CO_2 objective solution in 2050 in Zernez. In Altstetten, all solutions miss the energy strategy targets.

5.2 Performance of the Case Studies in the Context of the Swiss Energy Strategy 2050

Figure 8, the results from Figure 7 have been replotted with respect to the buildings energy density ($\frac{E}{A}$ from equation (30)) on the x-axis and the system CO_2 intensity ($\frac{C}{E}$ from equation (30)) in order to benchmark the feasible options against the energy targets.

Figure 8 shows the energy density values decreasing (or energy efficiency of the buildings increasing) in both case studies over time due to the continuous retrofit of buildings. The energy strategy targets are shown in the dashed grey lines for the years of 2020, 2035, and 2050 according to the Kaya identity calculations described in subsection 3.3. For the Zernez case study, it is seen that the 50% CO_2 minimization objective is able to meet the emissions targets in 2050 in all three future scenarios. In Altstetten, it is again seen that solutions miss the targets, which implies that solutions that meet targets are infeasible given the energy demand and renewable potentials available. This does not mean that the case study will be unable to meet its targets, but rather it will miss the targets by solely relying on the implementation of the DES concept and the presumed retrofit rates. The building stock in Altstetten is comprised of mostly older multi-family houses, resulting in a high heating density. There is also a high ratio of heated and electrified area vs. the available area for solar installations compared to the rural case study. Due to the low renewable potential, there is not enough renewable energy generated on-site to meet the targets. In order to improve the buildings energy performance, a higher retrofit rate should be adopted for the neighborhood, however even if the retrofit rates are increased, additional renewable energy would most likely still be required to meet the targets due to the shallow slope of the target curves in 2050. Renewable energy imports, such as biomass, biogas, or externally produced PV or wind would need to be imported into the DES in order to meet targets in this neighborhood.

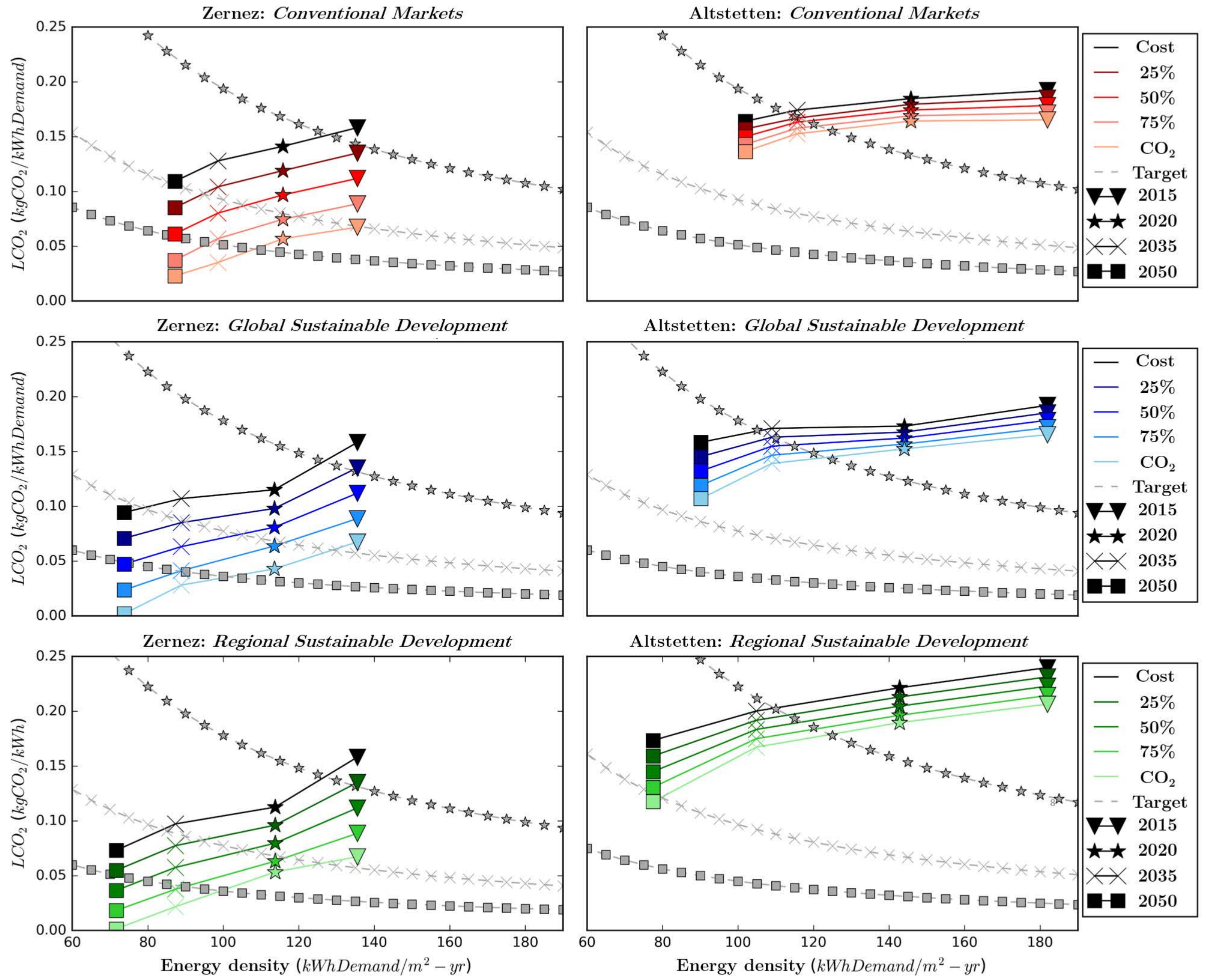


Figure 8: Building total (electricity and heat) energy density vs. the LCO_2 for all Pareto optimal solutions

5.3 Technology Sizing

The conversion and storage technology sizing associated with the 50% CO_2 minimization solutions are shown in Figure 9. The 50% CO_2 minimization objective is shown, as it represents the most cost effective solution that is able to meet the energy strategy targets in 2050 in Zernez in each future scenario. The technologies are separated by conversion technologies (both dispatchable and non-dispatchable) and storage technologies.

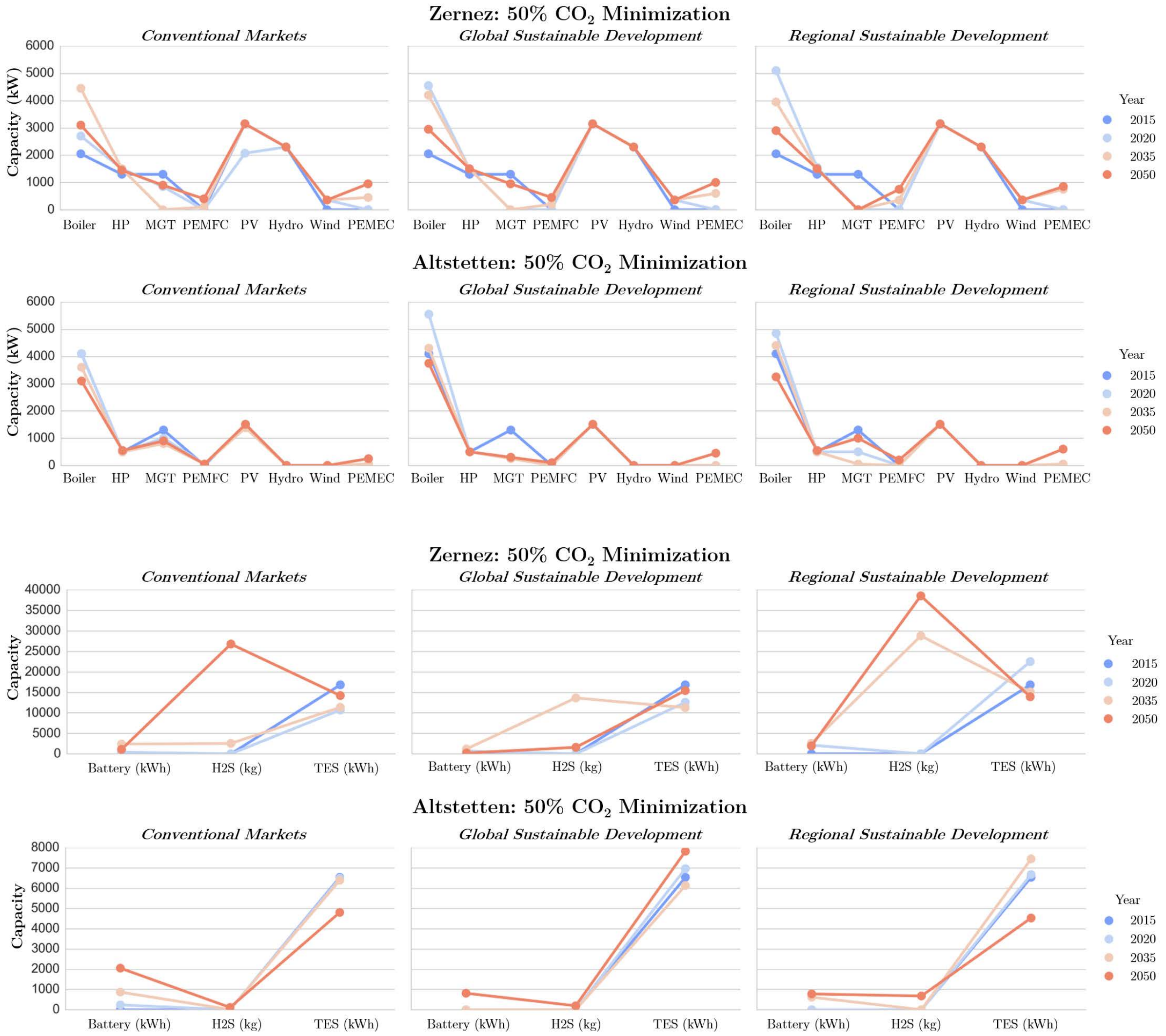


Figure 9: Conversion (above) and storage (below) technology sizing for the 50% CO$_2$ minimization objectives

Here, RES technologies such as PV and HPs are both cost effective and cost optimal as they are installed in their full capacity in almost all cases. Small-wind is also installed in the same fashion but to a lesser extent due to the high costs and low output of small-wind turbines. MGTs are often installed in the year of 2015 and in many of the CM solutions due to low gas prices, but are not installed when the prices increase in the GSD and RSD scenarios. Boilers are also installed in all cases as they are typically the back-up heating technology that is relied upon. Since heat demand cannot simply be purchased from a central grid in times of need, thermal storage systems and boilers are heavily relied upon due to the high heating demand of both case studies in winter.

PEMFC, H2S, and PEMEC represent technologies that must be installed to implement hydrogen storage systems. The size of hydrogen storage systems increases over time as the technology capital costs become cheaper, the performance of the equipment improves, there is a higher level of surplus energy, and electricity costs increase. In addition, it is seen that the largest H2S systems are installed in the RSD systems, followed by the CM and lastly the GSD. The difference is dependent on the feed-in tariff of the scenarios. The RSD and the CM scenarios both have a quick phase out of the feed-in tariff, while the GSD scenario keeps the feed-in tariff high until 2050. As a result, it is more profitable in the GSD scenario to sell surplus electricity back to the grid rather than storing it on-site. The RSD scenario has the largest hydrogen storage systems, as it has a higher level of surplus electricity than the CM scenario due it its lower demand. With a large amount of surplus electricity available, the system chooses to store this electricity rather than sell it to the grid at a low rate. The results find it is almost always optimal to install RES technologies, as it opts to purchase the maximum feasible amount available for nearly all objectives.

In the Altstetten case study, small hydrogen systems are installed. Due to the lower renewable potential, the system found it is preferable to install batteries and to use hydrogen storage for storage durations longer than one day (although seasonal storage is never used).

5.4 Increase in Share of Renewables over Time

Each of the 100 solutions previously shown not only represents the design of the system configuration and the sizes of the technologies but also their operation. Figure 10 shows the technology outputs that contribute to the total annual aggregated demand of the case studies for the years of 2015 to 2050. It is split by the demand carriers of electricity and heating.

Figure 10 shows that heat pumps, PV, and hydro all contribute greatly to the end energy demand. As the demand decreases over time, the same output from these devices allows boilers, gas turbines, and grid electricity to be used less. Stored energy is used in greater portions in 2050 with PEMFCs and batteries playing an increasing role, especially in the RSD case. Thermal storage is also used, but its potential is already maximized in 2015 and it remains constant until 2050 as its costs begin low and are predicted to remain constant over time. It is to be noted that although the percentages of hydro and PV use in Zernez appear to decrease over time their use is not actually decreasing, but rather more production is being used to charge the storage technologies as opposed to being used directly to meet demand (the future demand is lower due to retrofits). In addition, a higher portion of renewable energy is sold back to the grid, especially in the GSD case. In Altstetten, the demand in 2050 is still dependent on boilers, MGT, and grid electricity due to the lack of renewables.

These figures show that heat pumps and PV play a key role in both case studies. Their total potential is restricted due to available area of installation specific to each case study, but nevertheless they are predicted to be the most cost effective and low carbon technology available for the futures of both case studies for heating and electricity demands respectively. In addition, the RSD scenario has the highest portion of storage usage by 2050. The high feed-in tariffs in the GSD case disincentives storage of renewables on-site and promotes selling electricity back to the grid. This implies that the feed-in tariff does not promote the use of on-site storage systems, and thus does not foster self-sustainability in the local neighborhood. A high feed-in tariff with a high penetration of RES could cause many producers to sell their electricity back at the same time, resulting in centralized grid overloading issues. The use of on-site storage can prevent these issues by allowing neighborhoods to store this energy rather than selling it back to the grid. This study therefore recommends a phase out of the feed-in tariff between 2020 and 2030 to incentivize the use of local storage solutions, thus promoting on-site consumption.

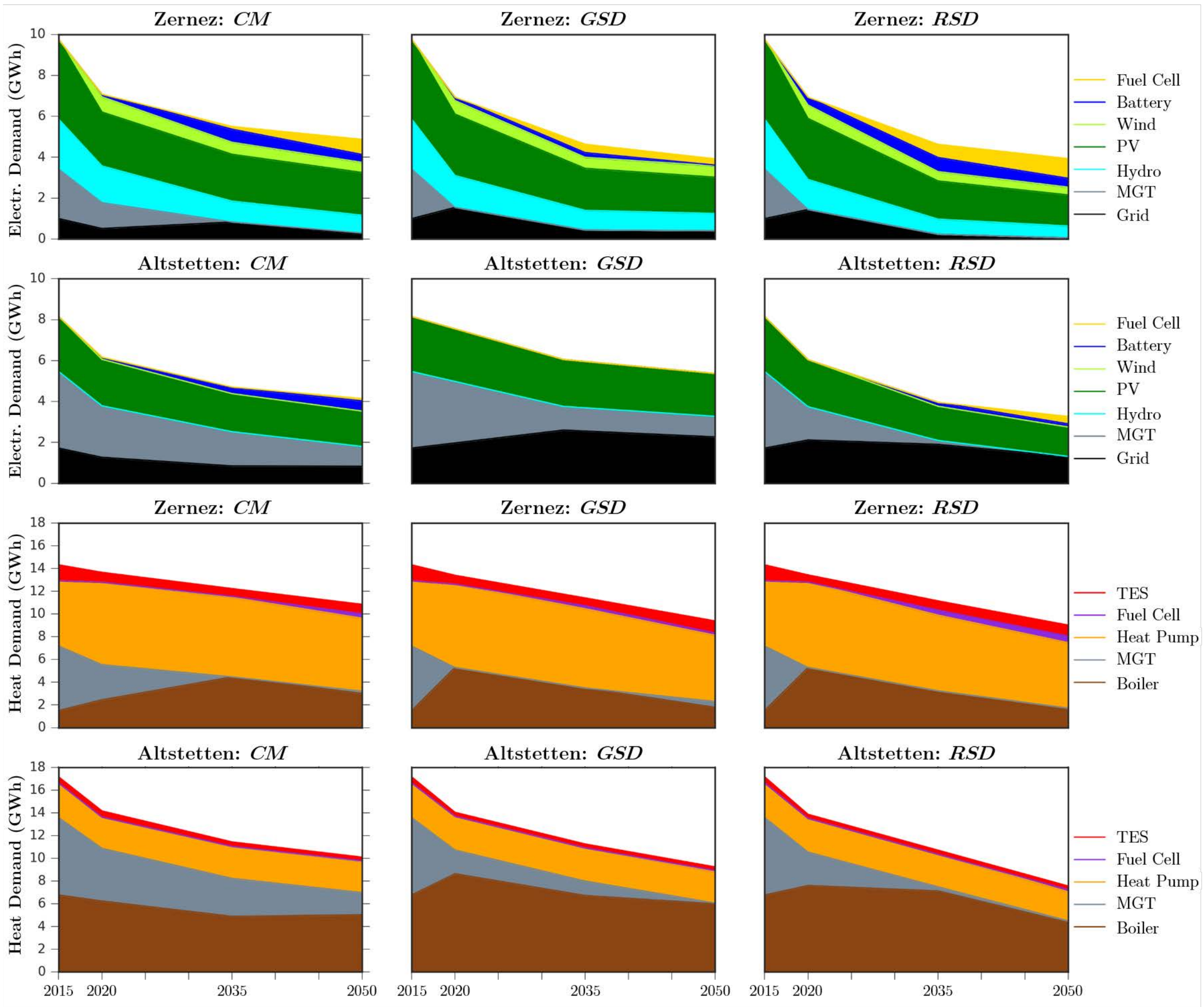


Figure 10: Energy demand (electricity and heat) met by each energy source from 2015 to 2050 for the 50% CO_2 minimization solutions. Please note that renewable technology output (i.e., PV, wind and hydro) refers to only demand that is directly met from these technologies rather than renewable energy stored in storage systems. Renewable energy from storage systems is shown as energy met from the Battery, TES, and fuel cell (which, although not a storage technology is powered by stored hydrogen)

5.5 Storage Performance

In order to further compare the load shifting with the storage systems in each scenario, Figure 11 shows the charging and discharging of each of the three storage systems over the full simulation year in 2050 for the 50% CO_2 minimization solution. For hydrogen storage, charging energy is represented by the amount of electricity input into the electrolyzer and the discharging energy is accounted for in two streams: hydrogen directly injected into the natural gas grid and energy (both heat and electricity) produced from the PEMFC. Both the battery and thermal storage are also shown with their charging and discharging energy.

In Zernez, the storage systems are used to a larger extent, as there is a higher renewable surplus. Although a P2H system is used in all three future scenarios in Zernez in 2050, it is used the least in the GSD case study due to the high feed-in tariff. In summer, there is only a small amount of heating demand for domestic hot water, and the electricity can be met directly from the hydro and PV resources, therefore the storage is not needed significantly in the short-term and the renewable electricity can be sold back to the grid for profit. In both the CM and RSD scenarios, the behavior of a long-term storage system can be observed as the surplus is used to charge the hydrogen storage predominantly in the summer, as it is no longer profitable to sell the surplus back to the grid due to the phase out of the feed-in tariff. The surplus of hydrogen charged in the summer is then used by the fuel cell in the winter, thus taking advantage of a seasonal shift in energy. In the RSD case, the long-term hydrogen storage is used to a greater extent due to the higher renewable surplus caused by the lower demands.

In Altstetten, the hydrogen system is only used in the summer when there is a renewable surplus and is used to shift energy over a few days at maximum. In the GSD and RSD scenarios, the hydrogen storage is able to shift a similar amount of energy compared to the thermal and battery storages but it does not shift the energy demand from month to month, as was done in Zernez. The CM scenario uses short-term storage more than the hydrogen storage. Due to the lower renewable surplus, short-term storage is preferable to long-term storage as it is more efficient.

When comparing the optimal storage technologies in the two cases, it is clear that hydrogen storage requires a high level of renewable surplus in order to be feasible as a long-term storage. In neighborhoods where the renewable potential is too low, it will not have enough load to shift for long-term storage to be feasible. In addition, if the feed-in tariff remains high, hydrogen storage is less likely to be used as the profits of selling surplus electricity back to the grid will be higher than the value of stored energy in the hydrogen system. This is observed in the GSD scenario in both case studies, where the surplus electricity is sold to the grid rather than stored in the hydrogen system during the summer’s renewable electricity surplus.

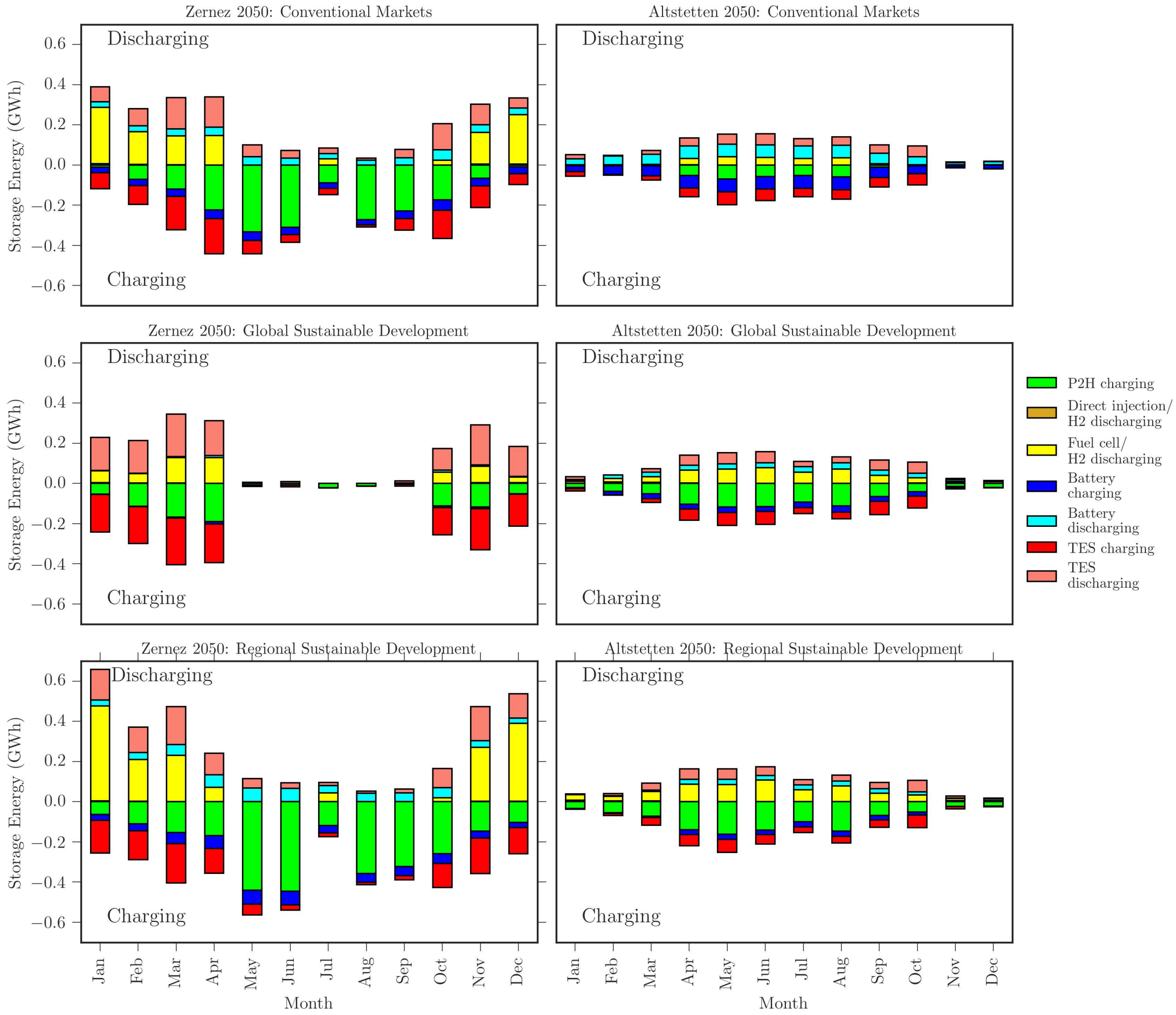


Figure 11: Charging and discharging of the storage technologies for the 50% CO_2 objective minimization solutions in 2050 for each month in the 2050. Negative values indicate the charging of the storage technologies and positive values indicate the discharging of storage technologies

6 Conclusion

In this paper, we have developed a methodology to assess the potential of long and short-term storage in future scenarios with a multi-from 2015 to 2050. The model has a specific emphasis on the evaluation of a decentralized long-term P2H system. In order to properly capture the operation of these technologies, part-load PWA functions are used for the fuel cells and electrolyzers and a full year time horizon is used to establish storage continuity over a full year in order to evaluate charge and discharge cycles up to one year in length (seasonal storage). Three future scenarios, framed from the IPCC, Special Report on Emissions Scenarios, were used for evaluation of the future years of 2020, 2035, and 2050. They are titled *Conventional Markets*, representing global markets with a strong economic focus, *Global Sustainable Development* representing global markets with a strong environmental focus, and *Regional Sustainable Development* representing regional markets with a strong environmental focus.

This model can be used for evaluation of any decentralized energy system. It will be able to highlight the technologies that are the most cost effective to decarbonize the building stock and can to determine if the targets will be able to be met from renewable energy produced onsite or whether alternatives (i.e., external renewable energy certificates) will have to be considered to meet national emissions targets. Energy planners tasked with deciding which technologies, systems, or methods will be the most effective and least expensive to meet targets for the buildings in their communities can use such a model to evaluate their own project or community within certain boundaries. Policy makers can use such a model to assess a variety of neighborhoods to see which technologies they should promote in certain areas and to what extent retrofit rates should be increased.

To demonstrate this, the model was evaluated with two case studies in different settings: one urban and one rural, both with different amounts of renewable potential. Pareto optimal solutions were run for all combinations of future years, future scenarios, and case studies. The solutions are compared against the national future energy strategy targets, which provides valuable information for policy makers and energy planners. In addition, the full-year horizon directly targets the differences between long-term and short-term storage.

Separate conclusions can be made from the findings of the two case studies. For the rural case study (Zernez), the high renewable potential allows for several solutions that were able to meet the energy targets. Due to the high level of renewables, long-term storage was an asset in the design after 2035 when the feed-in tariff was phased out. The urban case study (Altstetten) could not meet the targets in any scenario due to the lack of available renewables and the remaining high level of energy demand due to the older building stock. Although the retrofit rates were the same for both case studies, the higher energy demand of the older building stock in the urban case study would have benefited more from a higher retrofit rate as an energy reduction strategy. Long-term storage was not feasible in this case as there was not enough renewable surplus to shift with the storage. Instead, short-term storage was sufficient to shift the load for this case study. From this analysis, we can conclude that long-term storage is only attractive for case studies with a sufficiently high level of renewable surplus. In summary, the specific analysis into long-term P2H storage did show that the technology is both technically feasible with sufficient amounts of renewable surplus and that it likely will become more attractive in the future, particularly in case studies where a deep decarbonization is wanted or required.

Aside from the storage systems, it was found that retrofit and renewable energy integration were both required to meet the energy strategy targets. For the neighborhood with less renewable potential and an old building stock, in this case the urban case study, the importance of retrofits should be particularly emphasized as the targets could not be met. The population density in the urban case study resulted in a lower amount of rooftop space for PV relative to the energy density of the buildings. In an urban area, alternative strategies to solar technologies would be difficult to include due to the lack of available area to install other technologies. To further decrease the use of fossil fuels, external renewable energy must be imported into the neighborhood (i.e., the community could purchase renewable energy shares or certificates).

The results of the three future scenarios show that storage systems were the most favored in the RSD scenario. This was due to the lower local demand resulting in higher surplus electricity. Due to low feed-in tariffs and increasing electricity prices, it was more cost effective to install a storage system and use this energy at a later time rather than selling it back to the grid at a low cost. The CM scenario also favored storage despite having the lowest renewable surplus of all scenarios, which implies that the feed-in tariff has a strong effect on storage system selection and capacity. The GSD scenario was also effective at reducing emissions and was the most cost favorable scenario due to the feed-in tariff profits, however it choose to sell most of its surplus back to the grid which may result in stress on the centralized grid and a lower self-sustainability ratio. All three scenarios were able to meet the emissions reduction targets for the rural case study and its storage systems. This suggests that both long and short-term storage could play an important role in helping DES in settings with large renewable potential meet their energy strategy targets.

When planning for the future, decision makers should also consider the effects that the input parameters have on the optimal system configuration and thus on their ability to contribute to emission reduction targets. Results show that feed-in tariff and the level of surplus energy (which is highly impacted by the building energy demand and the level of available renewable potential) have a high impact on the optimal system design. If the realized parameters for these values in the future vary strongly from the predictions, then the conclusions of this paper will differ. In such a model, uncertainty in the input parameters and their effect on the model must be considered and the effects of these future outcomes should be known before decisions are made regarding the implementation of these systems.

In order to further investigate the impacts of input parameters, an uncertainty analysis and sensitivity analysis of this model parameters should be performed, although the computational time of the model would likely have to be reduced to conduct a proper uncertainty analysis with a Monte Carlo method (typically requiring thousands of runs). More simulations would have to be run on the identified parameters of interest (i.e., feed-in tariff, electricity price, capital cost of storage and RES, and retrofit rate) to draw further conclusions.

These additions would strongly build on the method of multi-objective optimization for DES that is investigated in this paper and would allow for the better identification of energy strategies for decarbonization, which could be a powerful tool to meeting the climate change goals by 2050.

Acknowledgements

This research is part of the "Integration of sustainable multi-energy hub systems at the neighbourhood scale from the buildings perspective" project (IMES-BP 407040-153890) and the "Economic assessment of multi-energy-hub systems integration at the neighbourhood scale" (IMES-ECO 407040-153781) in the Energy Turnaround NRP70 Research Programme. Funding for this research is provided by the Swiss National Science Foundation (SNF).

The authors would like to thank all IMES project partners, especially Bastien Girod for his contributions for the development of the scenarios. We would also like to thank Paolo Gabrielli for his assistance in setting the parameters for the future scenarios and development of the PWA for the fuel cell and electrolyzer.

Appendix

(A) Future parameters (Table A.1-A.3), (B) cost breakdown (Figure B.1), (C) supplementary material.

References

Altfeld, K., Pinchbeck, D., 2013. Admissible hydrogen concentrations in natural gas systems, Gas for Energy.

Amos, W.A., 1998. Costs of Storing and Transporting Hydrogen. Colorado.

Aventa Ltd., 2016. The AV-7 LoWind Turbine [WWW Document]. Technical Data. URL http://aventa.ch/en/leichtwindanlage-av-7.html (accessed 4 July, 2018).

Battke, B., Schmidt, T.S., Grosspietsch, D., Hoffmann, V.H., 2013. A review and probabilistic model of lifecycle costs of stationary batteries in multiple applications. Renewable and Sustainable Energy Reviews 25, 240–250.

Beaudin, M., Zareipour, H., Schellenberglabe, A., Rosehart, W., 2010. Energy storage for mitigating the variability of renewable electricity sources: An updated review. Energy for Sustainable Development 14, 302–314.

Bernal-Agustín, J.L., Dufo-López, R., 2010. Techno-economical optimization of the production of hydrogen from PV-Wind systems connected to the electrical grid. Renewable Energy 35, 747–758.

Capstone Turbine Corporation, 2018. Capstone Products [WWW Document]. Products. URL https://www.capstoneturbine.com/products/ (accessed 4 July, 2018).

Danish Energy Agency, 2016. Technology data for energy plants - Generation of Electricity and District Heating, Energy Storage and Energy Carrier Generation and Conversion. Copenhagen.

Dodds, P.E., Staffell, I., Hawkes, A.D., Li, F., Grünewald, P., McDowall, W., Ekins, P., 2015. Hydrogen and fuel cell technologies for heating: A review. International Journal of Hydrogen Energy 40, 2065–2083.

Dufo-López, R., Bernal-Agustín, J.L., 2008. Multi-objective design of PV-wind-diesel-hydrogen-battery systems. Renewable Energy 33, 2559–2572.

Ecoplan, 2015. Auswirkungen eines Klima- und Energielenkungssystems für 2030: Analyse mit einem berechenbaren Gleichgewichtsmodell für die Schweiz. Bern.

Eidgenössisches Departement für Wirtschaft Bildung und Forschung WBF, 2018. Website des Preisüberwachers zu den Gaspreisen [WWW Document]. Bundesverwaltung admin.ch. URL http://gaspreise.preisueberwacher.ch/web/index.asp (accessed 22 May, 2018).

EPRI, 2010. Electric Energy Storage Technology Options: A White Paper Primer on Applications, Costs and Benefits, Technical Update.

Fazlollahi, S., 2014. Decomposition optimization strategy for the design and operation of district energy systems. EPFL.

Federal Office of Topography, 2014. swisstopo onlineshop [WWW Document]. swissBUILDINGS3d 2.0. URL https://shop.swisstopo.admin.ch/en/ (accessed 4 July, 2018).

Federal Statistical Office, 2018. Federal Register of Buildings and Dwellings [WWW Document]. Bundesamt für Statistik (BFS). URL https://www.bfs.admin.ch/bfs/de/home/register/gebaeude-wohnungsregister.html (accessed 4 July, 2018).

Gabrielli, P., Flamm, B., Eichler, A., Gazzani, M., Lygeros, J., Mazzotti, M., 2016. Modeling for Optimal Operation of PEM Fuel Cells and Electrolyzers, in: 2016 IEEE 16th International Conference on Environment and Electrical Engineering (EEEIC). p. 7.

Geidl, M., Andersson, G., 2006. Operational and Structural Optimization of Multi-Carrier Energy Systems, in: International Conference on Future Power Systems. pp. 1–16.

Girod, B., Wiek, A., Mieg, H., Hulme, M., 2009. The evolution of the IPCC's emissions scenarios. Environmental Science and Policy 12, 103–118.

Götz, M., Lefebvre, J., Mörs, F., McDaniel Koch, A., Graf, F., Bajohr, S., Reimert, R., Kolb, T., 2016. Renewable Power-to-Gas: A technological and economic review. Renewable Energy 85, 1371–1390.

Hajimiragha, H., Canizares, C., Fowler, M., Geidl, M., Andersson, G., 2007. Optimal Energy Flow of Integrated Energy Systems with Hydrogen Economy Considerations, in: Bulk Power System Dynamics and Control – VII.

Han, S., Won, W., Kim, J., 2017. Scenario-based approach for design and comparatively analysis of conventional and renewable energy systems. Energy 129, 86–100.

IEA, 2015. Technology Roadmap: Hydrogen and Fuel Cells, International Energy Agency (IEA). Paris.

IEA, 2010. Renewable Energy Essentials: Hydropower, International Energy Agency (IEA). Paris.

Itten, R., Frischknecht, R., Stucki, M., 2014. Life Cycle Inventories of Electricity Mixes and Grid, Paul Scherrer Institut (PSI).

Jakob, M., 2016. INSPIRE Tool (Version 1.48) [WWW Document]. Dokumentation zum INSPIRE-Tool. URL https://www.energieschweiz.ch/page/de-ch/inspire-tool (accessed 22 May, 2018).

Keirstead, J., Samsatli, N., Shah, N., Weber, C., 2012. The impact of CHP (combined heat and power) planning restrictions on the efficiency of urban energy systems. Energy 41, 93–103.

Knopf, C.F., 2011. Modeling, Analysis and Optimization of Process and Energy Systems. John Wiley & Sons, Inc.

Körner, A., 2015. Technology Roadmap: Hydrogen and Fuel Cells. International Energy Agency (IEA), Paris.

Korpås, M., Holen, A.T., 2006. Operation planning of hydrogen storage connected to wind power operating in a power market. IEEE Transactions on Energy Conversion 21, 742–749.

Lang, T., Gloerfeld, E., Girod, B., 2015. Don't just follow the sun - A global assessment of economic performance for residential building photovoltaic. Renewable and Sustainable Energy Reviews. 42, 932–951.

Laumanns, M., Thiele, L., Zitzler, E., 2005. An Adaptive Scheme to Generate the Pareto Front Based on the Epsilon-Constraint Method, in: Dagstuhl Seminar Proceedings "Practical Approaches to Multi-Objective Optimization." p. 11.

Lehner, M., Tichler, R., Steinmüller, H., Koppe, M., 2014. Power-to-Gas: Technology and Business Models. Springer International Publishing.

Li, B., Roche, R., Paire, D., Miraoui, A., 2017. Sizing of a stand-alone microgrid considering electric power, cooling/heating, hydrogen loads and hydrogen storage degradation. Applied Energy 205, 1244–1259.

Lott, M.C., Kim, S.-I., 2014. Technology Roadmap: Energy storage, Energy Technology Perspectives. Paris.

Lunz, B., Stöcker, P., Eckstein, S., Nebel, A., Samadi, S., Erlach, B., Fischedick, M., Elsner, P., Sauer, D.U., 2016. Scenario-based comparative assessment of potential future electricity systems - A new methodological approach using Germany in 2050 as an example. Applied Energy 171, 555–580.

Maroufmashat, A., Fowler, M., Sattari Khavas, S., Elkamel, A., Roshandel, R., Hajimiragha, A., 2016. Mixed integer linear programing based approach for optimal planning and operation of a smart urban energy network to support the hydrogen economy. International Journal of Hydrogen Energy 41, 7700–7716.

Marquant, J.F., Evins, R., Carmeliet, J., 2015. Reducing computation time with a rolling horizon approach applied to a MILP formulation of multiple urban energy hub system. Procedia Computer Science 51, 2137–2146.

Mavromatidis, G., Orehounig, K., Carmeliet, J., 2015. Evaluation of photovoltaic integration potential in a village. Solar Energy 121, 152–168.

Mavromatidis, G., Orehounig, K., Richner, P., Carmeliet, J., 2016. A strategy for reducing CO2 emissions from buildings with the Kaya identity - A Swiss energy system analysis and a case study. Energy Policy 88, 343–354.

McKenna, R., Merkel, E., Fichtner, W., 2017. Energy autonomy in residential buildings: A techno-economic model-based analysis of the scale effects. Applied Energy 189, 800–815.

Miglani, S., Orehounig, K., Carmeliet, J., 2016. Assessment of the ground source heat potential at building level applied to an urban case study, in: Status-Seminar "Forschen Für Den Bau Im Kontext von Energie Und Umwelt."

Moss, R.H., Edmonds, J.A., Hibbard, K.A., Manning, M.R., Rose, S.K., Van Vuuren, D.P., Carter, T.R., Emori, S., Kainuma, M., Kram, T., Meehl, G.A., Mitchell, J.F.B., Nakicenovic, N., Riahi, K., Smith, S.J., Stouffer, R.J., Thomson, A.M., Weyant, J.P., Wilbanks, T.J., 2010. The next generation of scenarios for climate change research and assessment. Nature 463, 747–756.

Nakicenovic, N., Swart, R., 2000. IPCC Special Report on Emissions Scenarios, Emissions Scenarios. Cambridge University Press.

Nascimento, M.A.R. do, Rodrigues, L. de O., Santos, E.C. dos, Gomes, E.E.B., Dias, F.L.G., Velásques, E.I.G., Carrillo, R.A.M., 2013. Micro Gas Turbine Engine: A Review, in: Ernesto Benini (Ed.), Progress in Gas Turbine Performance. IntechOpen, pp. 107–141.

Northwest Power and Conservation Council, 2010. Sixth Northwest Conservation and Electric Power Plan - Appendix N: Financial Assumptions and Discount Rate. Northwest Power and Conservation Council, Portland.

Orehounig, K., Mavromatidis, G., Evins, R., Dorer, V., Carmeliet, J., 2014. Towards an energy sustainable community: An energy system analysis for a village in Switzerland. Energy and Buildings 84, 277–286.

Paish, O., 2002. Small hydro power: Technology and current status. Renewable and Sustainable Energy Reviews 6, 537–556.

Parag, Y., Sovacool, B.K., 2016. Electricity market design for the prosumer era. Nature Energy 1, 16032.

Petruschke, P., Gasparovic, G., Voll, P., Krajačić, G., Duić, N., Bardow, A., 2014. A hybrid approach for the efficient synthesis of renewable energy systems. Applied Energy 135, 625–633.

Prognos AG, 2012. Die Energieperspektiven für die Schweiz bis 2050 - Energienachfrage und Elektrizitätsangebot in der Schweiz 2000 – 2050. Bern.

Remund, J., Müller, S.C., Schilter, C., Rihm, B., 2010. The use of Meteonorm weather generator for climate change studies, in: EMS Annual Meeting Abstracts.

Ren, H., Gao, W., 2010. A MILP model for integrated plan and evaluation of distributed energy systems. Applied Energy 87, 1001–1014.

Sanner, B., 2003. Current status of ground source heat pumps in Europe, in: 9th Int. Conf. on Thermal Energy Storage "Futurestock 2003." pp. 695–703.

Schoots, K., Kramer, G.J., van der Zwaan, B.C.C., 2010. Technology learning for fuel cells: An assessment of past and potential cost reductions. Energy Policy 38, 2887–2897.

Sgobbi, A., Nijs, W., De Miglio, R., Chiodi, A., Gargiulo, M., Thiel, C., 2016. How far away is hydrogen? Its role in the medium and long-term decarbonisation of the European energy system. International Journal of Hydrogen Energy 41, 19–35.

Simoes, S., Nijs, W., Ruiz, P., Sgobbi, A., Radu, D., Bolat, P., Thiel, C., Peteves, S., 2013. The JRC-EU-TIMES model. Assessing the long-term role of the SET Plan Energy technologies, EUR – Scientific and Technical Research series.

Stadler, M., 2008. Distributed Energy Resources On-Site Optimization for Commercial Buildings with Electric and Thermal Storage Technologies.

Swiss Federal Electricity Commission ElCom, 2018. Strompreis-Webseite [WWW Document]. Eidgenössische Elektrizitätskommission ElCom. URL https://www.strompreis.elcom.admin.ch/ (accessed 22 May, 2018).

SwissSolar, 2018. KEV und Einmalvergütung [WWW Document]. KEV und EIV. URL https://www.swissolar.ch/topthemen/kev-und-eiv/ (accessed 22 May, 2018).

Tsuchiya, H., Kobayashi, O., 2004. Mass production cost of PEM fuel cell by learning curve. International Journal of Hydrogen Energy 29, 985–990.

U.S. Energy Information Administration (EIA), 2015. Annual Energy Outlook 2015 with projections to 2040. U.S. Department of Energy (DOE), Washington.

van Vuuren, D.P., Kok, M.T.J., Girod, B., Lucas, P.L., de Vries, B., 2012. Scenarios in Global Environmental Assessments: Key characteristics and lessons for future use. Global Environmental Change 22, 884–895.

Wang, C., Nehrir, M.H., Shaw, S.R., 2005. Dynamic models and model validation for PEM fuel cells using electrical circuits. IEEE Transactions on Energy Conversion 20, 442–451.

Wang, D., Landolt, J., Mavromatidis, G., Orehounig, K., Carmeliet, J., 2018. CESAR: A bottom-up building stock modelling tool for Switzerland to address sustainable energy transformation strategies. Energy and Buildings 169, 9–26.

Weber, C., Shah, N., 2011. Optimisation based design of a district energy system for an eco-town in the United Kingdom. Energy 36, 1292–1308.

Yang, H., Xiong, T., Qiu, J., Qiu, D., Dong, Z.Y., 2016. Optimal operation of DES/CCHP based regional multi-energy prosumer with demand response. Applied Energy 167, 353–365.

Yazdanie, M., Densing, M., Wokaun, A., 2017. Cost optimal urban energy systems planning in the context of national energy policies: A case study for the city of Basel. Energy Policy 110, 176–190.

Zhang, Y., Campana, P.E., Lundblad, A., Yan, J., 2017. Comparative study of hydrogen storage and battery storage in grid connected photovoltaic system: Storage sizing and rule-based operation. Applied Energy 201, 397–411.

Appendix

Appendix A: Future Parameters

The parameters used in the optimization are listed in this section. Table A.1 lists the economic and market parameters, Table A.2 lists the technology parameters, and Table A.3 lists the lifetimes of technologies.

Table A.1: Future Scenario Economic and Market Parameters

	Baseline	**CM**			**GSD**			**RSD**		
Parameter	**2015**	**2020**	**2035**	**2050**	**2020**	**2035**	**2050**	**2020**	**2035**	**2050**
Elec. price (CHF/kWh)	0.198	0.206	0.235	0.231	0.212	0.251	0.262	0.212	0.251	0.262
Reference(s)	(Prognos AG, 2012; Swiss Federal Electricity Commission ElCom, 2018)									
Gas price (CHF/kWh)	0.067	0.037	0.052	0.061	0.095	0.129	0.148	0.193	0.270	0.305
Reference(s)	(Eidgenössisches Departement für Wirtschaft Bildung und Forschung WBF, 2018; U.S. Energy Information Administration (EIA), 2015)									
Feed-in tariff (CHF/kWh)	0.176	0.087	0	0	0.176	0.176	0.176	0.087	0.011	0.001
Reference(s)	(Prognos AG, 2012; SwissSolar, 2018)									
Grid CO_2 (kg CO_2/kWh)	0.124	0.150	0.150	0.150	0.100	0.089	0.072	0.100	0.089	0.074
Reference(s)	(Itten et al., 2014)									
CO_2 tax (CHF/t CO_2)	84	84	84	84	120	240	240	120	240	240
Reference(s)	(Ecoplan, 2015)									
Discount rate (%)	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0
Reference(s)	(Northwest Power and Conservation Council, 2010)									
Retrofit rate (%)	1.0	1.0	1.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
Reference(s)	(Prognos AG, 2012)									

Table A.2: Future Scenario Technology Parameters

Technology	Parameter	Baseline	CM			GSD			RSD		
		2015	2020	2035	2050	2020	2035	2050	2020	2035	2050
PV	Capital Cost (CHF/m^2)	334	334	334	334	225	136	124	225	136	124
	Reference(s)	(Danish Energy Agency, 2016; Jakob, 2016)									
	OMV cost (CHF/kWh)	0.034	0.034	0.034	0.034	0.025	0.014	0.012	0.025	0.014	0.012
	Reference(s)	(Danish Energy Agency, 2016)									
	Nominal efficiency	17.0%	17.0%	17.0%	17.0%	17.0%	17.0%	17.0%	17.0%	17.0%	17%
	Reference(s)	(Lang et al., 2015)									
Small-hydro	Capital Cost (CHF/kW)	3478	3478	3478	3478	3478	3478	3478	3478	3478	3478
	Reference(s)	(IEA, 2010)									
	OMF cost (CHF/kW)	104	104	104	104	104	104	104	104	104	104
	Reference(s)	(IEA, 2010)									
	Nominal efficiency	80%	80%	80%	80%	80%	80%	80%	80%	80%	80%
	Reference(s)	(Paish, 2002)									
Small-wind	Capital Cost (CHF/kW)	9200	9200	9200	9200	8674	8477	8017	8674	8477	8017
	Reference(s)	(Danish Energy Agency, 2016)									
	OMV cost (CHF/kWh)	0.014	0.014	0.014	0.014	0.014	0.014	0.014	0.014	0.014	0.014
	Reference(s)	(Danish Energy Agency, 2016)									
Heat pump	Capital Cost (CHF/kW)	1977	1977	1977	1977	1600	1500	1400	1600	1500	1400
	Reference(s)	(Danish Energy Agency, 2016; Jakob, 2016)									
	OMF cost (CHF/kW)	5.4	5.4	5.4	5.4	4.4	4.1	3.9	4.4	4.1	3.9
	Reference(s)	(Danish Energy Agency, 2016)									
	Nominal COP	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2
	Reference(s)	(Sanner, 2003)									
Gas boiler	Capital Cost (CHF/kW)	260	260	260	260	260	260	260	260	260	260
	Reference(s)	(Jakob, 2016)									
	OMF cost (CHF/kW)	3.7	3.7	3.7	3.7	3.7	3.7	3.7	3.7	3.7	3.7
	Reference(s)	(Jakob, 2016)									
	Nominal efficiency	85%	85%	85%	85%	85%	85%	85%	85%	85%	85%
	Reference(s)	(Danish Energy Agency, 2016)									
PEMFC	Capital Cost (CHF/kW)	6252	2886	1443	962	2886	1443	962	2886	1443	962
	Reference(s)	(IEA, 2015)									
	OMV cost (CHF/kWh)	0.025	0.025	0.025	0.025	0.025	0.025	0.025	0.025	0.025	0.025
	Reference(s)	(Amos, 1998)									
	Nom. Elec. efficiency	50%	55%	58%	60%	55%	58%	60%	55%	58%	60%
	Reference(s)	(Dodds et al., 2015; Schoots et al., 2010; Tsuchiya and Kobayashi, 2004; Wang et al., 2005)									
	Thermal efficiency	48%	43%	37%	35%	43%	37%	35%	43%	37%	35%
	Reference(s)	(Dodds et al., 2015; Schoots et al., 2010; Tsuchiya and Kobayashi, 2004; Wang et al., 2005)									
MGT	Capital Cost (CHF/kW)	900	750	620	500	750	620	500	750	620	500
	Reference(s)	(Nascimento et al., 2013)									
	OMV cost (CHF/kWh)	0.013	0.013	0.013	0.013	0.013	0.013	0.013	0.013	0.013	0.013
	Reference(s)	(Nascimento et al., 2013)									
	Nom. Elec. efficiency	25%	28%	30%	32%	28%	30%	32%	28%	30%	32%
	Reference(s)	(Nascimento et al., 2013)									
	Thermal efficiency	70%	70%	70%	70%	70%	70%	70%	70%	70%	70%
	Reference(s)	(Nascimento et al., 2013)									

Table A.2: Future Scenario Technology Parameters (continued)

Technology	Parameter	Baseline	CM			GSD			RSD		
		2015	2020	2035	2050	2020	2035	2050	2020	2035	2050
PEMEC	Capital Cost (CHF/kW)	2650	2200	1500	760	2200	1500	760	2200	1500	760
	Reference(s)	(IEA, 2015)									
	OMF cost (%Cap)	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%
	Reference(s)	(Lehner et al., 2014)									
	Nominal Efficiency (kWh/Nm^3)	6.00	5.5	5	4.5	5.5	5	4.5	5.5	5	4.5
	Reference(s)	(IEA, 2015)									
Li-ion battery	Capital Cost (CHF/kWh)	674	578	482	385	260	260	260	260	260	260
	Reference(s)	(Lott and Kim, 2014)									
	OMF cost (CHF/kWh)	25	25	25	25	25	25	25	25	25	25
	Reference(s)	(EPRI, 2010)									
	Overall efficiency	92.5%	92.5%	92.5%	92.5%	92.5%	92.5%	92.5%	92.5%	92.5%	92.5%
	Reference(s)	(Battke et al., 2013)									
Thermal storage	Capital Cost (CHF/m^3)	650	650	650	650	650	650	650	650	650	650
	Reference(s)	(Jakob, 2016)									
	Overall efficiency	90%	90%	90%	90%	90%	90%	90%	90%	90%	90%
	Reference(s)	(Stadler, 2008)									
Hydrogen storage	Capital Cost (CHF/kgH$_2$)	950	680	510	460	680	510	460	680	510	460
	Reference(s)	(Amos, 1998; IEA, 2015)									

Table A.3: Future Scenario Technology Lifetimes

Technology	Lifetime (yrs)	Reference(s)	Operating hours	Reference(s)
PV	25	(Jordan and Kurtz, 2012)	-	
Small-hydro	50	(International Energy Agency, 2010)	-	
Small-wind	25	(Danish Energy Agency, 2016)	-	
Heat pump	20	(Danish Energy Agency, 2016)	-	
Gas boiler	20	(Danish Energy Agency, 2016)	-	
PEMFC	-		60,000	(International Energy Agency, 2015)
MGT	10	(Nascimento et al., 2013)	30,000	(Nascimento et al., 2013)
PEMEC	-		60,000	(International Energy Agency, 2015)
Li-ion battery	11.5	(Battke et al., 2013)	-	
TES	17	(Stadler, 2008)	-	
H2S	22	(Amos, 1998)	-	

Appendix B: Cost Breakdown

The costs displayed in Figure 7 are further broken down into five categories in Figure B.1: conversion technology capital, storage technology capital, operation and maintenance, fuel, and electricity costs.

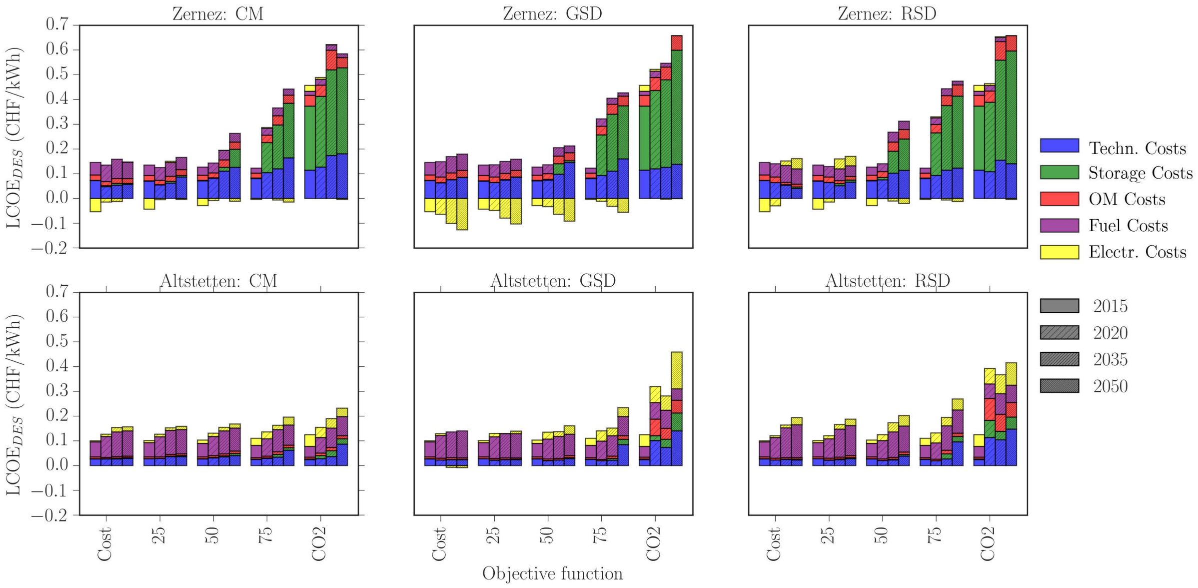


Figure B.1: Cost objective composition for Pareto optimal solutions

The GSD scenario achieves the lowest cost solutions, while the CM scenario has the highest costs. In the cost optimal solutions for the Zernez case study, there are observed negative electricity costs (profits). This is also true for the 25% and 50% solutions for the in the GSD scenario. These are all cases with a high feed-in tariff. In cost optimal solutions, the capital costs of storage and the conversion technologies are responsible for the majority of the costs. This is due to large hydrogen storage systems being installed. More reasonably sized systems are installed in the 50% and 75% cases. In Altstetten, the costs are dominated by natural gas as the case study is strongly dependent on gas boilers to meet its heating demand.

Appendix C: Supplementary Material

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.apenergy.2018.08.106.

Article IV

Working Draft (targeted towards *Research Policy*)

The Role of Policy in Fostering the Diffusion of Low-Carbon Innovations

David Grosspietsch*, Bastien Girod, Manuel Kant, Mario Kugler, and Volker H. Hoffmann

ETH Zurich
Department of Management, Technology, and Economics
Weinbergstrasse 56/58, 8092 Zurich, Switzerland

* Corresponding author
Phone: +41-44 633 88 91
Email: dgrosspietsch@ethz.ch

Abstract

To foster the decarbonization of the economy, the diffusion of low-carbon innovations needs to be accelerated. Research has recognized the role of policy as a substantial driver for this diffusion. However, a better understanding is required of whether and how policy support needs to be tailored to specific technologies. This article aims at identifying mechanisms that explain how policy support can effectively accelerate the diffusion of low-carbon innovations. To do so, we examine long-term developments in the diffusion of three energy-efficient building technologies that have successfully diffused due to substantial policy intervention: heat pump, low-e glazing, and comfort ventilation. We focus on the Swiss market, which fulfilled a lead market role in the diffusion of these technologies. Technology developments and diffusion patterns, and the related policy support, are retrospectively retraced based on archival data and expert interviews. We find that the level of technological maturity and the diffusion status are important dimensions for tailoring policy support. Immature technologies require nurturing through a variety of policies. For technologies above a certain level of maturity, labels and standards are effective ways to stimulate demand. Based on these findings, we propose a framework to support an effective acceleration of diffusion using different types of policy. Our work contributes to the environmental policy literature and provides guidance to business and policy decision makers.

Keywords

Diffusion, innovation, low-carbon technologies, policy, maturity

Highlights

- We evaluate how policy support needs to be tailored to technologies.
- Three successfully diffused energy efficiency technologies build the empirical basis.
- Technological maturity and diffusion stage are key factors to be considered.
- The resulting framework provides guidance for an effective tailoring of policy.

1 Introduction

To meet international climate targets, a better understanding of how to accelerate the decarbonization of our economy is required (IPCC, 2014a). Today there are many low-carbon technologies commercially available, which are – or have the potential to be – economically and ecologically superior to their "high-carbon" competitors (Bruckner et al., 2014; GEA, 2012). However, these innovations exhibit large variations in their diffusion patterns, that is, in their time to market or deployment, and oftentimes fail to sufficiently diffuse into the market altogether (Bento and Wilson, 2016; Grübler et al., 1999; Iyer et al., 2015; Jaffe et al., 2002; Wilson and Grübler, 2011). The insufficient diffusion of low-carbon technologies is one of the main reasons that emission reduction lags behind international climate targets (Rogelj et al., 2016).

Policy has been acknowledged as an important driver for technological change (Jaffe et al., 2002; Nemet, 2009; Nill and Kemp, 2009). However, it remains unclear how policies should be designed and tailored to provide effective support for specific technologies (del Río González, 2009; Somanthan et al., 2014; Stucki and Woerter, 2016). The general approach to supporting the innovation and diffusion of low-carbon technologies with policies is well understood (Grübler et al., 2012) and typically begins with technology-push policies, such as RD&D support, followed by demand-pull policies, such as feed-in tariffs (Di Stefano et al., 2012; Halsnæs et al., 2007; Nemet, 2009; Sandén and Azar, 2005). However, to effectively spur the diffusion of innovations, such an idealized, quasi-linear policy approach might need to reflect the distinctive characteristics of different (low-carbon) technologies (Fichter and Clausen, 2013; Huenteler et al., 2016; Stoneman and Diederen, 1994). For example, while some technologies require continuous policy support throughout their development and diffusion (Kiss et al., 2012), for other technologies selective support measures might be enough to sufficiently kick off market deployment (Jakob and Madlener, 2004). At the same time, many technologies are not merely exposed to a single policy, but rather are subjected to a comprehensive policy mix (Reichardt et al., 2016; Rogge and Reichardt, 2016). These findings mirror a wider debate related to the nature of effective policy support with some argumentations for policy intervention in a tailored, mechanistic manner, and others that suggest flexible policy design and continued policy adaptation as the most expedient way (Hoppmann et al., 2014; Voß and Kemp, 2005).

This study therefore investigates how different policies affect the diffusion of low-carbon technologies across different phases. We are interested in how policy requirements change as technologies mature and are more widely diffused. In this way, we aim to improve the understanding of the link between technology diffusion and the policy efforts that trigger it. To address this, we examine the diffusion from both political and socio-technical perspectives to fully capture the influence of policy support (Cherp et al., 2018). We use a qualitative analysis of three case studies of low-carbon technologies in the Swiss built environment, and retrospectively assess the link between their diffusion patterns and the respective policy interventions. In doing so, we derive indications of how policies can be adapted to specific technologies in order to effectively accelerate the diffusion of low-carbon innovation.

Specifically, we investigate technological maturity and diffusion status as two important characteristics within this link.

This article is structured as follows: Section 2 describes the state of knowledge by reviewing the relevant literature. Section 3 outlines the methodology used in our study, first through the introduction of the sampling strategy of the case studies, then by a description of the data collection. The obtained results are presented in Section 4 for each of the three case studies. Section 5 sums up the observed overarching findings in a framework and discusses the implications for business and policy decision makers. Section 6 concludes.

2 Literature

2.1 Determinants of Technological Change

Technological change describes the evolution of new technology paradigms and their transformation of the surrounding innovation system (Nelson, 2007; Tushman and Rosenkopf, 1992). Scholars have broken down the processes of technological change into the invention, innovation, and diffusion phases of new technologies, coined as the Schumpeterian trilogy (Schumpeter, 1942). While these phases lack a sharp delineation, they are determined by feedback loops and iterations between them. The most discernible one to the broader public is the diffusion phase, where the cumulative adoption of a new technology is captured in the concept of S-shaped diffusion curves (Bass, 1969; Rogers, 2003). Determinants of technological change in general, and of the diffusion phase in particular, have been comprehensively described (Dosi, 1982; Tushman and Rosenkopf, 1992).

These determinants can be grouped into factors that influence diffusion from the demand or from the supply side of a new technology (Hall and Khan, 2003; Suriñach et al., 2009). By "probing more deeply at the technological level itself", Rosenberg identifies factors on the supply side that are important for the diffusion of innovation, such as "improvements after first introduction", "complementarities", and "institutional context" (Rosenberg, 1972). On the demand side, diffusion determinants can be classified into either technology-specific factors or factors related to the adoption environment (Grübler et al., 2016; Rogers, 2003; Rosenberg, 1972; Wilson, 2012). According to Rogers, technology-specific determinants affect decision-making at the individual level and comprise perceived characteristics, such as compatibility, trialability, or relative advantage (Rogers, 2003). The adoption environment goes beyond the individual level and is highly dependent upon context, for instance, on the nature of the surrounding social system or on the existence of and efforts by change agents (Grübler et al., 2016; Rogers, 2003; Rosenberg, 1972).

For the diffusion of low-carbon technologies, factors related to the adoption environment play an important role as they can often be more easily influenced than technology-specific determinants, which are mainly shaped by manufacturers. Transition studies focus on the adoption environment by investigating the societal and institutional levels rather than the individual or technology levels (Carlsson and Stankiewicz, 1991). For example, the innovation system concept is frequently used to investigate socio-technical transitions (i.e., transitions from one regime to another), thus capturing the development, diffusion, and usage of an innovation within its system (cf. technology innovation system (TIS) from Markard et al., (2012)). There are other common specifications of systems of innovation. Some embrace a spatial (national (Nelson, 2013) or regional innovation system (Cooke et al., 1997)) or an industry (sectoral innovation system (Breschi and Malerba, 1998)) perspective and, along with the mix of implemented policies, are considered important determinants of technological change (Markard and Truffer, 2008).

In fact, in addition to socio-economic, technological, cultural, legal, and individual factors (Nagra and Gopal, 2014), policy is widely recognized as a pivotal trigger for influencing the diffusion of low-carbon technologies (Bento and Wilson, 2016; Iyer et al., 2015; Mercure et al., 2014; Mowery et al., 2010; Popp et al., 2010). However, there is still little knowledge about the causal links between the various types of policy support and the diffusion of low-carbon technologies (Boza-Kiss et al., 2013; del Río González, 2009; Grübler et al., 2012).

2.2 The Role of Policy in Technological Change

A plethora of studies has examined how policies can spur (the determinants of) technological change, particularly in the low-carbon realm (Newell, 2010; OECD, 2001). There is broad consensus about the idealized approach of policy support from the initial development of an innovation to its subsequent diffusion. Scholars, such as Grubb (2004), Grubler et al. (2012), and Halsnæs et al. (2007), have thoroughly documented this quasi-linear[1] process across five phases: i.) basic research and development (R&D), ii.) applied R&D and demonstration (RD&D), iii.) market demonstration, iv.) commercialization and market formation, and v.) diffusion. While the technology-push concept is associated with the earlier phases, the demand-pull concept accounts for the later ones. Even though a sharp separation between these two concepts throughout the phases is neither feasible nor necessary, this important dichotomy implies the use of different policy types and instruments. Policy types can be classified as: i.) support of research, development, and demonstration (RD&D); ii.) information and education; iii.) monetary incentives; iv.) labels; and v.) standards (Girod et al., 2017; IEA, 2018).

These policy types can be comprised of various policy instruments, which can each be designed in multiple ways and have different effects on technology diffusion. For example, Boza-Kiss et al. (2013) analyze the effectiveness of multiple policy instruments for a series of energy-efficient building technologies in different countries. They conclude that these instruments cannot be prioritized and that their effectiveness is highly dependent on how they are designed and tailored to the specific context (e.g., local resources, capacities, cultures). Kemp & Pontoglio (2011) assign less importance to the role of policy instruments, but specifically emphasize policy design as a crucial factor for the effectiveness of supporting innovation activities and diffusion by providing eight key aspects (e.g., stringency, enforcement).

Despite the availability of such a broad range of policy types, instruments, and designs, scholars have observed large discrepancies in temporal and spatial patterns of the diffusion for low-carbon technologies, such as wind turbine, compact fluorescent lamp (CFL), or bioenergy (Bento and Wilson, 2016; Grübler et al., 1999; Iyer et al., 2015; Wilson and Grübler, 2011).

In order to understand these discrepancies, individual case studies have investigated the relation between policy support and the technology diffusion, and have sought to reflect the peculiarities of technologies and their specific contexts. Two remarkable observations emerge from these studies. On

---

[1] Quasi-linear because of the bidirectional knowledge flow as well as the feedback loops and overlaps between the phases.

the one side, some cases underpin the necessity of the entire range of policy support (from RD&D and information to incentives, labels, and standards), such as the diffusion of the heat pump in Sweden and Switzerland (Kiss et al., 2013). On the other side, in some cases selective support measures have proven to be sufficient to kick off diffusion, as demonstrated, for instance, by a study of household appliances in Japan, which highlights the crucial role of performance standards in large-scale market deployment (Kimura, 2013). However, the extant literature lacks a connection between these different forms of policy support. This is why an analysis is necessary that allows for a direct comparison between several technologies within the same policy context that have been exposed to disparate policy support during their diffusion.

Despite the larger debate about the general nature of policy intervention, to date there is only a limited understanding about the link between policy support and its adaptation for individual technologies and their specific natures (del Río González, 2009; IEA, 2015; Stucki and Woerter, 2016). This is extremely relevant as it would enable policy makers to tailor their support to the particularities of each innovation, and thus would contribute to rendering these efforts more effective and help make more informed decisions.

3 Data and Methodology

To address the literature gap, this study investigates the effects of different policy types during the diffusion phase of three low-carbon technologies in their “core” region, that is, the geographic area that delineates an innovation’s appearance, initial spread, and market take-off. By focusing on three different technology cases within the same national context, we control for variations, for instance, in governmental, societal, and economic aspects.

3.1 Case Selection and Sampling Strategy

We selected our case studies according to three criteria: First, the technologies needed to be subject to policy support within the same context. That is, we considered innovations whose development and diffusion have been shaped by policy intervention to a notable extent. To control for variations in spatial contexts (e.g., from a governmental, societal, or economic perspective), which could exert additional impact on the technology development and diffusion, we had to fix the context of the analysis to the same country. Second, the diffusion had to be observed in a lead market so that side effects on the diffusion by technological or policy related developments outside the country could be prevented. Here, “lead market” or “core (innovator) market” (Grübler et al., 2016) refers to the geographic area that delineates an innovation’s appearance, initial spread, and market take-off. Third, the technologies need to demonstrate successful historical diffusions and exhibit differences in their diffusion patterns. This means that we draw from innovations that have already diffused adequately into the market. Thus, the new technology has already transitioned from an early market phase of below 16% market share[2] (or from a “formative phase” of below 10% market share (Bento and Wilson, 2016; Wilson, 2012)) to a late or mass market phase in which it captures a market share above 16%. Successfully diffused technologies have the advantage of having passed these diffusion phases and thus provide valuable insights into the mechanisms behind the deployed policy support at a certain phase.

Based on the first criterion, we chose the building sector as our focus area as it has long been subject to policy intervention, given its pivotal role in the economy and as a large contributor to the total energy demand. Related to the second criterion, we identified Switzerland as a suitable country given its general pioneer role in low-carbon innovation in research and practice, as well as for reasons of data access and availability. Switzerland was the lead market (or among the initial markets) that shaped the development and diffusion of three energy-efficient technologies in the built environment that we chose for our analysis: heat pump, comfort ventilation, and low-e glazing. By now, these technologies either have a significantly higher market share in Switzerland than they do in comparable countries (Austria, Germany), or they reached this market share earlier in Switzerland than in other

---

[2] The total of 16% is equal to the sum of innovators (2.5%) and early adopters (13.5%), according to Rogers (2003), and represents an innovation’s early market phase.

countries. In line with the third criterion, they all show a sufficient level of diffusion in the Swiss market (above 30% in 2015) but vary widely in their time span from first appearance of the innovation to the late market phase. All of the three technologies are reported as being promising strategies for reducing energy consumption or CO_2 emissions of buildings.

Table 1 provides an overview of the described selection criteria and the three energy-efficient technologies that we identified as case studies.

Table 1: Selection criteria and sampled case studies

			Case studies		
Criteria			**Heat pump**	**Comfort ventilation**	**Low-e glazing** (double insulating)
1		**Targeted by policy** main type(s) in Switzerland	RD&D, information, incentive, label, standard	RD&D, information, label	Label, standard
2		**Lead markets**	SUI, SWE	Scandinavia, SUI, GER	SUI, GER
3		**Diffusion status**			
Switzerland		First appearance	1970	1990	1980
	Market share	Early (10%)	1992	2004	1986
		Medium (30%)	2001	2010	1987
		Late (80%)	2007	-	1999
		Time span (appearance to medium market share) [years]	31	20	7

3.2 Data Collection and Analysis

We collected two main types of data: Secondary data from archival sources and primary data from semi-structured interviews with different experts. We used archival data to map prevailing policies, the dynamics of technology performance, and changes in exogenous influences. Expert interviews helped us to understand the historic development of the technology throughout the diffusion process and to evaluate the influence of individual events and policy types on that development.

From November 2014 to July 2015, we conducted semi-structured interviews with 21 experts in total, of which ten experts were designated to the heat pump case, five experts were from the comfort ventilation case, and six were affiliated with the low-e glazing case. We generated our group of expert interviewees through applying a combination of purposive sampling and snowball sampling. That is, we first aimed to identify potential interviewees through an extensive web search for the main stakeholders from industry, academia, and policy. We then used snowballing to add additional experts who had been mentioned multiple times during the first round of interviews. Table A1 (see Appendix) presents an overview and categorization of the interview partners along with their most recent positions. Interviews were conducted either in person or via telephone according to the interviewee's preference, and lasted between 45 and 120 minutes. We recorded the interviews and then transcribed them using f4 transcription software.

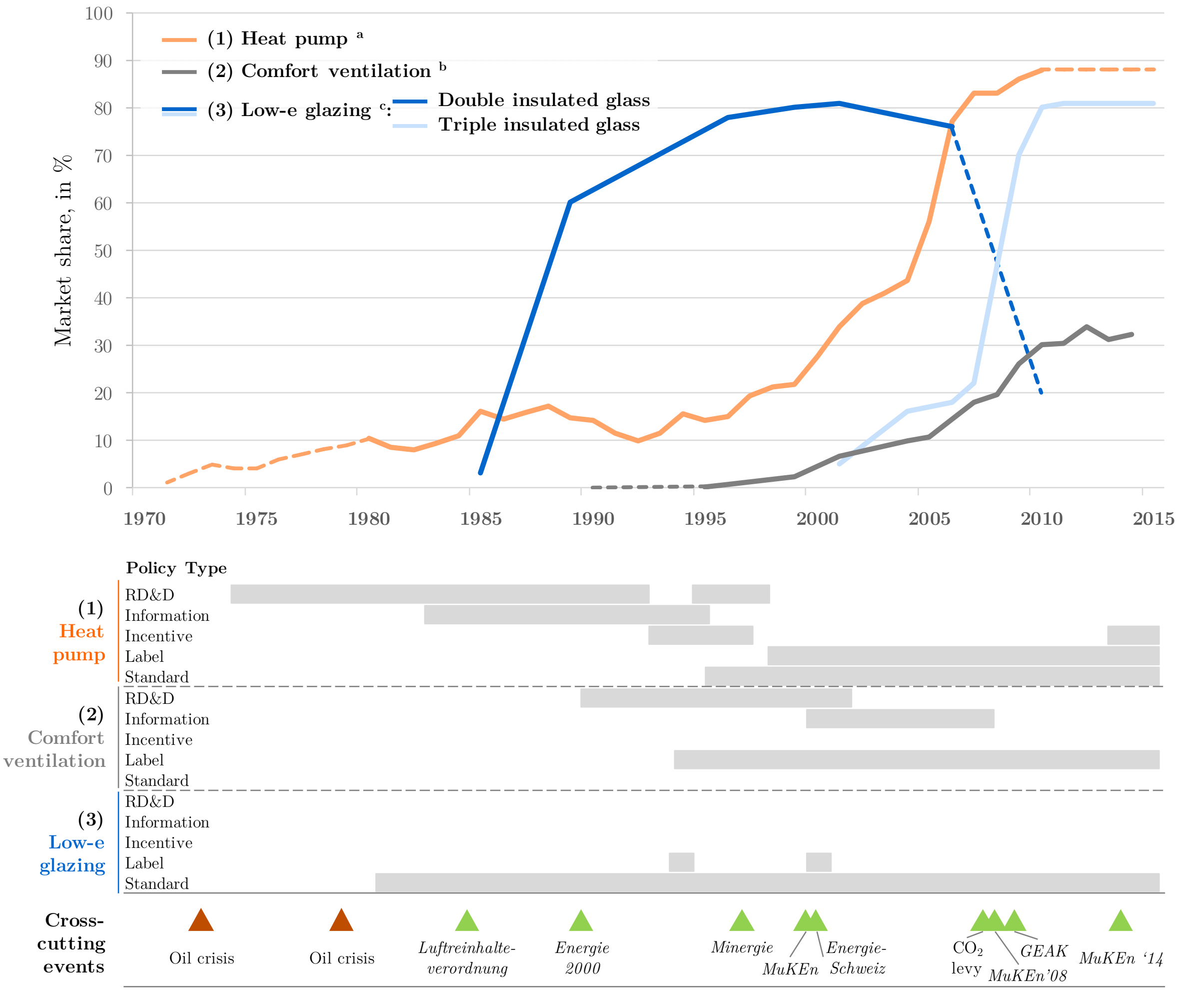
For the analysis, we used a triangulation of methods to obtain results from both of our information sources, the archival data and our semi-structured interviews. We reviewed the interview transcripts and processed them using an inductively based analytical strategy, as described by Saunders et al. (2009). This strategy is composed of three steps: i.) open coding (disaggregated into isolated units/codes and consequent clustering into categories), ii.) axial coding (creation of relationships between code labels and structuring in hierarchical form), and iii.) selective coding (categories are reevaluated to identify core categories on higher levels of aggregation/abstraction). As described by Langley (1999) in her "synthetic strategy" for sensemaking, we drew on and iterated between empirical data and different literature strands, as the combination of these two enables a better understanding of the main mechanisms and helps to derive "relatively simple theoretical formulations […]". Using this process, we were able to depict the main developments along the diffusion curves for the three technologies over several decades.

4 Results

In this section, we first present the findings from all three technologies on a more aggregated level and then describe our results for the individual technologies in subsections (4.1–4.3).

Figure 1 displays the historical development of market shares for the heat pump, comfort ventilation, and low-e glazing technology from 1970 to 2015, along with the corresponding policy support. Two main observations can be made: First, the diffusion curves vary greatly in length and shape. While, for example, the heat pump technology required 37 years from first its commercial appearance to achieving a market share of 80%, the low-e glazing technology (double insulation) diffused almost twice as fast within 19 years. Despite the typical S-shape curve, the diffusion pattern of the heat pump technology, for instance, displays an unusual up-and-down stage during its early market phase (1970–1996). Second, the policies (i.e., type, timing, sequence) that were applied are markedly different, which highlights their impact on the respective diffusion patterns. In fact, we observed that policy support was a response used to address the prevailing issues that were limiting further diffusion in each market phase (see details in subsections 4.1–4.3).

In addition to these two main observations, it is important to point out that all of the technologies we observed benefitted from several cross-cutting events and policy efforts, which have clearly shaped the energy-efficient built environment. The two global oil crises (1973, 1979), for instance, gave rise to environmental awareness and led to public policy initiatives at the national level in Switzerland, such as air pollution regulation ("Luftreinhalteverordnung", 1985), energy programs ("Energie 2000" in 1990 and its successor "EnergieSchweiz" in 2001), and the implementation of the CO_2 tax (2008). In the same vein, regulatory measures and standards (i.e., precise definitions of performance limits or bandwidths) were imposed in Switzerland at the cantonal level but under the recommended national umbrella, such as the regulatory framework for cantonal energy "Mustervorschriften der Kantone im Energiebereich (MuKEn)" in 2000, which was further revised in 2008 and 2014. Private labels, such as "Minergie", established in 1997, or the "Gebäudeenergieausweis der Kantone (GEAK)", established in 2009, have also had an overarching positive impact on the context of our three selected technologies. We illuminate the specific differences in the diffusion patterns for each technology in the following subsections.



a Market share for new single- and two-family houses
b Market share in # of units sold / # of new-build apartments p.a.
c Market share for new-build and retrofit buildings
Dashed lines: approximated market shares based on expert interviews

▲ global
▲ Swiss

Figure 1: Diffusion of three low-carbon technologies in the Swiss built environment and the supporting policies (based on Jakob (2008), Kiss et al. (2012), Nussbaumer (2015) and experts)

4.1 Heat pump

A heat pump is a device that delivers space heating to a building by transferring heat from a low temperature source to a high temperature source using thermodynamic principles. Since the required amount of electric power is lower than the extracted heat, heat pumps count as an energy-efficient technology with an energy reduction potential of 50–75% compared to their fossil-fueled rival technologies (e.g., oil or gas boilers), and they allow for reducing CO_2 emissions close to zero if powered by fossil-free sources.

As seen in Figure 1, the market share for heat pump technology remained below 16% for more than 25 years from its first commercial appearance in 1970 to 1997, during which time policy support for the technology mostly focused on technology-push measures (RD&D support). Yet in the late market phase, from 1997 onwards, policy support has mostly been shaped by demand-pull policies (information, incentives, labels, and standards).

Table 2 provides a chronological overview of the major events structured by market phases and issues that were key barriers to diffusion of the technology. The table also shows the policy types that were applied and outlines the storyline with evidence from the interviews.

The early market phase (1970–1997) can be separated into two parts. First, once the general feasibility of the heat pump technology had been tested and approved through several demonstration projects, firms anticipated a gold rush and hastily introduced their products to the market. As one of our experts explained, *"Firms quickly entered the market with dubious offers, to jump on the bandwagon. The result was overpriced and poor quality products. This caused a bad reputation"* [IP6]. Second, after the market for the technology had started to take off in the mid-1980s, insufficient technical maturity forced a market decline and required an overhaul in the development before the market was able to stabilize and resurge in the mid-1990s. The lack of awareness, reliability, and legitimacy was a key issue for the diffusion of heat pump technology, especially in the early market phase. As another expert explained for the late 1970s: *"[…] Nobody really understood this business and therefore many installations were causing problems. Installations that completely broke down. Installations that never really functioned well"* [IP5].

These issues of reliability were addressed by the RD&D policy type, e.g., by R&D grants, testing facilities, field testing trainings, and guidelines/handbook, as well as with information campaigns that helped to increase awareness and legitimacy, e.g., by the FWS association, a support association for heat pumps in Switzerland ("Fachvereinigung Wärmepumpen Schweiz"), its conferences, and its trade fair. As one of the experts stated: *"We unified and founded the FWS. We started targeted marketing to do educational work. The acceptance for this topic increased […] Open days offered an opportunity to give the end-customer some deeper insights. And of course quality assurance played a vital role"* [IP6].

In order to have a successful second attempt to enter the next market phase, the heat pump technology had to overcome the initial teething problems, such as malfunctioning or inadequate dimensioning, and to reach a satisfying level of technical maturity and reliability. Several experts (as well as archival documents) stressed the significant influence FWS had on the reliability and quality of installed heat pumps, which resulted in increasing trust in and acceptance for the technology, and thereby a strong push towards market diffusion.

In the late market phase (from 1997 onwards), the key issue shifted towards marketability[3], which involved surmounting system inertia that favored incumbent solutions and their partial cost benefits. Expert IP1 mentioned: *"Nowadays, the discussion around the heat pump is 90% about the price. There is no discussion whether they are properly functioning. The market of heat pumps is only price-oriented."*

---

[3] Marketability refers to the ease with which the innovation appeals to and is bought by consumers.

Table 2: Chronological overview of major events (with policy types and year), structured by market phase and issue, along with the explanation [including interview quotes, see Table B1 in Appendix B] related to the heat pump technology in Switzerland (based on Kiss et al. (2013) and experts)

Phase	Issue	Policy Type	Year/s	Events	Explanation [Quote]
Early Market Phase	Reliability, Awareness	RD&D	1974	1st guidelines of the Swiss Association for Refrigeration	▪ High RD&D efforts (public and private) to launch solid products and cope with quality issues. ▪ Still, early providers/ manufacturers in gold-rush atmosphere, favored by increasing environmental awareness (oil crises). [Q2, Q4-6, Q19] ▪ Early market is picking up with ~15% market share in the mid-/ end-1980s. [Q6] ▪ Technical issues (malfunctioning, lack of skilled service providers) cause a market decline in the early 1990s and required an overhaul in the development. [Q1-2, Q4-7] ▪ Additional efforts in RD&D, information campaigns (both at the supply side and marketing measures at the demand side) and incentives allow resolving technical shortcomings and reducing mistrust. [Q9-14, Q16-17] ▪ Finally, the market stabilized and resurge in the mid-1990s. [Q10, Q15]
		RD&D	1980	1st conference on heat pump technology in Switzerland	
		RD&D	1980	1st heat pump testing facility (EPFL)	
		RD&D	1981/82	Start of heat pump system field testing (NEFF and SFOE)	
		RD&D	1983	Simplification of approval procedure (SFOE and authorities), guidelines	
	Legitimacy, Reliability, Awareness	Information	1992	Heat pump promotion program (“Energie 2000”)	
		RD&D	1993	Additional heat pump testing facility (Winterthur-Töss)	
		Information	1993	Foundation of the Swiss heat pump promotion association (FWS)	
		Incentive	1993–95	Subsidy for heat pumps in existing buildings	
		RD&D	1993–96	Handbooks for better heat pump installations	
		RD&D	1995	FAWA - heat pump systems, field testing (SFOE)	
		Information	1996	1st heat pump exhibition (trade fair for the general public)	
		Incentive	1996	Peak of direct financial subsidies (approx. CHF 9 mio p.a.)	
Late Market Phase	Marketability	Incentive	1997	Subsidies supported by some electricity utilities	▪ The marketing measures by FWS materialize as the market continues to grow. [Q11, Q13-18] ▪ In addition, monetary incentives (subsidies), the DACH label, and the standard foster the marketability and help overcome system inertia towards incumbent technologies. [Q8-9, Q16-18, Q20-22] ▪ By the mid- and late 2000s, the heat pump became the dominant heating technology. [Q7, Q9]
		Standard	1997	Public standard limiting the use of non-renewable energies for domestic and water heating of new buildings to max. 80%	
		Label	1998	Creation of heat pump quality label DACH (GER, AUT, SUI)	
		RD&D	1998	Heat pump retrofit program and competition (R&D and subsidies)	

EPFL: Swiss Federal Institute of Technology in Lausanne (“École Polytechnique Fédérale de Lausanne”)
NEFF: Private national energy research fund (“Nationaler Energieforschungs Fonds”)
SFOE: Swiss Federal Office for Energy
FWS: Support association for heat pumps in Switzerland (“Fachvereinigung Wärmepumpen Schweiz”)
FAWA: Field testing of heat pumps (“Feldanalyse Wärmepumpen”)
DACH: Country group of Germany (D, GER), Austria (A, AUT), and Switzerland (CH, SUI)

This issue was specifically addressed by the following policy types: i.) monetary incentives, e.g., subsidies and discounts that lower economic hurdles in the purchase decision-making process; ii.) labels, e.g., the Minergie and the DACH labels provide a guarantee of both quality and increased real estate value; and iii.) standards, e.g., an environmental standard requiring a 20% rate of non-fossil based heating effectively made the heat pump and wood pallet heating almost obligatory. One of the experts, for example, stated: *“[…] it’s great what the FWS has done. To provide certificates and quality labels and then came the related subsidies. Consequently, the interaction increased the quality level extremely […]”* [IP1].

Altogether, in line with the existing literature (Kiss et al., 2012), we find the diffusion of heat pump technology has been influenced by a step by step application of numerous policies representing the entire range of policy support. While the first hasty attempts to capture market share failed because of deficient technical maturity, the effective tackling and solving of the key issues – via the related policy support – seemed to be a necessity to achieving market diffusion.

4.2 Comfort Ventilation

Defined by its application area, comfort ventilation is a ventilation system for residential buildings or apartments that supplies fresh air while reducing heat loss by exchanging heat between intake and exhaust airflow. In doing so, the comfort ventilation technology directly complements insulation measures and truly qualifies as an energy efficiency innovation[4].

Figure 1 displays how, in the early market phase from 1990 to 2006, support measures (RD&D support and information campaigns) enabled the push for market readiness for comfort ventilation technology, while it was mostly pulled by labels during the late market phase. Table 3 lists a chronological overview of the major events, the applied policy types, and an outline of the storyline with evidence from the interviews.

---

[4] Comfort ventilation allows for savings of around 30% (Nussbaumer, 2015) on heating energy and up to 70% on ventilation losses (Verein Komfortlüftung.at, 2014) compared to a regular manual exchange of room air.

Table 3: Chronological overview of major events (with policy types and year), structured by market phase and issue, along with the explanation [including interview quotes, see Table C3 in Appendix C] related to comfort ventilation technology in Switzerland (based on Nussbaumer (2015) and experts)

Phase	Issue	Policy Type	Year/s	Events	Explanation [Quote]
Early Market Phase	Reliability, Legitimacy	RD&D	1990	First pilot and demonstration project (energy autarkic housing complex, Waedenswil)	▪ From singular projects (P&D) in the mid-1990s, reliability was mostly proven (with minor quality problems) and a pioneer market evolved in the early 2000s. [Q1-3, Q5-12, Q15] ▪ Support campaigns by SFOE (information/training) and the cantonal compliance to the Minergie label set comfort ventilation as the quasi-standard and initiated mass-market kick-off. [Q13-14, Q19-20, Q24, Q26-34]
		Incentive	1990	Performance guarantee offered by SFOE	
		RD&D	1994-2002	Further demonstration projects by SFOE in Riehen (1994), Winterthur (1996), Nussbaumen (1999), Daellikon (2000), and Staefa, Dielsdorf and Renggli (2002)	
		Label	1997	Voluntary building label “Minergie”	
Late Market Phase	Legitimacy, Marketability	Standard	2008	Release of instruction sheet to SIA 2023 (“Lüftung in Wohnbauten”)	▪ Years 2005 to 2011, sales increased rapidly with annual growth rates of up to 53% (2005). ▪ The standard SIA 2023 and labels (and especially their support by MuKEn) generated additional market demand and rendered comfort ventilation as a quasi-standard. [Q16-18, Q21-23, Q35]
		Label	2011	Launch of the voluntary product label “Modul Komfortlüftung” by Minergie association	
		Label	2012	Launch of voluntary label “Deklaration” by Energie-Cluster	

Considered a necessary complement to the massive improvements in insulation of building envelopes, comfort ventilation technology’s early market phase was determined by singular pilot and demonstration projects to showcase the successful downscaling of its predecessor, standard ventilation systems, in large-scale applications. However, until the early 2000s, comfort ventilation was affected by issues of reliability (e.g., lack of product maturity or insufficient expertise and installer capabilities) and legitimacy (e.g., system inertia towards incumbent solutions). One expert stated: “*For me, the biggest issue is and was the biggest opponent of the comfort ventilation […] the architects. Because they thought […] that it does not fit or because it is a new field, they do not know [it] and do not want [it]. And which additionally would only restrict them in a certain manner*” [IV4].

To address these issues, RD&D (namely pilot and demonstration projects) and information campaigns (mostly targeted towards architects and planners), were applied. The SFOE (Swiss Federal Office for Energy) played a vital role as initiator of P&D projects and distributor of information during the early market phase. *“Well, the SFOE has supported pilot and demonstration projects for quite a while. And some of those explicitly highlighted the comfort ventilation. As an outcome, the topic became popular among architects”,* said expert IV2.

The path to the late market phase was paved, above all, by the voluntary Minergie label, which exerted the highest influence on diffusion by creating significant market demand. This demand was triggered largely in building owners by addressing the perceived values (i.e., increase in comfort and property value) of comfort ventilation technology. Implementation of comfort ventilation was almost a requirement to qualify for the Minergie label. Public support for Minergie created the necessary trust in the technology and helped overcome reputational issues caused by the remaining quality concerns (hygiene and noise exposure). Our interviews provided strong evidence of the influence of the Minergie label on diffusion, with numerous quotes emphasizing its importance. One of the experts summarizes it as follows: *"I would say, finally the public sector, via the Minergie tool, [stimulated the market diffusion] […] and certainly with this tool they achieved this large success"* [IV2].

In the very late market, the public energy standard MuKEn supported the market formation activities of the voluntary labels (Minergie and its "Modul Komfortlüftung", as well as Energie-Cluster's "Deklaration") by declaring comfort ventilation technology a quasi-standard for new-builds, thus further spurring its diffusion. *"Precisely, to construct according to Minergie requirements has, especially among building owners, a high image, from the beginning until today, I would say. And we accepted that it would normally include comfort ventilation to be in line with Minergie. And therefore, we did not build according to Minergie to install a comfort ventilation, but we installed a comfort ventilation because it is part of Minergie"*, stressed expert IV2.

4.3 Low-e Glazing

Low-e glazing technology is a type of insulating glass that uses low emissivity[5] (thus "low-e") float glass coated with a layer of a specific metal to reduce the heat transfer coefficient. Low-e glazing qualifies as an energy-efficient innovation because it improves the insulation of the building envelope by up to 50% (against a standard insulating glass).

As demonstrated in Figure 1, the market share of the low-e glazing technology (in particular the double insulated glass) rapidly grew to 60% within less than five years from its first commercial appearance in 1985 to 1989, solely benefitting from demand-pull measures (in this case, regulatory standards and selective labels).

Similar to Tables 2 and 3, Table 4 summarizes the major events structured by market phases and issues that were key barriers to diffusion of the low-e glazing technology based on expert statements and Jakob (2008). Again, it also shows the policy types that were applied and sketches out the storyline substantiated with selected interview quotes.

---

[5] Low emissivity describes the condition of surfaces that have reduced emissions of radiant thermal energy, thus can better capture the heat.

Table 4: Chronological overview of major events (with policy types and year), structured by market phase and issue, along with the explanation [including interview quotes, see Table D1 in Appendix D] related to the double/triple low-e glazing technology in Switzerland (based on Jakob (2008) and experts)

	Phase	Issue	Policy Type	Year/s	Events	Explanation [Quote]
Double insulated glazing (2-IG)	Early Market Phase	Inertia / Economics	Standard	1981	Regulation for windows in canton Zurich (as one of the first)	▪ In the late 1970s, first glass manufacturers introduce product offerings for low-e coated glass, with a price premium compared to incumbent solutions. [Q1, Q3-4] ▪ Regulatory standards, at the cantonal then national level, pull 2-IG into the mass market. [Q10, Q12-13, Q16] ▪ From 1985, the 2-IG market exhibits fast growth rates with market shares of 60% (1989) and a peak of 80% (2001).
			Standard	1986	Introduction of first public standard on the national level, “Musterverordnung” (MVO)	
	Late Market Phase		Standard	1992	Renewal of MVO	
			Standard	2000	Public standard on national level, “Mustervorschriften der Kantone im Energiebereich” (MuKEn)	
Triple insulated glazing (3-IG)	Early Market Phase	Inertia / Economics	Label	2001	Launch of the voluntary product label (“Modul Fenster”) by Minergie association	▪ The smooth transition towards low-e’s next generation, 3-IG, starts in the early 2000s, with increasing shares of 3-IG, while 2-IG’s shares declined. [Q2] ▪ Both the label and the monetary incentive trigger the initial demand for the 3-IG technology. [Q5-10] ▪ The true market pull again resulted from regulatory standards defined within the MuKEn. [Q10-16]
			Incentive	2006	Financial incentive program to foster insulation of building envelopes (“Gebäudeprogramm”)	
	Late Market Phase		Standard	2008	Renewal of MuKEn	
			Incentive	2010	Relaunch of financial incentive program (“Gebäudeprogramm”)	
			Standard	2014	Renewal of MuKEn	

Some window installers showed a certain reluctance (inertia) due to the higher costs of the novel technology, but there was no serious opposition that would have hampered the market kick-off. *“There were no limiting factors, because, well I would say maybe some glass manufacturers were trying to explain that [...] the glazing could cause complications when they are increasing in thickness/size. But all in all, there was no big movement against triple insulating glass”*, confirmed IG4.

The importance of regulatory standards (MVO, MuKEn) and their gradual adaptation was the key element to address not only this issue, but to steer the entire diffusion of low-e glazing effectively. Thereby, a higher stringency was reached through a systematic reduction of the limits for the heat transfer coefficient (U-value) in line with the developing technological feasibility. One expert summed it up as follows: *“The standard, explicitly the prescription of heat insulation, always monitored what is possible. And then, one has strengthened it”* [IG5]. And another expert complemented this, saying: *“The values that need to be achieved are crucial. [...] In the end, that is what matters, one needs to* *achieve certain values, now regarding energy efficiency […]"* [IG3]. Glass manufacturers seemed to have anticipated the gradual tightening of the regulatory requirements, and thus they were prepared to launch new technologies as the standards were tightened.

A major prerequisite for this approach lies in the characterization of the technology in scope and its quantification by means of a distinct measure or key performance indicator. For building insulation in general, and windows in particular, the U-value is a well-established indicator whose value can be easily determined and used to navigate technological development and market requirements alike.

In the case of the triple insulated glazing technology (3-IG) in particular, monetary incentives ("Gebäudeprogramm") and voluntary labels (Minergie and its "Modul Fenster") played an important role by successfully spurring market demand and also initiating the transition from double insulated glazing (2-IG) to 3-IG. For example, one expert stated: *"Labels and support, these are the important things. You need a label/emblem …zack… that is Minergie, plus incentives, these are, 30 Swiss Francs… that's it. If one of had existed, the market would be totally different"* [IG6].

5 Discussion

In this section, we discuss the overarching findings from the observations we made in the three case studies with respect to technology diffusion patterns and the corresponding policy support. First, we argue for policy support that is tailored to a technology's maturity level and its diffusion stage (5.1). Next, we debate the role of technology characteristics (5.2) and, finally, we derive implications for policy makers and scholars alike (5.3).

5.1 Need for Tailored Policy Support

While the case of the heat pump technology revealed the need for substantial RD&D support and a step by step application of policy along the idealized policy approach (Grübler et al., 2012; Halsnæs et al., 2007), the cases of the comfort ventilation and the low-e glazing technology portray a different situation with less emphasis on the technology-push side. Instead, their diffusion patterns are strongly influenced by different kinds of demand-pull support: Comfort ventilation was mostly pulled into the market using the vehicle of an established label, whereas the major market pull for low-e glazing was created by technology-specific performance standards. In both cases, monetary incentives complemented the demand-pull support but did not play a primary role.

The early market phase of the heat pump provides particularly important insights as its diffusion curve displays a remarkable development. After the oil crises, the technology captured a non-negligible market share – despite its existing reliability issues. This can be explained by the high level of forgiveness that innovators and early adopters share (Rogers, 2003; Shama, 1983). While these issues seemed to not to concern those adopter groups, they were severe enough to prevent the large majority from adopting the technology, and they forced the market share to decline again due to the caused reputational damage. By that time, the heat pump had not (yet) managed to "cross the chasm", a phenomenon that is described in the literature (Moore, 2006), and needed additional RD&D support to overcome these quality and reliability issues. Entrance into the mass market was only possible after these issues were solved.

Generalizing these findings, two dimensions can be identified as critical for tailoring technology support policies: First, the technological maturity of an innovation, in the sense of its quality and reliability levels. Second, the diffusion phase should be broken down into market entry, early market, and late market phases.

Lower maturity levels (i.e., low reliability or quality) can explain the higher need for RD&D support in the case of the heat pump and, to a lesser extent, also for the comfort ventilation technology. Demand-pull support can only be effective after a technology has reached a certain maturity threshold. The case of the heat pump shows that, without a sufficient level of technological maturity, demand-pull support can run into acceptance issues and a potential rebound in market share.

During the early market phase, demand-pull policies differ according to technological maturity. While for medium levels of maturity more flexible support, such as financial incentives, seems appropriate, for high levels of maturity standards can effectively pull the technology directly from the beginning. Labels play an intermediate role between these demand-pull policies. Although building labels need to guarantee a certain quality to be successful – and therefore cannot afford to promote and pull unreliable technologies – the flexibility is higher and the potential damage is lower when compared to regulatory performance standards for all buildings.

Figure 2 illustrates our suggested framework by combining the stylized diffusion (in % adoption or market share) with the level of technological maturity (indicated with low/medium/high), as well as the interplay between technology-push and demand-pull policies. Our empirical analysis covers the three archetypes that are sketched out in the framework and the role of effective policy support for each.

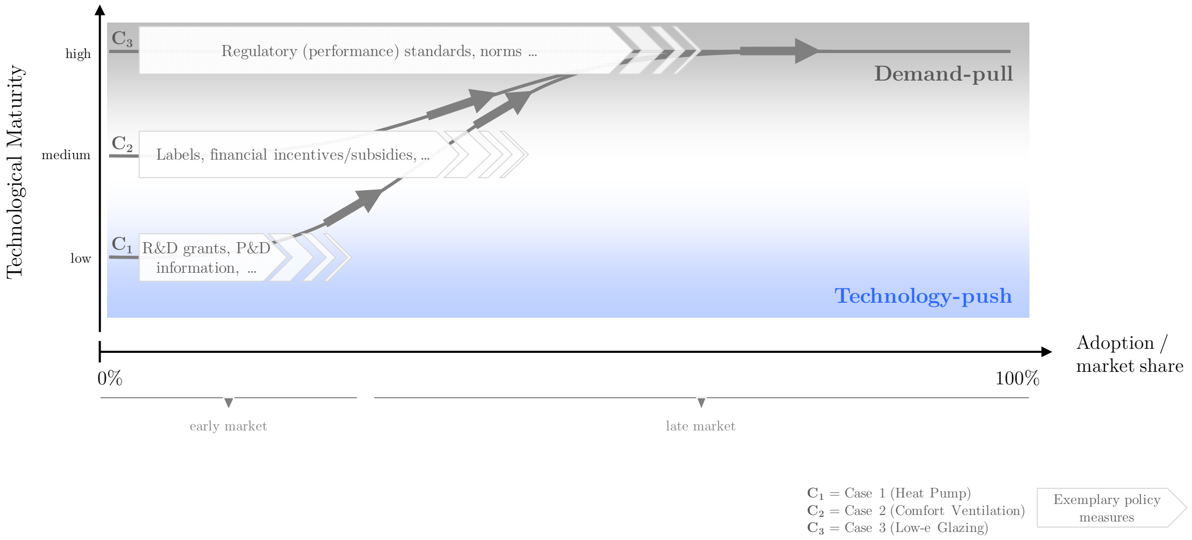


Figure 2: Framework for tailored policy support in accelerating the diffusion of low-carbon innovations

Based on our findings, we expect policy support to be effective when following the stylized pathways of the archetypes in the outlined framework. The question of effectiveness[6] is important in the policy debate, which is why we discuss it briefly below. However, the suggested framework does not claim to fully capture the complex mechanisms behind a policy's effectiveness, but rather to provide guidance in the debate about tailored policy support.

For illustration purposes, let us assume the case of an immature innovation that is trying to be pulled into the markets, for example by labels or regulatory standards. If it has an overhasty market-pull before quality issues have been eliminated and reliability has been established (i.e., knowledge is

---

[6] Based on IPCC's "environmental effectiveness", we define effectiveness as a policy's ability to support the achievement of a desired diffusion level (IPCC, 2014b).

underdeveloped at various stages in the system), the innovation runs a high risk of reputational losses on the consumer side. In being hasty, the policy maker jeopardizes acceptance of the innovation in both the short- and long-term. The early hype in the heat pump technology (1983–93) gave a glimpse of how substantially an insufficient maturity could affect a technology's diffusion, even though the market-pull was not policy induced. In addition, a premature market-pull can be ineffective, e.g., by leading to technological lock-in, as the gradual phase-out of incandescent bulbs from 2009 to 2016 by the European Union demonstrated. Here, a high diffusion of the compact fluorescent lamp was supported, despite the superiority (both economic and environmental) of the LED technology.

In the same vein, a sustained phase of technology-push support far into the late market phase would also not be very useful. Thus, in addition to the level of technological maturity, the diffusion status is the other essential dimension, which needs to be considered for tailoring policy support. If the innovation is already partially diffused, for example, has successfully crossed the chasm and reached the late market phase, its diffusion would benefit substantially more from demand-driven instruments. On the one hand, unnecessarily prolonged financial support for all promising low-carbon technologies would be very cost-intensive, while, on the other hand, a shift towards performance standards, for example, could favor the diffusion much more.

With the illustrations above, we aim to underline the necessity of adequately assessing the nature of an innovation (by thoroughly evaluating its technological maturity level) and its diffusion status in order to be able to tailor policy instruments accordingly. Even though the two dimensions, maturity and diffusion stage, are interrelated to a certain extent, it seems crucial – especially in an early phase – to identify an innovation's status prior to the design of policy intervention. Additionally, due to their dynamic nature, both dimensions require continuous re-evaluation to tailor both the amount and nature of potential policy support.

5.2 The Role of Technology Characteristics

By providing first evidence that policy support to accelerate the diffusion of low-carbon technologies should be tailored to the specificities of an innovation, our case study observations open the debate about which other technology characteristics could be of importance. While we distilled technological maturity, in terms of quality and reliability, as a key characteristic, the literature provides additional technology characteristics that could offer guidance on the tailoring of policy support.

On the one side, scholars consider characteristics related to the production of a technology, such as complexity (of the product architecture), scale (of the production process), or market structure (Davies, 1997; Huenteler et al., 2016). For instance, innovations with high architectural complexity are likely to require larger amounts of RD&D support to prevent malfunctioning and to ensure a seamless integration of the modular components, as compared to less complex innovations.

On the other side, Rogers (2003) distinguishes five characteristics related to the end-use (or consumption) of a technology as perceived by the individual adopters: Relative advantage, compatibility (to user habits), complexity (of use), trialability, and observability. For instance, if the complexity for end-users is high, such is often the case with digital innovations and their mostly novel business models, policy support related to demonstration and information targeted towards the end-user would allow for reducing complexity and helping to put the innovation across. At the other end of the complexity-simplicity continuum, e.g., for a commodity-like innovation, RD&D support or information campaigns could very likely be reduced because large amounts of new knowledge are not required to use this kind of innovation. Rogers' adopter characteristics are widely acknowledged and have been applied in literature for different low-carbon technologies, such as solar power systems (Faiers and Neame, 2006) and thermostats (Peffer et al., 2011).

Besides focusing on these two ends of an innovation's value chain, production, and consumption, the overall adoption environment – the surrounding system of agents and institutions – is vital for an innovation. For example, recent literature has identified the complexity and the maturity of technological systems (Bento and Wilson, 2016; Grübler et al., 2016) as important characteristics. Given an innovation with a technological system that is nascent and rather complex, policy efforts are presumably more effective when they focus on the technology-push side (e.g., RD&D support) in comparison to innovations with mature and established systems of limited complexity. This is yet another potential explanation for the large differences in diffusion speed (cf. duration of early market phase) and the very diverse approaches to policy support.

While we find indications in the literature of potential alternative explanatory approaches regarding important technology characteristics, according to which policy support could be adjusted, the findings of this study do not support an overarching solution to this final question. Today, there is still limited understanding of what would be beneficial to facilitate policy makers' decisions ex ante. While this study provides a first contribution to bridge this gap, there are numerous possible further investigations that could refine this work's contribution. We expect that a broader empirical base (e.g., various policy contexts, other technologies or sectors) could build upon our research and provide additional benefits to the scientific community and policy makers alike.

5.3 Implications for Policy Makers

As both the extant literature and our case study of three energy-efficient building technologies have shown, policy is a substantial lever for accelerating the diffusion of low-carbon innovation. To be effective, policy support must be adjusted towards the specific nature of an innovation; thus, a thorough understanding of the technology's maturity level and diffusion status is needed before effective policy support can be designed. Additionally, policy support needs to be adjusted with the technology's dynamics, both in maturity and diffusion status, which would require a periodic re-evaluation of both dimensions. More specifically, if an innovation's maturity level is low, further RD&D is required before starting with a demand-pull. A premature demand-pull can lead to a rebound, because of declining acceptance (e.g., if malfunctioning heat pumps are installed). Such a rebound would become more likely if inflexible pull policies are applied, for instance, with a standard that prescribes an unreliable technology. However, once a sufficient maturity level is achieved, it would render a continuing support by flexible measures, such as subsidies, inefficient, while by contrast, standards would lead to faster and less costly diffusion.

6 Conclusions

This study aims to understand how policy support needs to be tailored to technology specifics to effectively accelerate the diffusion of low-carbon innovations.

To do so, we analyzed the long-term developments and the diffusion patterns of three selected technologies: heat pump, low-e glazing, and comfort ventilation technology. We chose Switzerland and its policy context, as it proves to be the lead market for the diffusion of these technologies; thus by keeping the political and contextual environments constant we have tried to capture the integral mechanisms of policy support. To examine the developments retrospectively, we collected archival data and conducted expert interviews, both of which we then analyzed.

We find that an innovation's technological maturity level and its diffusion status are important dimensions for tailoring policy support. We show that innovations of insufficient maturity, that is, of limited reliability and quality, would benefit from a technology-specific support (e.g., via R&D grants, conferences/fairs, P&D projects), while demand-driven support (e.g., via labels, performance standards) can only be effective once a certain maturity threshold is achieved.

This work contributes to the existing literature by combining aspects of diffusion theory with environmental policy and technological evolution. Additionally, it aims to provide guidance to policy makers to help understand the need for and the mechanisms behind tailoring policy support towards the pursuit of a more energy-efficient and decarbonized economy.

Acknowledgements

This research has been financially supported by Innosuisse within the SCCER FEEB&D (Grant No. 1155000149). We thank Jörn Hoppmann, Christof Knoeri, and Jochen Markard for their valuable comments on earlier versions of this manuscript.

Appendix

(A) Expert interviews, (B) heat pump, (C) comfort ventilation, (D) low-e glazing.

References

Bass, F.M., 1969. A New Product Growth for Model Consumer Durables. Management Science 15, 215–227.

Bento, N., Wilson, C., 2016. Environmental Innovation and Societal Transitions Measuring the duration of formative phases for energy technologies. Environmental Innovation and Societal Transitions 21, 95–112.

Boza-Kiss, B., Moles-Grueso, S., Urge-Vorsatz, D., 2013. Evaluating policy instruments to foster energy efficiency for the sustainable transformation of buildings. Current Opinion in Environmental Sustainability 5, 163–176.

Breschi, S., Malerba, 1998. Sectoral Innovation Systems: Technological Regimes, Schumpeterian Dynamics, and Spatial Boundaries, in: Edquist, C. (Ed.), Systems of Innovation: Technologies, Institutions and Organizations. Abingdon, Oxon, p. 333.

Bruckner, T., Bashmakov, I.A., Mulugetta, Y., Chum, H., de la Vega Navarro, A., Edmonds, J., Faaij, A., Fungtammasan, B., Garg, A., Hertwich, E., Honnery, D., Infield, D., Kainuma, M., Khennas, S., Kim, S., Nimir, H.B., Riahi, K., Strachan, N., Wiser, R., Zhang, X., 2014. Energy Systems, in: Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 527–532.

Carlsson, B., Stankiewicz, R., 1991. On the nature, function and composition of technological systems. Journal of Evolutionary Economics 1, 93–118.

Cherp, A., Vinichenko, V., Jewell, J., Brutschin, E., Sovacool, B., 2018. Integrating techno-economic, socio-technical and political perspectives on national energy transitions: A meta-theoretical framework. Energy Research and Social Science 37, 175–190.

Cooke, P., Uranga, M.G., Etxebarria, G., 1997. Regional innovation systems: Institutional and organisational dimensions. Research Policy 26, 475–491.

Davies, A., 1997. The life cycle of a complex product system. International Journal of Innovation Management 1, 229–256.

del Río González, P., 2009. The empirical analysis of the determinants for environmental technological change: A research agenda. Ecological Economics 68, 861–878.

Di Stefano, G., Gambardella, A., Verona, G., 2012. Technology push and demand pull perspectives in innovation studies: Current findings and future research directions. Research Policy 41, 1283–1295.

Dosi, G., 1982. Technological paradigms and technological trajectories. Research Policy 11, 147–162.

Efficient Window Collaborative, 2016. Window Technologies: Low-E Coatings [WWW Document]. URL http://www.efficientwindows.org/lowe.php (accessed 29 July, 2016).

Faiers, A., Neame, C., 2006. Consumer attitudes towards domestic solar power systems. Energy Policy 34, 1797–1806.

Fichter, K., Clausen, J., 2013. Erfolg und Scheitern „grüner“ Innovationen. Warum einige Nachhaltigkeitsinnovationen am Markt erfolgreich sind und andere nicht. Marburg: Metropolis.

GEA, 2012. Global Energy Assessment - Toward a Sustainable Future. Cambridge University Press, Cambridge, UK and New York, NY, USA.

Girod, B., Stucki, T., Woerter, M., 2017. How do policies for efficient energy use in the household sector induce energy-efficiency innovation? An evaluation of European countries. Energy Policy 103, 223–237.

Grubb, M., 2004. Title Technology Innovation and Climate Change Policy : An Overview of Issues and Options. Keio Economic Studies 41, 103–132.

Grübler, A., Aguayo, F., Gallagher, K., Hekkert, M., Jiang, K., Mytelka, L., Neij, L., Nemet, G., Wilson, C., 2012. Policies for the Energy Technology Innovation System (ETIS), in: T.B. Johansson, N. Nakicenovic, A. Patwardhan, L.G.-E. (Ed.), Global Energy Assessment - Toward a Sustainable Future. Cambridge University Press, Cambridge, pp. 1665–1744.

Grübler, A., Nakicenovic, N., Victor, D.G., 1999. Dynamics of energy technologies and global change. Energy Policy 27, 247–280.

Grübler, A., Wilson, C., Nemet, G., 2016. Apples, oranges, and consistent comparisons of the temporal dynamics of energy transitions. Energy Research and Social Science 22, 18–25.

Hall, B.H., Khan, B., 2003. Adoption of New Technology. New Economy Handbook 1–38.

Halsnæs, K., Shukla, P., Ahuja, D., Akumu, G., Beale, R., Edmonds, J., Gollier, C., Grübler, A., Duong, M.H., Markandya, A., McFarland, M., Nikitina, E., Sugiyama, T., Villavicencio, A., Zou, J., 2007. Framing issues, in: Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK and New York, NY, USA.

Hoppmann, J., Huenteler, J., Girod, B., 2014. Compulsive policy-making—The evolution of the German feed-in tariff system for solar photovoltaic power. Research Policy 43, 1422–1441.

Huenteler, J., Schmidt, T.S., Ossenbrink, J., Hoffmann, V.H., 2016. Technology life-cycles in the energy sector - Technological characteristics and the role of deployment for innovation. Technological Forecasting and Social Change 104, 102–121.

IEA, 2018. Policies and Measures Databases [WWW Document]. International Energy Agency (IEA). URL https://www.iea.org/policiesandmeasures/ (accessed 12 April, 2018).

IEA, 2015. Energy Technology Perspectives 2015 - Mobilising Innovation to Accelerate Climate Action. Paris.

IPCC, 2014a. Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

IPCC, 2014b. Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. [Core Writing Team R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland.

Iyer, G., Hultman, N., Eom, J., McJeon, H., Patel, P., Clarke, L., 2015. Diffusion of low-carbon technologies and the feasibility of long-term climate targets. Technological Forecasting and Social Change 90, 103–118.

Jaffe, A.B., Newell, R.G., Stavins, R.N., 2002. Environmental policy and technological change. Environmental and Resource Economics 22, 41–69.

Jakob, M., 2008. Grundlagen zur Wirkungsabschätzung der Energiepolitik der Kantone im Gebäudebereich.

Jakob, M., Madlener, R., 2004. Riding down the experience curve for energy-efficient building envelopes: the Swiss case for 1970-2020. International Journal of Energy Technology and Policy 2, 153–178.

Kemp, R., Pontoglio, S., 2011. The innovation effects of environmental policy instruments—A typical case of the blind men and the elephant? Ecological Economics 72, 28–36.

Kimura, O., 2013. The role of standards: The Japanese Top Runner Program for end-use efficiency. Historical case studies of enegy technology innovation, in: Energy Technology Innovation: Learning from Historical Successes and Failures. Cambridge University Press, pp. 231–243.

Kiss, B., Keij, L., Jakob, M., 2012. Heat Pumps: A Comparative Assessment of Innovation and Diffusion Policies in Sweden and Switzerland, in: The Global Energy Assessment. Cambridge University Press, pp. 118–132.

Kiss, B., Neij, L., Jakob, M., 2013. Heat pumps: A comparative assessment of innovation and diffusion policies in Sweden and Switzerland, in: Energy Technology Innovation: Learning from Historical Successes and Failures. Cambridge University Press, pp. 118–132.

Langley, A.N.N., 1999. Strategies for Theorizing From Process Data. Academy of Management Review 24, 691–710.

Markard, J., Raven, R., Truffer, B., 2012. Sustainability transitions: An emerging field of research and its prospects. Research Policy 41, 955–967.

Markard, J., Truffer, B., 2008. Technological innovation systems and the multi-level perspective: Towards an integrated framework. Research Policy 37, 596–615.

Mercure, J., Pollitt, H., Chewpreecha, U., Salas, P., Foley, A.M., 2014. The dynamics of technology diffusion and the impacts of climate policy instruments in the decarbonisation of the global electricity sector. Energy Policy 73, 686–700.

Moore, G.A., 2006. Crossing the Chasm. HarperCollins Publsihers, New York.

Mowery, D.C., Nelson, R.R., Martin, B.R., 2010. Technology policy and global warming: Why new policy models are needed (or why putting new wine in old bottles won’t work). Research Policy 39, 1011–1023.

Nagra, G., Gopal, R., 2014. A Study of Factors Affecting Diffusion of Innovation. International Journal of Business Management & Research (IJBMR) 4, 15–24.

Nelson, R.R., 2013. National Innovation Systems, in: Acs, Z. (Ed.), Regional Innovation, Knowledge And Global Change. Routledge, London.

Nelson, R.R., 2007. Building Effective “Innovation Systems” Versus Dealing with “Market Failures” as Ways of Thinking about Technology Policy, Manchester Business School Working Paper No 548.

Nemet, G.F., 2009. Demand-pull, technology-push, and government-led incentives for non-incremental technical change. Research Policy 38, 700–709.

Newell, R.G., 2010. The role of markets and policies in delivering innovation for climate change mitigation. Oxford Review of Economic Policy 26, 253–269.

Nill, J., Kemp, R., 2009. Evolutionary approaches for sustainable innovation policies: From niche to paradigm? Research Policy 38, 668–680.

Nussbaumer, B., 2015. Komfortlüftungen in der Schweiz; Markt- und Technologieentwicklung, Kompetenzen, Potentiale. Bern.

OECD, 2001. Policies to Enhance Sustainable Development. Paris.

Peffer, T., Pritoni, M., Meier, A., Aragon, C., Perry, D., 2011. How people use thermostats in homes: A review. Building and Environment 46, 2529–2541.

Popp, D., Newell, R.G., Jaffe, A.B., 2010. Energy, the Environment, and Technological Change, in: Handbook of the Economics of Innovation- Vol-II. Elsevier B.V., Burlington, pp. 873–938.

Reichardt, K., Negro, S.O., Rogge, K.S., Hekkert, M.P., 2016. Analyzing interdependencies between policy mixes and technological innovation systems: The case of offshore wind in Germany. Technological Forecasting and Social Change 106, 11–21.

Rogelj, J., Elzen, M. Den, Höhne, N., Fransen, T., Fekete, H., Winkler, H., Schaeffer, R., Sha, F., 2016. Paris Agreement climate proposals need a boost to keep warming well below 2 ° C.

Rogers, E.M., 2003. Diffusion of innovations, 5th ed, Diffusion of Innovation. Free Press, New York.

Rogge, K.S., Reichardt, K., 2016. Policy mixes for sustainability transitions: An extended concept and framework for analysis. Research Policy 45, 1620–1635.

Rosenberg, N., 1972. Factors affecting the diffusion of technoloogy. Explorations in Economic History 10, 3–33.

Sandén, B. a., Azar, C., 2005. Near-term technology policies for long-term climate targets—economy wide versus technology specific approaches. Energy Policy 33, 1557–1576.

Saunders, M., Lewis, P., Thornhill, A., 2009. Research Methods for Business Students, 5th ed. Pearson Education, Essex.

Schumpeter, J., 1942. Capitalism, socialism and democracy. Harper, New York.

Shama, A., 1983. Energy conservation in US buildings. Solving the high potential/low adoption paradox from a behavioural perspective. Energy Policy 11, 148–167.

Somanthan, E., Sterner, T., Sugiyama, T., Chimanikire, D., Dubash, N.K., Essandoh-Yeddu, J., Fifita, S., Goulder, L., Jaffe, A., Labandeira, X., Managi, S., Mitchell, C., Montero, J.P., Teng, F., Zylicz, T., 2014. National and Sub-national Policies and Institutions, in: Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1141–1206.

Stoneman, P., Diederen, P., 1994. Technology Diffusion and Public Policy. The Economic Journal 104, 918–930.

Stucki, T., Woerter, M., 2016. Intra-firm diffusion of green energy technologies and the choice of policy instruments. Journal of Cleaner Production 131, 545–560.

Suriñach, J., Autant-Bernard, C., Manca, F., Massard, N., Moreno, R., 2009. The diffusion/adoption of innovation in the Internal Market.

Tushman, M.L., Rosenkopf, L., 1992. Organizational Determinants of technological change: Technological evolution. Research in organizational behavior 14, 311–347.

Verein Komfortlüftung.at, 2014. Energieeffizienz Komfortlüftung [WWW Document]. URL http://www.komfortlüftung.at/energieeffizienz/ (accessed 29 July, 2016).

Voß, J.-P., Kemp, R., 2005. Reflexive Governance for Sustainable Development – Incorporating feedback in social problem solving, in: Sustainable Development. pp. 1–31.

Wilson, C., 2012. Up-scaling, formative phases, and learning in the historical diffusion of energy technologies. Energy Policy 50, 81–94.

Wilson, C., Grübler, A., 2011. Lessons from the history of technological change for clean energy scenarios and policies. Natural Resources Forum 35, 165–184.

Appendix

Appendix A: Expert Interviews

Table A1: Overview of expert interviews

ID	Category	Position
Heat pump		
IP1	Manufacturer	General manager
IP2	Association	General manager of a planning office
IP3	Academia	Heating engineer
IP4	Association	Marketing manager of an association
IP5	Association	General manager of a planning office
IP6	Manufacturer	General manager
IP7	Manufacturer	Technical journalist for heating manufacturers / distributers
IP8	Association	Product manager
IP9	Manufacturer	General manager
IP10	Manufacturer	Sales person for a heat pump distributer
Comfort ventilation		
IV1	Manufacturer / Association	CEO of energy consultancy / Member of label association
IV2	Association / Academia	Professor for building technologies / Founder and head of label association
IV3	Manufacturer	Head of an energy consultancy
IV4	Manufacturer	Project manager
IV5	Association	Associate at a professional association
Low-e glazing		
IG1	Manufacturer	Group manager/ Communications of a major glass manufacturer
IG2	Manufacturer	Business unit manager of a major glass manufacturer
IG3	Academia	Lecturer for building physics at an applied university
IG4	Association	Board member of a glass association
IG5	Manufacturer	Business unit manager of a major glass manufacturer
IG6	Academia	Professor for building technologies

Appendix B: Heat Pump

Table B1: Interview quotes regarding the diffusion of the heat pump in Switzerland

#	Quote	Expert
Q1	*'[...] The heating pump was never bad. There were only plenty of bad execution planers. [...] And still today we have trouble in finding qualified people. [...] Thus, we have a lack of experts and skilled people. In the planning, assembly, service, everywhere.'*	IP1
Q2	*'Yes. I think that in the first place it is the reputation. But I think, these are things which are normal for us. [...] The consultancy makes the difference between the serious and unserious companies. And some companies are focusing on sales only. This placed heating pumps into a bad light.'*	IP1
Q3	*'In a certain way it was a secret. I can remember the company I worked with [...]. They had their own heat pump and it was a relative expensive story. There were uncertainties and one haven't absorbed it. It is a relative costly to develop a heat pump.'*	IP3
Q4	*'[...] around 74/75, the heat pump arised. Everybody was talking about heat pumps und each installer had the feeling the he also does heat pumps. Nobody understood this business and therefore, there have been many trouble installations. Installations which broke and which never really functioned well und therewith heat pump market [...] shrinked towards zero.'*	IP5
Q5	*'It was the entire development process. There was a new high-tech development entering the market. Now one had to stay on track, to jump on the bandwagon with fast and doubtful offers. The consequence would be either costly or qualitative lacking products, and this resulted into bad reputation. It was quasi a healing process – the market would clear itself.'*	IP6
Q6	*'Particularly, afterwards the industry – if I may say this in this context – was not at all willing to plan, to install and to maintain the products somehow. So this mini-boom is not appropriately pictured here. Principally it declined very fast, I will just say it: Because the industry was not ready and the professional knowledge was lacking. But one may not forget, that this unsuccessful beginning affected the image of heat pumps severely.'*	IP7
Q7	*'At the beginning we lacked expertise. The installers knew, how boilers function. Until today there are companies which exchange them, but they do not have the know-how for heat pumps. Still today, when everybody knows and heat pumps are common.'*	IP5
Q8	*'But the installers in the past. One may overestimate them. They were craft workers in mid-sized companies and they wanted to do the things they could and in which they had experience. And they didn't push it forward.'*	IP3
Q9	*'Nowadays, the heat pump is a discussion 90% about the price. There is no discussion, whether they are bad. The market of heat pumps is only price oriented. There is no discussion different from this. [...]'*	IP1
Q10	*'The RAVEL had quite a positive influence, but later the quality assurance, the professional education and all those things. Surely, they helped and supported that in the mid-90s it could be established as a mainstream heating system.'*	IP8
Q11	*'Therefore, a heat pump cannot be bought like an oil boiler. A heat pump requires more information. You need to know more about the technology, because it is more complex. [...] And this requires professional education and training. Everybody who does so does fine.'*	IP5
Q12	*'Because of AWP you could achieve a more secure installation. It can be acknowledged, that they were supported, that you knew as installer, what to take care of while mounting the system. They were named AWP guidelines. These were not too complicated, but easily understandable concrete hints. When you do geothermal probes, you need to calculate them.'*	IP9
Q13	*'Since the foundation of the FWS, the heat pump spread rapidly'*	IP5
Q14	*'This has been coordinated by FWS during the phase. Nowadays, the marketing activities of FWS is not as big as before, but they invested a lot for years. From the beginning until around 2000 they invested six-digit numbers until half a million francs in information activities each year.'*	IP5
Q15	*'Yes, heat pumps are more and more established thanks to information campaigns on the one hand and to the effect that "the neighbor has also a heat pump". This effect is in favor of heat pumps.'*	IP5
Q16	*'The main target for FWS was information about heat pumps, about the market of heat pumps and later on quality assurance and even later around 1997, qualification and trainings of market players.'* *'Yes, they did understand this and went for qualification and trainings. It required another resort, which needed to improve. Today, qualification and trainings is beside quality sealing and quality assurance, the third mainstay of FWS.'*	IP5

Q17	*'We unified and founded the FWS (Association for heat pumps Switzerland). We started, targeted marketing to do educational work. The acceptance for this topic increased. Additionally, the federal government promised subsidies (1994/1995) – this made the renovation market interesting. Open days offered an opportunity to give the end customer some deeper insights. And for sure, quality increase was an issue.'*	IP6
Q18	*'On the one hand it's great what the FWS has done. To provide certificates and quality seals and to create subsidies related to these certificates. The interaction increased the quality level extremely […]'*	IP1
Q19	*'Well, the people did not want to have oil anymore. They wanted to switch to heat pumps. This effect had a large contribution why the technology, heat pumps, succeeded. In my opinion that happened on the market. But you must acknowledge that the FWS contributed to this process over years. It contributed on marketing. Surely, as well it contributed with the controls and supervision.'*	IP1
Q20	*'Later on, there were subsidies for upgrading to heat pumps. When private people get some money, they spend more. This made the technology rise with the support of the government.'*	IP3
Q21	*'When there was more providers for heat pumps, the advertisement was a bit higher. And the big growth is due to the money (governmental support).'*	IP3
Q22	*'For the first time, there were more providers, prices were decreasing, and installation got more compact. The trust increased, so the initial support and subsidies the government offered helped. Nowadays, the prescriptions of renewable energies. This was a reason.'*	IP3

Operating principle

A heat pump is a device that transfers heat from a low temperature source to a high temperature source using thermodynamic principles. There are three main low temperature sources, air-, water- and ground-sources (yet, air- and ground-sourced heat pumps are most common in residential applications). The process of transferring heat from a low to a high temperature source requires a certain amount of electric energy. The working principle behind a heat pump is a specific thermodynamic cycle, the vapor compression cycle, which consists of four elements: compressor, evaporator, condenser and expansion valve. The compressor is the only element, which is powered by and uses electric energy. Since the required amount of electric power is lower than the extracted heat, heat pumps count as an energy-efficient technology. Compared to their fossil-fueled rival technologies, namely oil or gas boiler, the heat pump technology reduces the required energy by 50 to 75% and additionally limits CO_2 emissions, depending on the carbon intensity of the electricity used. By electrifying the heating of buildings, heat pumps contribute to the mitigation of climate change as electricity allows for an easier decarbonization.

Market and diffusion

Heat pumps were already constructed and installed in the first half of the 20th century. However, an actual market for heat pumps did not develop until the late 1970s. Diffusion data for Switzerland shows that heat pump sales fluctuated between 1970 and the early 1990s and experienced a severe collapse in the late 1980s. The market stabilized and resurged in the mid-1990s and subsequently experienced a phase of rapid growth until 2008. Annual sales rose from 2.260 units in 1992 to 20.670 units in 2008, representing an increase in market share from 10% in 1992 to above 80% in 2008 for newly built one- and two-family houses. After the peak in 2008, annual sales dropped slightly and stabilized at a high level of 19.350 units in 2013, and a plateauing market share at around 80%.

Technology performance

According to the interviewees, three technical indicators were important for the diffusion of heat pumps: the seasonal performance factor[7] (SPF), capital and operating costs, and reliability. Figure S1 displays the evolution of the SPF, which increased significantly from 1990 to 1993. In the early 1990s, heat pumps had higher efficiencies and smaller sizes than heat pumps in the mid-1980s. The continuous performance improvement through development and replacement of components caused the efficiency gains from the early 1990s on.

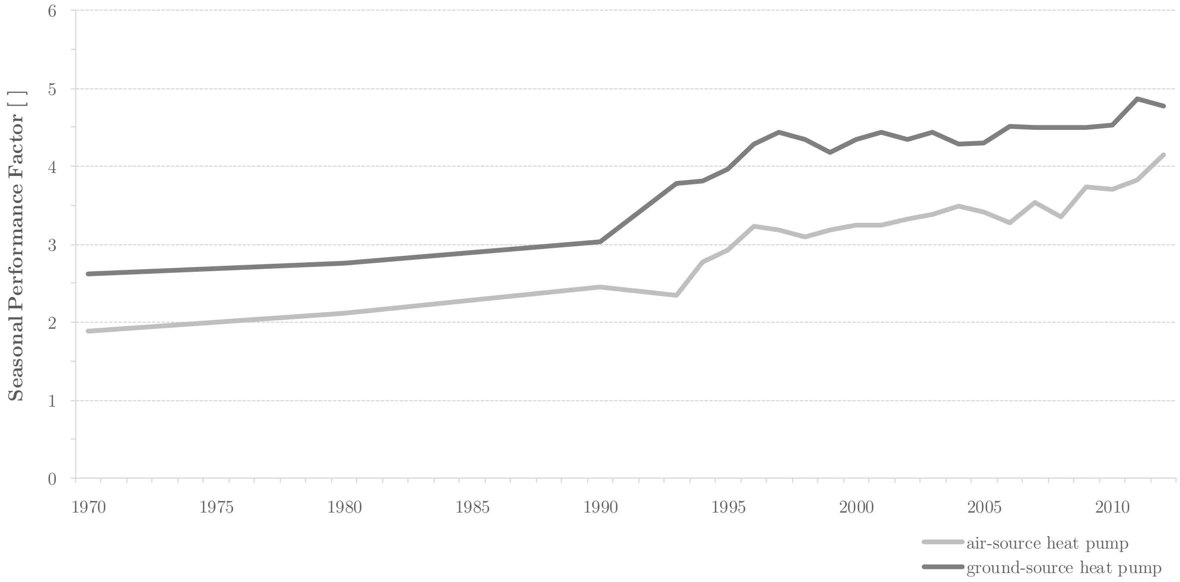


Figure B1: Seasonal Performance Factor (SPF) from 1970 to 2014 (1970-1990: according to experts, 1993-2009: according to heat pump test center ("WPZ"))

High investment costs and insufficient profitability (total costs over lifetime) were reported reasons for heat pumps to not fully capture their market potential in an early phase. However, until 1992, capital costs decreased to around 65% of the capital costs in 1980. The continuous reduction of investment cost was mainly resulting from lowering production costs via standardization of components (economies of scale) in 1990s, which facilitated the subsequent series production in the late 1990s. Operating and maintenance costs decreased over time due to better control systems, which simplified problem-solving processes.

With regard to reliability, heat pumps in the early phase, until the late 1980s, had several technical teething problems (malfunctioning, noise, and lifetime) which caused bad reputation and, therefore, mistrust by customers. As with the efficiency, from the 1990s on, reliability was reached by continuous improvement and quality measures (e.g., reduction of noise emissions by sound insulation and

---

[7] SPF is the average coefficient of performance (COP) over the heating season and is therefore a more relevant performance measure.

smoothly operating components). In addition, the performance duration of heat pumps was guaranteed to around 25 years in 2014.

Technological system

A large variety of actor groups was involved in the development, production and diffusion of heat pumps. In addition to end consumers, we can distinguish between actors associated with the production and installation of heat pumps (e.g., manufacturer, architects/planners, installation suppliers), organizations (e.g., R&D organizations), and institutions (e.g., certifying bodies, test institutions, authorities).

During the beginning of the market formation in the 1970s, actors were small and operated locally. From the beginning of the 1970s onwards, more and more firms entered the market avid to profit from the desired gold rush. The use of low cost components and undersized designs led to a lack of reliability in heat pumps, which was one reason for malfunctioning HPs and the resulting mistrust towards the technology. Quality oriented firms started to enter the market in the early 1980s and numbers of actors increased. After the market collapsed with falling oil prices in the mid-1980s, numbers of actors dropped dramatically, thus causing a diminishment of the pool of workers in manufacturing, retail and maintenance. Organizations and actor networks did not start to evolve until the mid-1990s.

Policy description

The support for residential heat pumps started in 1979 with the “Eidgenössische Abwärmekommission”, the predecessor of BFE’s ambient heat department, fostering the technological development of heat pumps for residential buildings. Until 1980s, policy instruments included information and education campaigns in the form of conferences and guidelines to train the workforce. Then, policy activities expanded to the founding of test facilities, at EPFL in 1980, and the planning of pilot and demonstration (P&D) projects in 1981/82 by the national energy research fond (NEFF) and the SFOE. In 1985, the regulatory environment was complemented by an air pollution regulation (“Luftreinhalteverordnung”) which limited the emissions by fossil heating devices. The SFOE launched the public leadership program “Energy 2000” in 1990, which, among many other aspects, aimed at fostering the diffusion of heat pumps.

The year 1993 was marked by the foundation of the Swiss heat pump promotion association (FWS) which was as an initiative by “Energy 2000”. FWS members represented all relevant actors of the nascent industry/market. FWS fostered coordination as well as education, training and networking activities and was enacted as a “strategic and coordinated program to re-ignite the market” (Kiss et al., 2012). Other policy measures of the renewed support phase included the foundation of an additional test facility in Winterthur-Töss in 1993 and the first heat pump exhibition in 1996. Furthermore, information campaigns were developed and guidelines for an appropriate dimensioning of heat pumps published.

Form an economic perspective, public financial subsidies (both direct and indirect) were launched in order to support testing and deployment activities like R&D and quality assurance. Total financial support peaked in 1996 with an annual spending of approximately CHF 12 million, subsequently decreased to CHF 6 million 1998, and did not decrease much afterwards. A subsidy for ground-sourced heat pumps was introduced in 2014 where house builders were granted a discount of CHF 3.000. Financial subsidies were considered as “strategic incentive and catalyst”. In 1997, a standard was introduced limiting the share of non-renewable energy use for domestic and water heating up to 80% in new buildings. Public standards were first introduced by canton Zurich but quickly diffused to the remaining cantons. In 2000, the SFOE replaced “Energy 2000” by “Swiss Energy”. Last major policy instrument was the implementation of a CO_2 levy in 2008, which initially penalized CO_2 production with CHF 12 per ton CO_2. Later, the stringency of this levy increased to CHF 36 per ton CO_2 in 2010 and CHF 60 per ton CO_2 in 2014.

Appendix C: Comfort Ventilation

Table C1: Interview quotes regarding the diffusion of the comfort ventilation in Switzerland

#	Quote	Expert
Q1	*'From the perspective of the installation the energetic performance properties improved significantly during the last 15 years. Firstly, it started with heat exchangers. [...] That was a step. And secondly, it was about ventilation. A long time we used AC motors in small devices and with the development of DC motor, so called direct current motors, it improved tremendously. And I think, that this was an important technological step for this industry.'*	IV2
Q2	*'It depends. Well, the tightness of the devices improves. We nearly do not have any internal leakage. Getting better. The device, in general, is more watertight. So, everything is getting better.'*	IV1
Q3	*'And the ventilation industry screwed it up by itself, because they have malfunctioning installations. [...] They can only blame themselves. By providing bad quality.'*	IV4
Q4	*'Well, the planer is largely relevant for installations. Architect and planer. And installer about how to install it. It depends a lot on who this is. And unfortunately those people are not only ventilation-system manufacturers, but also heating installers, sanitary professionals or else. And when they do not know better, things which should not happen, happen. Connections are not connected or some other bullshit.'* *'Yes, you know that. You also know, when an installer received an order from a planer. [...] Then he wanted to do as much as he may on site. Because he wanted to invoice that. [...] But unfortunately, he has never done this before That happens and that is fault-prone. It is just bad.'*	IV1
Q5	*'For sure, there are rotten apples acting on the market, which install our appliance wrong and then, they do not function as good as expected. That exists. Or they are maybe wrongly designed. [...] That is a risk. When some appliances get bought by a black sheep und it does nonsense one gets a negative touch. That's a threat.'*	IV1
Q6	*'Not from the beginning. [Customers] were skeptical at the beginning. [...] Yes, there was a large amount of skepticism. And it is still not overcome. On the contrary, currently the amount in the population which has the feeling [...] the ventilation is uncomfortable, or draughts or something else, and noise, it is unhealthy, and bacteria, and anything else, this is the amount of people with emotional resistance, which is currently increasing. Or at least it is stable and not shrinking.'*	IV3
Q7	*Barriers: 'Yes, exactly. [Price] goes together with competition. Additionally, image. I could imagine. Just like bad image from bad information. Or maybe the prohibition to open windows. Wrongly installed appliances. This is the image. This is still today, you can hear it often. It is about a certain mistrust.'*	IV1
Q8	*'And that's been a niche almost from the beginning. For people who really wanted it. [They] say "for me that's important, health, fresh air and humidity in winter" and then they bought the system, although it was much more expensive than others.'*	IV1
Q9	*'For me, a big issue is and was the biggest opponent of building ventilation [...] the architects. Because they thought [...] that it does not fit or because it is a new area, they do not know and do not want. And which additionally restricts in a certain manner.'*	IV4
Q10	*'There are people in society, who do not like this, because you harm their business. There are plenty of those, for sure old installers, who do not want to learn something new. And [...] they fight it with all they got against Minergie buildings. And therefore they say a Minergie building must be unhealthy anyhow. And the ventilation is louder, for sure. And then it only needs a few cases in which the ventilation is actually louder and they publish it with pleasure in the news. But that is not about the mean, but rather about some problem cases and they exaggerate and try to stoke emotions. And that has nothing to do with proved or not proved.'*	IV3
Q11	*'I believe that one of the biggest barriers was the ventilation industry itself, which created barriers on their own, by receiving bad critics in the news about HVAC. And this resulted in resistance at the beginning.'*	IV4
Q12	*'And the skepticism towards hygiene, saying bacteria or spores can come via air pipes into flats. [...] Really just the feeling, a gut feeling, unease and unknowing, such types of skepticism. And rarely really proven things by hard facts. [...] And really seldom there are real weaknesses. [...] Yes, and costs. For sure and finally not only institutional building developers and cooperatives are skeptical. Basically, they are not against it, but it increases building costs.'*	IV2

Q13	*'[...] how a comfort ventilation has to look like. Minergie filled this gap. And additionally the Swiss Federal Office of Energy (SFOE) offered trainings, material and other advices for planning and execution.'*	IV2
Q14	*'Yes, that's the result. It is association activities. [...] I think, that 'Energie Cluster' provides this professional training. There is this new profession, specialist for comfort ventilation. You can do it today.'*	IV1
Q15	*'At the beginning it was special in so-called pilot projects. This was an influence from the SFOE. The SFOE has, well, the SFOE has supported pilot and demonstration projects for quite a while. And in some of those it explicitly highlighted the comfort ventilation. As an outcome, the topic got popular among architects.'*	IV2
Q16	*'So, we work [according to norms like SIA 2023], but there are some, they do not care about it. Well…about those norms. They are considered or not. But it should be the standard'*	IV1
Q17	*'There is SIA, Swiss Society of Engineers and Architects. And it…or the association… defines in their perspective, what a residential ventilation is and which requirements it needs to fulfill. That is an important part. For this reason there is the SIA 2023.'*	IV3
Q18	*'No, no. Well you know the [SIA] 2023. Ok. This is, I'd say, the present bible. This is a technical bulletin."*	IV4
Q19	*'Particularly, the German speaking cantons, in so-called 'Energiefachstellen'. There, they were positively motivated. When in documents or energy consultancy the comfort ventilation was mentioned positively, it offers confidence in technology.'*	IV2
Q20	*'The entire talking about Minergie, meanwhile this is the standard. More and more buildings were constructed by this standard. And then… well it's obligatory. You need to have forced ventilation, I would say, installed in such buildings. Otherwise you will problem with the building structure.'*	IV1
Q21	*'Today it is clear. Today it is the standard. Well, Minergie is [...] not anymore a special certificate, I would say. It is the standard of today and it would not require a label anymore. As a standard that is the way you construct today and surely ventilation is a part of the big picture. And anyhow the new MuKEn, in the new regulation it is required by default.'*	IV1
Q22	*'Until now labels were quite a good instrument. The declaration. We have also influenced it a bit. So, maybe we should enter the market.'*	IV1
Q23	*'So, [declaration/labels have] surely had influence. So people, who wants to have an effective appliances, they looked for it here … or in the Topten or how they call it. All those things. I would say maybe a third of customers are searching in there, if they are interested.'*	IV1
Q24	*'Yes, [Minergie] had a large influence. Maybe during the last 10-15 years. I guess.'*	IV1
Q25	*'People don't do so, because they want to save money. People do so, because they think that their house price increases, because they think that it is more comfortable. They have fresh air, no dust, no noise from outside. Those are arguments. And finally they say, yes, it is fine, that in the end we use less energy.'*	IV3
Q26	*'Yes, it helped us. Minergie or labels at all have helped us. The regulation. The [energy] crisis [and energy strategy 2050] have helped us as well, generally spoken.'*	IV1
Q27	*'And really, around 10 years ago, when Minergie – I would claim – started to be successful we could draw a striking increase. [...] That was the time with immense growth.'*	IV2
Q28	*'Precisely, to construct according to Minergie requirements has especially among building owners a high image, from the beginning until today, I would say. And we accepted that it normally includes comfort ventilation corresponding to Minergie. And therefore, we did not create Minergie, because we install comfort ventilation, but we install comfort ventilation, because it is part of Minergie.'*	IV2
Q29	*'Because of Minergie… part of it was marketing, the appearance, that someone said, you need to have comfort ventilation, although other ventilation systems are Minergie suitable. [...] I would claim that Minergie was successful not least because of the marketing performance.'*	IV2
Q30	*'I would say, finally the public sector, via the tool Minergie. [...] And certainly with this tool they achieved this large success.'*	IV2
Q31	*'With Minergie you did not only solve energy as a problem, but rather energy, comfort and value, because you want to educate people and energy efficiency is hardly correlated with comfort and value. And it worked well. [...] And government must change this with a brand, else it won't work. And that's the reason why we created Minergie.'*	IV3
Q32	*'The advertisement of Minergie and the interest in the industry [was an elementary factor for the market diffusion]. It was essential that the cantons began early to use Minergie as an instrument of advertisement. It was also essential that in the early stages large building developers decided to build only with Minergie. That was very … it had a different impact on building owners.'*	IV3

Q33	*'With the start of Minergie this topic came up and thanks to Minergie it went off the ground and could fly. I believe that Minergie was a driving force for residential ventilation. And that caused [...] a lighthouse effect and that rubbed off on other things.'*	IV4
Q34	*'At the beginning mainly the Swiss Federal Office of Energy (SFOE) supported energy efficiency in buildings. There was information material, trainings [...] SFOE is open minded and positively towards comfort ventilation. [...]* *And the big driver was Minergie. One can say that this is the main political incentive. Because the cantons decided to go for Minergie as a standard and Minergie required comfort ventilation. That generated the fast growing market diffusion.'*	IV2
Q35	*'Actually it helps us. Thus, a regulation helps comfort ventilation industry. The new MuKEn. Well, it does not force the operator or owner to install one, but it suggests him. This is the direction in which they will be pushed.'*	IV1

Operating principle

Comfort ventilation is a stylized term[8] mainly used in Switzerland that was introduced by the Swiss Federal Office for Energy (SFOE) and primarily influenced by the Minergie label and its corresponding association. Defined by its application area, a comfort ventilation is a ventilation system for residential buildings and apartments with only minor technological differences to conventional ventilation systems for larger buildings, such as office buildings or industrial complexes. From a functional viewpoint the comfort ventilation comprises of two things: first, an air-intake and exhaust system (a ventilator and an air distribution pipe system), and second, a heat exchanger. The purpose of a comfort ventilation is to supply fresh air while reducing heat losses by exchanging heat between intake and exhaust airflow. Several high-end products additionally include a humidity or moisture exchanger in order to overcome arising problems concerning air humidity. With better insulated building envelopes (cf. progress in facade and window insulation), the need for air exchange becomes relevant for the inhabitants, as fresh air provides higher comfort, and for the building itself by preventing mold formation. Therefore, the comfort ventilation technology directly complements insulation measures that increase efficiency. In comparison to a regular manual exchange of room air – besides the time-consuming manual effort of airing – the comfort ventilation technology allows to save around 30% (Nussbaumer, 2015) on heating energy and up to 70% on ventilation losses (Verein Komfortlüftung.at, 2014), thus truly represents an energy efficiency innovation.

Market and diffusion

Extensive interest in comfort ventilation systems started to spread in Scandinavian countries in 1985 since heat loss through air exchange was mainly caused by a colder climate and reinforced the advantages of installing comfort ventilation technology. In Germany, comfort ventilation systems started to diffuse in the 1990s whereas Switzerland experienced an emerging demand in 1995. Prior to that, singular projects were realized in Switzerland deploying a comfort ventilation. The demand for comfort ventilation systems grew from the mid-1990s on with initial sales at a low annual level of

---

[8] Other terms in use are *residential ventilation systems*, *small ventilation systems* and *controlled domestic ventilation.*

89 units (1995). Considerations to install comfort ventilations in larger scale projects boosted annual sales to 1356 units in the year 2000. Consequently, a pioneer market developed between 2000 and 2005, which later evolved into a mass market. According to the experts' statements, a mass market started between 2004 and 2007. Between 2005 and 2011, sales increased rapidly with annual growth rates of up to 53% (2005). In the following years, relative sales growth stagnated, reaching today's market share of slightly above 30% for new-build apartments.

Technology performance

As briefly stated above, the development and diffusion of the comfort ventilation technology are strongly linked to the technological development in the field of building envelope insulation. The massive improvements in the insulation of the building envelope were a result of the better insulation of its components, that is, better wall, window, and door insulation. This progress affected the demand for comfort ventilation. On the one hand, improving insulation also triggered an increasing air sealing. Problems arising from this issue, such as comfort loss due to bad air quality or building damages (mold due to high air humidity), can be solved by installing a comfort ventilation. On the other hand, comfort ventilation was considered a necessary complement to further reduce building energy consumption by exploiting the insulation measures in the future.

The technological development of comfort ventilation systems is determined by its predecessor, standard ventilation systems, in large-scale applications. With similar technical characteristics (e.g., same filter qualities), the comfort ventilation is a good example for technological downscaling. During the last 20 years, several technological developments enhanced the comfort ventilation, both on the side of the air intake and exhaust system, as well as on the side of the heat exchanger. Initial systems were equipped with parallel heat exchangers and regular ventilators, thereby achieving energy recovery rates of 50 to 60%. Over time, electronically commutated (EC) motor were incorporated in ventilators and counter-flow heat exchangers replaced parallel heat exchangers. First comfort ventilation systems that implemented both technical innovations were commercially available by 1999. The former technological enhancement (EC motor) was quickly adapted by most manufacturers and was broadly established in 2005. The successful establishment of the latter enhancement (counter-flow heat exchanger) took several years longer until 2010.

As of today, comfort ventilation systems have energy recovery rates of 80 to 90%. However, the energy recovery rate as an indicator for performance is reported to not affecting the decision process. Besides improving energy recovery rates, there were also improvements in the air distribution system. Semi-flexible plastic tubes were introduced, which facilitated encasing the distribution system in concrete.

On the one side, the core technology, that is, ventilator and heat exchanger, is nowadays well understood and feature reliable and good quality. On the other side, quality issues (hygiene and noise exposure) might arise during the installation of the comfort ventilation and its corresponding distribution system. These quality issues are subject to continuous improvements, but low margins sometimes compromise the operational quality of manufacturers and installers, thus impacting the quality comfort ventilation systems.

Technological system

The technological system of the comfort ventilation technology is mainly characterized by three industries: the ventilation industry (with manufacturers and installation firms), the sanitary industry (with installation companies), and the building industry. The ventilation industry comprises 20 to 30 manufacturers from which only five are of high relevance with regards to market share. Common to the formative phase of an emerging industry, manufacturers experienced a phase of turmoil, followed by a consolidation phase. Prior to that, the entries of cross industries from adjacent branches (sanitary industry) shaped the formative phase, as the ventilation industry displayed initial restraint towards the comfort ventilation technology (due to a deficiency of skilled workforces). The fact that other industrial branches, such as the sanitary installation industry, gained most of the market shares due to existing synergies however, prevented the optimal use of technological know-how inherent in the traditional ventilation industry.

In the early 2000s, large international firms entered the Swiss market, followed by price declines (which resulted in decreasing product qualities). The manufacturers addressed this by two separate approaches, either offering low-cost products or a differentiation through service and quality. In the latter approach, they relied on training programs for executive actors (such as architects, planners, and installers) in order to raise the comfort ventilation's quality in specific installations. However, responsiveness of executive actors for training programs was rather low.

Policy description

Policy support for the comfort ventilation technology started in 1990 with a first pilot and demonstration project, an energy autarkic housing complex constructed in Waedenswil by the department for energy Zurich. Also in 1990, the SFOE offered a performance guarantee for comfort ventilation systems. In the following years, the SFOE became more and more involved and launched in 1990 the public leadership program "Energy2000", which was followed by "Swiss Energy" in 2000. Consequently, other pilot and demonstration projects were implemented by the SFOE, such as in 1995 (Riechen), 1996 (Winterthur), 1999 (Nussbaumen), 2000 (Daellikon) and 2002 (Staefa, Dielsdorf and Renggli). In the same vein, SFOE launched an awareness raising campaign by proactively distributing project specifications to potential planers and end customers.

In 1994, the voluntary Minergie label was founded by members of the department for energy Zurich. Even though, Minergie promoted the installation of comfort ventilations, its building certification did not explicitly prescribe their installation. Yet, Minergie requirements for energy consumption rates were difficult to achieve without a comfort ventilation system. Nowadays, about 98% of Minergie certified buildings feature a comfort ventilation system. Minergie's takeover by cantons Zurich and Bern in 1997 and the subsequent compliance of the remaining cantons in 1998 indicated a rising support of the public sector towards the use of the comfort ventilation technology. In addition, several cantons started public leadership projects such as canton Basel (retrofit program) and canton Zurich. In 2011, the Minergie association launched the voluntary product label “Modul Komfortlüftung”. To comply with this certification, comfort ventilations were systemically evaluated by both designated producers and installers. A similar label “Deklaration” was created by the Energie-Cluster in 2012.

For a long time, private standards were underrepresented with ventilation but not comfort ventilation specific norms, such as SIA 382/14 and SIA 382/25. This lack was partly remedied with the release of the instruction sheet to SIA 2023 in 2008. With the launch of the public standard MuKEn in 2000, public involvement in the creation of a regulatory environment increased. It restricted the share of consumed energy from fossil energy carriers to 80%. Subsequent versions of MuKEn (2008 and 2014) lowered the limits for energy consumption and referred to the use of comfort ventilation systems as a standard solution for achieving those limits.

Appendix D: Low-e Glazing

Table D1: Interview quotes regarding the diffusion of the low-e glazing technology in Switzerland

#	Quote	Expert
Q1	*'Main barrier was the lack of knowledge of the market players or simply: It was something new. That is normal. There is resistance for new things, that's usual. Do we need it? It just creates more effort. Those were the common barriers, but regarding the product there was no higher environmental impact, but rather it was positive for environment.'*	IG1
Q2	*'There were no limiting factors, because, well I would say maybe some window making company, trying to explain that […] the glazing could cause complications when they are large sized. But finally, there was no big movement against triple glazing.'*	IG4
Q3	*'Finally the price [is the main barrier]. Otherwise,…I mean, everyone wants to have windows in their building. And the trend is towards residential buildings with large glazing.'*	IG2
Q4	*'On the one hand they are costly, for sure. It must be affordable somehow, whereby we can discuss, what is affordable. […] it must be profitable. […] And secondly […] the technical realization. Those things must be producible for mass markets. The coating of insulating glass must be produced on a standard machine. […] Actually, it is the same message. Costs will decrease when we produce efficiently.'*	IG3
Q5	*'Glazing is all Minergie suitable. The question is, what does the customer want? It is the brand.'*	IG6
Q6	*'Customers have been guided by incentives and the Minergie aspect. One wanted to go with the market. You needed to have Minergie and it was clear to everyone that you have to save energy, so you go for Minergie. That was the sign. Plus the government distributed incentives.'*	IG6
Q7	*'The commercialization or the reason why the demand existed at all is related to two factors. For one thing there is a label, called Minergie in Switzerland. […] Previously, if you wanted to achieve Minergie, you needed low-emissivity coating. For instance for a passive house one needs the same with krypton in between the glass spacer, because it is not possible without. The U-g value is once again significantly different. Secondly, the governmental incentives for renovation, the construction program in Switzerland, has a so-called bonus system […] Thus, I have a much better insulation and no additional costs. Those were the two things which influenced most.'*	IG6
Q8	*'Labelling and support, these are the important things. You need an emblem …zack… that is Minergie, plus incentives, these are, 30 francs… that's it. If one of those would lack… the market would be totally different.'*	IG6
Q9	*'[…] well, when I consider the main driver in the renovation sector from today's the federal government has pushed immensely. For sure, ultimately because it has the possibilities. There is the construction program, which basically exists still today. This included subsidies for energetical renovations and this was an insane driver, because the financial aspect stimulated.'*	IG3
Q10	*'Yes this is a subsidy. Whereby it is part of the federal funding, the 30 CHF/m2. But most cantons even spend additional funding […] I do not know the numbers by heart, but I guess that Basel finally doubles the incentives easily. I mean, ok that helps. But generally spoken…it is like this, when I do something I need to satisfy a certain standard. That means, when I must exchange my windows, I need to achieve a certain level, consequently I must spend money. For example, if the entire exchange costs about 15,000 CHF and I get 3-4 thousands back … It helps for sure.'*	IG2
Q11	*'[…] And the price was an issue. But obviously performance as well. Suddenly we had such great values. And, I summarize normative regulations like Minergie, SIA 180 und others, you can participate in promotional programs. That matters obviously.'*	IG1
Q12	*'Determining are the values, which must be achieved. As association, we actively develop standards of energy certification, Minergie-certification, such topics. Finally, it is all about accomplishing certain values, regarding energy efficiency, or with respect to noise cancelation or break-in attempt, but not how to do that.'*	IG3
Q13	*'Well, I would consider the norms as central element. Because they decide about the products to be sold […] In my opinion, the norms should be in the central focus of the consideration. So, I claim, if the new norms restricted the energy transmission, then probably it would be requested quickly on the market.'*	IG3
Q14	*'But I think that today we would have 20-30% triple-glazing in Switzerland, if not for the respective regulations for glazing as a standard.'*	IG4

Q15	*'Summarizing for me, the reason why triple-glazing is the standard today is the factor: glass industry, which wants to offer these products to achieve better insulation values. Related are involved regulation on Minergie labels, energy etiquettes, but also certain minima required for windows. As a package those are the factors which led to the triple-glazing standard of today.'*	IG4
Q16	*'The standard, explicitly the prescription of heat insulation evaluated, what is possible. And then, one has strengthened it. We wondered, how fast the glass industry developed. Actually, the politics lagged behind the industry. They were faster.'*	IG5

Operating principle

The low-e glazing technology indicates that low emissivity (thus "low-e") coated float glass was used for the manufacturing of a given window. The term low-e coating describes a layer of a specific metal, which is coated onto one or more sheets of regular float glass. The characteristic property of this specific coating is a reduced emissivity, which ultimately reduces the heat transfer coefficient, the u-value, an indicator to quantify heat losses through a given object, given in W/m^{2}K. Due to its main purpose, the reduction of heat loss, low-e glazing is usually deployed in buildings in which heat loss through windows is especially critical, for example in residential buildings. The common term for this type of glass is insulating glass or insulated glazing. Initially, a typical insulating glass consists out of three elements: float glass wrapped with one-sided low-e coating, a gas filled interspace, and a spacer. This type of glass is designated as "two times insulating glass" which we refer to as 2-IG. Nowadays, "three times insulating glass" (3-IG) is the established glass standard in Switzerland. This term refers to a glass design with two gas filled interspaces and two low-e coatings. The low-e glazing technology improves the insulation of the building envelope by around 50% (reduction in u-value from a standard insulating glass to a 2-IG low-e glass) but it also allows lower solar heat gain coefficients, thus reducing cooling efforts in summer by less solar transmittance (Efficient Window Collaborative, 2016). Therefore, low-e glazing is considered an energy-efficient innovation that contributes largely to a reduction in energy demand in the built environment, especially as it targets, new-built, retrofit, and renovation likewise.

Market and diffusion

In 1973, first glass manufacturers in Switzerland attempted to innovate their current product portfolios and single companies started to offer first 2-IG products in 1973. Other companies started to integrate low-e coated glass to their portfolio between the end of the 1970s and the beginning of the 1980s. From 1985, the market started to take off accompanied by a fast growth rate. Between 1985 and 1990, the market share for low-e glass (2-IG) grew from zero to 60% with an absolute annual increase of approximately 12%. According to Rogers' definition, a mass market was already reached in 1987 which complies with many interview statements. After the initial growth phase between 1985 and 1990, growth slowed down and market share for 2-IG peaked in 2001 at around 80%. In 1998, low-e coated glass (2-IG) was "recognized as a commodity", according to one of our experts. Subsequently, growth rates declined slowly until 2006 and then quickly dropped simultaneously to the smooth transition towards low-e's next generation, the 3-IG.

Similar to 2-IG, low-e 3-IG products were already available in 1980 before the actual market started to spread from the early 2000s. According to our interviewees, the mass market for 3-IG was reached between 2003 and 2004 when big glass manufacturers started to switch their production line to 3-IG, with certain companies achieving 3-IG production capacities of 50% in 2005. Market share rapidly increased from 2007 onwards and peaked in 2009/2010 with an annual doubling of market shares. An estimation of today's market share of 3-IG in Switzerland is based on the documented production capacities of two major glass manufacturers. Expert estimations vary between 80% and 90%.

Technology performance

Development of better insulating windows was mainly promoted as an initiative to better insulate the building envelope and therefore reduce heat loss. As observability is fairly low, the low-e coating of glass did not change the working principles of the product "window" itself and low-e glazing is not perceived as an independent technology by processing industries and customers. Instead, technology performance in the form of KPIs are considered as relevant.

The standard window consists out of two main elements, glazing and frame. Consumers themselves only experience the product window and do not perceive glazing as a separate technology. Developers tried to improve the architecture of the whole window in order to reduce the u-value, which was reported as the main key performance indicator (KPI). As changes of the frame design are considered to be negligible, the development for better windows was driven by the evolution of glass design and the modification of physical properties. Both technologies, 2-IG and 3-IG, consist of several constructive components, such as coating, glass, spacer and gas filling. The design of each element influences the parameter of the end product. However, applying low-e coating to the glass achieves the biggest u-value related improvements compared to changes of other constructive components. The U-values evolved with the technologies, from 2.1-2.4 W/m^{2}K for an uncoated, three-layered window design to 1.2-1.5 W/m^{2}K for the coated two-layered window (low-e 2-IG) to 0.7-1.1 W/m^{2}K for the coated three-layered window (low-e 3-IG). Before 2011, the manufacturers differentiated their products according to measurable physical properties, especially the U-value. With the collapse of the exchange rate in 2011, imports from low cost regions such as Eastern Europe and China increased, which led to an increasing price competition. Thereafter, differentiation between manufacturers was mainly marked by service (delivery times, just-in-time) and cost.

Technological system

Several main industries and actor groups are affecting the technological system of low-e glazing: the glass industry, building industry, window and facade producers, and public authorities. The number of individual actors and actor types as well as the interconnectedness between them indicate a highly complex system. As of today, the glass industry itself is quite consolidated and consists of a small number of big multinational companies (between five and six manufacturers). The consolidation process started between 1990 and 1995 and ended between 2000 and 2005. Given the commodity nature of glass, the competitive environment between producers is regarded as aggressive and price driven, also due to rising imports. The few manufacturers face an asset-heavy production process and are widely regarded as very innovative and proactive.

The processing industries (i.e., window and facade producers) are distinguished through many small actors (firms) which lack the capacity to oversee regulatory and technological developments. Professional associations, “Schweizerischer Fachverband Fenster- und Fassadenbranche” (FFF) and “Schweizerische Zentrale Fenster und Fassaden” (SZFF) filled this functional gap by informing their members about ongoing technological and regulatory trends and emerging products as well as by providing professional trainings. In addition, these associations are also involved in the formulation and distribution of private standards as well as the creation of public standards (such as “MuKEn”) and mandatory labels (such as “Energieetikette für Fenster”). Yet, several experts questioned the importance of professional associations in the diffusion process of the low-e glazing technology in Switzerland, in comparison to rather powerful professional associations, as for example in Germany. Apart from the above, several public and private organizations influenced the technological system. The most important being the Minergie association, “Konferenz kantonaler Energiedirektoren” (KKED), cantonal “Energiefachstellen” as well as the “Schweizerischer Ingenieur- und Architektenverein” (SIA).

The analysis of system cumulates in three insights. First, a mature and innovative glass producing industry exists which proactively influences the system dynamics. Second, professional associations provide a link between the industries and are involved in the creation of policies. Third, the influence of actors in the decision process varies in magnitude and type. Our interviews indicate that architects and engineers have a great influence in the decision process and act as opinion leaders.

Policy description

After the oil crisis, first policy measures aimed at creating a regulatory environment for insulation of building envelopes in general and insulation of windows in particular. Before 1981, private standards, in particular the norm SIA 180, were the only regulatory guidelines to build windows. In 1981, canton Zurich launched a regulation for windows as one of the first big cantons. Following years were shaped by cantonal involvement in policy design until first standards at the national level were introduced in 1986 with “Musterverordnung” (MVO), and subsequently renewed in 1992 (MVO 92), in 2000 with “Mustervorschriften der Kantone im Energiebereich” (MuKEn), which was renewed in 2008 and 2014. Dynamics between public and private standards led to a successive increase of regulatory stringency concerning the heating coefficient (decrease in U-value limits) as Figure D1 shows exemplarily for canton Zurich.

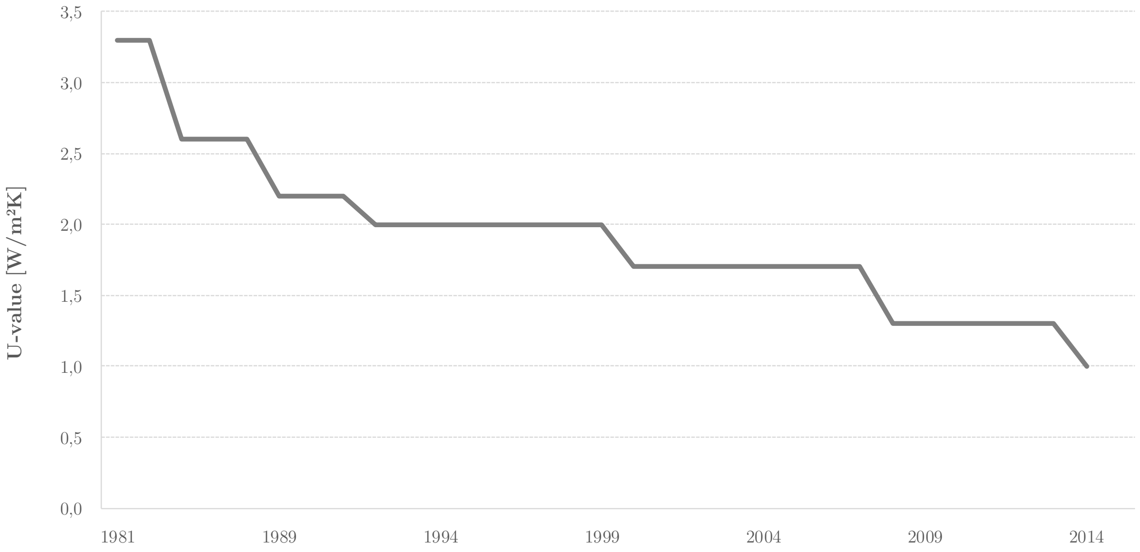


Figure D1: Development of U-value regulation in canton Zurich, 1981-2014

Due to its pioneer role in the implementation of policy, canton Zurich can be considered as a reference for cantonal public standards, particularly as a reference for the strictest standards at the national level. The voluntary building label Minergie, which was founded in 1994, created a consciousness towards high performance buildings and was initially backed by the cantons Zurich and Bern. However, in 1998 with the foundation of the Minergie association political support was guaranteed by all Swiss cantons. Minergie required the usage of 3-IG in order to fulfill the requirements postulated by the label. In 2001, the Minergie association introduced an additional voluntary label for the qualitative assessment of windows (namely Modul Fenster). Certification of windows through Modul Fenster became a standard, which forced manufacturers to offer products compliant to these requirements. In the case of window specification, nowadays, the Minergie label becomes more and obsolete, since requirements of public standards, in particular of MuKEn 2008 and successively MuKEn 2014, approached those of Minergie.

In 2006, a financial incentive program was enacted to foster insulation of building envelopes (so-called "Gebäudeprogramm") by supporting retrofit and construction of energy-efficient buildings. The program was successively relaunched in 2010 due to the economic recession following the financial crisis in 2008. The extent of financial support for windows was defined according to private standards (hence, by U-value) and clearly promoted 3-IG (with 70 CHF/m^2) over 2-IG (20 CHF/m^2). Requirements for financial support, in terms of minimal exchanged window surface area, were successively increased and the amount of financial support diminished to 30 CHF/m^2, which therefore affected building as well as retrofit activities. The GEAK ("Gebäudeenergieausweis der Kantone") certificate was launched in 2009 as a voluntary measure to classify energy efficiencies of buildings. Six years later, in 2015, the mandatory label for the classification of energetic parameters in windows ("Energieetikette für Fenster") was introduced on the national level by the Swiss Federal Office for Energy (SFOE).