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ORIGINAL ARTICLE

Will policies to promote energy efficiency help or hinder achieving a 1.5 °C climate target?

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Abstract There is a large literature suggesting that improvements in energy efficiency support efforts at climate mitigation. Addressing a conceptual gap in that literature, however, we evaluate whether there are any conditions under which policies to promote improvements in energy efficiency could be counterproductive to efforts to limit climate change to 1.5 °C global warming from pre-industrial times. We identify three conditions under which this could be the case. The first condition is if policies for energy efficiency have a political opportunity cost, in terms of crowding out or delaying policies aimed at decarbonizing energy supply. There is an extensive literature in the fields of political science and policy studies to suggest that this is possible, but there have been no studies examining whether it has actually happened or is likely to happen in the future. The second condition is if investments in energy efficiency improvements come at a higher cost, per unit of fossil energy avoided, than do investments in new renewable energy supply. Current cost estimates suggest that there are some energy efficiency investments for which this is the case, but it is difficult to predict whether this will remain the case in the future. The third condition is if policies for energy efficiency, or specific investments in energy efficiency, were to delay the complete decarbonization of energy supply by more than some critical value. We show that critical delay is quite short—measured in weeks to months—in the case of a 1.5 °C temperature target, assuming constrained availability of negative emission technologies. It is impossible to say whether any of these conditions is likely, but in theory, each of them would appear to be possible.

Keywords Energy efficiency · Climate change · Climate policy · Advocacy coalition framework

Introduction

When Barack Obama entered office as President of the USA in 2009, he had three legislative priorities: responding to the immediate economic and financial crisis, reforming the national health care system, and instituting national climate policy. Obama chose to sequence the three policy proposals before Congress in that order. As history shows, he was able to pass legislation on the first two of these, but not the third, within his first 2 years in office. At that point, his party lost political control of Congress, before climate legislation could make it through the legislative process. No economic analysis would suggest that climate policy competes against financial regulation or health care reform, but at a practical level, that is exactly what happened.

Consider another example of competition at a different scale, a hypothetical homeowner's desire to reduce the carbon footprint of her house. Two possible options would be to install solar photovoltaic panels (PV) on the roof, and to insulate the building shell. Both options would pass a cost-benefit test, in terms of delivering

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annual savings (or, in the case of PV, revenues) that would exceeding the amortized costs. From an economic perspective, she should do both, immediately. In practice, she may have enough money immediately available for one of the projects, but not for both, regardless of whether she desires to self-finance the projects, or seeks a home equity loan from a bank. Additionally, planning each of the projects, including obtaining the necessary permits, and actually doing the work (or identifying contractors to do the work) is a time-consuming process. It is easy to imagine that, for both reasons, she may decide that it is simply too much to do all at once: she will complete one project now, and delay the second project by several years. In a practical sense, the two projects are competing against each other for her bank account and her time.

When investments are in competition with each other, then a good investment could turn out to be counterproductive if it has the effect of crowding out or delaying another investment that would have been even better. The same can be said of policies designed to support particular kinds of investments. In this paper, we consider whether this logic could be relevant for considering policies and investments geared towards greater energy efficiency, in the context of promoting a societal goal of limiting global warming to no more than 1.5 °C.

There is little doubt that in the context of the 1.5 °C target, or really any climate change target, improving energy efficiency would be a good thing. There is a large literature that reaches this finding, quite convincingly. None of the studies in that literature, however, has considered whether attention to energy efficiency could crowd out or delay the switching from fossil to non-fossil sources of primary energy, and if so, whether the net effect on climate protection would be positive or negative. That is the gap that we begin to fill with this paper. Our analysis proceeds in four steps, the first two of which are rooted in a review of relevant literature, and the next two of which involve simple numerical analyses.

Energy efficiency and climate mitigation

The energy sector accounts for the majority of greenhouse gas (GHG) emissions, primarily in the form of CO_2 from the combustion of fossil fuels (Blanco et al., 2014). A common practice is to decompose emissions into a set of different driving factors. The Kaya identity (Eq. 1) represents a highly simplified heuristic, and while refinements on it have allowed for specific insights into how the four factors interact in the case of real-world economic development (e.g., York et al., 2003), its basic form has been frequently used to analyze emissions and their drivers (Blanco et al., 2014). The identity reframes total emissions C over a period of time as the product of human population P, affluence (gross economic product G per capita P), energy intensity (energy use E per unit of economic product G), and carbon intensity (CO_2 emissions C per unit of energy use E):

$$\boldsymbol{C} = \boldsymbol{P} \times \frac{\boldsymbol{G}}{\boldsymbol{P}} \times \frac{\boldsymbol{E}}{\boldsymbol{G}} \times \frac{\boldsymbol{C}}{\boldsymbol{E}} \tag{1}$$

There are numerous arguments for reducing population (Hardin, 1968) and affluence (Skidelsky and Skidelsky, 2012; Sustainable Development Commission, 2009), yet most climate policy analyses treat it as axiomatic that the goal of climate policy should be to reduce or eliminate CO_2 emissions while allowing for the greatest possible growth in economic affluence. Hence, they seek policies that reduce energy intensity and/or carbon intensity, in a manner that allows the product of population and affluence to remain high. In other words, most climate policies are aimed at reducing the third and fourth terms on the right-hand side of Eq. 1.

It is important to recognize that achieving any temperature target close to 1.5 °C demands that net emissions from the energy sector fall to zero or below; moving to more ambitious targets (e.g., 1.5 instead of 2 °C) requires the elimination of emissions to happen faster (Rogelj et al. 2018). Hence, at least one of the latter two terms—energy intensity or carbon intensity—needs eventually to reach zero. We take it as axiomatic that this would be highly undesirable, at least for the foreseeable future, in the case of energy intensity: the technologies that would allow the power and waste heat from muscles alone to sustain an economy of several billion people simply do not exist. By contrast, it *is* possible to imagine reducing carbon intensity to zero in the next few decades. This would involve switching all primary energy supply from fossil fuels to other things, including nuclear power and renewable energy sources, or to add carbon capture and storage (CCS) to fossil fuel combustion. The economic potential for renewable energy vastly exceeds current energy demand

(Chow et al. 2003). Certainly, a switch entirely away from fossil fuels to other energy sources would create technical challenges, including energy storage and the synthesis of energy-dense liquid fuels for certain applications, but it appears that technologies for all of these issues do or soon will exist (Patt 2015). Hence, the Prime Minister of Sweden could announce to the United Nations General Assembly that his country would become fossil-fuel free, without being declared insane (Bolton 2015). It is thus clear that climate mitigation requires the carbon intensity term in Eq. 1 to reach zero, and that once this has happened, none of the other terms will have an impact on carbon emissions.

Until the day when carbon intensity does hit zero, however, reducing energy intensity can also lead to a decline in emissions. There are two main pathways by which this occurs. The first pathway is a structural transformation of the economy, such as a shift from industrial manufacturing to service provision (Sorrell 2015; Voigt et al. 2014). Empirically, however, structural changes or shifts have not been associated with any marked absolute decline in energy consumption (Sorrell 2015; Suh 2006; Sustainable Development Commission 2009). Explaining national data is the fact that structural changes typically happen in response to an overall increase in total consumption within the economy, with the two effects balancing each other (Sustainable Development Commission 2009). Further explaining global data is the fact that structural changes have been associated with a relocation of energy-intensive industry to new regions of the world, such as from Europe to Asia, meaning that declines in energy consumption from such activities in one place have been compensated by increases elsewhere (Voigt et al. 2014; Zhao et al. 2010).

The second pathway is through technology diffusion within economic sectors. Improvements in technology, and the processes making use of technology, can increase the ratio of useful energy services to the energy input required, whether in manufacturing, transportation, heating, or lighting (Backlund et al. 2012; Patterson 1996). Technological change can also lead to a rebound effect (Madlener and Alcott 2009). First, as Sorrell (2015) notes, the innovations to support a decline in energy intensity correlate closely with those that lead to economic growth. Second, many improvements in energy efficiency come at a net cost savings, freeing money for other activities that also use energy (Gillingham et al. 2016). Estimates of the magnitude of the rebound effect vary widely (Gillingham et al. 2013). Empirically, however, investments into technology explain essentially all of the observed global variance in the rate of decline of total energy use (Voigt et al. 2014).

Most analysts believe these investments to be worthwhile. For example, 19 of the G20 countries have specifically declared improvements in energy efficiency to be a key element of transforming their energy systems to achieve ambitious climate targets, citing the United Nations Sustainable Development Goals' (SDGs) similar ambition of doubling the rate of improvement in energy efficiency (G20 2017). Likewise, the International Energy Agency declares energy efficiency to be vital to achieving numerous energy-related goals, including achieving climate change targets (IEA 2016). Within the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5), every chapter covering sectoral possibilities for emission reductions concentrates on those possible from improvements in energy efficiency (Edenhofer et al. 2014), supporting a finding that cost optimal pathways to climate mitigation include devoting substantial financial resources to improvements in energy efficiency (Gupta et al. 2014).

Putting this advice into practice would require a significant redirection of policy. Wilson et al. (2012) identify a large discrepancy between the advantages, in terms of economic and other social benefits, of policies to promote learning and diffusion of technologies for energy efficiency, and those that focus on energy supply. Basing their analysis in the framework of the Global Energy Assessment (GEA 2012), they assess the immediate social return on investment to be far higher in the case of technologies for efficiency. At the same time, they note, most government policies, across a wide set of countries, focus on developing new energy supply technologies. For example, of the € 268 million that the European Union (EU) budgeted for energy research in 2011, only 13% went for end-use efficiency, whereas 60% went for the study of energy supply. Current policies, according to their analysis, are far from optimum.

Reducing both carbon intensity and energy intensity, then, require initial investments into new technologies and infrastructure in order to yield a decline in energy-related emissions over time. The commonly used tool to investigate the relative effects of different technological pathways is the integrated assessment model (IAM), which integrates models of the energy system, the economy, and some aspects of the carbon cycle. As far as we know, every IAM-based study to have considered the effects of improvements in energy efficiency has reached the conclusion that these help in the efforts to achieve ambitious climate targets such as 1.5 °C.

Luderer et al. (2013), for example, examine the costs of achieving the Paris Agreement targets of limiting temperature rise to below 2 °C, and potentially 1.5 °C. Among the many scenarios the authors consider, several include the situation envisioned by the SDGs of improvements in energy efficiency doubling from their historical values. The exogenous and costless improvement in energy efficiency reduces the economic costs of achieving the 1.5 °C target by roughly 20%. Other studies reach qualitatively similar conclusions, all based on the assumption that efficiency improvements come at no economic cost (Bertram et al. 2015; Riahi et al. 2015). This assumption of costless improvements in energy intensity is well justified, given the widespread potential for energy saving investments that pay for themselves in terms of reduced energy costs later on (Gillingham and Palmer 2014).

Several other studies provide useful policy scenario comparisons. Rogelj et al. (2018, 2015) find that those scenarios that contain rapid exogenous declines in energy intensity achieve lower temperature targets. Van Vuuren et al. (2018) examine this same question in light of an additional desire to reduce the need for negative emissions technologies, and similarly find that improvements in energy intensity are part of those scenarios that are able to limit temperature ride to below 1.5 °C.

So, two things appear well settled. First, if society manages to achieve any of a range of ambitious climate targets, then incorporating policies leading to greater energy efficiency will improve the prospects for economic growth as emission reductions are taking place. Second, adding a component of rapid reduction in energy intensity to a scenario envisioning a rapid restructuring of energy supply improves the prospects for achieving the most ambitious climate temperature targets.

But IAMs do not consider the possibility of competition. They frequently assume limits to the pace at which energy supply infrastructure can be brought online, or turned over, but they do not assume that investments in energy supply and those in energy efficiency compete against each other for scarce investment capital. They also do not include any explicit attention to legislative and regulatory processes, which can mean that putting one set of policies in place can lead to other policies having to wait, or potentially never coming on the political agenda at all.

Political competition and win-win solutions

In this section, we examine whether the potential exists for political competition between policies for energy efficiency and those devoted to transforming energy supply. First, we review the political science literature on policy processes and framing, to identify how competition may arise. Second, we examine whether there is any evidence of competition having taken place between energy efficiency and energy decarbonization. Third, we examine whether competition is a practical issue for climate policy, or rather whether the main options are in fact win-win, improving both energy intensity and carbon intensity at the same time.

With respect to the first issue, there is an extensive empirically grounded literature in political science showing that alternative policy instruments are often in competition with each other. The basis of this literature is the Advocacy Coalition Framework (ACF) proposed by Sabatier (1988). In the ACF model of the policy-making process, political interests align around different policy solutions to a particular problem, setting up a political competition between different solution strategies, in which the relative political resources of the respective coalitions determine which solution strategy is eventually adopted. Since its original publication 30 years ago, there have been hundreds of papers demonstrating this dynamic across a wide variety of policy contexts (Weible and Jenkins-Smith 2016). Research have developed the theory to understand the drivers of shared belief systems that form the heart of any given coalition (Ingold et al. 2016), as well as the factors influencing political power, while the core idea that the different coalitions compete against each other, with different ideas of how to solve a problem, remains robust (Weible and Jenkins-Smith 2016).

Closely aligned with the ACF is the “multiple streams” model of policy-making processes (Howlett et al. 2016), original proposed by Kingdon (1995). In this model, there are also a number of different ways in which a given social problem can be framed, as well as a number of credible solution strategies. Events in the world—a war in the Middle East, an economic recession, or an oil spill off the coast of California or France—can generate media attention and public concern, creating a "window of opportunity" for making major policy changes. Such changes occur if there is alignment between the focusing event and at least one of the problem frames, and at least one of the credible solution strategies that addresses the problem as framed in this way. Alignment needs to be preexisting, as time is limited: eventually the public will grow bored of the problem, turn their attention to other matters, and policy makers will see no rewards for continuing to invest political capital to try and solve the problem. The quickest way for the window of opportunity to close is if policy-makers convince the public that they have solved the problem. In a contested political atmosphere, many attempt to do just this. This can mean that only one policy, or set of policies, will be enacted to fix the perceived problem.

Certainly, a single strategy can lead to the adoption of a number of separate regulatory instruments. The United States Clean Air Act of 1970, for example, led to the adoption of a wide variety of technology standards to address different pollutants (Portney and Stavins 2000). Even here, however, the literature suggests that one particular problem framing typically prevails, and can preclude adoption of policies based on other framings (Chong and Druckman 2007).

Have there been studies demonstrating energy intensity and carbon intensity competing with each other as alternative solution strategies for climate change? None that do so directly, but several studies provide limited evidence in this direction. Kivimaa and Mickwitz (2011) document a shift in bio-energy policy framing in Finland over time, from that of reducing fuel imports to improve energy security in the 1970s and 1980s, to promoting Finnish bioenergy competitiveness in the 1990s, to more recently that of developing bio-energy as part of a climate mitigation portfolio. The changes in framing were associated with changes to policy instruments; from the 1980s to the 1990s, for example, there emerged a set of support mechanisms to enhance the development of wood-based energy systems. In Germany, the strengthening of the feed-in tariff system resulted from a reframing of energy debates from issues of economic and energy efficiency to ones of local economic empowerment (Patt 2015). The reframing was associated with a change in policy instruments from ones designed to correct an externalities-based market failure, to specific support for the development of new solar, wind, and biogas capacity. At roughly the same time in Switzerland, climate and energy policy framing coalesced instead at this time around the global disparity in energy consumption and GHG emissions, and this resulted in the adoption of climate policies geared towards reducing Swiss energy consumption to the global average of 2000 W per capita, with far less emphasis in Switzerland than in Germany on supporting new renewable energy supply (Stulz et al. 2011). Scrase and Ockwell (2010) document for the UK how there has been political competition between framings of energy policy built around job creation and investment on the one hand, and import reduction and energy efficiency on the other. Advocacy coalitions formed, membership determined by particular interests. Promoters of nuclear power, including those supporting nuclear power because of its ties to nuclear weapons production and national security, aligned themselves with the political framing built around job creation, for example.

One critical question is whether there are some policy instruments that are particularly effective at promoting both, creating a win-win outcome. The most frequently cited are market-based instruments such as carbon taxes and tradable emission allowances (Portney and Stavins 2000).

Numerous papers apply neo-classical economic models to support not only the idea that market-based instruments are the best for promoting emission reduction in general, but also that they result in an efficient allocation of innovation and investment across both energy savings and new supply technologies (Acemoglu et al. 2012; Jaffe et al. 2003). Empirically, the question has been harder to tease apart. Several studies empirically show that market instruments promote improvements in energy efficiency, through a combination of technological investment and structural change (Fisher-Vanden et al. 2004; Wang et al. 2014; Zhao et al. 2010). Two studies directly and empirically examine the question of whether market-based instruments have stimulated improvements in energy intensity, carbon intensity through expansion of carbon-free energy supply, or both. Both of these suggest that market instruments have led to energy intensity improvements, but not to improvements in carbon intensity (Noailly and Smeets 2015; Wurlod and Noailly 2016). These results are consistent with a group of papers that empirically document the failure of market-based instruments adopted so far to address risks and structural barriers that are particular high in the case of carbon-free energy supply (Blyth et al. 2007; Bürer and Wüstenhagen 2009; Eskeland et al. 2010; Held et al.

2006; Huang and Barker 2009; Johnstone et al. 2010; Knight 2010), as well as theory-based arguments as to why this should be the case, based on evolutionary models (Grubb 2014; Patt 2015).

There is also contradictory empirical evidence, offering limited support for the proposition that carbon taxes lead to greater innovation into non-carbon technologies. Aghion et al. (2016) analyze panel data on new patents in the car industries of the USA, UK, France, Germany, and Japan: they find marginally significant evidence (at the 90% confidence level) for higher fuel prices leading to innovation (thought not diffusion) of clean technologies such as electric drive trains. The two other papers find an effect of the European Emissions Trading System on investments in clean technology R&D; like Aghion et al. (2016), they do not examine clean technology diffusion (Calel 2018; Calel and Dechezleprêtre 2016).

What can we conclude? The empirical literature on political framings suggests that there is the very real possibility that adopting policies addressing climate change through efficiency improvement and demand reduction can come at the cost of adopting policies focusing on supply transition, and vice versa, although there are no studies that have empirically documented this to have taken place. There is a likewise a theoretical argument based in neo-classical economics, suggesting that market-based instruments offer an escape valve, by virtue of promoting both demand reduction and supply transformation. The empirical evidence offers strong evidence that market-based instruments do lead to demand reduction, weak evidence that they lead to innovation in clean energy supply technologies, and no evidence that they lead to enhanced investment and diffusion of these technologies. Theoretical arguments based outside of neo-classical economics offer explanations for why market-based instruments may fail to lead to the diffusion of clean energy technologies, even should market-based instruments be made more stringent. At the end of the day, theory offers arguments for why and how political competition may come about, but the empirical basis to support this remains weak.

Competition for a limited pool of finance

Technologies for demand reduction may compete with those for new supply options not only at the political level, but also for available project finance. Estimates for the investment needed in clean energy and energy efficiency vary widely. The IPCC, for example, presents a median estimate of an additional $300 billion annually, representing a 25% increase on current investment of $1.2 trillion (Gupta et al. 2014). The Organization for Economic Cooperation and Development (OECD), by contrast, presents a higher estimate of $53 trillion over the next 20 years, which would represent more than a doubling of financial flows (OECD 2015). Numerous authors have identified the availability of finance as limiting the pace of investment into new infrastructure and technology, and hence being a significant barrier to achieving ambitious mitigation targets (Bowen et al. 2014; Patt 2015). This is particularly so in developing countries, where private borrowing costs are exceedingly high. Leveraging a limited infusion of public sector investment capital is necessary to reduce the risks to private second lender and investors, reducing finance costs sufficiently to make investments into climate mitigation technologies competitive and attractive (Labordena et al. 2017; Ondraczek et al. 2015; Schmidt 2014). At the same time, however, promises of multilateral public sector finance from parties to the United Nations Framework Convention on Climate Change have so far failed to be realized (Buchner et al. 2011; OECD 2015).

Given the possible competition, it is useful to compare the investment costs associated with improvements in energy efficiency with those of new renewable energy supply. Now and moving into the future, which is likely to cost less: displacing a kWh of fossil energy with new renewable energy supply, or eliminating the need for that kWh through investments in demand reduction? Until recently, it seemed clear that investments in energy efficiency were in most cases cost effective, but the last decade has seen dramatic reductions in the costs of renewable energy (Obama 2017), making the choice more difficult.

Both renewable energy and energy efficiency projects have the characteristic of requiring initial investment, but typically little in the way of operation and maintenance costs later on; it is valid to compare the levelized costs of energy either generated or saved. We surveyed major assessment reports, as well as the survey papers they cite, to find a range of estimates, presented in Table 1. What is noteworthy is that the large cost reductions that have taken place for renewable energy now put the costs of adding renewable energy supply

Table 1 Levelized cost estimates

Area of investment	Cost ($/kWh)	Report	Reference
Residential heating efficiency, new construction, cold climates	0.13	IPCC	(Harvey 2013)
Residential heating, new construction, moderate climates	0.26	IPCC	(Harvey 2013)
Residential heating, passive new construction	0.08	GEA	(Ürge-Vorsatz et al. 2012)
Commercial heating and cooling, new construction	< 0	IPCC, GEA	(Lucon et al. 2014; Ürge-Vorsatz et al. 2012)
Residential and commercial heating, existing stock renovation	0.11–0.28	IPCC	(Lucon et al. 2014)
Industrial efficiency, pumping systems	0.06	GEA	(Banerjee et al. 2012)
Industrial efficiency	0.04	IPCC	(Worrell et al. 2008)
Transportation efficiency	No estimates	GEA, IPCC	(Kahn Ribeiro et al. 2012; Sims et al. 2014)
Portfolio of PV and onshore wind	0.05	IRENA	(IRENA 2016)

within the middle of the band of costs for efficiency improvements, reducing the need for supply.

At the same time, several uncertainties make it impossible to predict with any accuracy how these average levelized costs are likely to evolve over time. The first and more researched of these uncertainties is with respect to technological learning. For solar and wind technologies, studies have shown costs to decline by as much as 30% in response to a doubling of installed capacity (Lilliestam et al. 2017), although more typical values for sustained learning rates lie in the range of 10–20% (Neij 2008; Rubin et al. 2015). Similar learning rates have been found in the area of devices that account for energy demand (Nykvist and Nilsson 2015; Smith et al. 2016; Weiss et al. 2010a, b), as well as for the incremental costs of energy efficiency enhancement technologies (Karali et al. 2015; Van Buskirk et al. 2014). Across all of these technologies, then, learning tends to push the costs down as a result of the technologies' diffusion.

At the same time, however, there is a countervailing force that tends to push the costs up over time, namely the progression from low hanging fruit to those more difficult to reach. This force affects technologies for both energy efficiency and renewable energy, although in slightly different ways.

In the area of renewable energy, rising costs can be imagined in cases where the best sites in a given country would be developed for wind or solar power first, and then subsequent development must be located in places with less wind and sunshine, and hence higher levelized costs. The empirical literature, however, suggests that this is not a major issue (Lilliestam et al. 2017; Wiser et al. 2016; Wiser and Bolinger 2014), perhaps because the solar and wind economic potentials so great exceed total energy demand (Chow et al. 2003). What is a major issue for renewables, however, is the satisfying of demand niches where renewable energy can be used at the time and place of generation, without having to invest in long-distance transmission, storage, or conversion into liquid fuels. These costs—what we call system integration costs—could lead the total costs of developing renewable energy sources to rise over time. A large number of papers point to the need to address system integration through a variety of technological and institutional mechanisms, and a growing number of papers are beginning to make specific cost estimates for future scenarios (Pietzcker et al. 2017). For example, Scholz et al. (2017) examine a number of decarbonization scenarios for Europe, and estimate integration costs ranging from $0.01 to $0.04/kWh, comprising roughly 10–30% of total energy system costs. Pfenninger et al. (2014) examine the added costs to provide overcapacity to enable a single technology—CSP with thermal storage—to provide load following capacity, suggesting a need to double the capacity averaged across the world regions considered, implying 50% of the total system costs going towards integration. Other studies have shown that the necessary long-distance transmission would add very little to that price (Labordena et al. 2017; Lilliestam et al. 2016). Since reliance on a single technology to provide overcapacity and backup generation implicitly seems to be an inefficient strategy, we take this 50% value as an indicative upper bound on system integration costs, recognizing that this may also be an underestimate. Another study, Diaz et al. (2017), develops scenarios for Switzerland to achieve completely renewable power. They report a 4% curtailment in energy production from wind and solar in a fully stable system. Given Switzerland's high existing capacity for flexible hydropower and pumped storage, one would expect system integration costs to be particularly low for this country, and this 4% value could reflect a lower bound more generally.

In the area of energy efficiency, the dynamics are slightly different. Individual technologies represent often a small incremental improvement, and in any given sector, the different improvements come on top of each other over time to continually push down energy intensity. An automobile, for example, may see a series of changes over time—a change in shape to reduce drag, then improvements to the engine to increase combustion efficiency, and finally substitution of carbon fiber for steel to reduce vehicle weight—resulting a continual improvement in the ratio of fuel consumption to vehicle weight and performance. This process is typically modeled as a progression from lesser to more expensive technological options, with the range in costs being over an order of magnitude (Vogt-Schilb and Hallegatte 2014).

The two factors—technological learning and technological progression—oppose each other in terms of their effects on costs, and it remains unclear what the net effects of time and technology diffusion are likely to be. For neither renewable energy nor energy efficiency have there been any studies directly examining which effect is likely to dominate, and hence whether the incremental costs of reducing the need for fossil generation are likely to rise or fall over time.

In Fig. 1, we examine how uncertain the net effects are, in the context of one highly simplified and highly unlikely scenario: we assume that for energy efficiency improvements, the effects of technological learning and technological progression exactly balance each other. Given this unlikely assumption, we examine the combined effects of technological learning and system integration costs on the present day levelized cost of \$0.05/kWh (from Table 1), and juxtapose these with indicative costs of energy saved through additional investments into energy efficiency (also from Table 1). To define the size of the renewable energy system needing to be built, we assume that society limits future energy sector emissions to 400 $GtCO_2$ and maintains current rates of improvement in energy intensity. We represent the potential for learning on the *x*-axis, in terms of a cost coefficient ranging from 0.75 (corresponding to a 25% learning rate) to 1.00 (corresponding to no learning). We indicate the likely range between 0.8 and 0.9 with gray shading. On the *y*-axis, we present ranges of values for system integration costs, which would include new investments in energy storage or transmission, and again indicate the likely range between 4 and 50% with gray shading. The more darkly shaded rectangle indicates the overlap of the two shaded regions, and hence a likely range of average costs for new renewable energy over the timeframe when fossil fuels are eliminated. Most of this box lies to the lower left of the \$0.05/kWh current cost isopleth, indicating renewable energy to be getting less expensive over time. That box also lies to the lower left of many of the current cost estimates for sectoral-specific improvements in energy efficiency. Under this one particular scenario, then, it may make more financial sense to eliminate the need for fossil fuels by building renewable energy supply, rather than through the relatively expensive sectoral improvements in energy efficiency.

We need to emphasize that Fig. 1 represents only one thought experiment, an exploration of a single scenario where investments in energy efficiency could prove more costly than investments in new renewable energy supply. In the likely case where the effects of technological learning for energy efficiency outweigh the effects of technological progression, then the relative attractiveness of energy efficiency improvements would be higher. At the end of the day, we simply do not know which type of investment will be the more effective use of limited financial capital.

Rates of substitution between energy intensity and carbon intensity

In the past two sections, we have evaluated the potential for improvements in energy intensity coming into conflict with improvements in carbon intensity, and shown this potential to be theoretically viable. The effect of this conflict would be that rapid progress on one could come at the expense of rapid progress on the other. In this section, we evaluate the rates of substitution, in the context of highly constrained global carbon budgets.

For either the 2 or 1.5 °C temperature targets, a given carbon budget represents the maximum amount of CO_2 that humanity can still put into the atmosphere. The budgets have a wide potential range; they are sensitive to uncertainties in the future availability of negative emissions through carbon dioxide removal (CDR)

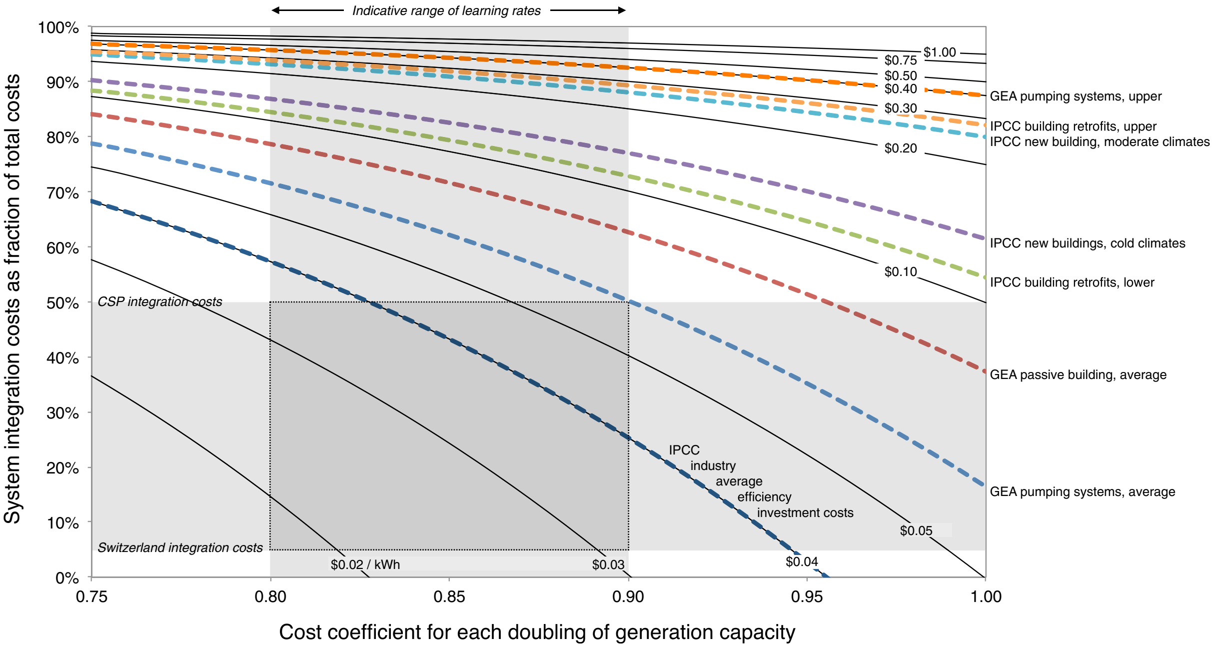

Fig. 1 Comparing cost of renewable power produced with cost of power saved. The figure suggests a space of marginal solar and wind generation costs, as a function of technological learning and new system integration costs. The shaded bands indicate indicative likely ranges for each, with the darker shaded rectangle indicating their intersection. The thin black isopleths map out new generation cost frontiers within this space, in USD/kWh. The dashed lines indicate the costs of energy saved for a number of different efficiency improvements reported in the text

(Fuss et al. 2016, 2014; Smith et al. 2015), uncertainties associated with climate forcing, including carbon feedbacks such as methane release due to the melting of Arctic permafrost (Rogelj et al. 2016). If one assume no future CDR, a reasonable lower estimate for the carbon budget to achieve 1.5 °C is one that society has already depleted, while a medium estimate suggests approximately 30 $GtCO_2$ remaining, and an upper estimate 140 $GtCO_2$. By contrast, the medium estimate for the 2 °C target suggests 700 $GtCO_2$, and an upper estimate suggests 900 $GtCO_2$ (MCC 2017). All of these values include emissions outside the energy sector, meaning that the budget for the energy sector alone would be substantially less. For our analysis, we consider illustrative budgets for the energy sector of 100, 200, 400, and 800 $GtCO_2$. The former roughly corresponds to the maximum budget for achieving 1.5 °C if CDR is not available, while the others assume limited availability of CDR. The final value—800 $GtCO_2$—also approximates an upper value for the 2 °C target should CDR not be available.

A detailed IAM could possibly offer precise quantitative estimates of substitution rates, given possible feedbacks between energy sector investments and economic growth. We use the Kaya identity instead, as it provides a far simpler framework to reach a set of qualitative insights. We assume that policies are unlikely to be implemented if they would deliberately and substantially reduce population or economic growth; hence, we make use of a single scenario for these two factors. For population, we make assumptions consistent with median United Nations scenarios (United Nations Population Division 2007), starting at 7.5 billion in 2017 and rising to 8.3 billion by 2050. For affluence, we assume increases in global per capita consumption of 1.5% per year, from a starting value of $10,000 (CIA 2016; World Bank 2017).

We focus our attention on energy intensity and carbon intensity, taking starting values of 1.6 kWh/$ and 300 gCO_2/kWh, respectively (IEA 2016; World Bank 2017). We assume simplified diffusion processes to result in changes to these two values over time. In the case of energy intensity, we assume changes to result from numerous and incremental small investments, across a multitude of separate technologies in the full range of sectors, which together bring about a fractional decline in energy intensity from year to year. In the recent past, this decline has average roughly 1.5% per year (Blanco et al. 2014). We assume that an increased level of policy-driven investment occurring every year could increase this rate of decline. This annual rate of decline is the first key parameter we consider.

We assume a somewhat different diffusion process to affect carbon intensity. We assume the requirement to replace existing fossil fuel infrastructure with completely decarbonized infrastructure, most likely renewable energy sources such as solar or wind power, within one or two investment cycles. Rather than a sequence of incremental steps that build on each other, we see these investments as representing the diffusion of a more limited set of zero-carbon energy supply technologies, which would replace fossil fuel combustion. Following Grübler et al. (1999), we represent this diffusion process with an S-shaped logistic function. We assume that once the new energy technologies have reached a market penetration of more than 99%, all remaining fossil fuel infrastructure can be retired. The year in which this event occurs is the second key parameter we consider.

Figure 2 shows the combinations of the two parameters consistent with each of the four carbon budgets we consider, given the many simplifying assumptions we have made. It covers ranges of values for the two parameters that almost certainly far exceed what is technically, socially, and economically possible, such as an annual decline in energy intensity of 8%, or a switching off of all fossil carbon energy production in 2020.

As Fig. 2 shows, the benefits of accelerated improvements in energy intensity—in terms of buying time for complete decarbonization—grow smaller with more ambitious temperature targets, even if we assume that some CDR may be available. The 800 $GtCO_2$ budget corresponds to an upper bound to achieve the 2 °C target without the benefit of CDR. Staying within this budget while maintaining a 1.5% annual decline in energy intensity would require complete decarbonization by about 2058—40 years from now—but doubling the rate of decline in energy intensity would push this back by 10 years, a 25% delay. The comparable budget for achieving the 1.5 °C target is 100 $GtCO_2$, which is nearly vertical; doubling the decline in energy intensity would push back the deadline for complete decarbonization by only a few weeks. Even if we assume some CDR availability, such as with the 400 $GtCO_2$ budget, the time bought through accelerated decline in energy intensity are minor: doubling the rate of decline from 1.5 to 3% would push back the deadline for complete decarbonization from 2037 to 2039.

Achieving ambitious mitigation targets such as 2 or even 1.5 °C will be extremely challenging, unless CDR does become available in large volume. It will require the reduction of carbon intensity to 0, such as through the elimination of fossil fuels, within the next two to three decades. Of course this change is unprecedented, simply because fossil fuels have been the dominant

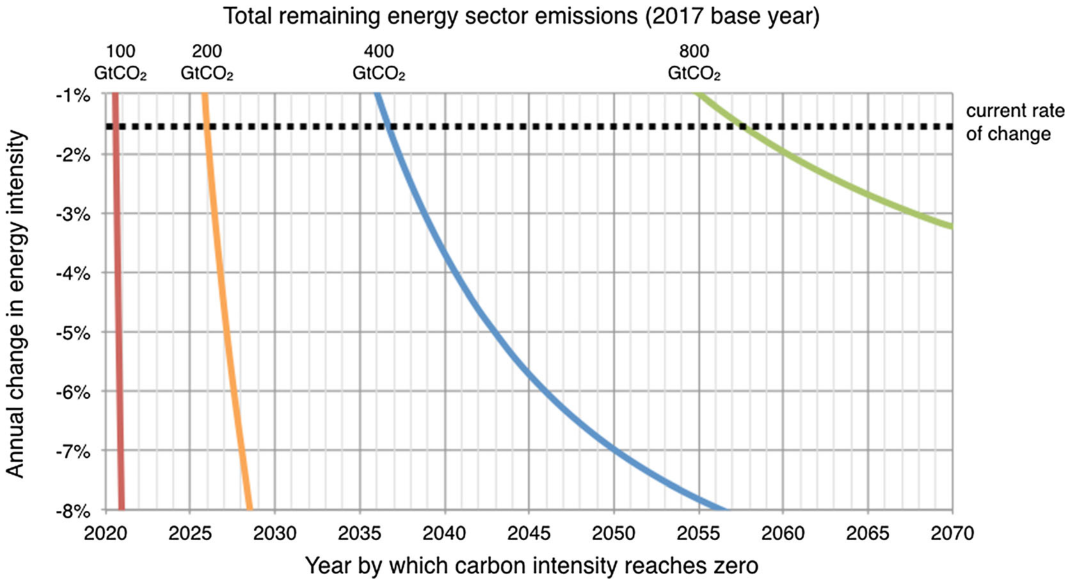

Fig. 2 Relationship between carbon budgets, annual changes in energy intensity, and years of attaining zero carbon intensity

energy source for the entire period of time since the beginning of the industrial revolution. The rate of change is, however, consistent with the historical rates of transformation observed in other systems, such as road transport or telecommunication (Geels 2005; Patt 2015). Even very rapid marginal improvements in energy efficiency, also representing rates of change that are unprecedented within the energy system, would do little to change this. One would need to substitute a great deal of improvement in energy efficiency to have a very small effect on the required pace of decarbonization.

Discussion

To achieve the most ambitious climate targets, such as 1.5 °C, society has to move extremely fast to eliminate fossil fuel emissions. This almost certainly means replacing all use of fossil fuels with something else, such as renewable energy sources. The literature to date is universal in suggesting that a concurrent effort to improve energy efficiency would be beneficial for this transition: improved energy efficiency would reduce emissions during the period of time when fossil fuels are still in use, and would reduce the total size of the renewable energy system needing to be built. So are there any conditions under which efforts to improve energy efficiency would instead be counterproductive? We have explored three.

The first condition is that policies to promote energy efficiency and those to support the diffusion of non-fossil energy sources come into political conflict with each other. There is no clear evidence that this is taking place. There is, however, a great deal of evidence of this kind of competition occurring in policy processes generally, reflected in well-accepted theories of policy-making, making it possible to imagine it taking place in the energy sector.

The second condition is that new investments in energy efficiency would require more investments finance, per unit of fossil energy displaced, than new investments in renewable energy supply. The reason this matters is that the pool of investment finance available for the energy sector may well be limited, especially in developing countries. It appears to us to be quite unclear as to how future costs will stand, relative to another. We constructed a scenario in which investments in renewable energy are likely to be more cost-effective than many investments in energy efficiency. We could have just as easily constructed a different scenario, in which this was not the case.

The third condition is that political efforts to improve energy efficiency would cause a delay the ultimate phase-out of fossil fuels from the energy mix by more than some critical amount of time. Through simple calculations based on the Kaya identity, we show critical amount of time shrinks substantially as the temperature targets become more ambitious. In the context of a 2 °C target, for example, a doubling of the rate of improvement in energy intensity could delay the required phase-out of fossil fuels by as much as a decade. In the context of a 1.5 °C target, the delay would instead be measured in weeks to months.

Are these three conditions likely? Our review of the literature shows large empirical gaps, making it impossible to answer this question. The only claim that we can make here is that the literature suggests that they are possible. Given that, we should not automatically assume that improvements in energy efficiency will help us to limit climate change to 1.5 °C, but must instead continually evaluate the benefits of energy efficiency improvements in relation to both direct and opportunity costs.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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