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Economic Opportunities of Climate Policies

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presented by
NOE NICOLAS REIDT
MA Economics, University of Zurich
born on 16.10.1992
citizen of Switzerland

accepted on the recommendation of
Prof. Dr. Lucas Bretschger
Prof. Dr. Massimo Filippini

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Thesis Summary

There is scientific consensus on the need to reduce carbon emissions globally to address the threat posed by global warming. As a response, 197 countries have endorsed the Paris Climate Agreement, aiming to limit the global temperature increase in this century to 2 degrees Celsius. That requires far-reaching climate policies to redirect the current fossil fuel-based global economy towards sustainability. In designing these climate policies, it is crucial to account for economic concerns. Extensive economic costs due to climate policies reduce their social acceptance, potentially preventing their viability. Accordingly, the economic effect of climate policies is particularly relevant for achieving a socially compatible transition towards a sustainable future. The onus is on national politics to determine climate policies decreasing emissions in line with economic interests.

This dissertation examines the effects of climate policy measures on carbon emissions and the economy. To do so, it employs economic models capturing the linkages between climate policies and the economy to derive recommendations for economically sound climate policies. The thesis contributes to answering the fundamental question of achieving climate targets under the best economic conditions as seen from two perspectives: the labor market and the transport sector.

The first chapter underlines the relevance of climate policies redirecting the economy towards sustainability. It argues that the current period, marked by the Covid-19 pandemic, established a momentum of change favoring the effectiveness of climate policies to reduce carbon emissions while raising concerns about their

economic impact. In this regard, the chapter introduces the concept of the double dividend effect stating that climate policy measures can have positive economic and environmental effects if they eliminate pre-existing inefficiencies. This principle is the basis of Chapter 2.

The second chapter investigates the effect of climate policies on labor markets in developing countries. Labor market effects arise from heterogeneous impacts of policies on the relative sectoral profitability, which changes the allocation of workers. Therefore, climate policies can be a tool to allocate labor more efficiently. This is especially important in developing countries, where a high percentage of workers are in the unproductive informal sector. Thus, given that labor market effects are taken into consideration, the informal sector provides the potential for environmentally and economically beneficial climate policies. In particular, Chapter 2 employs a dynamic computational general equilibrium model to study the impact of climate policy measures on labor markets in developing countries and to identify double dividend effects. It shows that developing countries can—using climate policies that account for their labor market effects—improve welfare and average working conditions while reaching their climate targets.

Inefficiencies other than those in labor markets can also be addressed to obtain positive economic effects with climate policy measures. For instance, a lack of charging infrastructure hampers the diffusion of climate-friendly technologies like battery electric vehicles, as discussed in Chapter 3.

The third chapter examines relevant channels for a large-scale diffusion of battery electric vehicles. In particular, it investigates the role of network effects between battery electric vehicles and charging stations. In this regard, network effects denote a barrier to the further diffusion of battery electric vehicles. The chapter uses a theoretical economic model to show how climate policy measures can overcome this barrier and promote diffusing climate-friendly passenger cars. Further, the optimal policy utilizes network effects to boost economic output and improve environmental quality, thus yielding a double dividend.

Promoting the diffusion of battery electric vehicles can reduce emissions from passenger transportation. However, decarbonizing the passenger transport sector in optimal economic terms also requires including public transport, technological progress, and changes to passenger behavior. Chapter 4 thus focuses on a holistic approach to finding the optimal decarbonization pathway for the passenger transport sector.

The fourth chapter presents an in-depth analysis of different decarbonization strategies for passenger transport, looking at the case of Switzerland. It combines a dynamic computational general equilibrium model with two transport models allowing for an economic analysis based on a highly disaggregated transport system. This framework is calibrated for Switzerland to identify the environmental and economic impact of different decarbonization pathways based on technological improvements, behavioral changes, and market-based instruments. Chapter 4 shows that the pathways considered increase welfare while reducing CO_2 emissions of Swiss passenger transport significantly. The reduction is, however, not sufficient to reach Switzerland‘s net-zero target until 2050. The chapter argues that Switzerland needs to consider climate policy measures based on bans, such as for purchasing emission-intensive passenger cars, to decarbonize its passenger transport sector.

Kurzfassung

Es besteht ein wissenschaftlicher Konsens darüber, dass die Kohlenstoffemissionen weltweit reduziert werden müssen, um der Bedrohung durch die globale Erwärmung zu begegnen. Als Reaktion darauf haben 197 Länder dem Pariser Klimaabkommen zugestimmt, welches darauf abzielt, den globalen Temperaturanstieg in diesem Jahrhundert auf zwei Grad Celsius zu begrenzen. Es erfordert eine weitreichende Klimapolitik, um die derzeitige, auf fossilen Brennstoffen basierende Weltwirtschaft in Richtung Nachhaltigkeit umzusteuern. Bei der Gestaltung der dafür notwendigen Klimapolitik ist es entscheidend, dass auch wirtschaftliche Belange berücksichtigt werden. Erhebliche ökonomische Kosten im Zusammenhang mit klimapolitischen Maßnahmen verringern die gesellschaftliche Akzeptanz und daher möglicherweise deren Durchführbarkeit. Dementsprechend ist die ökonomische Wirkung von Klimapolitiken besonders relevant, um einen sozialverträglichen Übergang in eine nachhaltige Zukunft zu erreichen. Es liegt also in der Verantwortung der nationalen Politik, eine emissionssenkende Klimapolitik im Einklang mit den wirtschaftlichen Interessen festzulegen.

Diese Dissertation untersucht die Auswirkungen klimapolitischer Maßnahmen auf die Wirtschaft und deren Emissionen. Dazu werden ökonomische Modelle eingesetzt, welche die Zusammenhänge zwischen Klimapolitik und Wirtschaft erfassen, um daraus Empfehlungen für eine ökonomisch sinnvolle Klimapolitik abzuleiten. Die Arbeit leistet einen Beitrag zur Beantwortung der grundlegenden Frage nach der Erreichung von Klimazielen unter den besten ökonomischen Bedingungen aus

zwei Perspektiven: dem Arbeitsmarkt und dem Verkehrssektor.

Das erste Kapitel unterstreicht die Relevanz klimapolitischer Massnahmen, um die Wirtschaft in Richtung Nachhaltigkeit umzulenken. Es wird argumentiert, dass die aktuelle, durch die Covid-19 Pandemie gekennzeichnete Periode eine Dynamik des Wandels hervorgerufen hat, die die Effektivität von Klimapolitiken zur Reduktion von Kohlenstoffemissionen begünstigt, während sie gleichzeitig Bedenken hinsichtlich ihrer wirtschaftlichen Auswirkungen verstärkt. In diesem Zusammenhang führt das Kapitel das Konzept des Doppeldividendeneffekts ein, das besagt, dass klimapolitische Maßnahmen positive ökonomische und ökologische Effekte haben können, wenn sie bestehende Ineffizienzen beseitigen. Dieses Prinzip ist die Grundlage von Kapitel 2.

Das zweite Kapitel untersucht die Auswirkungen von klimapolitischen Massnahmen auf die Arbeitsmärkte in Entwicklungsländern. Arbeitsmarkteffekte ergeben sich aus den heterogenen Auswirkungen der Politik auf die relative sektorale Profitabilität, welche die Allokation der Arbeitskräfte verändert. Daher können klimapolitische Maßnahmen auch dazu verwendet werden, um Arbeitskräfte effizienter zu allozieren. Dies ist insbesondere in Entwicklungsländern wichtig, wo ein hoher Anteil der Arbeitenden im unproduktiven informellen Sektor tätig ist. Somit bietet das Vorhandensein eines informellen Sektors Spielraum für eine ökologisch und ökonomisch vorteilhafte Klimapolitik, sofern Arbeitsmarkteffekte berücksichtigt werden. Kapitel 2 verwendet ein dynamisches computergestütztes allgemeines Gleichgewichtsmodell, um die Auswirkungen von klimapolitischen Maßnahmen auf die Arbeitsmärkte in Entwicklungsländern zu untersuchen und damit doppelte Dividendeneffekte zu identifizieren. Es wird gezeigt, dass Entwicklungsländer durch klimapolitische Maßnahmen, die ihre Arbeitsmarkteffekte berücksichtigen, die Wohlfahrt und die durchschnittlichen Arbeitsbedingungen verbessern und gleichzeitig ihre Klimaziele erreichen können.

Auch andere Ineffizienzen als die der Arbeitsmärkte können angegangen werden, um positive wirtschaftliche Effekte mittels klimapolitischer Massnahmen zu erzielen. So behindert beispielsweise eine fehlende Ladeinfrastruktur die Verbreitung klimafreundlicher Technologien wie der Elektroantrieb bei Personenkraftwagen, was in Kapitel 3 diskutiert wird.

Das dritte Kapitel untersucht die relevanten Kanäle für eine großflächige Diffusion von batteriebetriebenen Elektrofahrzeugen. Insbesondere wird auf die Existenz von Netzwerkeffekten zwischen batteriebetriebenen Elektrofahrzeugen und Ladestationen eingegangen, wobei erörtert wird, dass solche Effekte ein Hindernis für eine weitere Ausbreitung sein können. Das Kapitel zeigt anhand eines theoretischen ökonomischen Modells, wie klimapolitische Maßnahmen dieses Hindernis überwinden, um damit die Diffusion klimafreundlicher Personenkraftwagen zu fördern. Darüber hinaus nutzt die optimale klimapolitische Massnahme Netzwerkeffekte, um die Wirtschaftsleistung zu steigern und gleichzeitig die Umweltqualität zu verbessern, so dass eine doppelte Dividende erzielt werden kann.

Die Förderung der Verbreitung von batteriebetriebenen Elektrofahrzeugen kann die Emissionen des Personenverkehrs reduzieren. Um die Dekarbonisierung des Personentransportsektors unter optimalen wirtschaftlichen Bedingungen zu erreichen, müssen jedoch auch der öffentliche Verkehr, der technologische Fortschritt und Änderungen im Mobilitätsverhalten berücksichtigt werden. Kapitel 4 konzentriert sich daher auf einen ganzheitlichen Ansatz, um den optimalen Dekarbonisierungspfad für den Personenverkehrssektor zu finden.

Das vierte Kapitel präsentiert eine eingehende Analyse verschiedener Dekarbonisierungsstrategien für den Personenverkehr, wobei der Fall der Schweiz betrachtet wird. Es kombiniert ein dynamisches computergestütztes allgemeines Gleichgewichtsmodell mit zwei Verkehrsmodellen, was eine wirtschaftliche Analyse auf der Grundlage eines hochgradig disaggregierten Verkehrssystems ermöglicht. Dieses aus drei Modellen bestehende Framework wird für die Schweiz kalibriert, um die ökologischen und ökonomischen Auswirkungen verschiedener Dekarbonisierungspfade basierend auf marktbasierten Instrumenten, technologischen Veränderungen und Verhaltensanpassungen zu identifizieren. Kapitel 4 zeigt, dass die betrachteten

Pfade die Wohlfahrt erhöhen und gleichzeitig die CO_2-Emissionen des Schweizer Personenverkehrs deutlich reduzieren. Die Reduktion ist jedoch nicht ausreichend, um das Netto-Null-Ziel der Schweiz bis 2050 zu erreichen. Das Kapitel argumentiert, dass die Schweiz klimapolitische Maßnahmen basierend auf Verboten, wie beispielsweise von emissionsintensive Personenkraftwagen, in Betracht ziehen muss, um ihren Personenverkehr zu dekarbonisieren.

Chapter 1

Introduction

In 2015, 197 parties to the United Nations Framework Convention on Climate Change (UNFCCC) responded to the global threat of climate change by consenting to the Paris Agreement. The aim is to limit global warming to well below 2 degrees Celsius, preferably 1.5 degrees Celsius above pre-industrial levels. Participants agreed to submit nationally determined targets on their planned contribution to reach the global climate goals. The Paris Agreement is considered a breakthrough in jointly addressing global warming. Its success, however, depends heavily on the social and political will to undertake the necessary transformation in time.

According to Olhoff and Christensen (2019), global greenhouse gas emissions must fall by 7.6% per year over the next decade to reach the 1.5-degree target. In 2020, we came closest to this threshold as emissions dropped by 6.4%, which ended the trend of increasing emissions since 2010 (Jeff Tollefson 2021). This vast drop is, however, misleading as that year was marked by the devastating Covid-19 pandemic. During the pandemic, various countries were compelled to impose lockdowns minimizing the social and economic activities to prevent the spread of the virus. The slowdown of the economy was dramatic: global growth is expected to be -4.9% in 2020, which is by far the lowest rate since the second world war

(IMF 2020).[1]

It is striking that the drastic decline in economic activities is still insufficient to be in line with the 1.5 degrees Celsius target. Thus, far-reaching climate policy measures are needed to induce a transition from today's fossil fuel-based economy towards sustainability. On the one hand, the time to introduce such measures is currently favorable because the Covid-19 pandemic has created a momentum of change that can positively affect the emission reduction potential of climate policies. On the other hand, the pandemic also puts economies under pressure, amplifying the need for economically compatible climate policies. That is important because the social acceptability, and thus the viability of climate policies, is closely linked to their economic impact. Therefore, policies realizing improvements on the economy and the environment need to be identified, referred to as policies with a double dividend effect. A double dividend effect arises when environmental taxes reduce pollution (first dividend), while the revenue of this tax can be used to lower another "more" distortive tax, for example, a labor income tax, which results in economic improvement (second dividend). Such policies create synergies between environmental and economic interests. Thus, they can facilitate the recovery after the Covid-19 pandemic while changing the global economy to become more resource-efficient.

Designing a climate policy requires accounting for its impact on the disaggregated economy, which allows identifying and utilizing double dividend effects in specific economic segments with tailored climate policy measures. To achieve that, a profound understanding of how climate policies affect the economy is needed. This dissertation studies the economic and environmental impact of climate policy measures in the context of two of the most pressing topics: the labor market and the transport sector.

These two topics are commonly recognized as deal-breakers to reach the climate targets. Labor market effects are crucial for the political viability of climate

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[1] The financial crisis in 2009 is second with -1.7% (World Bank Group 2021).

policies as negative labor responses could lower the acceptance of such measures considerably. The transport sector interlinks the economic agents, making a well-functioning transport system fundamental. It poses a challenge to decarbonize the emission-intensive transport sector in time without extensive economic costs. The present thesis identifies double dividend effects and contributes to the build-up of knowledge required to design climate policies in an environmentally and economically optimal way. In what follows, I first discuss the effect of climate policies on the labor market in developing countries and then on the transport sector.

1.1 Climate policies and labor markets

Climate policies impact all segments of the economy, including labor markets. In developed countries, there is great concern that such policies could harm the labor market by increasing the unemployment rate, which lowers their political viability. Similar issues also exist in developing countries, but, in their case, the focus is on the impact on employment quality rather than on the unemployment rate. That is because developing countries are suffering from an employment problem: a lack of an efficient social security system often leaves no option other than to work, resulting in a relatively low unemployment rate (Fields 2011). Individuals who do not get one of the few "high-quality" jobs need to work in "low-quality" jobs to make a living under poor conditions and with low wages because being unemployed is financially unattractive.

An important aspect of labor markets in developing countries is the presence of an extensive informal sector, which does not conform with government-imposed regulations like taxes and laws (De Soto et al. 1989). According to Loayza (2016), 70% of the workforce is informal in a typical developing country. Such informal jobs have no social protection, leaving their workers exposed to exploitation. However, for many, the informal sector is the only option to work and earn money. In addition, it is hard to switch to the formal sector once working in its informal counterpart. This means that labor markets in developing countries are segmented into different employment groups and that the labor mobility between these groups is imperfect. In segmented labor markets, job losses often come with a social downfall, with one suddenly finding oneself in a low-quality job. Initially, this is a temporary strategy to survive but often results in a permanent status due to difficulties getting out of the segmented labor force again. In such an environment, the political viability of policies is closely connected to their effect on the labor market. That is particularly the case for climate policies, which, at least since the Paris Agreement of 2015, became relevant for developing countries. Such climate policies are generally conceived as being unfair since developing countries only marginally contributed to the emissions already emitted. Moreover, the argument of long-term climate improvements loses importance in a context where a loss of jobs due to climate policies could lead to severe consequences. Therefore, the success of climate policies crucially depends on labor market effects.

Chapter 2 examines how climate policies affect the economy in developing countries when disaggregated labor market effects are taken into account. In order to describe the labor market in developing countries, the chapter builds on a search and match approach in the spirit of Pissarides (1985) to capture the flow of workers between different labor segments, where search frictions prevent the labor market from being fully mobile. The most common characteristics of developing countries, such as the split between formal and informal sectors, are considered. The contribution of Chapter 2 is the development of a model, which allows studying the impact of climate policy measures on labor markets and economies of developing countries to identify economically and environmentally sound climate policies.

1.2 Climate policies in the transport sector

The importance of the transport sector has been rising considerably during globalization. Due to the increasing demand and requirements for transportation, the transport system has been constantly developed to become even more efficient and cost-effective. Sustainability considerations, however, have long been ignored, resulting in the transport sector emitting 24% of global CO_2 emissions in 2018, second only to the the electricity and heat generation sector. Most of these emissions are caused by passenger road vehicles accounting for nearly 45% of transport emissions (IEA 2021). With the advent of the climate debate, it has become clear that the transport system must change in the direction of sustainability and resource efficiency. As the means used for transport, such as cars, trucks, or ships, are often long-lived and climate targets are pressing, it is essential to start the transition in time. Currently, the situation is favorable for far-reaching policies in the transport sector: mobility behavior changed globally towards less traveling due to the Covid-19 pandemic. That offers governments a unique opportunity to build on this behavioral change by introducing climate policies utilizing the momentum to establish a sustainable transport system. The following two sections elaborate on different climate policies targeting the transport sector. The first section addresses network effects between battery electric vehicles (BEVs) and charging stations, and the second the decarbonization of the Swiss passenger transport system.

1.2.1 Network effects

With the advent of BEVs, a climate-friendly alternative to the prevailing internal combustion engine vehicles (ICEVs) has emerged. Norway, for example, has increased the number of BEVs by nearly 400% since 2015, resulting in a BEV-share of 13% in 2020 (Statistics Norway 2021). The extensive diffusion of BEVs has led to a sharp reduction in average vehicle emissions. This development, however, was only possible thanks to far-reaching climate policies favoring sustainable transport modes. Without such policies, high purchase costs, range anxiety, or insufficient charging infrastructure with long charging times stand in the way of widespread adoption (Agora-Verkehrwende 2017). The latter consideration leads to the well-known chicken-egg problem: poor charging infrastructure decreases the value for

BEVs, which reduces their sales. That, in turn, reduces the profitability of charging stations and lessens the incentive to install one. Consequently, sales of BEVs and installing charging stations are linked by so-called positive network effects. In such an environment, government interventions can be amplified by the network effects, making them highly effective.

Chapter 3 elaborates on climate policy measures to foster the adoption of BEVs when network effects are present. To describe the diffusion process of BEVs and to model their network effects with charging stations, a two-sided market approach is used in Chapter 3, based on Rochet and Tirole (2003) and Springel (2016). One side of the market represents the BEV owners and the other retailers, which install charging stations to attract more consumers. These sides are connected via positive network externalities as BEV owners profit from the charging stations, while the retailer supplying a charging opportunity can welcome more clients. Thus, the number of BEVs (charging stations) positively affects the incentive to buy a charging station (BEV). Chapter 3 develops a theoretical model incorporating such network effects to identify climate policy measures that utilize network effects in an economically and environmentally optimal way.

1.2.2 Decarbonizing the Swiss passenger transport

Switzerland has embarked on the ambitious challenge to decarbonize its transport sector until 2050 as part of its net-zero emissions target. Achieving this goal requires a substantial transformation of the transport sector, which emits about 40% of total CO_2 emissions in Switzerland. Contrary to other sectors, the Swiss transportation sector is not yet on a clear emissions reduction path: since 1990, CO_2 emissions have been reduced significantly in most other sectors, whereas they have been increasing by 3% in the transport sector (BAFU 2020).[2] While countries such as the United Kingdom and France announced plans to introduce abrupt measures

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[2] As an example, according to BAFU (2020), the CO_2 emissions of the industry sector decreased by 18% in the same period.

such as a sale ban for ICEVs, Switzerland has, so far, refrained from doing so despite the relatively large share of transport emissions.

Chapter 4 examines whether Switzerland can achieve the net-zero emission target without such abrupt measures relying on technological improvements, behavioral changes, and "non-abrupt" market-based instruments. To incorporate a highly disaggregated passenger transport system into the broader economic analysis, Chapter 4 follows a multi-model approach, interlinking a dynamic computational general equilibrium model of the economy of Switzerland with two external passenger transport models. With this framework, the economic impact and the emission-saving potential of different decarbonization pathways for Swiss passenger transport are analyzed to evaluate the measures needed to reach the climate target.

1.3 Outline of the thesis

This dissertation utilizes economic models to capture the economic impact of climate policies on the labor market in developing countries and the transportation sector. By identifying double dividend effects, economically and environmentally sound climate policies are unveiled. The thesis addresses the following research questions:

- Chapter 2: How do climate policies affect labor markets in developing countries, and how do they need to be designed when considering labor market effects?
- Chapter 3: What is the role of network effects in the transition to a low-carbon passenger transport sector? What are the welfare implications of reducing the share of polluting vehicles using climate policies in the presence of network effects?
- Chapter 4: What is the economic impact and emission reduction potential of a decarbonization pathway of Swiss passenger transport based on technological

> improvements, economic-based instruments, and behavioral changes? Are those pathways sufficient to achieve net-zero emissions by 2050 for Swiss passenger transportation?

Methodologies from different strands of economic literature are required to answer the research questions of each chapter. Chapter 2 follows a macroeconomic approach and develops a computational general equilibrium model with a search and match mechanism based on Pissarides (1985), which is extended to capture typical features of labor markets in developing countries. Chapter 3 builds on the literature on two-sided markets in the spirit of Rochet and Tirole (2003). In Chapter 4, insights of the strand of literature about macroeconomics and transportation are used to develop a multi-model framework consisting of a dynamic general equilibrium model and two transportation models.

Chapter 2 investigates the impact of climate policies on the labor markets in developing countries characterized by a large informal economy. The analysis is conducted employing a dynamic general equilibrium model, which incorporates the three prevalent working groups in developing countries: informal self-employment, informal employment, and formal employment. To capture the mobility of workers between these groups, the chapter uses a search and match mechanism with search frictions for formal and informal firms and with on-the-job search. The model is calibrated to India to elaborate on the impact of climate policies envisioning a tax on energy with different redistribution schemes of the tax revenue. The results show that climate policies strengthening the position of the productive formal sector can lead to a triple dividend effect: emissions drop due to the energy tax, whereas the redistribution scheme increases the formal labor share and welfare. Developing countries with widespread informality can utilize climate policies to improve labor conditions while reaching their climate targets.

Decarbonizing the transportation sector is a key measure to reduce carbon emissions at the global level. A crucial factor to achieve a sustainable transportation system is the diffusion of electric vehicles. Accordingly, Chapter 3 studies the network effects inducing a positive relationship between electric vehicles and charging stations. To do so, a two-sided market model that captures such network externalities is developed. A platform provides one side of the market with electric and internal combustion engine vehicles to consumers, while it supplies retailers with charging stations on the other side. This framework is used to study policies tackling different sides of the market. In the presence of network effects and environmental damage from polluting cars, optimal policies can lead to a double dividend: decreasing the quantity of internal combustion engine vehicles can be economically improving while reducing the negative impact of pollution.[3]

Switzerland committed to reaching net-zero emissions in 2050. This goal is particularly ambitious for the Swiss passenger transport system, which emits more than one third of Swiss CO_2 emissions, and is not yet on a clear emission reduction path. The chapter investigates the economic impact and the emission-saving potential of a decarbonization pathway for the Swiss transport sector based on three edge case scenarios and on a combination of them: (1) improved fuel/engine technology and fostered diffusion of battery electric vehicle, (2) increased capacity use of passenger cars, and (3) enhanced modal shift towards public transport. The analysis is conducted using a multi-model framework, which interlinks a computational general equilibrium model with two external transportation models. This approach allows us to incorporate a highly disaggregated passenger transport system into the economic analysis. The framework is calibrated to Swiss data to assess the optimal scenario mix in terms of emissions and economic impact. The optimal decarbonization pathway mix slightly increases welfare and lowers CO_2 emissions of passenger transport in 2050 from 6 to 1.7 million tons CO_2 compared to the reference scenario. Despite the sharp reduction in emissions, a decarbonization pathway based on the considered scenarios is insufficient to reach the net-zero emission target.[4]

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[3] In Chapter 3, I contributed to developing the theoretical model and the simulation analysis.

[4] My contribution in Chapter 4 lies in developing the cohort model, the regression model, data collection and processing, and supporting the simulation of the model.

Chapter 2

Climate Policies and Labor Markets in Developing Countries

Abstract

Chapter 2 investigates the impact of climate policies on the labor markets in developing countries characterized by a large informal economy. I conduct the analysis employing a dynamic general equilibrium model, which incorporates the three prevalent working groups in developing countries: informal self-employment, informal employment, and formal employment. To capture the mobility of workers between these groups, I use a search and match mechanism with search frictions for formal and informal firms and with on-the-job search. The model is calibrated to India to elaborate on the impact of climate policies envisioning a tax on energy with different redistribution schemes of the tax revenue. The results show that climate policies strengthening the position of the productive formal sector can lead to a triple dividend effect: emissions drop due to the energy tax, whereas the redistribution scheme increases the formal labor share and welfare. Developing countries with widespread informality can utilize climate policies to improve labor

conditions while reaching their climate targets.

2.1 Introduction

> "What the developing countries have is an employment problem - that is, poverty amongst those who work - rather than an unemployment problem."(Fields 2011, p.18)

Living in a developing country without an effective social security system often leaves no option other than to work. That typically results in a low unemployment rate but is accompanied by widespread working poverty. Individuals not getting one of the few "high-quality" jobs need to work in "low-quality" jobs to make a living under poor conditions and with low wages. Those low-quality jobs are essential, and a job loss, for example, due to a policy with a negative impact on the labor market, could lead to severe consequences. In such an environment, the political viability of policies is closely connected to their effect on the labor market. That is particularly the case for climate policies, which, at least since the Paris agreement of 2015, became relevant for developing countries. Such climate policies are generally conceived as being unfair since developing countries only marginally contributed to the emissions already emitted. Moreover, the argument of long-term climate improvements loses importance in a context where a loss of jobs due to climate policies could lead to immediate consequences. This chapter studies how climate policies affect labor markets in developing countries. The objective is to explore the optimal design of climate policies in developing countries considering labor market effects.

The topic of climate policies and their effect on labor markets gained relevance in recent years due to global efforts addressing the challenges of climate change: on the one hand, such policies work as "job killers" for polluting industries because they decrease their relative profitability, and on the other hand, they create new "green jobs" for less-polluting industries. Alongside the direct impact on the industry targeted by a climate policy, these two effects impact the economic-wide employment and wage structure. In this regard, Hafstead and Williams (2018) develop a general equilibrium model capturing the entire labor market to elaborate on the net-job effect of a climate policy in developed countries. Their analysis focuses on the quantitative job effect of a climate policy. Developing countries, however, face a job-quality problem, meaning that focusing on the quantitative aspect is not sufficient. Thus, studying the labor market in developing countries requires analyzing the green job versus the job killer effect in quantitative and qualitative terms. So far, the economic literature does not deliver answers to this fundamental issue.

According to Loayza (2016), the employment of around 70% of the workforce in a typical developing country is not in accordance with government-imposed regulations and laws, making them the informal labor force in the economy (De Soto et al. 1989). Such informal jobs have no social protection, leaving their workers exposed to exploitation. Thus, the employment problem arises from the existence of an extensive informal sector in developing countries. It is widely recognized that the widespread informal sector in developing countries is a cause and, at the same time, a consequence of underdevelopment. The informal sector operates outside the legal framework, lowering the effectiveness of governmental-imposed policies that would favor development. The informal sector is, however, for many, the only viable option to work and earn money in underdeveloped countries. That leads to another issue regarding labor markets in developing countries closely related to informality - the segmented labor force.[1] Some individuals cannot switch to the formal sector even if they would be capable and willing to work there, leaving them trapped in the informal sector. In this regard, researchers developed various search and match models based on Mortensen and Pissarides (1994), where search frictions prevent informal workers from finding a job in the formal sector. These models deliver useful insights into a wide range of different aspects of the developing country‘s

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[1] See Fields (2009) for a review of segmented labor market models in developing countries.

labor markets. The effect of climate policies, however, remains to be addressed. Therefore, a general equilibrium model containing search frictions for developing countries is needed to capture the effect of climate policies on the labor markets, as highlighted by Hafstead, Williams, Golub, Meijer, Narayanan, Nyamweya and Steinbuks (2018).

India is a major emitter of greenhouse gas emissions and thus of particular interest to study climate policies and labor market effects. Moreover, according to Mehrotra et al. (2019), around 90% of the workers in India are in the informal sector, making it the largest informal workforce worldwide. The informal sector is not homogenous and consists of two main groups: (informal) self-employment and informal firm employment. More than half of the workforce in India is self-, respectively, family-employed. Those individuals are engaged in own-production, which typically displays a high labor intensity and low productivity (e.g. family farms). The remaining informal workers mainly work in informal firms. Due to the informality, their employment is not in accordance with governmental regulations and differs substantially from formal employment. Furthermore, there is evidence showing that informal and formal firms differ in their structure. Informal firms tend to be smaller and less productive than their formal counterpart (e.g. Bigsten et al. (2004); Prado (2011); La Porta and Shleifer (2014)). These variations imply that climate policies can affect labor segments differently. Thus, it is important to distinguish between informality and formality and also within informality. In what follows, I briefly explain how I include those elements in my model and how this chapter contributes to the literature.

2.1.1 Contribution

I develop a dynamic general equilibrium model with heterogeneous households. Considering the employment problem of developing countries, the model does not include unemployment. Instead, I disaggregate the workforce of each sector into the three prevalent working groups in developing countries: (informal) self-employment, informal (firm) employment, and formal (firm) employment. The model relies on three main elements: on-the-job-search, search frictions, and a "three-stage matching process". I assume that working individuals use their spare time to search for a better job in each period. To create matches with searching individuals, informal and formal firms need to employ (costly) recruiters, meaning that firms have search frictions. That is in contrast to self-employment, which does not face search frictions, making it the outside option for firm employment. Also, I include a search and match mechanism. To do so, I extend the "two-stage matching process", based on Mortensen and Pissarides (1994), to a "three-stage matching process" with self-, informal- and formal employment, whereby individuals can search for any better job, irrespective of where they are currently working. I assume that self-employed individuals match with informal and formal firms and informally employed individuals with formal firms only. Thus, informal employment is an intermediate step between self-and formal employment, where switching to informal employment leaves the possibility open to match with formal firms. That structure allows me to capture the matches within informality and between informality and formality. Consequently, my model incorporates the flow of workers between the prevalent working groups in developing countries. Moreover, because the energy for production and consumption is included, I can evaluate the disaggregated labor market effects caused by climate policies.

I establish a tractable model that could be applied to a wide range of developing countries. For this chapter, the model is calibrated to India using the Input-Output table from the Asian Development Bank (2012), and labor data from Mehrotra et al. (2019) for the year 2011/2012. To capture the sector-specific labor response, I incorporate three sectors: agriculture, industry, and services. I simulate the impact of a climate policy decreasing the energy use up to 20%.[2] In my framework,

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[2] In 2012, the energy mix in India consisted mainly of non-renewable resources such as coal and crude oil. Without a significant share of renewable energy sources, energy use goes hand in hand with emissions, as switching to clean energy is, at least in the short term, not possible. Thus, I treat energy use as a proxy for the emissions in my model.

I implement a tax on energy use, where its revenue is redistributed according to four measures: (1) equal lump-sum redistribution, (2) lump-sum redistribution to self-employed individuals, (3) decreasing the formal labor tax, and (4) lowering the bureaucratic costs per formal worker. Considering utilitarian welfare, the design of the optimal policy mix depends on its stringency. It is optimal to decrease the formal labor tax and lowering formal bureaucratic costs for an energy decrease up to 15%. From 15% onwards, the optimal policy mix additionally includes lump-sum transfers to self-employed individuals. I find that, until 18.5%, this policy mix leads to an increase of formal employment at the expense of self-and informal employment. Thus, the green job effect outweighs the job killer effect quantitatively (more jobs) and qualitatively (better jobs).[3] Moreover, next to reducing emissions, the optimal climate policy mix positively affects welfare for an energy reduction up to 13.4%. Thus, there is a range of energy taxes leading to a triple dividend effect. This policy mix, however, magnifies inequality. Such effects on inequality could hamper the political viability of the climate policy. Thus, I additionally evaluate the optimal policy mix keeping inequality constant. In that case, the revenue should be used to decrease the formal bureaucratic costs and for lump-sum transfers to the self-employed individuals. This policy mix leads to an increase in self-and formal employment while informal employment shrinks. Thus, fewer but better jobs are available, meaning that the green job effect outweighs the job killer effect in qualitative but not quantitative terms. Moreover, the policy mix enhances utilitarian welfare for an energy decrease up to 8.5%. These results are based on the following mechanisms:

First, energy providers can generally observe the energy use of all economic players. Consequently, in contrast to labor taxes, which only affect the formal economy, energy taxes are a valuable instrument to tax the informal sector (Heine and Black 2019).

Second, using the energy tax revenue to lower formal labor income taxes or formal

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[3] I consider firm employment as jobs and self-employment as no jobs to analyze the green job versus job killer effect of a climate policy.

bureaucratic costs per worker decreases formal labor costs. That boosts formal employment mainly at the expense of its informal counterpart leading to favorable labor market outcomes. These two measures, however, differ substantially in their impact on the labor market. That is mainly because of contrary wage effects. Decreasing the labor income tax positively affects formal wages. That, in turn, mitigates the negative impact of the measure on the formal labor costs. Thus, the labor response is relatively low. In contrast, lowering the formal bureaucratic costs per worker does not directly affect the wages. Consequently, this measure leads to an extensive labor response. This finding is in accordance with the empirical literature, which indicates that policies helping firms overcoming issues like bureaucratic costs are more promising in creating new jobs than intervening in the labor supply with wage subsidies (McKenzie 2017).

Last, lump-sum redistribution schemes decrease the incentive to work and are thus, in combination with energy taxes, neither beneficial for the labor market nor utilitarian welfare. They are, however, an efficient instrument to improve equality.

2.1.2 Relation to literature

In the last years, researchers started to develop general equilibrium search and match models to elaborate on the overall effect of climate policies on labor markets.[4] Most studies, however, focus on the developed countries, despite the high relevance for developing countries. An exception is Kuralbayeva (2018), which develops a general equilibrium model using search frictions to analyze the effect of climate policies on the labor market in Mexico. This model focuses on rural-urban migration and, therefore, belongs to the search and match models based on the seminal work of Harris and Todaro (1970).[5] The model introduced here differs substantially in three key aspects. First, I consider formal and informal firms with search frictions in my model, whereas Kuralbayeva (2018) includes an urban, for-

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[4] See Aubert and Chiroleu-Assouline (2019) and Hafstead and Williams (2018).

[5] See Fugazza and Jacques (2004), Albrecht et al. (2009) and Günther and Launov (2012).

mal sector with search frictions and an urban and rural informal sector without frictions. Considering that all firms are hiring workers and thus have search frictions, this approach only relies on self-employment. Therefore, it leaves out the crucial role of informal firms in developing countries. Second, I do not differentiate between urban and rural employment. In my model, all individuals, irrespective of where they are located, can search for a job in a firm. Thus, search frictions in the labor market define labor mobility. That is in contrast to the migration mechanism used in Kuralbayeva (2018): if the expected urban wage is higher than its rural counterpart plus migration costs, then some rural individuals are incentivized to migrate to the urban sector to try their "luck" there. This assumption was first questioned by Banerjee (1984), who shows empirically that a sizable proportion of urban migrants did not just migrate to try their "luck", but rather because they already have a specific job in prospect. That indicates that not only the urban individuals engage in search activities but also the rural individuals. Last, I calibrate the model to India, using extensive economic and labor data, to get a computational general equilibrium model for India.

The present chapter is organized as follows. Section 2.2 describes the multi-sectoral model with search frictions for developing countries. Section 2.3 sets up the steady-state conditions and provides an analysis of the wage mechanism in a three-stage matching process. The calibration of the model with Indian data is explained in Section 2.4. Section 2.5 analyzes the effect of an energy tax and different redistribution schemes, and Section 2.6 concludes the chapter.

2.2 A multi-sectoral model with search frictions for developing countries

I build up a dynamic general equilibrium model incorporating search frictions, particularly suitable for developing countries. In particular, I extend the search and match model of Hafstead and Williams (2018) for developed countries introducing important properties of labor markets in developing countries. The main difference between search models based on Pissarides (1985) and Mortensen and Pissarides (1994) is that the presented model is not about unemployment but about working individuals using their spare time to search for a better job. Thus, my model allows for on-the-job search. Considering that developing countries face an employment problem, this becomes crucial to capture labor markets in developing countries where unemployment plays a minor role.

The model incorporates heterogeneous households. These households differ with respect to where they are currently working: self-employment, informal (firm) employment, or formal (firm) employment. They choose the working hours depending on the labor income. With the remaining hours of the day, they automatically search for better jobs. Consequently, the search intensity of a household, and, thus, the probability of finding a better job, depends on the choice of working hours and is household-specific.

The sectoral output is produced using three different production technologies: own-production, informal firm production, and formal firm production. Own-production uses energy, labor, and materials (EL(M)) as inputs, whereas firm production additionally uses capital (KE-L(M)). Following Anand and Khera (2016), these technologies are imperfect substitutes and mainly differ by their productivity. Formal firms are the most productive, followed by informal firms and then by own-production. Self-employed individuals are working in own-production. This technology serves as the "last resort" for the labor market. Individuals not finding a job in a firm can enter without (search) frictions, and, thus, self-employment is the outside option to firm employment. This technology is relatively labor-intensive and, as there are no frictions, has competitive wages. That is in contrast to firm production, where search frictions are present. Each period, some individuals are separating from firm employment to self-employment according to an exogenous separation rate. To counteract this outflow of workers, firms can allocate some of their labor to recruitment. Recruiters meet with all individuals searching for a better job to create matches for the coming periods. Thus, my model has a three-stage matching process with self-, informally, and formally employed individuals. I assume that self-employed individuals match with informal and formal firms and informally employed individuals with formal firms. That structure allows me to capture the flow of workers within informality (from self-employment to informal employment) and also between informality and formality. Further, I include different labor strategies.[6]

The scale of the flow of workers is based on a firm-specific matching function. This function includes the search effort of the individuals, the recruitment effort of a specific firm, and the aggregated recruitment effort of all firms to determine the number of matches created by a particular firm during the matching process. The firms need to optimally distribute the stock of labor to production for today and production for tomorrow, where recruiters hire new workers for the next period (which then can be used for production). Thus, firms are solving a dynamic optimization problem, where the search costs (wage payments for recruiters) prevent wages from being competitive. Instead, I endogenize wages using a Nash-bargaining process, which divides the firm‘s matching surplus and the averaged matching surplus of the households according to a bargaining power parameter.

2.2.1 Households

In this model, all households are equally endowed and have similar abilities. They value leisure and choose the hours they want to work to receive labor income. Additionally, they use their spare time to search for a superior job. This mechanism is similar to Pissarides (1985), where unemployed individuals enjoy their leisure and automatically search for a job. The difference to the model of Pissarides, where a household can either work or search, is that in my model, a household can spend some hours working and automatically search for a better job with the remaining

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[6] For example, self-employed individuals can climb the job ladder stepwise, going first to informal firm employment and continue searching for a job in a formal firm there, or they directly jump to formal employment, which is, however, harder to do.

hours.

I abstract from household savings and, therefore, households are living hand-to-mouth.[7] Although this is a simplifying assumption, the advantage of this approach is that it allows me abstracting from the usually assumed full insurance assumption within households based on Merz (1995). This assumption is reasonable for developed countries but has limitations for developing countries, as poor households often cannot insure against transitory shocks (Blundell et al. 2008).

In the model, there are $n_{i,l}$ individuals of the same household type. They operate in sector i and are $l \in \{F, I, S\}$ employed, where F stands for formal, I for informal, and S for self. I normalize the total number of individuals to 1. They work $h_{i,l}$ hours and receive an hourly wage $w_{i,l}$. The households employed in a formal firm have to pay labor income taxes at a rate $\tau_F > 0$, whereas $\tau_I = \tau_S = 0$ holds, as households working informally do not pay labor income taxes. The period utility function is

$$U_{i,l} = Log(c_{i,l} + 1) - \psi \frac{h_{i,l}^{1+\chi}}{1+\chi} \tag{2.1}$$

where $c_{i,l}$ is the final good consumption, ψ the disutility from work parameter, and $\frac{1}{\chi}$ the Frisch elasticity of labor supply. The budget constraint is

$$w_{i,l} h_{i,l} (1 - \tau_l) \leq P_c c_{i,l}. \tag{2.2}$$

where P_c is the price of the final consumption good. Based on that, I can set up the Lagrangian according to

$$\mathcal{L}_{i,l} = Log(c_{i,l} + 1) + \lambda_{i,l} (w_{i,l} h_{i,l} (1 - \tau_l) - P_c c_{i,l}) - \psi \frac{h_{i,l}^{1+\chi}}{1+\chi} \tag{2.3}$$

which allows me to solve for the optimal hours and consumption. I assume that households do not account for searching when they make their labor choice, meaning that they take the job-finding probability as exogenous.

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[7] I assume that households discount the future at a given discount rate Q as they are impatient.

2.2.2 The three-stage matching process

I start by assuming that it is best to be employed at a formal firm, then by an informal firm, and worst to be self-employed. This pattern is typically present in developing countries.[8] This assumption induces that self-employed households operating in sector i would prefer to work in a formal or in an informal firm. Therefore, they indiscriminately search $(T - h_{i,S})$ hours, where T is the available time per day, for a job outside of self-employment. In turn, the households employed in an informal firm would prefer to work in a formal firm but not to be self-employed. As a consequence, they search $(T - h_{i,I})$ hours for a job at a formal firm.[9] However, the households employed in a formal firm do not have a better option and do not search. Consequently, the self-employed household operating in sector i can match with an informal firm in sector j, $m_{i,S}^{j,I}$, or a formal firm in sector j, $m_{i,S}^{j,F}$, whereas an employee of an informal firm in sector i can match with a formal firm in sector j, $m_{i,I}^{j,F}$. Therefore, my model uses a "three-stage matching process", where I include informal employment as an intermediate step to formal employment. The flow of workers between these three stages is based on the matching function, which I describe next.

Matching Function

In the definition of the matching functions, I follow Hafstead and Williams (2018) setting up a matching function for multiple sectors, where a firm employs recruiters to create matches with individuals interested in the job. I extend this matching function by accounting for the searching time of the individuals and the disparity

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[8] Note that, in reality, the earnings of self-employed individuals often differ and can be high. However, in developing countries, it is generally the case that individuals are self-employed to get enough to survive. Therefore, in this model, I focus on self-employment in the spirit of the "last resort" idea.

[9] To simplify the model, I assume that a household only searches for a better job outside of her current employment status (self-employed, informal, or formal employed). Consequently, there is no job-to-job transition between sectors within the same employment status. However, if a household changes its employment status, it can change the sector it is operating in.

of formal and informal matching based on the three-stage matching process. In my model, a $k \in \{F, I\}$ firm operating in sector i employs recruiters, $v_{i,k}$, which work $h_{i,k}$ per day. Thus, the firm has a recruitment effort of $v_{i,k}h_{i,k}$ per day. The recruiters meet with individuals interested in the job, who search for $(T - h)$ hours per day, to create matches, $m_{i,k}$, for the upcoming period. The number of matches depends positively on the firm-specific recruitment effort and the household‘s searching effort. Additionally, several firms want to create matches with individuals of the same household. Thus, the aggregated recruitment effort of all firms competing for a particular household negatively affects the number of matches for a specific firm with that household.

The self-employed households are searching indiscriminately for a formal and informal employment. Therefore, the number of matches, $m_{i,S}^{j,k}$, of self-employed households operating in sector i with a k firm in sector j is given by the matching function

$$m_{i,S}^{j,k} = \mu_{j,k}[(T - h_{i,S})n_{i,S}]^{\gamma_{j,k}}(v_{j,k}h_{j,k})\left(\sum_g \sum_z v_{g,z}h_{g,z}\right)^{-\gamma_{j,k}} \tag{2.4}$$

where $\mu_{j,k}$ is the matching efficiency and $\gamma_{j,k}$ the matching elasticity parameter. $m_{i,S}^{j,k}$ is dependent on the recruiting effort of the firm, $v_{j,k}h_{j,k}$, and the total searching effort of the respective self-employed households, $(T - h_{i,S})n_{i,S}$. Moreover, all firms are competing for matches with the self-employed individuals. Thus, $\left(\sum_g \sum_z v_{g,z}h_{g,z}\right)$ represents the aggregate recruiting effort of all firms.

In the three-stage matching process, the self-employed individuals are the only ones who search for a job in the informal firm. Thus, I set

$$m_{j,I} = \sum_i m_{i,S}^{j,I}, \tag{2.5}$$

where $m_{j,I}$ is the aggregated number of matches of the informal firm operating in sector j. For formal employment, however, self-and informally employed individuals are interested in getting a job. Consequently, a formal firm in sector j additionally creates matches with workers employed in an informal firm operating in sector i, which is given by

$$m_{i,I}^{j,F} = \mu_{j,F}[(T - h_{i,I})n_{i,I}]^{\gamma_{j,F}}(v_{j,F}h_{j,F})\left(\sum_z v_{F,z}h_{F,z}\right)^{-\gamma_{j,F}}, \tag{2.6}$$

where $(T - h_{i,I})n_{i,I}$ is the search effort of an informally employed individual. The aggregate recruiting effort, $(\sum_z v_{F,z}h_{F,z})$, does not contain the recruiters of the informal firms, as only the recruiters of the formal firms are competing for informally employed households. The aggregated number of matches for a formal firm in sector j consists of matches with self-employed and informal households:

$$m_{j,F} = \sum_i (m_{i,I}^{j,F} + m_{i,S}^{j,F}) \tag{2.7}$$

Job-Finding probability

Each household faces a specific probability of finding a better job per hour, θ. The number of matches in a sector must be equal to the total searching effort times the probability of the households finding a job in this sector. Therefore, for the self-employed households in sector i, it has to hold that

$$m_{i,S}^{j,k} = ((T - h_{i,S})n_{i,S})\theta_{i,S}^{j,k}, \tag{2.8}$$

whereas for the households employed in an informal firm in sector i,

$$m_{i,I}^{j,F} = ((T - h_{i,I})n_{i,I})\theta_{i,I}^{j,F} \tag{2.9}$$

has to hold. Setting that equal to Equation (2.4), respectively to Equation (2.6), gives

$$\theta_{i,S}^{j,k} = \mu_{j,k}[(T - h_{i,S})n_{i,S}]^{\gamma_{j,k}-1}(v_{j,k}h_{j,k})\left(\sum_g \sum_z v_{g,z}h_{g,z}\right)^{-\gamma_{j,k}} \tag{2.10}$$

and

$$\theta_{i,I}^{j,F} = \mu_{j,F}[(T - h_{i,I})n_{i,I}]^{\gamma_{j,F}-1}(v_{j,F}h_{j,F})\left(\sum_{g} v_{g,F}h_{g,F}\right)^{-\gamma_{j,F}}, \tag{2.11}$$

which shows that the probability of getting a job is endogenous as it depends on the sector-specific labor market tightness. Furthermore, the term for aggregating recruitment effort in Equation (2.10) and (2.11) indicates that it is easier to get a job in a formal firm for households employed in an informal firm than for self-employed households. The reason for that is the assumption that the total recruiting effort negatively affects the number of matches. This effect is stronger for self-employed households than for the informally employed ones because formal and informal firms are competing for self-employed households, while only the formal firms are competing for the latter ones. That pattern is typical for developing countries, where self-employment is usually located in rural areas and informal and formal jobs in urban areas. That makes it more difficult to find a formal job for self-employed individuals. Moreover, individuals employed in an informal firm generally gain more relevant experience for formal employment than self-employed individuals.

Recruiting productivity

I consider the number of matches a recruiter can create per hour as the recruiting productivity. Each firm has a recruiting productivity of $H_{j,k}$. The recruiting effort times the recruiting productivity has to equalize with the number of matches, $m_{j,k} = v_{j,k}h_{j,k}H_{j,k}$. Setting that equal to the total number of matches $m_{j,k}$ from Equation (2.7), respectively from Equation (2.5), and inserting it in Equation (2.4) and Equation (2.6) allows me to solve for $H_{j,k}$. That shows that similar to the probability of getting a job, the recruiting productivity is endogenous.

2.2.3 Production

The production technology of each sector is formulated as a nested constant elasticity of substitution function (CES) as shown in Figure 4.3.2. In this structure, imported goods are imperfect substitutes for domestically produced goods. Moreover, the sectoral output is produced using three production technologies: own-production, informal firm production, and formal firm production. I follow Ju-e and You-min (2009) assuming a KE-L(M) production structure for firm production. Own-production does not use capital and has an E-L(M) production structure. Furthermore, similar to Anand and Khera (2016), I assume that informal and formal goods are substitutable. In what follows, I describe the production process nest after nest. Note that variables are written in capital and parameters in small letters. For simplicity, I omit time-subscripts.

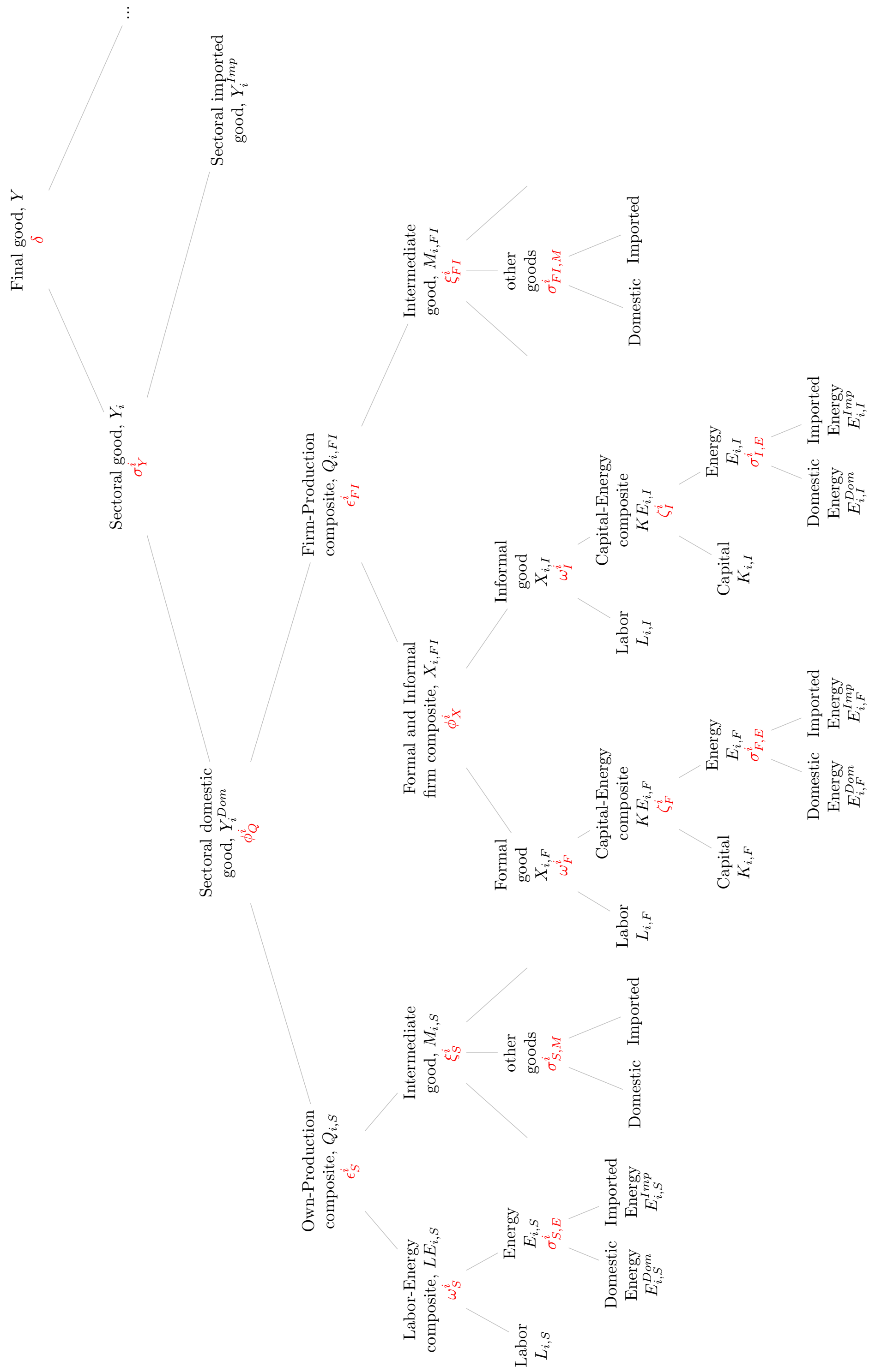

Figure 2.1: Production structure

Final good production

At the top level, a representative final good producer produces Y according to

$$Y = \left(\sum_i a_i Y_i^{\frac{\delta-1}{\delta}} \right)^{\frac{\delta}{\delta-1}}, \tag{2.12}$$

where Y_i is the sectoral good of sector i, a_i the value share of this sectoral good and δ the elasticity of substitution (EoS) between the sectoral goods. I assume perfect competition, meaning that the producer takes the prices of inputs and outputs as given. In each sector, the final good producer maximizes profits according to

$$\max_{\{Y_i\}} P_y * Y - \sum_i (P_i * Y_i) \tag{2.13}$$

$$\text{s.t. } (2.12),$$

where P_y is the final good price and P_i the sectoral good price of sector i. Solving Equation (2.13) and combining the resulting optimal demand for all sectoral goods gives the condition for the optimal input use.[10] The condition is given by

$$\frac{Y_j}{Y_i} = \left(\frac{P_i}{P_j} \right)^{\delta} \left(\frac{a_j}{a_i} \right)^{\delta}. \tag{2.14}$$

I define the sectoral good production as

$$Y_i = \left(a_{i,Dom} Y_{i,Dom}^{\frac{\sigma_Y^i - 1}{\sigma_Y^i}} + (1 - a_{i,Dom}) Y_{i,Imp}^{\frac{\sigma_Y^i - 1}{\sigma_Y^i}} \right)^{\frac{\sigma_Y^i}{\sigma_Y^i - 1}}, \tag{2.15}$$

where $a_{i,Dom}$ represents the value share of sectoral domestic goods. σ_Y^i is the EoS between sectoral domestic goods, $Y_{i,Dom}$, and sectoral imported goods, $Y_{i,Imp}$. For

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[10] Except for the informal and formal good production, I use this solving process based on the full competition assumption. Thus, given the CES production function, the producer behavior can explicitly be described as the maximization of their profits. For brevity, I describe the other nests without solving them explicitly and refer to this case for the solution method.

the sectoral domestic production, I make a distinction between a composite good of own-production, $Q_{i,S}$, which is produced by self-employed households, and a composite good of the firms, $Q_{i,FI}$. That allows me to include competition between the own- and the firm production composite. $Y_{i,Dom}$ is given as

$$Y_{i,Dom} = \left(a^{Q}_{i,S} Q_{i,S}^{\frac{\phi^i_Q - 1}{\phi^i_Q}} + (1 - a^{Q}_{i,S}) Q_{i,FI}^{\frac{\phi^i_Q - 1}{\phi^i_Q}} \right)^{\frac{\phi^i_Q}{\phi^i_Q - 1}}, \tag{2.16}$$

where $a_{i,S}$ is the value share of own-production and ϕ^i_Q the EoS between the own-production composite and the firm-production composite.

Firm Production

The firm-production composite is defined as

$$Q_{i,FI} = \left(a^{X}_{i,FI} X_{i,FI}^{\frac{\epsilon^i_{FI} - 1}{\epsilon^i_{FI}}} + (1 - a^{X}_{i,FI}) M_{i,FI}^{\frac{\epsilon^i_{FI} - 1}{\epsilon^i_{FI}}} \right)^{\frac{\epsilon^i_{FI}}{\epsilon^i_{FI} - 1}}, \tag{2.17}$$

where $X_{i,FI}$ is a formal and informal firm composite, $M_{i,FI}$ the intermediate good, $a_{i,FI}$ the value share of the formal and informal firm composite, and ϵ^i_{FI} the EoS between those two goods. The intermediate good is produced using intermediates of all non-energy sectors, which can either be domestically produced, $M^{j,Dom}_{i,FI}$, or be imported, $M^{j,Imp}_{i,FI}$. Thus, the intermediate good production is defined as

$$M_{i,FI} = \left(\sum_{j \neq E} a^{j,M}_{i,FI} M^{j}_{i,FI}{}^{\frac{\xi^i_{FI} - 1}{\xi^i_{FI}}} \right)^{\frac{\xi^i_{FI}}{\xi^i_{FI} - 1}}, \tag{2.18}$$

where

$$M^{j}_{i,FI} = \left(a^{j,M,Dom}_{i,FI} {M^{j,Dom}_{i,FI}}^{\frac{\sigma^{i}_{FI,M}-1}{\sigma^{i}_{FI,M}}} + (1 - a^{j,M,Dom}_{i,FI}) {M^{j,Imp}_{i,FI}}^{\frac{\sigma^{i}_{FI,M}-1}{\sigma^{i}_{FI,M}}} \right)^{\frac{\sigma^{i}_{FI,M}}{\sigma^{i}_{FI,M}-1}} . \tag{2.19}$$

$a^{j,M}_{i,FI}$ represents the value share of a good j and $a^{j,M,Dom}_{i,FI}$ the value share of this good produced domestically. ξ^{i}_{FI} is the EoS between the different intermediate goods and $\sigma^{i}_{FI,M}$ the one between domestic and imported intermediates.
The formal and informal firm composite production is given as

$$X_{i,FI} = \left(a^{X}_{i,F} X_{i,F}^{\frac{\phi^{i}_{X}-1}{\phi^{i}_{X}}} + (1 - a^{X}_{i,F}) X_{i,I}^{\frac{\phi^{i}_{X}-1}{\phi^{i}_{X}}} \right)^{\frac{\phi^{i}_{X}}{\phi^{i}_{X}-1}} , \tag{2.20}$$

where $X_{i,F}$ is the formal good, $X_{i,I}$ the informal good, $a_{i,F}$ the value share of the formal good, and ϕ^{i}_{X} the EoS between the two goods. Thus, similar to Anand and Khera (2016), I allow for competition between the formal and informal good. For the firm production of the informal and formal good, I follow Ju-e and Youmin (2009) who finds that a KE-L nesting structure is appropriate in the case of China.[11] As I calibrate my model to India which is relatively close to China in Section 2.4, I assume that firms have a KE-L nesting structure. A k firm in sector i produces good $X_{i,k}$ according to

$$X_{i,k} = A_{i,k} \left(a^{L}_{i,k} (L_{i,k})^{\frac{\omega^{i}_{k}-1}{\omega^{i}_{k}}} + (1 - a^{L}_{i,k}) KE_{i,k}^{\frac{\omega^{i}_{k}-1}{\omega^{i}_{k}}} \right)^{\frac{\omega^{i}_{k}}{\omega^{i}_{k}-1}} , \tag{2.21}$$

where $A_{i,k}$ is the firm-specific technology factor, $L_{i,k}$ the labor input, $KE_{i,k}$ the capital-energy composite, $a^{L}_{i,k}$ the value share of labor and ω^{i}_{k} the EoS between Labor and the capital-energy composite. I follow Hafstead, Williams and Chen

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[11] See Burniaux and Truong (2002) and Van der Mensbrugghe (1994) for models with a KE-L production structure.

(2018) for the description of the labor input. Each period a firm inherits a stock of workers, $n_{i,k}$. The firm then has to allocate the workers between recruitment, $v_{i,k}$, and labor for production, $L_{i,k} \equiv (n_{i,k} - v_{i,k})h_{i,k}$. I assume that, in each period, some individuals are separating from the firm according to an exogenous separation rate $\beta_{i,k}$ and go back to self-employment. That means that firms face a trade-off between using labor to produce more goods today and using labor to hire more individuals for the next period. Consequently, firms are solving a dynamic problem. They choose the distribution of labor and the capital-energy composite good to maximize the value of the firm. As firms are owned by their corresponding households discounting the future at a given discounting rate of Q, the future profits of the firm are discounted at this factor. Based on that, I can set up the Bellman equation for a firm in sector i as

$$\begin{aligned} J(n_{i,k}) = \max_{\{KE_{i,k}, v_{i,k}\}} & P_{i,k}X_{i,k} - ((1+\tau_{p,k})h_{i,k}w_{i,k} + b_{i,k})n_{i,k} - P^{KE}_{i,k}KE_{i,k} \\ & + \mathbb{E}\left[QJ(n'_{i,k})\right] \end{aligned} \tag{2.22}$$

where $P_{i,k}$ is the selling price, $\tau_{p,k}$ the labor tax, $w_{i,k}$ the wage per hour, $P^{KE}_{i,k}$ the price of the capital-energy composite good and $b_{i,k}$ a bureaucratic cost per worker. Bureaucratic costs are an important determinant of informality in developing countries that can create barriers to enter formal employment (Perry et al. 2007). Moreover, India‘s bureaucracy is perceived as one of the worst in Asia, making it necessary to include such costs in the model. Note that only the formal firm has to pay labor taxes, which means that $\tau_{p,F} > 0$ and $\tau_{p,I} = 0$ holds.

The law of motion for formal employment is defined as

$$n'_{i,F} = (1 - \beta_{i,F})n_{i,F} + H_{i,F}h_{i,F}v_{i,F} \tag{2.23}$$

and for informal employment as

$$n'_{i,I} = (1 - \beta_{i,I})n_{i,I} + H_{i,I}h_{i,I}v_{i,I} - (T - h_{i,I})n_{i,I}(\sum_j \theta^{j,F}_{i,I}), \tag{2.24}$$

where $(T - h_{i,I})n_{i,I}(\sum_j \theta_{i,I}^{j,F})$ is the outflow of workers from the informal firm to the formal firms. It is assumed that the firms take the recruiter productivity and the probability that a worker finds a job as given. The first order constraint with respect to the capital-energy composite good leads to

$$P_{i,k}\frac{\partial X_{i,k}}{\partial KE_{i,k}} = P_{i,k}^{KE}. \tag{2.25}$$

Furthermore, the condition

$$P_{i,k}\frac{\partial X_{i,k}}{\partial L_{i,k}} = H_{i,k}\mathbb{E}\left[Q\frac{\partial J(n'_{i,k})}{\partial n'_{i,k}}\right] \tag{2.26}$$

is derived from the first-order condition with respect to the number of recruiters, $v_{i,k}$, where $\mathbb{E}\left[Q\frac{\partial J(n'_{i,k})}{\partial n'_{i,k}}\right]$ is the current value of an additional employee in the next period. This condition induces that a firm is adding recruiters until the marginal cost of an additional recruiter is equal to the expected value of recruitment. Using the envelope condition with respect to the number of workers, $n_{i,k}$, leads to the following condition for the marginal value of an additional worker for a formal firm

$$\begin{aligned}\frac{\partial J(n_{i,F})}{\partial n_{i,F}} =& P_{i,F}\frac{\partial X_{i,F}}{\partial n_{i,F}} - (1+\tau_{p,F})h_{i,F}w_{i,F} - b_{i,F} + (1-\beta_{i,F}) \\ &* \mathbb{E}\left[Q\frac{\partial J(n'_{i,F})}{\partial n'_{i,F}}\right].\end{aligned} \tag{2.27}$$

This condition equalizes the value of an additional worker to its marginal revenue subtracting its compensation and adding the expected value of the worker in the next period if the worker does not separate from the firm. The informal firms do not only have to consider the separation rate but as well the possibility that a worker changes to a formal firm. Therefore, the condition for the informal firms slightly changes to

$$\begin{aligned}\frac{\partial J(n_{i,I})}{\partial n_{i,I}} =& P_{i,I}\frac{\partial X_{i,I}}{\partial n_{i,I}} - h_{i,I}w_{i,I} - b_{i,I} + (1 - \beta_{i,I} - (T - h_{i,I})(\sum_j \theta^{j,F}_{i,I})) \\ & * \mathbb{E}\left[Q\frac{\partial J(n'_{i,I})}{\partial n'_{i,I}}\right].\end{aligned} \tag{2.28}$$

The capital-energy composite good is produced according to

$$KE_{i,k} = \left(a^K_{i,k}K_{i,k}^{\frac{\zeta^i_k-1}{\zeta^i_k}}(1-a^K_{i,k})E_{i,k}^{\frac{\zeta^i_k-1}{\zeta^i_k}}\right)^{\frac{\zeta^i_k}{\zeta^i_k-1}}, \tag{2.29}$$

where $a^K_{i,k}$ is the value share parameter of capital, $K_{i,k}$ the capital input, $E_{i,k}$ the energy input and ζ^i_k the elasticity of substitution between capital and energy. As my model focuses on labor, I make the simplifying assumption that capital is rented in each period from the rest of the world and is, therefore, imported.[12] Energy $E_{i,k}$ is produced using domestic and imported energy according to

$$E_{i,k} = \left(a^{E,Dom}_{i,k}E^{Dom}_{i,k}{}^{\frac{\sigma^i_{k,E}-1}{\sigma^i_{k,E}}} + (1-a^{E,Dom}_{i,k})E^{Imp}_{i,k}{}^{\frac{\sigma^i_{k,E}-1}{\sigma^i_{k,E}}}\right)^{\frac{\sigma^i_{k,E}}{\sigma^i_{k,E}-1}}, \tag{2.30}$$

where $a^{E,Dom}_{i,k}$ is the value share of domestic energy, $E^{Dom}_{i,k}$, and $\sigma^i_{k,E}$ the elasticity of substitution between domestic energy and imported energy.

Own-Production

In contrast to firm production, own-production does not use capital as an input and has an E-L(M) production structure. The reason for that is that my model focuses on low productive self-employed individuals. In developing countries, these individuals traditionally do not rely on capital for production. Moreover, own-

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[12] A different method is to include a “capitalist” in the model which owns the capital and has savings. However, focusing on labor effects, the inclusion of a capitalist is not needed.

production does not have search frictions. The own-production composite good $Q_{i,S}$ is produced according to

$$Q_{i,S} = \left(a^{LE}_{i,S} LE_{i,S}^{\frac{\epsilon^i_S - 1}{\epsilon^i_S}} + (1 - a^{LE}_{i,S}) M_{i,S}^{\frac{\epsilon^i_S - 1}{\epsilon^i_S}} \right)^{\frac{\epsilon^i_S}{\epsilon^i_S - 1}}, \tag{2.31}$$

where $LE_{i,S}$ represents the labor-energy composite, $M_{i,S}$ the non-energy intermediates, $a^{LE}_{i,S}$ the value share of labor-energy composite and ϵ^i_S the EoS between the two goods. $M_{i,S}$ is produces similar to Equation (2.18) and (2.19), and given by

$$M_{i,S} = \left(\sum_{j \neq E} a^{j,M}_{i,S} M^j_{i,S}{}^{\frac{\xi^i_S - 1}{\xi^i_S}} \right)^{\frac{\xi^i_S}{\xi^i_S - 1}} \tag{2.32}$$

where

$$M^j_{i,S} = \left(a^{j,M,Dom}_{i,S} M^{j,Dom}_{i,S}{}^{\frac{\sigma^i_{S,M} - 1}{\sigma^i_{S,M}}} + (1 - a^{j,M,Dom}_{i,S}) M^{j,Imp}_{i,S}{}^{\frac{\sigma^i_{S,M} - 1}{\sigma^i_{S,M}}} \right)^{\frac{\sigma^i_{S,M}}{\sigma^i_{S,M} - 1}}. \tag{2.33}$$

The labor-energy composite is produced using labor, $L_{i,S}$, and energy, $E_{i,S}$, according to

$$LE_{i,S} = \left(a^L_{i,S} L_{i,S}^{\frac{\omega^i_S - 1}{\omega^i_S}} + (1 - a^L_{i,S}) E_{i,S}^{\frac{\omega^i_S - 1}{\omega^i_S}} \right)^{\frac{\omega^i_S}{\omega^i_S - 1}}, \tag{2.34}$$

where $a_{i,S}$ is the value share of Labor and ω^i_S the EoS between labor and energy. Own-production does not need recruiters as there are no search frictions. Therefore, labor is given as $L_{i,S} = n_{i,S} h_{i,S}$. Similar to Equation (2.30), energy production is defined as

$$E_{i,S} = \left(a_{i,S}^{E,Dom} E_{i,S}^{Dom\,\frac{\sigma^i_{S,E}-1}{\sigma^i_{S,E}}} + (1 - a_{i,S}^{E,Dom}) E_{i,S}^{Imp\,\frac{\sigma^i_{S,E}-1}{\sigma^i_{S,E}}} \right)^{\frac{\sigma^i_{S,E}}{\sigma^i_{S,E}-1}} . \tag{2.35}$$

International trade

In the model, import goods are imperfect substitutes for domestically produced goods. Regarding exports, I assume that the final good, Y, is divided into exports, EX, and domestically supplied goods, D. The producer maximizes its profits according to the transformation function

$$\max_{\{EX,D,Y\}} = P_{EX}EX + P_c D - P_y Y \tag{2.36}$$

subject to the transformation technology

$$Y = \left(a_{EX} EX^{\frac{\rho_{EX}-1}{\rho_{EX}}} + (1 - a_{EX}) D^{\frac{\rho_{EX}-1}{\rho_{EX}}} \right)^{\frac{\rho_{EX}}{\rho_{EX}-1}} . \tag{2.37}$$

P_{EX} is the price of the export good in terms of the domestic currency, P_y is the final good price, a_{EX} the value share of exports, and ρ_{EX} is the transformation elasticity between exports and domestic supplied goods. The domestic prices for exports, P^{EX}, and imports, P^{Imp} are given as $P_{EX} = PFX * P_{EX}^{world}$ and $P_{Imp} = PFX * P_{Imp}^{world}$. PFX is the exchange rate, P_{EX}^{world} the given export price in foreign currency, and P_{Imp}^{world} the given import price in foreign currency.[13] Furthermore, I assume that trade is balanced in each period. Consequently,

$$P_{EX}^{world} * EX = P_{Imp}^{world} * Imp \tag{2.38}$$

has to hold.[14]

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[13] I follow the common small country assumption, meaning that the country can not influence the world market prices.

[14] Note that I set up Equation (2.38) in general form. In my model, different sectors and firms are importing goods facing potentially different import prices. For simplicity, I summarize that

2.2.4 Wage bargaining

I follow the standard search and match literature based on Pissarides (1985) and assume a Nash-bargaining for wages in each period. That induces that optimized wages are such that the matching surplus is maximized. The standard search and matching literature incorporates the matching surplus from a firm and a particular household in the Nash-Bargaining. I extend that by including an "averaged" matching surplus between different households. In my three-stage matching process, multiple households differing in their matching surpluses can get a job in a specific firm. Taking into account that the wage bargaining between firms and labor unions considers the aggregated needs of the workforce, the equilibrium wages are derived from

$$\max_{\{w_{i,k}\}} \left(\frac{\partial J(n_{i,k})}{\partial n_{i,k}} \right)^{\eta_{i,k}} V_{n_{i,k}}^{1-\eta_{i,k}} \tag{2.39}$$

where $\eta_{i,k}$ is the bargaining power of the employer, $\frac{\partial J(n_{i,k})}{\partial n_{i,k}}$ is the marginal value of an additional worker for the firm and $V_{n_{i,k}}$ is the average matching surplus for the households. It holds that

$$V_{n_{i,k}} = W_{i,k} - O_{i,k}^{avg}, \tag{2.40}$$

where $W_{i,k}$ is the value of employment for a worker at a specific firm and $O_{i,k}^{avg}$ is the averaged outside option of the different households participating in the wage bargaining. I first derive the value of employment for a worker at a specific firm, which depends on the periodic utility of the current job and the probability to get a different job in the next period times the value of employment in the new position. In my three-stage matching process, a formal worker can either keep her current job or lose it and go to self-employment. Thus, the value of formal employment in

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here to $P_{Imp}^{world} * Imp$.

sector i is given as

$$W_{i,F} = \mathcal{L}_{i,F} + Q\Delta_{i,F} \tag{2.41}$$

where the expected value of employment in the next period, $\Delta_{i,F}$, is

$$\Delta_{i,F} = \sum_j \left(\beta^j_{i,F} W'_{j,S} + (1 - \beta_{i,F}) W'_{i,F}\right). \tag{2.42}$$

$\beta^j_{i,F}$ is the probability to lose the job and to go to self-employment in sector j, $W'_{j,S}$ the next periods value of self-employment in sector j, $\beta_{i,F} = \sum_j \beta^j_{i,F}$ the total (exogenous) separation rate of the specific formal firm and $(1 - \beta_{i,F})$ the probability of staying in the job and receiving the next periods value of the current job, $W'_{i,F}$.

An informal worker can either stay in her current position or switch to self- or formal employment. Thus, the value of informal employment includes the probability to get a formal job, $(T - h_{i,I})\theta^{j,F}_{i,I}$, and can be defined as

$$W_{i,I} = \mathcal{L}_{i,I} + Q\Delta_{i,I}, \tag{2.43}$$

where

$$\Delta_{i,I} = \sum_j \left(\beta^j_{i,I} W'_{j,S} + (T - h_{i,I})\theta^{j,F}_{i,I} W'_{j,F} + (1 - \beta_{i,I} - (T - h_{i,I})\theta^{j,F}_{i,I}) W'_{i,I}\right) \tag{2.44}$$

holds. Finally, self-employed individuals can either stay or switch to formal or informal employment. Consequently, the value of self-employment is given as

$$W_{i,S} = \mathcal{L}_{i,S} + Q\Delta_{i,S} \tag{2.45}$$

where

$$\Delta_{i,S} = \sum_j \left(\sum_k \left((T - h_{i,S})\theta_{i,S}^{j,k} W'_{j,k} + (1 - (T - h_{i,S})\theta_{i,S}^{j,k}) W'_{i,S} \right) \right) \tag{2.46}$$

holds. The next step is to set up the outside option of a household which is simply the value of its original employment. To get the averaged outside option, I need to include the share of matches of a particular household type to the total number of matches of a specific firm given by Ω. A formal firm operating in sector i has matches with the self-employed households and with the informally employed households. Therefore, its averaged outside option is given as

$$O_{i,F}^{avg} = \sum_j \left(\Omega_{j,S}^{i,F} W_{j,S} + \Omega_{j,I}^{i,F} W_{j,I} \right), \tag{2.47}$$

where $\Omega_{j,S}^{i,F} = \frac{m_{j,S}^{i,F}}{m_{i,F}}$ and $\Omega_{j,I}^{i,F} = \frac{m_{j,I}^{i,F}}{m_{i,F}}$. As the informal firm in sector i only matches with self-employed households, its averaged outside option is defined as

$$O_{i,I}^{avg} = \sum_j \left(\Omega_{j,S}^{i,I} W_{j,S} \right), \tag{2.48}$$

where $\Omega_{j,S}^{i,I} = \frac{m_{j,S}^{i,I}}{m_{i,I}} = 1$ holds.

This allows me to maximize the averaged matching surplus and to solve for the after-tax total wage that an employed worker receives:

$$\begin{aligned} w_{i,k} h_{i,k} (1 - \tau_k) = \frac{\eta_{i,k}}{\lambda_{i,k}} \left(O_{i,k}^{avg} + c_{i,k} P_c \lambda_{i,k} + \psi \frac{h_{i,k}^{1+\chi}}{1+\chi} - Log(c_{i,k} + 1) - Q\Delta_{i,k} \right) \\ + (1 - \eta_{i,k}) \frac{1 - \tau_k}{1 + \tau_{p,k}} \left((1 - \beta_{i,k}) \mathbb{E} \left[Q \frac{\partial J(n'_{i,k})}{\partial n'_{i,k}} \right] + P_{i,k} \frac{\partial X_{i,k}}{\partial n_{i,k}} - b_{i,k} \right) \end{aligned} \tag{2.49}$$

Equation (2.49) induces a division of the average matching surplus according to a constant share rule. Similar to Hafstead and Williams (2018), I find that workers need to be compensated for the opportunity costs they are facing, which are displayed by the first term on the right-hand side. The second term includes the marginal revenue of an additional worker, which positively affects the after-tax total wages due to the bargaining mechanism.[15] The wage mechanism in my model is further discussed in Section 2.3.

2.2.5 Government

The government is assumed to run a balanced budget and to use its revenues to consume the final good according to the following condition

$$\sum_i ((\tau_F + \tau_{p,F}) w_{i,F} h_{i,F} n_{i,F} + \tau_E E) = P_c c_{gov} \tag{2.50}$$

where τ_E is a tax on energy, E the total energy consumption and c_{gov} the governmental consumption.[16]

2.3 Steady-State conditions and wage mechanism

In a steady-state, the variables need to be constant over time, meaning that they are equal in period t and period $t+1$. Therefore, for the value of an additional worker for a firm,

$$\frac{\partial J(n^*_{i,k})}{\partial n^*_{i,k}} = \frac{\partial J({n_{i,k}}'^*)}{\partial {n_{i,k}}'^*}, \tag{2.51}$$

has to hold and employment needs to be constant

$$n^*_{i,k} = {n_{i,k}}'^*, \tag{2.52}$$

as well as the value of employment for the individuals:

$$W^*_{j,l} = {W_{j,l}}'^* \tag{2.53}$$

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[15] See Shimer et al. (2010) and Hafstead and Williams (2018) for a more detailed explanation.

[16] τ_E is assumed to be zero in the baseline case.

I can now derive the steady-state using the Equations (2.1) - (2.50) in Section 2.2 solving for working hours, quantities, and prices which satisfy the first-order conditions of households and firms and clear the goods and factor markets.

The wage mechanism is the most important driver of the outcome of search and match models with Nash-Bargaining. In this section, I analyze the wage mechanism in a three-stage matching process. Moreover, I explain differences to the two-staged matching process used in the standard literature. To do so, I build on Equation (2.49) in Sections 2.2 and add the steady-state conditions.[17] I assume that the steady-state conditions (2.51), (2.52), and (2.53) hold and solve for the wages w_F^* and w_I^*.[18] In this section, I ignore the employment and households decision, assuming that they are independent of wages and, thus, exogenously defined. Under these conditions, the wages in the different stages are interlinked such that a specific status quo with respect to employment and working hours is maintained. Specifically, this induces that a firm adjusts its wage to keep the average matching surplus of households constant, meaning that potential workers have unchanged incentives to join the firm. That enables me to explicitly analyze the wage mechanism in the three-stage matching process by disentangling it from other effects. To compare the wage response in my model with the standard two-stage matching process, I elaborate on the effect of changing the wage of self-employment on w_F^* and w_I^*. Thus, I derive w_F^* and w_I^* with respect to w_S which results into

$$\frac{\partial w_F^*}{\partial w_S}\Big|_{\frac{\partial n_l}{\partial w_S}=0} = \frac{\left(\frac{h_S \lambda_S}{1+Q(-1+Q(\Gamma_I^F-\Gamma_S^F)\Gamma_S^I)}\right)}{\left(\frac{h_F \lambda_F (1-\tau_F)}{1-Q}\right)} \tag{2.54}$$

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[17] For simplicity, I assume that there is only one sector for this exercise. I replace $\frac{\partial J(n'_{i,k})}{\partial n'_{i,k}}$, $\Delta_{i,l}$ and $O_{i,k}^{avg}$ by their full-terms displayed in Equations (2.27), (2.28), (2.42), (2.44), (2.46), (2.47) and (2.48).

[18] The solutions are displayed in Appendix 5.2.3.

and

$$\frac{\partial w_I^*}{\partial w_S}\Big|_{\frac{\partial n_l}{\partial w_S}=0} = \frac{\left(\frac{h_S \lambda_S}{1+Q(-1+Q(\Gamma_I^F-\Gamma_S^F)\Gamma_S^I)}\right)}{\left(\frac{h_I \lambda_I}{1+Q(-1+Q(1-\beta_I-\Gamma_I^F)(\Gamma_I^F-\Gamma_S^F)}\right)} \tag{2.55}$$

where $\Gamma_S^F = (T-h_S)\delta_S^F$, $\Gamma_I^F = (T-h_I)\delta_I^F$ and $\Gamma_S^I = (T-h_S)\delta_S^I$. The Γs represent the different job finding probabilities per day. Equations (2.54) and (2.55) show how wages need to change in response to an increase in w_S to maintain similar incentives to switch to firm employment, meaning that the average matching surplus $V_{n_{i,k}}$ remains constant.

It is helpful to distinguish between three effects to understand the wage mechanism: the “direct outside option effect”, the “indirect outside option effect” and the “feedback effect”. The direct outside option effect captures the initial increase of the outside option, whereas its indirect counterpart incorporates the change in the outside option caused by the feedback effect.[19]

Increasing w_S results in a higher outside option for firm employment. Formal and informal firms respond to that by increasing their wages to maintain similar incentives for self-employed individuals to switch to firm employment. Consequently, firms enhance the value of their employment due to the direct outside option effect, which then causes the feedback effect: a higher value of firm employment rebounds positively to the corresponding value of the lower stages of the matching process. For example, increasing W_F boosts W_S through Γ_S^F and W_I through Γ_I^F (see Equation (2.43) and (2.45)). That feedback effect enhances the outside option and triggers the indirect outside option effect. The latter works similarly to its direct counterpart: firms respond to it by adjusting their value of employment, which, in turn, affects the size of the feedback effect, rebounding back to the outside option again. This process continues until the prior average matching surplus is reached. While the indirect outside option and feedback effect offset each

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[19] Although the direct and indirect outside option effect works similarly, a distinction between these two is necessary to understand the differences between the wage mechanism in a two - and three-stage matching process.

other in a two-stage matching process, these two effects are decisive for the wage mechanism in a three-stage matching process, where the Γs capture their size as displayed in (2.54) and (2.55).

Proposition 1. *If* $\Gamma_I^F = \Gamma_S^F$ *holds, then the feedback and indirect outside option effect offset, and the wage mechanism only depends on the direct outside option effect.*

In that case, Equation (2.54) simplifies to $\partial w_F^* / \partial w_S = h_S \lambda_S / (h_F \lambda_F)(1 - \tau_F)$ and Equation (2.55) to $\partial w_I^* / \partial w_S = h_S \lambda_S / (h_I \lambda_I)$. Changing w_S has a positive impact on firm wages through the outside option resulting in a change of the value of formal and informal firm employment. Based on that, there is a feedback effect of the increase of W_F on W_I through Γ_I^F. In addition, the feedback effect of W_F also increases W_S through Γ_S^F, which indirectly raises the outside option for informal firm employment. If $\Gamma_I^F = \Gamma_S^F$ holds, then the indirect outside option and feedback effect offset each other and, thus, the wage response coincides with the wage mechanism in standard two-stage matching processes.

Proposition 2. *If* $\Gamma_I^F \neq \Gamma_S^F$ *holds, then the wage mechanism is based on the direct outside option effect, the indirect outside option effect, and the feedback effect.*

In that case, the size of the feedback and the indirect outside option effect differs in a three-stage matching process and affects the wage response. The term $(1 - \beta_I - \Gamma_I^F)(\Gamma_I^F - \Gamma_S^F)$ in Equation (2.55) captures the weighted feedback effect on the value of employment minus the increase of the outside option for informal firm employment due to the feedback effect on self-employment. $(1 - \beta_I - \Gamma_I^F)$ is the chance to stay in informal employment, Γ_I^F the direct effect of W_F on W_I and Γ_S^F the impact of W_F on the outside option of informal employment through W_S. The term $(\Gamma_I^F - \Gamma_S^F)\Gamma_S^I$ represents the weighted feedback effect for self-employment. Different from the feedback effect on the informal firm, $(\Gamma_I^F - \Gamma_S^F)$ is multiplied by Γ_S^I, which is the chance for self-employed individuals to get into informal employment. If, for example, $\Gamma_I^F > \Gamma_S^F$ and hours and the λs are equal, then, according to Equation

(2.54) and (2.55), $\frac{\partial w_F^*}{\partial w_S} > \frac{\partial w_I^*}{\partial w_S}$ holds. In this case, the formal wage affects the value of informal employment more than the corresponding outside option. Thus, an informal firm becomes relatively more attractive and changes its wage less as a response to an increase of w_S.

This simplified illustration shows that the wage mechanism in the three-stage matching process differs structurally from its two-stage counterpart. In the latter, changes in one stage affect the other stage one-dimensionally, where only the initial increase in the outside option is relevant for the wages. In contrast, the triangular nature of the former induces that changes in one stage affect the remaining two stages, which, in turn, impact each other. Consequently, the effect is multidimensional, meaning that the feedback and indirect outside option effect do not have to offset each other. In addition to the wage mechanism described before, the model described in Section 2.2 encompasses other effects: first, increasing wages raise the cost of labor, incentivizing firms to lower employment as a response. Second, firms of different sectors are competing not only on the goods market but also for potential workers (see the last term on the right-hand side of Equation (2.4) and (2.6)). Considering that an increase in a firm‘s wage decreases its incentive to employ recruiters (as labor becomes relatively more expensive), this positively affects the matchings of firms operating in other sectors. Third, the households decide, for example, on the hours dependent on the wages. Assuming a positive Frisch elasticity of labor supply, an increase in the wage incentivizes to work more. That, in turn, decreases the searching effort resulting in a negative impact on the corresponding Γ(s).

2.4 Calibration

This section starts with a brief background of the labor market in India. According to Mehrotra et al. (2019), India had a low unemployment rate of 2.2% in 2011/2012. The reason for that is mainly the insufficient unemployment benefit scheme. The agricultural sector is still the predominant employer in India. In the last thirty years, however, its labor share declined substantially and continues to shrink. The output of the service sector surpassed the agricultural sector many years ago. This ongoing development is perceived as the "Service revolution" of India (e.g. Gordon and Gupta (2005)). Despite that structural change, informality continues to play a crucial role in Indian's economy for decades. With around 90% of informal workers, India has a relatively extensive informal economy compared to other developing countries. Furthermore, more than half of the workforce is self-employed (Mehrotra et al. 2019). Researchers argue that the significant and persistent role of the informal economy in India is also a result of various policies in the past favoring informality. Consequently, the Indian informal sector is multidimensional and complex, making it hard to tackle it without harming the vast majority of Indian workers.

I calibrate the model to India for the year 2011/2012, disaggregating the economy into three sectors: agriculture, industries, and services. Energy is treated as an industrial product and is thus part of the industry sector. I use employment data disaggregated into formal, informal, and self-employed workers per sector from Mehrotra et al. (2019). Furthermore, I take the sectoral economic data of the input-output table from the Asian Development Bank (2012). Those data, however, do not contain the division into formality and informality (and own-production). To overcome that shortcoming, I rely on three main assumptions for my calibration strategy. First, I assume that there are only self-employed workers in the agricultural sector.[20] Second, self-employed individuals produce in the same way in all the sectors. These two assumptions allow me to calibrate the own-production separately from firm-production. And last, I assume that the production functions of the sub-nests of the formal and informal firms operating in the same sector are

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[20] According to the labor data, almost every worker in the agriculture sector is operating informally, and a vast majority of them are self-employed. Additionally, only 2.3% of the non-self-employed workers are regular workers, whereas the others are generally low earning casual workers.

similar. Based on that, the division of the economic data is a result of the model. As a consequence, the standard “nest-after-nest” calibration method for CGEs is not feasible. Instead, I calibrate the model in a step-wise approach, whereby I use the output of a step as an input for its subsequent. Table 2.1 summarizes the benchmark parameters. The asterisk indicates calibrated steady-state values. The time period of the model is one month.

Households				
Discount Factor	Q	0.994		
Disutility of work parameter	ψ	3.38*		
Taxes on formal labor income	τ_F	0.118		
Production		**Industry**	**Service**	**Agriculture**
Formal firm productivity	A_F	3.43*	4.03*	
Informal productivity relative to formal productivity	z_I	2/3	2/3	
Own-Production productivity	A_S	0.72*	0.72*	0.72*
Formal firm employment	n_F	0.0198	0.0536	
Informal firm employment	n_I	0.1489	0.0852	
Self-employment	n_S	0.1297	0.0737	0.4891
Payroll tax for formal firm	$\tau_{p,F}$	0.143	0.143	
Nash-Bargaining and Wages		**Industry**	**Service**	
Formal wage relative to informal industry wage	$\frac{w_F h_F}{w_{I,Ind} h_{I,Ind}}$	1.87	2.48	
Informal wage relative to informal industry wage	$\frac{w_I h_I}{w_{I,Ind} h_{I,Ind}}$	1	1.06	
Formal bargaining power	η_F	0.14*	0.05*	
Informal bargaining power	η_I	0.35*	0.5	
Matching				
Matching elasticity	γ	0.5		
Formal matching efficiency	μ_F	0.65*		
Informal matching efficiency	μ_I	3.04*		
Formal separation rate	β_F	0.1		
Informal separation rate	β_I	0.6		

Table 2.1: Calibration table

2.4.1 Household

I consider seven different household types; the self-employed households in each sector, and the formal and informal employed households in the industry and the service sector. Their discount rate Q is calibrated to replicate an average annualized interest rate of 7 percent. The Frisch-elasticity of labor supply is $\frac{1}{\chi} = 0.5$ which is similar to Tapsoba (2014). The disutility of work parameter ψ is calibrated such that the self-employed agricultural individuals work $h_{Agr,S} = 0.4$. This induces a 48-hours week which is consistent with the estimates of the Annual report on Periodic Labor Force Survey (PLFS) (2019) for the rural workforce in India. According to Gandullia et al. (2012) the labor income tax in India is on average $\tau_F = 0.118$.

2.4.2 Matching and Nash bargaining

Following Hafstead and Williams (2018), I set the matching elasticity γ to 0.5 and the recruiter productivity H to 25 (in the initial steady state) for all sectors and firms. As employment is constant in the steady-state, I can set $n_{i,k} = n'_{i,k}$. Based on that, I use Equation (2.23) and (2.24) to solve for the recruitment effort in each sector. I then use Equation (2.5) and (2.7) to solve for the match efficiency $\mu_{i,k}$.[21]

For the Nash-bargaining process, I fix the Nash-bargaining parameter of the informal service sector to 0.5 as a benchmark. The remaining Nash-bargaining-parameters are calibrated such that the daily wages for the employed household match with the data.[22] Note that the calibrated Nash-bargaining parameters of formal employers are smaller than the ones of informal employers. Considering that employment unions are stronger for formal employees in India, this structure is reasonable.

2.4.3 Production

I calibrate the production-side in a stepwise approach starting with own-production. Based on the outcome of own-production, it becomes possible to calibrate the

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[21] This approach is similar to Hafstead and Williams (2018). Therefore, I omit a more detailed description here.

[22] Own calculation based on Singhari and Madheswaran (2017) and Employment and Unemployment situation in India (2014).

firm-production in a second step. Lastly, I calibrate the remaining nests using a nest-after-nest approach. Table 5.1 in Appendix 5.1.2 displays the underlying elasticities of substitutions, which I assume to be the same in formal and informal firm production.[23]

Own-production

To calibrate the own-production, I start by calibrating the agriculture sector. I assume that only self-employed individuals are operating in the agriculture sector. Based on that, I can calibrate the agriculture sector in the standard way using the labor and economic data. Further, as I assume that the production structure of own-production is the same for all sectors, I can use the disaggregated labor data to calibrate the own-production of the other sectors.

Firm production

Taking the calibrated own-production into account, I can distinguish between own-production and firm-production in the input-output table. To differentiate between the output of the formal and informal firms, I set them equal in the initial steady-state.[24] I then use Equation (2.25) to set up the share per firm of the sectoral aggregated capital-energy composite received from the data.[25] As a next step, I calibrate the bureaucratic costs per worker such that it is coherent with the firm-specific labor input and the wage distribution received from the data.

According to Gandullia et al. (2012) the payroll tax paid by the formal firms is on average $\tau_p = 0.143$. I assume that the exogenous separation rate for the formal firm, $\beta_{i,F}$, is 0.1 while the exogenous separation rate of the informal firm, $\beta_{i,I}$, is 0.6.[26] Similar to Ulyssea (2010) and Anand and Khera (2016), I further

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[23] Note that I assume that own-production in each sector has the same elasticity of substitution as agriculture.

[24] This is similar to Anand and Khera (2016).

[25] I take the sectoral data for capital from Timmer et al. (2015).

[26] Empirical evidence finds that the separation rate of informal firms is higher than of formal firms (e.g. Maloney (1999)).

assume that the productivity of the informal firm is $A_{i,I} = \frac{2}{3} * A_{i,F}$. Considering the inputs and outputs evaluated before, this allows me to get an expression for the formal technology $A_{i,F}$. I then use the steady-state condition, $\frac{\partial J(n_{i,k})}{\partial n_{i,k}} = \frac{\partial J(n'_{i,k})}{\partial n_{i,k}}$, to calibrate for the firm-specific value share parameters.

Finally, the priorly stated assumption for similar sub-nests for firms in the same sector allows me to calibrate the sub-nests using the ratio of the capital-energy composite inputs between the formal and informal firms.

2.5 Climate policy

In this section, I simulate the impact of a climate policy decreasing the energy use of India up to 20%. In my framework, I implement a tax on energy use to achieve an exogenously defined climate target. I assume that all the agents (including the informal ones) have to pay energy taxes.[27] Moreover, the revenue of the energy tax can be redistributed according to four scenarios: in "Scenario 1", the revenue is equally distributed across all individuals as a lump-sum transfer, whereas in "Scenario 2", the lump-sum only goes to the self-employed households. In "Scenario 3", the revenue is used to decrease the labor income taxes, and in "Scenario 4", to lower the formal bureaucratic costs per worker. In the first step, I provide a detailed analysis of the effects in each scenario separately. Building on that, I evaluate the optimal climate policy mix combining all four measures for different climate targets. I assume that pre-tax governmental consumption is needed to run the government. Therefore, this level has to be reached in all scenarios. Additionally, I neglect the transition and only analyze the steady-state values.

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[27] Thus, I treat energy taxes differently than labor income taxes in my model. In developing countries, informal employment does not rely on an official contract. That makes it difficult for the government to observe and tax labor income. Energy consumption, however, is observable for the government. All the agents (including the informal ones) acquire energy from the market. Because the energy in India is usually provided by large, often state-owned (and formal) companies, it becomes possible to tax all energy providers, which can pass on the tax to the consumers.

2.5.1 Comparison of the scenario results

Figure 2.2 shows the effect on the labor market considering the employment status. The results in “Scenario 1” are based on two effects: first, the lump-sum transfer to everyone increases the outside option of the worker due to the concavity of the utility function. Second, the lump-sum transfer decreases the incentive to work, which results in lower working hours, as shown in Figure 2.3. These two effects make labor relatively more expensive for firms. Thus, firm employment decreases while self-employment increases. In “Scenario 2”, the second effect cancels out for firm employment. However, the first effect is amplified as the lump-sum transfer only goes to self-employed individuals. Compared to “Scenario 1”, this is particularly detrimental for informal firms because they only hire self-employed individuals. The last two scenarios commonly put the focus on strengthening the formal firms. In “Scenario 3” and partially in “Scenario 4”, the green job effect outweighs the job killer effect not only in quantitative terms but also in qualitative terms as formal firm employment increases at expenses on its informal counterpart.[28] The different impact on the labor market can be accounted to contrary wage effects, as shown in Figure 5.1 in Appendix 5.1.3. In “Scenario 3”, decreasing the labor income taxes directly affects the wage-bargaining process, pushing up the wages substantially, which keeps the labor response relatively small. In “Scenario 4”, lowering the bureaucratic costs is not connected to wages but to the number of workers. Therefore, wages remain constant. Consequently, formal employment increases by up to 20%, mainly at the expense of informal employment.

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[28] I consider firm-employment as jobs and self-employment as no jobs. That allows me to analyze the well-known green job versus job killer effect of a climate policy.

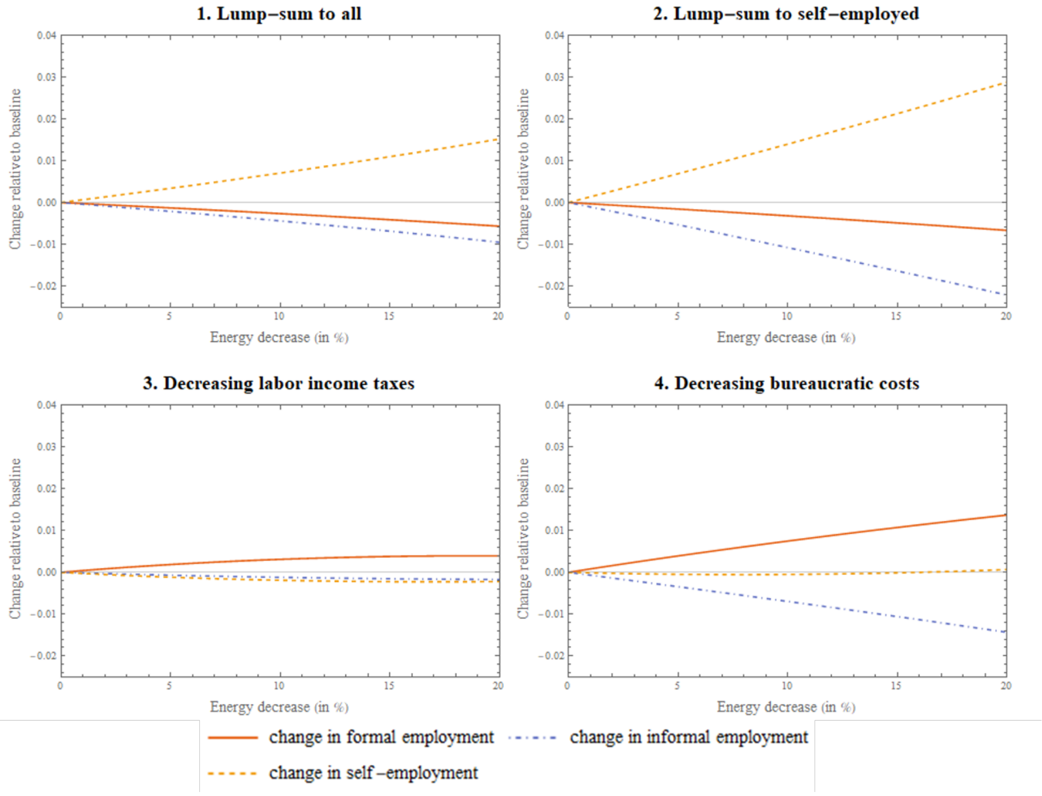

Figure 2.2: Effect on formal and informal employment

These results are in line with McKenzie (2017), who examines various empirical evaluations of different labor market policies in developing countries. He finds that wage subsidies lead to a relatively low labor response while helping the firm overcome obstacles, such as onerous regulations and labor laws, is more promising.[29] In addition, Figure 5.2 in Appendix 5.1.3 shows that supporting the formal labor force especially favors the formal service sector due to its high labor intensity.

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[29] Alternatively, the revenue of the energy tax could be used to enhance the enforcement of regulations for informal firms which increases $b_{i,I}$. Different from decreasing the formal bureaucratic costs, this would not only boost formal but also self-employment and, thus, lead to less favorable labor market results. That finding is similar to Ulyssea (2010) using Brazilian data.

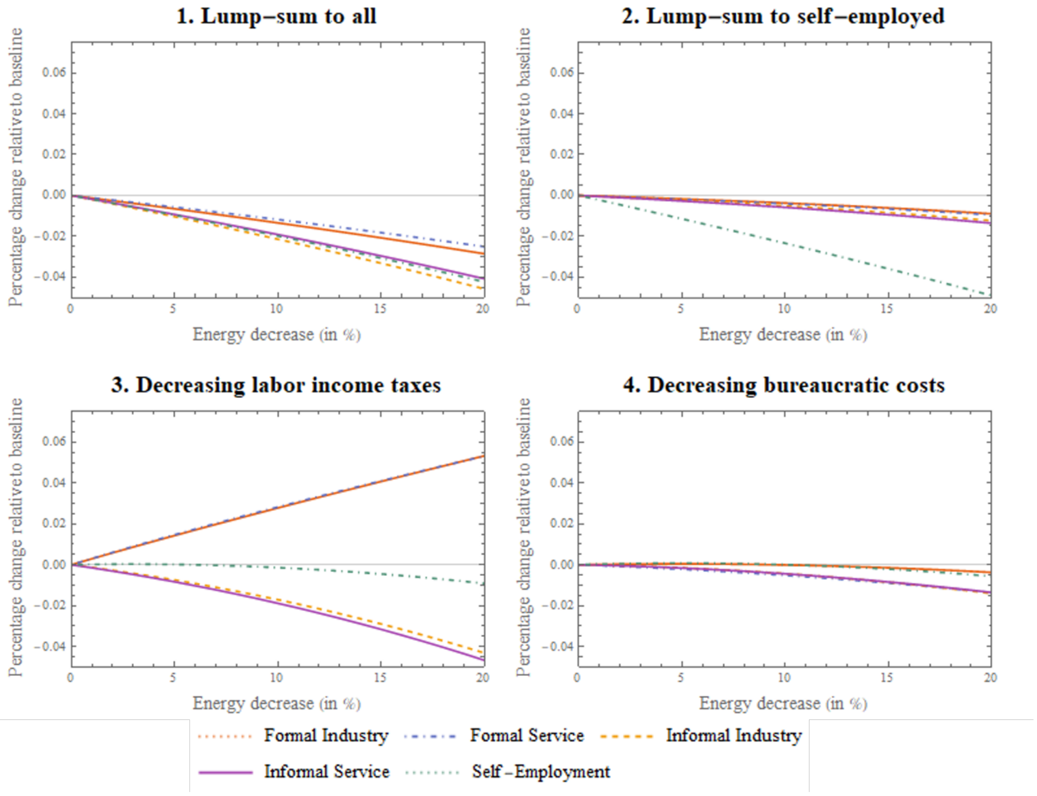

Figure 2.3: Effect on working hours per day

Figure 2.4 shows the development of utilitarian welfare and the Gini-coefficient in the four different scenarios.[30] In “Scenario 1”, the share of self-employment, which is relatively unproductive, increases. Furthermore, the lump-sum transfer decreases the incentive to work for everyone, which results in less “productive hours” in formal and informal firms. These two effects affect welfare negatively. Unlike “Scenario 1”, the lump-sum transfer in “Scenario 2” only reduces the incentive to work for the self-employed, so that “productive hours” of employed workers remain nearly constant. As a result, welfare is less negatively affected in “Scenario

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[30] Note that the Gini-coefficient only considers the income of the working individuals, which are included in my model. Therefore, the level differs from the Gini-coefficient in India received from the data.

2". Both lump-sum scenarios slightly decrease the Gini-coefficient and, therefore, improve equality. In "Scenario 3", the policy includes a subsidy for formal workers, being the top earners in the economy. Consequently, inequality increases substantially. In contrast, "Scenario 4" enhances the formal labor share keeping the formal wages constant, which results in a modest increase in inequality.

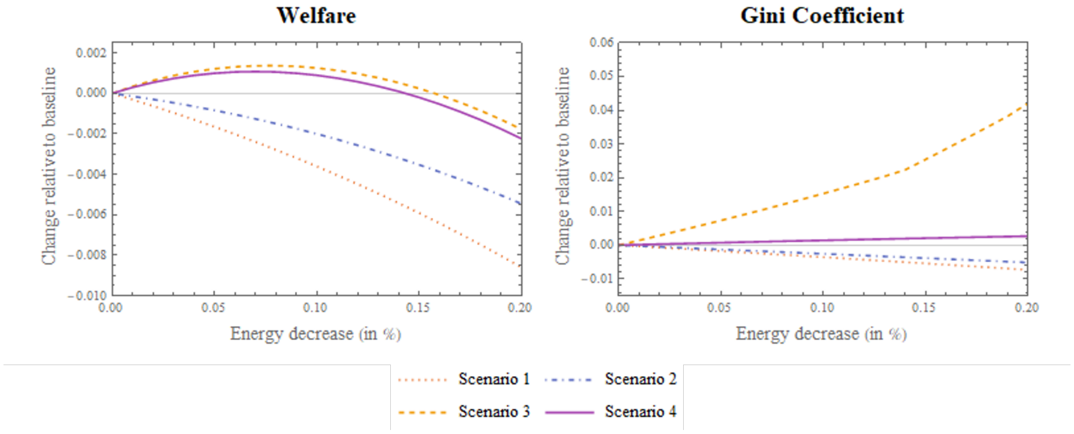

Figure 2.4: Comparison of welfare and the Gini-coefficient of different scenarios

The boost of the formal sector in "Scenario 3" and "Scenario 4" gives rise to a triple dividend effect: next to reducing the energy consumption, they increase the formal labor share and, for a moderate energy tax, enhance welfare. Note that "Scenario 3" exceeds "Scenario 4" in terms of welfare. The main reason for that is that the wage increase in "Scenario 3" positively affects the formal working hours. In both scenarios, the welfare declines sharply towards an energy decrease of 20%. The reason for this is twofold: after surpassing a specific threshold for the energy decrease, the positive effect on the formal sector decreases, and the negative one on the non-formal sectors increases.

2.5.2 Optimal policy mix

In this section, I evaluate the optimal climate policy mix for India. I impose a tax on energy use and assume that its revenue can be redistributed according to an optimal combination of the redistribution schemes of the four scenarios. Figure 2.5 displays how the net-energy tax revenue (policy expenditure) needs to be distributed to maximize utilitarian welfare. Up to 7%, it is optimal to decrease the formal labor income tax with the revenue from the energy tax. Between 7% and 15%, the revenue is used to decrease the labor income tax and reduce bureaucratic costs. From 15% onwards, the optimal policy mix additionally includes a lump-sum to self-employed individuals.[31]

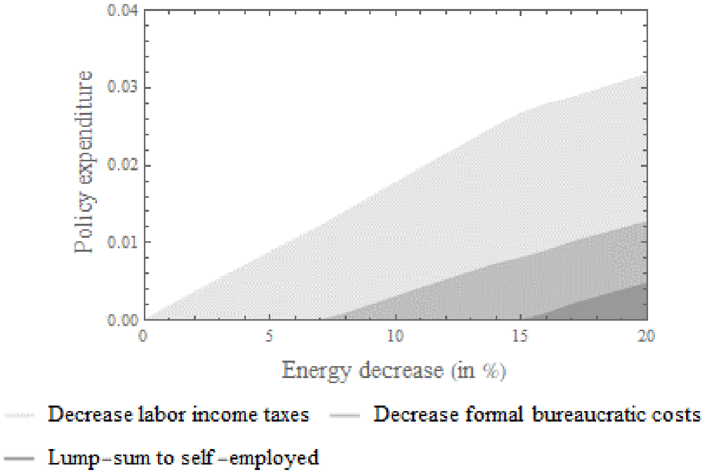

Figure 2.5: Optimal redistribution scheme

Table 2.2 shows the optimal climate policy mix and the outcome for different climate targets regarding energy usage up to a decrease of 20%. Decreasing en-

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[31] The kink at an energy decrease of 15% is due to the lump-sum transfers to self-employed individuals. Up to 15%, boosting the formal sector means that the redistribution scheme favors the energy-intensive firms in the economy. Thus, a higher energy tax is needed to reach the climate target. After 15%, the lump-sum transfers to self-employed negatively affect the formal sector, which, in turn, decreases their energy demand. Consequently, a lower tax is needed to reach the climate target.

ergy up to 15% enhances formal employment, whereby the formal service sector benefits most due to high labor intensity and productivity, while self-and informal employment shrinks. From 15% until 20%, the optimal mix incorporates a lump-sum redistribution to self-employed individuals. That, in turn, increases self-employment mainly at the expense of informal employment. The optimal climate policy mix leads to a triple dividend effect for an energy decrease up to 13.4%: next to reducing the emissions, the optimal climate policy mix increases the formal labor share and enhances welfare (see Figure 5.3 in Appendix 5.1.3). Moreover, in this range, the green job effect outweighs the job killer effect qualitatively (up to 7.5% more formal jobs) and quantitatively (up to 0.25% less self-employment).

The optimal climate policy mix, however, negatively affects equality. That could prevent specific climate policies from being accepted by the population in developing countries. Therefore, I additionally evaluate the optimal policy mix*, keeping the Gini-coefficient constant.

Figure 2.6 displays how the net-energy tax revenue needs to be distributed to maximize utilitarian welfare keeping the Gini-coefficient constant. The optimal policy mix* consists of lowering bureaucratic costs combined with lump-sum transfers to self-employed individuals. Thus, the policy decreases the formal labor costs while boosting the incentive to be self-employed.

Energy	**0%**	**-5%**	**-10%**	**-15%**	**-20%**	**-13.4%***
Optimal Climate Policy mix						
Energy tax	0%	+10.3%	+21.4%	+33.6%	+42.5%	+29.6%
Distribution of the tax revenue						
Scenario 1	0%	0%	0%	0%	0%	0%
Scenario 2	0%	0%	0%	0%	15%	0%
Scenario 3	0%	100%	83%	71%	60%	73%
Scenario 4	0%	0%	17%	29%	25%	27%
Outcome						
Formal employment	0.0734	0.0752 (+2.54%)	0.0772 (+5.21%)	0.0792 (+7.97%)	0.0776 (+5.74%)	0.0787 (+7.2%)
Industry	0.01981	0.01984 (+0.13%)	0.01987 (+0.23%)	0.01986 (+0.22%)	0.01926 (-2.82%)	0.01989 (+0.34%)
Service	0.05355	0.05539 (+3.43%)	0.05733 (+7.05%)	0.05936 (+10.84%)	0.05833 (+8.91%)	0.05877 (+9.74%)
Informal employment	0.2341	0.2334 (-0.29%)	0.232 (-0.9%)	0.23 (-1.75%)	0.2245 (-4.13%)	0.2306 (-1.5%)
Industry	0.1489	0.1488 (-0.10%)	0.1482 (-0.49%)	0.1473 (-1.1%)	0.1438 (-3.46%)	0.1475 (-0.94%)
Service	0.0852	0.847 (-0.63%)	0.0838 (-1.61%)	0.0827 (-2.9%)	0.0807 (-5.3%)	0.0831 (-2.48%)
Self-employment	0.6925	0.6913 (-0.169%)	0.6908 (-0.248%)	0.6908 (-0.252%)	0.698 (+0.788%)	0.6907 (-0.255%)
Gini-coefficent	0%	+7.78%	+13.98%	+19.04%	+18.23%	+17.22%
Welfare	0%	+0.46%	+0.35%	-0.24%	-1.17%	0%

Table 2.2: Optimal policy mix

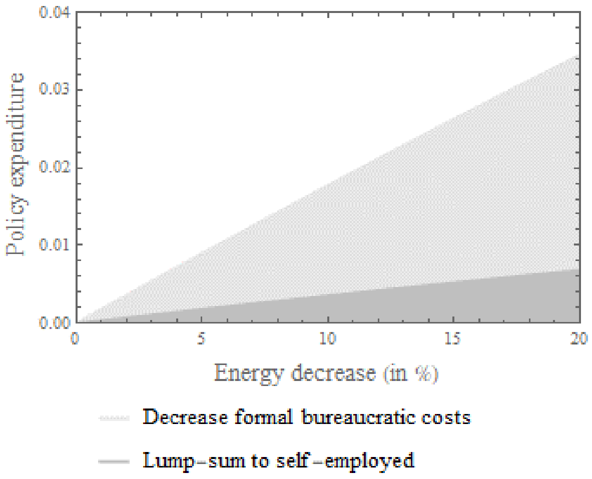

Figure 2.6: Optimal redistribution scheme with fixed Gini-coefficient

Table 2.3 shows the optimal climate policy mix* and the outcome for different climate targets regarding energy usage. Decreasing the use of energy increases self-and formal employment at the expense of informal employment. Keeping the Gini-coefficient constant lowers the effect of the policy on utilitarian welfare. As a consequence, the optimal climate policy mix* leads to a triple dividend effect for an energy decrease up to 8.53% instead of 13.4%. Moreover, the green-job effect outweighs the job-killing effect qualitatively (more formal jobs) but no longer quantitatively (more self-employment). That is due to the lump-sum transfers to self-employment.

Energy	**0%**	**-5%**	**-10%**	**-15%**	**-20%**	**-8.53%***
Optimal Climate Policy mix* (constant Gini-coefficient)						
Energy tax	0%	+9%	+18.9%	+29.8%	+41.8%	+15.9%
Distribution of the tax revenue						
Scenario 1	0%	0%	0%	0%	0%	0%
Scenario 2	0%	20.3%	20.1%	19.9%	19.7%	20.2%
Scenario 3	0%	0%	0%	0%	0%	0%
Scenario 4	0%	79.7%	79.9%	80.1%	80.3%	79.8%
Outcome						
Formal employment	0.0734	0.0754 (+2.73%)	0.0772 (+5.25%)	0.0789 (+7.6%)	0.0805 (+9.76%)	0.07669 (+4.53%)
Industry	0.01981	0.01994 (+0.63%)	0.02 (+0.92%)	0.01999 (+0.86%)	0.01991 (+0.46%)	0.01999 (+0.87%)
Service	0.05355	0.05542 (+3.5%)	0.05723 (+6.86%)	0.059 (+10.09%)	0.06062 (+13.2%)	0.0567 (+5.88%)
Informal employment	0.2341	0.23 (-1.76%)	0.2258 (-3.57%)	0.2214 (-5.42%)	0.217 (-7.32%)	0.227 (-3.03%)
Industry	0.1489	0.1461 (-1.86%)	0.1434 (-3.71%)	0.1407 (-5.55%)	0.1379 (-7.34%)	0.1442 (-3.17%)
Service	0.0852	0.0839 (-1.59%)	0.0824 (-3.31%)	0.0808 (-5.19%)	0.0791 (-7.21%)	0.0828 (-2.79%)
Self-employment	0.6925	0.6946 (+0.31%)	0.697 (0.65%)	0.6966 (1.03%)	0.7025 (+1.44%)	0.6963 (0.54%)
Welfare	0%	+0.12%	-0.1%	-0.66%	-1.58%	+0%

Table 2.3: Optimal policy mix with fixed Gini-coefficient

2.6 Conclusion

I investigate the economic effect of climate policies on developing countries characterized by a large informal economy. The analysis is conducted using a dynamic general equilibrium model with a search and match mechanism. The framework includes the three prevalent working groups in developing countries: informal self-employment, informal employment, and formal employment. I calibrate the model to India to elaborate on the impact of climate policies envisioning a tax on energy with different redistribution schemes of the tax revenue. The results show that India can, employing the optimal climate policy mix, benefit from a triple dividend effect for an energy decrease up to 13.4%: next to reducing the emissions, the optimal climate policy mix increases the formal labor share and enhances welfare. Moreover, the green job effect outweighs the job killer effect qualitatively (more formal jobs) and quantitatively (less self-employment). Two main mechanisms are decisive for that outcome: (1) energy taxes need to be paid by the informal (and the formal) economy, and (2) the revenue of that energy taxes can be used to boost the formal economy. Thus, the optimal climate policy mix favors formally employed individuals, which, in turn, magnifies inequality. Such an effect on inequality could hamper the political viability of the climate policy. I additionally evaluate the optimal climate policy mix holding inequality constant. In that case, the range of an energy decrease, where India could benefit from a triple dividend effect, decreases to 8.53%. The reason for that is the need for lump-sum transfers for self-employed individuals, which negatively affect the labor market outcome, to keep inequality constant.

In general, I highlight that developing countries with a large informal sector can utilize climate policies to deal with environmental problems *and* informality. Designing such climate policies requires incorporating their impact on the most prevalent formal and informal working groups. Therefore, the general equilibrium model with a search and match mechanism suggested in this chapter provides a tool for developing countries to design climate policies optimally, taking labor market effects into account.

The model opens many promising directions for future research: first, it would be interesting to further disaggregate energy into clean and dirty to elaborate on the role of clean energy for the impact of climate policies. Second, the model can be applied to a wide range of developing countries, and it would be fruitful to compare the results of other countries with those of India. Third, the analysis of the transition period would allow an assessment of the optimal policy mix, taking into account time. Finally, one can consider extending the model proposed here to examine the effects of, for example, trade policy or minimum wages.

Chapter 3

Green Transportation Policies: The Double Dividend Effect in a Two-sided Market*†

Decarbonizing the transportation sector is a key measure to reduce carbon emissions at the global level. A crucial factor to achieve a sustainable transportation system is the diffusion of electric vehicles. We study the network effects inducing a positive relationship between electric vehicles and charging stations. To do this, a two-sided market model capturing such network externalities is developed. A platform provides one side of the market with electric and internal combustion engine vehicles to consumers, while it supplies retailers with charging stations on the other side. We use this framework to show that in the presence of network effects and environmental damage from polluting cars, optimal policies can lead to a double dividend: decreasing the quantity of internal combustion engine vehicles can be economically improving, while reducing the negative impact of pollution.

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[*] This work is a joint effort with Chiara Colesanti Senni (CEP).

[†] This research was part of the activities of SCCER CREST, which was financially supported by Innosuisse (Suisse Innovation Agency).

3.1 Introduction

In 2019, the transport sector accounted for 23% of the global carbon emissions, making it the second largest contributor after the electricity and heat generation sector. Moreover, road traffic alone accounted for three-quarters of transportation emissions (IEA 2021). Reducing carbon emissions from the transportation sector is thus crucial for combating climate change. Electric vehicles (EVs) can play a major role in achieving this goal. However, economies are far from achieving the potential emission reduction offered by EVs. The reasons for their slow adoption are manifold:[1] among others, the purchase costs of EVs are still high compared to internal combustion engine vehicles (ICEVs) and the driving distances are limited. Moreover, the charging infrastructure is still inadequate due to the “chicken-egg” relationship existing between EVs and EV charging stations (EVCSs). The latter hinders a further expansion of the EV market: because the number of EVCSs is low, the value of EVs decreases, limiting EV sales and hence the profitability of charging stations (Caillaud and Jullien 2003). To overcome this deadlock, governments use a wide array of policy measures to expand the usage of EVs.[2] Furthermore, cars manufacturers increase their brand specific EVCS network to spur the adoption of their products. Recently, retailers assumed an important role in providing EVCSs. Shopping malls (such as IKEA, Rewe, Aldi) have started to install charging stations in their parking lots: the aim is to attract customers, by offering the possibility to charge their EVs while shopping. This class of actors and their interaction with the diffusion of EVs will be the focus of the present chapter.

To the best of our knowledge, to date there exists little research that explores which policies are optimal to advance EV sales, taking into account the network externality between EVs and charging stations. The aim of this chapter is to

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[1] See Hidrue et al. (2011), Koetse and Hoen (2014), Helveston et al. (2015), Zhou et al. (2016).

[2] For instance, income-tax credit or deduction for purchase of EVs, reduction of or exemption from purchase or registration tax, free battery charging, free parking, support for the deployment of charging infrastructure, grants for private installation of charging stations.

progress in this area by explicitly modeling the relationships between EVs adoption and EVCSs availability. For this purpose, we develop a two-sided market framework with network externalities, which we then use for a study of policies that foster the diffusion of EVs. Moreover, we account for the possibility of substitution between EVs and ICEVs. In the model, a monopolistic platform sells EVs and ICEVs to one side of the market (consumers) and EVCSs to the other side (retailers). Two-sided markets are particularly suited to capture the valuation of the existing charging station network by EV owners and of the circulating base of EVs by retailers. We introduce policies tackling the different sides of the market and we study how they affect quantities and prices. Finally, we analyze which policy mix maximizes welfare and how the latter is affected by a target reduction of the number of ICEVs in the presence of a negative environmental externality and network effects.

The main contribution of the chapter is to show that: (1) policies targeting one side of the market generate feedback effects on the other; network externalities affect outcomes through their absolute size and relative intensity; (2) in the presence of network effects and environmental damage from polluting cars, policies can lead to a double dividend: decreasing the quantity of internal combustion engine vehicles can be economically beneficial, while reducing the negative impact of pollution. This result can represent a turning point in today's discussion about policies fostering EVs: even if EVs are technologically less advanced than ICEVs, the presence of network effects implies that such policies can generate a double dividend. Hence, our analysis provides novel insights about the effects operating in the EV market and their implications for policymaking.

Two-sided markets are characterized by three elements (Rochet and Tirole 2004): first, the presence of a platform providing distinct services to two or more distinct groups of consumers, which rely on the platform to intermediate transaction between them; second, network externalities exist across groups of consumers: one side's utility from participation depends not only on the value of the goods themselves, but also on the number of users on the other side of the market. Network externalities generate feedback loops between the two sides that can exacerbate positive and negative shocks (arising, for instance, from policy implementations).[3] Only the platform internalizes the network effect as it recognizes that a larger network raises the users' willingness to pay and therefore its revenues; third, two-sided markets are characterized by a non-neutral price structure, designed so as to bring both sides on board. The pricing decision on each side depends on the demand faced on both sides of the market and on their interdependence through network externalities. Platforms can deviate from a competitive pricing in order to increase overall profits, for example by generating low revenues on one side and recouping the costs on the other side (Rochet and Tirole 2004). Thus, in a two-sided market we can observe prices below marginal cost.[4] The advantage of using a two-sided market to study our problem follows from the characteristics outlined above: first, car manufacturers produce both EVs and the charging stations, acting as a platform; second, the amount of EVCSs is a relevant element for consumers when purchasing an EV. Meanwhile, retailers only install charging stations if the number of EVs is sufficiently high, showing the existence of network externalities; third, the provision of free charging suggests a non-neutral price structure. Our methodology is close to Filistrucchi et al. (2017) who use a two-sided market structure to analyze the newspaper industry. We deviate from their approach by allowing for the presence of two goods on the same market side, namely EVs and EVCSs. Moreover, we derive the system of demand functions instead of assuming it.

There is a rich body of research analyzing the effect of environmental policies in the automobile market. Many studies focus on the effectiveness of fuel taxes and fuel standards as a response to environmental issues emerging from the transportation sector.[5] A policy approach analyzed in the literature is the establishment

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[3] The notion of network externality is not to be confused with the one of complementary goods; in the latter case, consumers internalize the purchase decision of the complement good (for example, razor and blades); when network effects operate, instead, the externality of the purchase decision is not internalized.

[4] For example, the selling for newspapers for free, covering the losses with the money from advertisement.

[5] See Jacobsen (2013), DeShazo et al. (2017), Alberini and Bareit (2017), Gerlagh et al. (2018),

of eco-friendly rules like the Corporate Fuel Economy standard that led to a 50% reduction of fuel consumption per passenger car mile (Greene et al. 2005). Other studies investigate policies targeting alternative fueled vehicles and the response of consumers to subsidies for EVs or installment of EVCSs.[6] Lin and (2011) analyze the impact of promoting charging infrastructure on EV usage, whereas Jin et al. (2014) study road tax exemptions, free use of bus lines and parking areas, subsidized home chargers and license fee reductions. Greaker and Midttømme (2016) study the diffusion of a clean substitute for a dirty durable good in a dynamic model in the presence of an optimal emission tax and the risk of excess inertia.

The literature has already used two-sided models to study the network effects between EVCSs and EVs. For example, Yu et al. (2016), Springel (2016), Li et al. (2017) and Jang et al. (2018) apply such models to analyze the introduction of environmental policies. Yu et al. (2016) consider a sequential game and depict an EVCS investors' operational decision-making, such as pricing and station location. Springel (2016) uses Norwegian data to study the impact of network externalities and a subsidy scheme on the diffusion of EVs, considering a simultaneous move game. Li et al. (2017) provide empirical evidence of existence of indirect network effects in the process of EV diffusion. Jang et al. (2018) consider two different platforms, one producing EVs and one producing ICEVs, competing to attract two types of agents (car consumers and energy suppliers). We deviate from those papers by modeling one market side supplied with two goods (EVs and ICEVs) and the other with one good only (EVCSs). Compared to Springel (2016) and Li et al. (2017), we allow for substitution possibilities between EVs and ICEVs in the analysis and evaluate the outcomes in terms of welfare. In contrast to previous works, our results do not rely on Hotelling's type preferences, but on linear demand functions derived from quasi-linear utilities.

The present chapter is organized as follows: Section 3.2 outlines the general

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Grigolon et al. (2018).

[6] See Sierzchula et al. (2014), Pöltz et al. (2014), Lieven (2015), Helveston et al. (2015), Langbroek et al. (2016), Zhou et al. (2016), Coffman et al. (2017).

model structure and computes the decentralized solution. Section 3.3 analyzes second-best policy instruments favoring the diffusion of EVs. Section 3.4 computes the first-best solution. Section 3.5 identifies the welfare-maximizing policies and shows the existence of a double dividend. In section 3.6, we provide an extension to the baseline model, which relaxes the assumptions of a monopolistic market structure. Section 3.7 concludes and proposes lines for future research.

3.2 Model

3.2.1 Consumers and retailers

We consider a two-sided market with a continuum of potential users on each side, with mass normalized to one. Our economy is populated by two types of agents: consumers (h) and retailers (a). The former purchase vehicles and can choose between EVs (q_c) and ICEVs (q_d), while the latter demand EVCSs (q_f). We denote by p_c and p_d the purchase prices for EVs and ICEVs and by p_f the price of EVCSs. A monopolistic platform (m) produces EVs, ICEVs and EVCSs and sells the goods to the two sides of the market (consumers and retailers). For a graphical illustration of the economic structure see Figure 3.1.

Consumers purchasing EVs and retailers purchasing EVCSs benefit from network effects due to positive externalities between the two goods. Following the empirical literature (Springel 2016, Li et al. 2017), we assume that the network effects are asymmetric: the impact of an additional charging station on the purchase decision of consumers is different from the impact of an additional EV on the purchase decision of retailers. We acknowledge that similar network effects exist between internal combustion engine vehicles and stations; however, we argue that they are of minor importance compared to those between EVs and EVCSs (Greaker and Midttømme 2016). This can be justified by two reasons: first, charging an EV requires more time than fueling an internal combustion engine car; which explains the strong incentive for retailers to install charging stations as consumers can charge their EVs while shopping; second, the marginal impact of a gasoline station is lower compared to that of a charging station, as the number of gasoline stations is already sufficiently high. Moreover, assuming the presence of network effects in the ICEV market, although to a lower degree, this does not affect our qualitative results. Based on this, we focus on the network effect for the new technology only. Accordingly, the number of gasoline stations does not enter the decision to buy an ICEV.

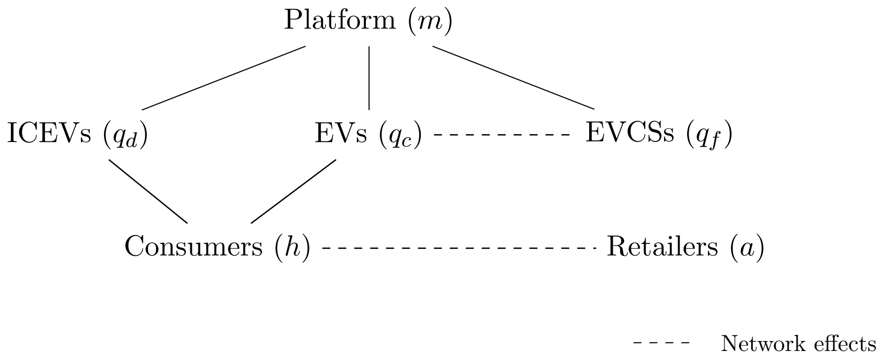

Figure 3.1: Market structure

Following Singh and Vives (1984), Häckner (2000) and Melitz and Ottaviano (2008), we assume that the aggregate utility function is quasi-linear. This specification implies no income effect; however, since the focus of this chapter is on vehicle consumption, the assumption that higher income will not lead to the purchase of more cars by the same individual is plausible.[7] Moreover, the quasi-linear utility function allows us to derive linear demand functions, which are standard in the two-sided market literature. The choice variables for the consumers are the quantities of EVs and ICEVs. Still, the quantity of EVCSs enters the utility of consumers because the value of EVs for consumers depends on the availability of EVCSs.

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[7] We acknowledge that there can be an argument for income effects as richer households are those who can switch first to EVs; however, in the present work we do not consider this effect in order to isolate the impact of network effects.

Assumption 1 (Consumers' utility function)**.** *The utility function of consumers reads*

$$U(q_{0,h}, q_c, q_d; q_f) = q_{0,h} + \sum_{i \in \{c,d\}} \alpha_i q_i - \frac{1}{2} \left[\sum_{i \in \{c,d\}} \beta_i q_i^2 + 2(\gamma_1 q_c q_d - \gamma_2 q_c q_f) \right], \tag{3.1}$$

where $\alpha_i, \beta_i > 0$*,* $\gamma_1 \in [0, \infty)$ *and* $\gamma_2 \in [0, \infty)$*.*

The parameter $q_{0,h} > 0$ represents the individual consumption level of the homogeneous numeraire good. We assume that the initial endowment of the homogeneous good is large enough for its consumption to be strictly positive at the market equilibrium. The positive demand parameters α_i and β_i measure the preference for the differentiated varieties with respect to the homogeneous good. The parameter $\alpha_i q_i$ represents the direct benefit of owning a car, whereas $\beta_i q_i^2$ represents car type-specific congestion costs (for example, congestion at charging points). The parameter γ_1 captures the substitution effect between EVs and ICEVs. The parameter γ_2 denotes the network effect between EVs and EVCSs so that $\gamma_2 q_c q_f$ represents consumers' indirect benefit from EVCS installment by retailers. Notice that consumers always derive utility from the purchase of EVs, even if q_f goes to zero. This assumption can be justified by the possibility of charging EVs at home. The term $\gamma_1 q_c q_d$ represents the congestion cost due to a higher number of EVs and ICEVs (for instance, traffic jams). We normalize the price of the numeraire good to one; hence, the aggregate budget constraint of consumers reads

$$q_{0,h} + p_c q_c + p_d q_d \leq m_c. \tag{3.2}$$

Given total income on the consumers' side, m_c, a share of it is allocated to the purchase of the numeraire good, a share to the purchase of EVs and a share to the purchase of ICEVs. The assumption of quasi-linear preferences allows us to measure gains and losses of utility in the same units as consumption. This implies that there is no revenue effect on car purchasing decision and that the quantities of q_c and q_d chosen do not depend on income. Any change in the quantities purchased is only attributable to the substitution effect.

Retailers maximize a quasi-linear payoff function, which depends on the number of EVCSs and EVs. The latter is, however, a choice variable of households and not of retailers.

Assumption 2 (Retailers' objective function)**.** *The objective function of retailers reads*

$$F(q_{0,a}, q_f; q_c) = q_{0,a} + \alpha_f q_f - \frac{1}{2}\left[\beta_f q_f^2 - 2\gamma_4 q_c q_f\right], \tag{3.3}$$

where $\alpha_f, \beta_f > 0$ *and* $\gamma_4 \in [0, \infty)$.

The parameter $q_{0,a} > 0$ is the purchase level of the numeraire good, whereas q_f is the consumption level of EVCSs. As before, $\alpha_f q_f$ captures the direct benefit for retailers from owning a charging station, whereas $\beta_f q_f^2$ represents the congestion cost due to an excessive number of EVCSs owned by the same retailer (for example, too many charging stations and too many EV charging at the retailer's stations might reduce the parking spots available for ICEVs). The payoff function of retailers also includes the indirect benefit, $\gamma_4 q_c q_f$, due to the usage of EVs by consumers. However, the intensity of the network effect between EVs and EVCSs perceived by retailers, γ_4, might be different from the one perceived by consumers, γ_2 (Li et al. 2017). So far, we have not made assumptions on the relative intensity of the network effects on consumers or retailers; still, this will be relevant for our policy analysis. Given the total income on the retailers' side, m_a, a share of it is allocated to the purchase of the numeraire good and a share to the purchase of EVCSs, that is,

$$q_{0,a} + p_f q_f \leq m_a. \tag{3.4}$$

The consumers' problem is given by

$$\max_{q_{0,h},q_c,q_d} U \quad \text{s.t.} \quad q_{0,h} = m_h - p_c q_c - p_d q_d, \tag{3.5}$$

whereas retailers solve

$$\max_{q_{0,a},q_f} F \quad \text{s.t.} \quad q_{0,a} = m_a - p_f q_f. \tag{3.6}$$

Both constraints hold with equality because U (F) is strictly increasing in $q_{0,h}$ $(q_{0,a})$. Assuming for simplicity $\beta_i = 1$ with $i \in \{c, d, f\}$, the FOCs derived from the maximization problems of consumers and retailers are

$$\begin{aligned} \lambda_h - 1 &= 0, \\ \alpha_c - q_c - \gamma_1 q_d + \gamma_2 q_f - \lambda_h p_c &= 0, \\ \alpha_d - q_d - \gamma_1 q_c - \lambda_h p_d &= 0, \\ \lambda_a - 1 &= 0, \\ \alpha_f - q_f + \gamma_4 q_c - \lambda_a p_f &= 0, \end{aligned} \tag{3.7}$$

where λ_h (λ_a) is the Lagrange multiplier of the consumers' (retailers') budget constraint. The demand functions for EVs, ICEVs and EVCSs are then given by

$$\begin{aligned} q_c &= \alpha_c - \gamma_1 q_d + \gamma_2 q_f - p_c, \\ q_d &= \alpha_d - \gamma_1 q_c - p_d, \\ q_f &= \alpha_f + \gamma_4 q_c - p_f. \end{aligned} \tag{3.8}$$

The choice of quasi-linear utility functions implies that demands are linear in the quantities of goods and prices. From Equation (3.8) we can see that the substitution between EVs and ICEVs leads to a negative impact on the quantities of both goods. On the contrary, the network effect between EVs and EVCSs implies a positive impact of the quantity of EVCSs (EVs) on the demand for EVs (EVCSs), as captured by γ_2 (γ_4). From (3.8) we can derive inverse demands as

$$\begin{aligned} p_c &= \alpha_c - q_c - \gamma_1 q_d + \gamma_2 q_f, \\ p_d &= \alpha_d - q_d - \gamma_1 q_c, \\ p_f &= \alpha_f - q_f + \gamma_4 q_c. \end{aligned} \tag{3.9}$$

In what follows, we assume a profit-maximizing monopolistic platform with perfect information about the demand functions.

3.2.2 Platform

In our setup of a two-sided market, the monopolistic platform chooses the profit-maximizing quantities or prices given the interrelated demands of the two groups of customers. In what follows, we focus on a quantity-setting platform. Car production incurs constant marginal costs c_c and c_d, while the marginal cost of producing charging stations is c_f.

Assumption 3 (Platform's profits)**.** *Total profits generated by the platform are given by*

$$\pi = (p_c - c_c)q_c + (p_d - c_d)q_d + (p_f - c_f)q_f, \tag{3.10}$$

where $p_i, c_i > 0$.

The first two terms represent profits extracted from consumers and the third term profits extracted from retailers. Given the demand function in Equation (3.8), the FOCs of the maximization problem are

$$\begin{aligned} \alpha_c - 2q_c - 2\gamma_1 q_d + (\gamma_2 + \gamma_4)q_f - c_c &= 0, \\ \alpha_d - 2q_d - 2\gamma_1 q_c - c_d &= 0, \\ \alpha_f - 2q_f + (\gamma_2 + \gamma_4)q_c - c_f &= 0. \end{aligned} \tag{3.11}$$

Proposition 1 (Profit-maximizing quantities)**.** *For an interior solution, the profit-maximizing quantities are then given by*

$$q_c^* = \frac{1}{X}\left[2(\alpha_c - c_c) - 2\gamma_1(\alpha_d - c_d) + (\gamma_2 + \gamma_4)(\alpha_f - c_f)\right], \tag{3.12}$$

$$q_d^* = \frac{1}{X}\left[-2\gamma_1(\alpha_c - c_c) + \left[2 - \frac{(\gamma_2 + \gamma_4)^2}{2}\right](\alpha_d - c_d) - \gamma_1(\gamma_2 + \gamma_4)(\alpha_f - c_f)\right], \tag{3.13}$$

$$q_f^* = \frac{1}{X}\left[(\gamma_2 + \gamma_4)(\alpha_c - c_c) - \gamma_1(\gamma_2 + \gamma_4)(\alpha_d - c_d) + 2(1 - \gamma_1^2)(\alpha_f - c_f)\right], \tag{3.14}$$

where $X = 4(1 - \gamma_1^2) - (\gamma_2 + \gamma_4)^2$.

Based on the literature, we assume $X > 0$ (Economides and Tåg 2012). We will refer to this condition as the *monopoly condition*.[8] The latter implies $\gamma_1 \in [0, 1]$, which allows us to derive an upper bound for the network effects, that is, γ_2, $\gamma_4 \in [0, 1)$. The network effects have a positive (negative) impact on the quantity of EVs (ICEVs). As the number of EVs (EVCSs) increases, it generates a positive externality on the retailers (consumers) purchasing EVCSs (EVs). If the number of ICEVs (EVs) increases, fewer EVs (ICEVs) are purchased, indirectly affecting the quantity of EVCSs as well.

Proposition 2 (Profit-maximizing prices)**.** *Given the optimal quantities derived in Proposition 1, we can find the profit-maximizing prices as*

$$p_c^* = \frac{1}{X}[(2(1 - \gamma_1^2) - \gamma_2\gamma_4)(\alpha_c + c_c) - (\gamma_4^2\alpha_c + \gamma_2^2 c_c) - \frac{\gamma_1}{2}(\gamma_2^2 - \gamma_4^2) \tag{3.15}$$
$$* (\alpha_d - c_d) + (1 - \gamma_1^2)(\gamma_2 - \gamma_4)(\alpha_f - c_f)],$$

$$p_d^* = \frac{1}{2}(\alpha_d + c_d), \tag{3.16}$$

$$p_f^* = \frac{1}{X}[-(\gamma_2 - \gamma_4)(\alpha_c - c_c) + \gamma_1(\gamma_2 - \gamma_4)(\alpha_d - c_d) + (2(1 - \gamma_1^2) - \gamma_2\gamma_4) \tag{3.17}$$
$$* (\alpha_f + c_f) - (\gamma_2^2\alpha_f + \gamma_4^2 c_f)].$$

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[8] Appendix 5.2.1 provides a study of the parameter space satisfying this condition.

Because of the network externalities, the prices of EVs and EVCSs depend on the demand parameters of both sides of the market. This means that when setting the profit-maximizing prices on one side of the market, the producer also takes into account the impact of her decision on the other side. This is a standard result in the literature of two-sided markets,[9] where the price structure is non-neutral because externalities across groups affect the determination of the price. Furthermore, the prices of EVs and EVCSs also depend on the parameters of demand for ICEVs, due to the substitution between EVs and ICEVs; on the contrary, the price of ICEVs only depends on the parameters of its own demand and does not equal marginal cost because of monopolistic power.[10] Note that if we assume the intensity of the network effects to be the same on both sides, that is, $\gamma_2 = \gamma_4$, prices for EVs and EVCSs would depend on the parameters of their own demand only.

3.3 Policy analysis

Several measures are available to policymakers in order to foster the development of the EV market. In our theoretical model, we focus on three such policy instruments: (1) subsidies to consumers for EV purchase (s_c): a price subsidy directly affects the buyers' decision to purchase a vehicle by making the price of an EVs comparable to (or even lower than) the price of a ICEVs; (2) taxes on the purchase of ICEVs (t_d); (3) subsidies to EVCS purchase (s_f): the government can subsidize the provision of charging stations by retailers in order to generate a positive externality on EV consumption (through the network effect).

In our analysis, we consider both the case in which the network effect is stronger for retailers ($\gamma_4 > \gamma_2$) and when it is stronger for consumers ($\gamma_2 > \gamma_4$). The first case implies that retailers care more about the number of EVs than consumers do about the availability of EVCSs. This assumption relies on an asymmetric information

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[9] See Rochet and Tirole (2004) and Armstrong (2006).

[10] The substitution effect does not affect the price of ICEVs because, when facing the demand for cars, the monopolist behaves as if the market was not two-sided; hence, the platform does not take into account the presence of externalities when setting the price for ICEVs.

argument: retailers are able to foresee future developments of the market and they can only provide electricity services through EVCSs if consumers buy EVs; hence, the number of EVs is of major importance for them. Moreover, consumers might have the option to charge their EVs at home so that the actual availability of charging stations is less relevant to them. The second case can be justified based on the findings by Li et al. (2017), which argue that a 10% growth in the number of public charging stations increases EV sales by about 8%, while a 10% growth in EV stock leads to a 6% increase in charging station deployment, meaning that the network effect is stronger on the consumers' side.

3.3.1 Policy impacts for $\gamma_4 > \gamma_2$

In what follows, we analyze the effect of policy intervention on quantities and prices when the network effect is stronger for retailers. The results summarized in Table 3.1 are based on analytical derivations provided in Appendix 5.2.2.

	EVs		ICEVs		EVCSs	
	Δq_c	Δp_c	Δq_d	Δp_d	Δq_f	Δp_f
s_c	$+$	$\pm$	$-$	0	$+$	$+$
t_d	$+$	$-$	$-$	$-$	$+$	$+$
s_f	$+$	$-$	$-$	0	$+$	$+$

Table 3.1: Policy impacts for $\gamma_4 > \gamma_2$

All quantities depend only on the total size of the network effects so that the impacts of subsidies and taxes are independent of the relative intensity of the network effects ($\gamma_4 > \gamma_2$ vs. $\gamma_2 > \gamma_4$).[11] Subsidizing EVs (s_c) and taxing ICEVs (t_d) increases the number of EVs. Moreover, q_c increases with a subsidy for EVCSs (s_f) because of the network effect operating between the two goods. The quantity of

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[11] This result is due to the assumption of a monopolistic platform and does not hold when considering different market structures.

ICEVs declines ($\Delta q_d = -$) with all the policies considered because of the substitution with EVs. The quantity of EVCSs increases ($\Delta q_f = +$) with subsidies (s_c and s_f) and taxes (t_d). Our results are in line with the previous literature (Springel 2016, Li et al. 2017) indicating that the positive feedback loops between EVCS and EV sales amplify the impact of subsidies on both sides of the market. Moreover, our model allows us to take into account the effect of policies in the ICEV sector.

The effect of policies on prices is more complex than for quantities; in particular, we observe different outcomes depending on the relative intensity of the network effects. When subsidizing EVs, the effect on their price is ambiguous ($\Delta p_c = \pm$) and depends on the substitution effect as well as on the network effects.[12] If the substitution between EVs and ICEVs is strong or if the network effects are large enough, s_c reduces the price of EVs. The effect on p_c when taxing ICEVs follows from the assumption on the relative intensity of network effects; in particular, the price is reduced ($\Delta p_c = -$) only when retailers attach more importance to the network than consumers. The same outcome occurs when subsidizing EVCSs ($\Delta p_c = -$). Hence, it appears that the monopolist has an incentive to reduce the price of the good which enjoys the stronger network effect and whose quantity is more sensitive to quantity changes on the other side. When $\gamma_4 > \gamma_2$, an increase in q_f lifts q_c strongly up; hence, the monopolist can reduce p_c and still earn profits from the EV market. Such a result depends on the two-sided market structure of the model, allowing the platform to set prices in order to extract the greatest possible profits from both groups of buyers (Rochet and Tirole 2004). The price of ICEVs only depends on the parameters of its own demand and it is not affected by s_c or s_f ($\Delta p_d = 0$). A tax on ICEV (t_d) decreases the price of ICEVs, that is, the monopolist decides to lower the price of the taxed good in order to create a positive demand despite the policy adopted. The price of EVCSs increases with the subsidy for EVs and by a tax on ICEVs ($\Delta p_f = +$); a result that is similar to

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[12] In particular the effect is positive (negative) if $2(1-\gamma_1^2) - \gamma_4(\gamma_2+\gamma_4) > (<) 0$ and $X > 0$. Figure 5.6 in Appendix 5.2.2 provides a graphical representation of parameter values leading to a positive price effect.

the one obtained for the price of EVs and which crucially relies on the assumption that the network effect is stronger on the retailers' side. The platform increases the price on the side of the market which enjoys the stronger network effect. A policy targeting the EVCS sector directly generates an increase in the price of EVCSs as demand is now higher and the monopolist can charge a higher price. In general, the effect of any subsidy or tax depends on which side of the market is targeted. Quantities and the price of ICEVs are, however, independent of the relative intensity of network effects.

3.3.2 Policy impacts for $\gamma_2 > \gamma_4$

The results obtained when the network effect is stronger on the consumers' side are summarized in Table 3.2. As previously outlined, the effects on the quantities are independent of the relative intensity of the network effects.

	EVs		ICEVs		EVCSs	
	Δq_c	Δp_c	Δq_d	Δp_d	Δq_f	Δp_f
s_c	$+$	$+$	$-$	0	$+$	$-$
t_d	$+$	$+$	$-$	$-$	$+$	$-$
s_f	$+$	$+$	$-$	0	$+$	$\pm$

Table 3.2: Policy impacts for $\gamma_2 > \gamma_4$

Considering prices, a subsidy for EVs (s_c) increases the respective price ($\Delta p_c = +$); this happens because the subsidy increases demand for EVs and hence the monopolist can charge a higher price. This result differs from the one we obtained for $\gamma_4 > \gamma_2$, where the impact of s_c on the price of EVs was ambiguous. A tax on ICEVs (t_d) or a subsidy for charging stations (s_f) increase the price of EVs, an opposite outcome compared to the case in which the network effect is stronger on the retailers' side. Since EVs have stronger network effects on charging stations, the platform's profit-maximizing behavior entails a price increase on the consumers' side and a price reduction on the retailers' side. The price of ICEVs behaves in the same way regardless of the relative intensity of the network effects, so it decreases when taxing ICEVs, as before. The price of EVCSs now decreases with both a subsidy for EVs and a tax on ICEVs ($\Delta p_f = -$). The reversed impact of these policies compared to the previous case follows on from the fact that the network effect on consumers is stronger that on retailers; hence, p_f can be reduced without incurring losses. Notice that the decrease in p_f is counteracted by an increase in p_c. Targeting the EVCS sector itself, the subsidy has an ambiguous impact on the price of EVCSs ($\Delta p_f = \pm$), depending on the substitution and network effects.[13] We also find that the effects of s_c on p_c and of s_f on p_f cannot be jointly negative.[14] The economic interpretation of this result derives from the two-sided market structure: as consumers and retailers represent two different sides of the market, the platform never reduces the price on both sides; on the contrary, as explained in the literature (Rochet and Tirole 2003), the platform chooses a price structure, which allows the price to be reduced on one side and covers losses by increasing the price on the other side. From our analysis, we can conclude that the relative intensity of the network effects influences the outcomes of the model in terms of prices[15]. In particular, due to the non-neutral price structure, the effects of some policies reverse depending on their relative intensity. Appendix 5.2.2 provides a deeper discussion of the policy impacts, including the results obtained for relevant values of the parameters.

3.4 First-best solution

In the first-best solution the social planner dictates the quantities that maximize welfare in the economy.[16] We assume that, in contrast to the atomistic agents, the

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[13] The condition for a positive (negative) impact on the price is given by $2(1-\gamma_1^2)-\gamma_2(\gamma_2+\gamma_4) > (<) 0$ and $X > 0$. Figure 5.9 in Appendix 5.2.2 provides a graphical representation of parameter values leading to a positive price effect on EVCSs.

[14] Figure 5.13 in Appendix 5.2.2 provides a reasoning for this result.

[15] See Figures 5.10, 5.11 and 5.12 in Appendix 5.2.2. The graphs show how the effect varies depending on the relative intensities of the network effects.

[16] See Appendix 5.2.3 for the derivation of the first-best solution.

social planner acknowledges the negative environmental externality; moreover, it fully internalizes the presence of network effects. The latter are only partly internalized in the decentralized equilibrium as we assume perfect information about the demand functions but the network effects have an additional impact on the utility and payoff functions of consumers and retailers respectively, which is ignored by the atomistic agents. The social planner maximizes welfare (W^P), which given the quasi-linear specification, can be written as the sum of utility, payoff function and profits minus the damage due to pollution

$$W^P(q_{0,h}, q_{0,a}, q_c, q_d, q_f) = U(q_{0,h}, q_c, q_d; q_f) + F(q_{0,a}, q_f; q_c) + \pi(q_c, q_d, q_f) - \phi q_d, \tag{3.18}$$

where $\phi \in (0, 1)$ represents the intensity of damages due to pollution. The social planner maximizes welfare subject to the resource constraint of the economy

$$q_{0,h} + q_{0,a} + p_c q_c + p_d q_d, + p_f q_f \leq m_h + m_a. \tag{3.19}$$

Due to the quasi-linear specification, welfare is strictly increasing in the numeraire good and the constraint holds with equality.

3.4.1 Ratio of EVs to ICEVs

Solving the social planner's problem we find the optimal ratio of EVs to ICEVs (ζ_{fb}) and we compare it to the ratio prevailing in the decentralized economy (ζ_m)

$$\zeta_{fb} = \frac{\alpha_c - c_c - \gamma_1(\alpha_d - c_d^P) + (\gamma_2 + \gamma_4)(\alpha_f - c_f)}{-\gamma_1(\alpha_c - c_c) + \left[1 - (\gamma_2 + \gamma_4)^2\right](\alpha_d - c_d^P) - \gamma_1(\gamma_2 + \gamma_4)(\alpha_f - c_f)}, \tag{3.20}$$

$$\zeta_m = \frac{2(\alpha_c - c_c) - 2\gamma_1(\alpha_d - c_d) + (\gamma_2 + \gamma_4)(\alpha_f - c_f)}{-2\gamma_1(\alpha_c - c_c) + \left[2 - \frac{1}{2}(\gamma_2 + \gamma_4)^2\right](\alpha_d - c_d) - \gamma_1(\gamma_2 + \gamma_4)(\alpha_f - c_f)}, \tag{3.21}$$

where $c_d^P = c_d + \phi$ represents the cost of producing ICEVs once the negative pollution externality is taken into account. We can show that, given the *monopoly* and *first-best condition*, $\partial\zeta_{fb}/\partial(\gamma_2+\gamma_4) > \partial\zeta_m/\partial(\gamma_2+\gamma_4)$ and $\partial\zeta_{fb}/\partial\phi > \partial\zeta_m/\partial\phi$, meaning that the ratio in the first-best increases more rapidly with the total network effect and environmental externality, compared to the ratio prevailing in the decentralized economy.

Proposition 3 (Optimal ratios of EVs to ICEVs)**.** *In the presence of network and/or environmental externalities, the ratio of EVs to ICEVs is higher in the first-best compared to the monopolistic case.*[17]

Our findings are represented in Figure 3.2, which demonstrates that the ratio in the first-best (solid line) always implies a larger number of EVs than in the monopoly.[18] The wedge increases for larger values of the total network effect because the decentralized equilibrium completely ignores the environmental damage and only partially internalizes the network externalities. This is because the social planner takes the impact of the network effects on both sides of the market into account, whereas in the decentralized case agents do not consider the positive feedback effect of their decisions on the other side of the market. The lower ratio of EVs to ICEVs in the decentralized economy paves the way for policy intervention in the form of support measures favoring the diffusion of EVs and EVCSs.

3.5 Welfare analysis

In this section, we introduce the possibility for a policymaker to choose the welfare-maximizing combination of subsidies and taxes, under the constraint of a balanced budget and taking into account the negative externality from ICEVs. Moreover,

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[17] This generally holds true, independently of the actual values for the demand parameters and the network effects under the assumption of an interior solution. See Appendix 5.2.3 for a proof of this result.

[18] Our model specification allows us to focus on the impact of network effects on welfare; since welfare depends only on the sum of network effects, there is no need to disentangle the relative intensities on the two sides of the market.

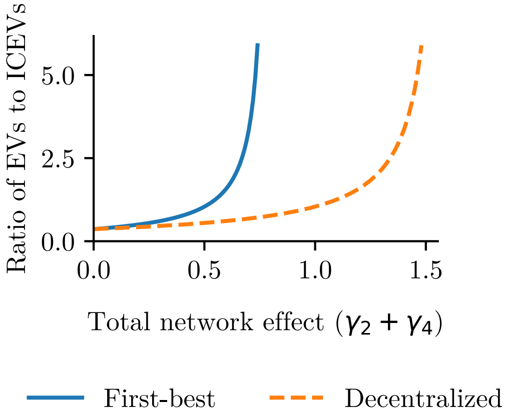

Figure 3.2: Ratio of EVs to ICEVs in the first-best and decentralized case as a function of the total network effect

we investigate how the presence of network effects impacts optimal welfare, that is, welfare once the optimal combination of policies is applied. In our simulations we focus on the effect of the sum of positive network externalities enjoyed by consumers and retailers rather than on the individual values assumed by γ_2 and γ_4. Our choice is justified by the fact that optimal welfare can be characterized through quantities alone, which only depend on the total network effect ($\gamma_2 + \gamma_4$).

We find that the optimal combination of policies includes subsidies for EVs and EVCSs (s_c and s_f) and taxes on ICEVs (t_d).[19] In order to show how the optimal policies influence the outcomes of the model, Figure 3.3 builds on Figure 3.2 and represents the ratio of EVs to ICEVs in the first-best (solid line), in the decentralized (dashed line) and when the optimal combination of policies is applied (dashed-dotted line). The optimal policies partially correct for the environmental externality from pollution and for the network effects: the ratio of EVs to ICEVs is higher compared to the monopoly case and the solution is closer to the first-best outcome. However, the assumption of a balanced budget does not allow the

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[19] Note that we use the term *optimal policies* to denote policies which correct for the externality due to the network effects and pollution. We do not consider policies tackling the monopoly externality as this is not the focus of this chapter.

policymaker to achieve the first-best solution.

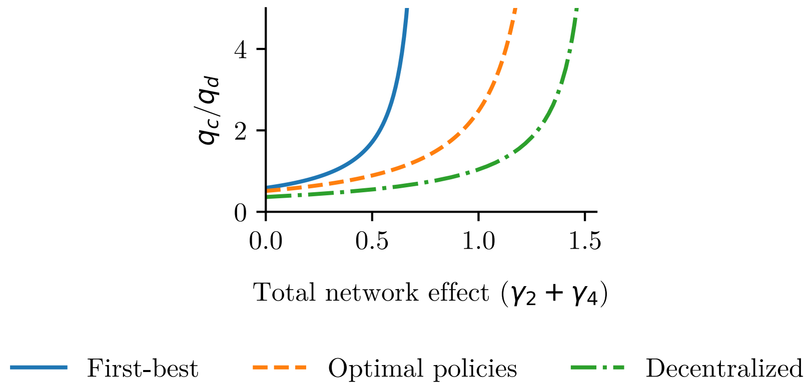

Figure 3.3: Ratios of EVs to ICEVs in the first-best, optimal and decentralized solution.

Figure 3.4 allows for a comparison between welfare in the optimal (dashed line) and in the decentralized case (dot-dashed line). When the optimal policies apply, welfare is higher than in the decentralized equilibrium; this holds true even when the network effects are zero because of the pollution externality, which is not taken into account by private agents. Moreover, in the presence of network effects the gap between the welfare widens because the externality due to network effects kicks in on top of the environmental externality. This means that policies are used to correct for the two externalities; the implications of this mechanism become apparent in the next section.

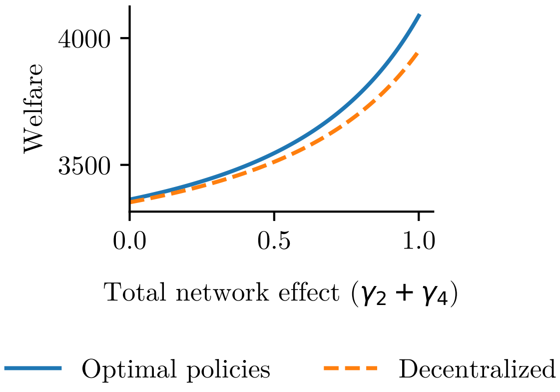

Figure 3.4: Optimal and decentralized welfare as a function of total network effect.

3.5.1 Double dividend

Countries have started to set targets in terms of reducing the number of polluting cars circulating; in order to achieve such targets, policymakers adopted subsidies to EVs and EVCSs and taxes on ICEVs. However, such measures - in particular taxes on ICEVs - have led to political pressure due to discontent in the general public.[20] Indeed, the environmental benefit derived from reducing the number of ICEVs is not sufficient to generate widespread support for such measures. For policies reducing the number of ICEVs to be well received, we need to draw attention to the economic benefits of having a lower number of ICEVs: in this section, we show that the presence of network effects can lead to the emergence of a double dividend, meaning that economic welfare can be improved while reducing the negative impact of pollution. Hence, awareness of the double dividend effect could play a crucial role in the political debate.

We assume that the policymaker maximizes welfare as before with the additional constraint of achieving a given target in terms of the number of ICEVs circulating. In particular, we consider a given target percentage reduction of ICEVs

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[20] See for example the "yellow vests" protests in 2018 in France.

compared to the decentralized level (q_d^*) and we simulate the impact on optimal welfare of different values of such target.[21] Figure 3.5 shows how optimal welfare changes with the percentage reduction of ICEVs. We see that using an optimal policy mix to reduce q_d can improve welfare. In the case of no network effects (solid line), the policymaker can maximize welfare by decreasing q_d to account for the negative environmental externality. Adding network effects, the policymaker faces a second externality and the q_d that maximizes welfare is therefore lower. This effect becomes stronger for higher values of the network effects.

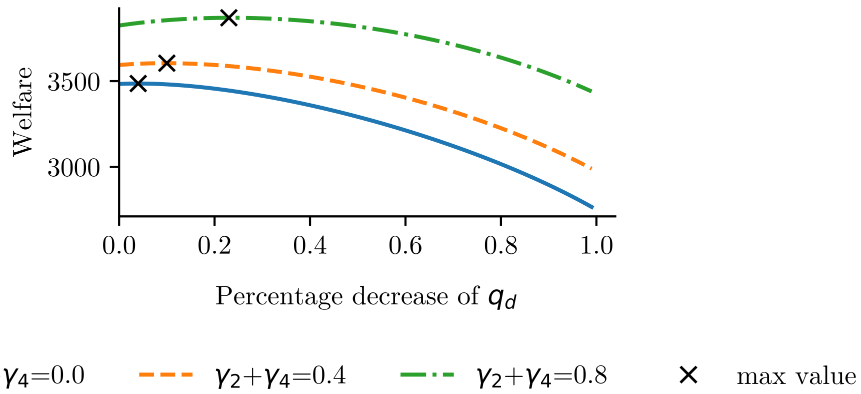

Figure 3.5: Optimal welfare as a function of a percentage decrease of ICEVs, for different values of the total network effect

In what follows, we disentangle the environmental and network externalities in order to show the existence of a double dividend. Figure 3.6 represents the evolution of economic welfare (W^E), which does not take the environment into account, and total welfare (W^P), as a function of the percentage reduction of ICEVs. The wedge between the two curves represents the environmental damage and it decreases as the number of ICEVs shrinks. Both for economic and total welfare, there is scope for improvement when policies aim at decreasing q_d. This scope is wider when considering total welfare as it takes into account the environmental externality next

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[21] We assume $q_d = q_d^*(1-r)$, with $r \in [0,1]$; hence, $r = 1$ means that no ICEVs exist in the economy.

to the network externality. For a decrease in the range from 0 to r^{dd}, the economic and total welfare increase because EVs enjoy network effects; moreover, increasing EVs compared to ICEVs reduces the negative externality due to pollution produced by ICEVs. Reducing q_d up to the threshold r^* increases total welfare, but from r^{dd} to r^* this comes at a cost in terms of economic welfare. Therefore, the policymaker faces a strong double dividend for a reduction of q_d in the shaded gray area. Such a double dividend is attributable to the presence of pollution and network effects.

Remark 3.5.1 (Double dividend)**.** *In the presence of network and environmental externalities a double dividend effect exists. Optimal policies can increase economic welfare while enhancing environmental quality.*

Notice that, combining the findings in Figure 3.5 and Figure 3.6 implies that the scope for a strong double dividend increases with the total network effects.

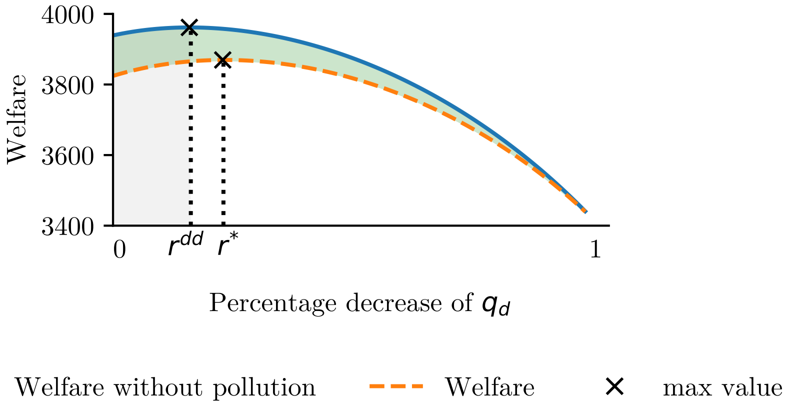

Figure 3.6: Double dividend

3.6 Extension: oligopoly

In this section we relax the assumption of a monopolistic market structure in favor of an oligopoly. We assume that n identical firms compete *à la Cournot*; each firm i with $i = 1, ..., N$ chooses the quantities of EVs, ICEVs and EVCSs taking into account the decisions of the other firms.[22] As in Figure 3.4 in the monopoly case, it can be shown that for fixed N welfare is increasing with the network effects. Figure 3.7 shows how welfare evolves with the percentage decrease of the quantity of ICEVs, for different numbers of firms. Compared to the monopoly case ($n = 1$), welfare is larger for higher number of firms for any value of the percentage reduction of ICEVs.

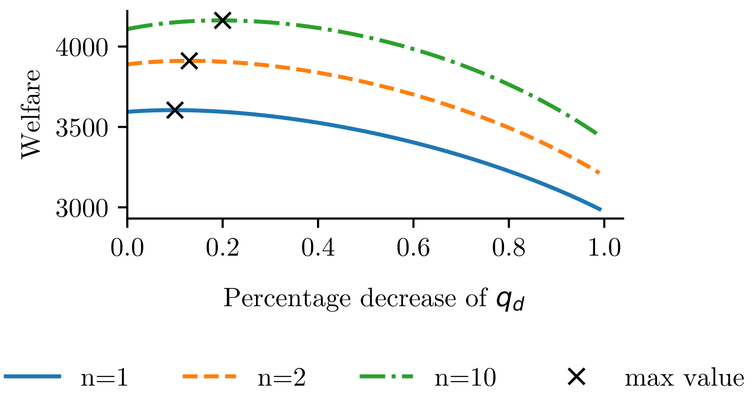

Figure 3.7: Welfare as a function of a percentage decrease in the quantity of ICEVs, for different n, with $\gamma_2 + \gamma_4 = 0.4$

Figure 3.8 shows that, when assuming an oligopolistic market structure, the double dividend effect is still present: in the gray shaded area welfare without accounting for pollution can be improved with no negative impact on the environment. Moreover, we find that increasing the number of firms, the double dividend effect becomes stronger and welfare is maximized for a lower number of ICEVs.

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[22] Appendix 5.2.4 provides the solution to the model when an oligopolistic market structure is assumed.

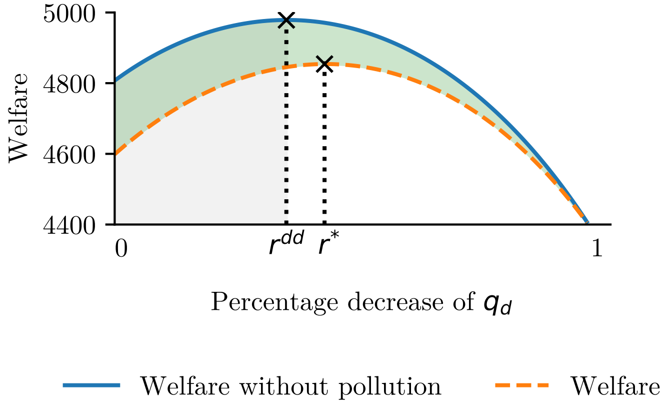

Figure 3.8: Double dividend assuming $n = 10$

3.7 Conclusion

In this part of the thesis we analyze how the transition to a low-carbon economy can take place in the transportation sector. Following the increasing potential attributed to electric vehicles (EVs) to decarbonize the transportation sector, which is at odd with their still limited diffusion, the debate about the design of policies supporting EV adoption has gained importance. One of the main obstacles identified and the focus of the present chapter is the lack of an appropriate charging infrastructure. This generates the so-called range anxiety, which reduces the possibility for consumers to perceive EVs and internal combustion engines vehicles (ICEVs) as substitutable. Besides government intervention, the retail sector can play a key role in expanding the charging network. However, the number of electric vehicle charging stations (EVCSs) purchased by retailers will not increase as long as the number of EVs is low. Hence, the market for EVs exhibits a “chicken-egg” problem due to the presence of network externalities operating between the two goods. With this chapter, we contribute to this debate by providing a theoretical framework that takes into account the two-sidedness of the EV market and the indirect network effects operating between EVs and EVCSs. Additionally, we account for the degree of substitutability between EVs and ICEVs, and for the pollution externality generated by ICEVs.

In our model, a platform sells EVs and ICEVs to consumers on one side of the market and EVCSs to retailers on the other side. Within this framework, consumers make their car purchasing decisions by maximizing utility, which is affected by the number of EVCSs, and retailers choose charging stations based on the maximization of their payoff function, which in turn, depends on the number of EVs. We introduce policies targeting prices of EVs, ICEVs and EVCSs and study how they affect the adoption of EVs in the presence of network externalities. We then introduce a negative externality from ICEVs and compute the welfare-maximizing combination of policies. Finally, we show how a reduction in the number of ICEVs affects optimal welfare.

The main results of the present chapter are: (1) the presence of network effects has an impact on the profit-maximizing quantities and prices: in particular, policies tackling one side of the market also affect the other side and thus generate feedback loops. The choice of subsidizing EVs does not only have a positive effect on the number of EVs *per se*, but also on the quantity of EVCSs. More charging stations, in turn, generate a positive feedback effect on the number of EVs. Since the network effects work both on the EV and EVCS side, the same positive outcome in terms of EV adoption occurs when subsidizing EVCSs; (2) policies are non-neutral, that is, subsidies to consumers or retailers are not equivalent; this is due to the dependence of prices on the relative intensity of network effects; (3) the set of welfare-maximizing policies implies subsidies to EVs and EVCSs as well as taxes on ICEVs; (4) in the presence of network effects and of a negative environmental externality from ICEVs, there is scope for a strong double dividend: decreasing the quantity of internal combustion engine vehicles can be economically improving, while reducing the negative impact of pollution. The findings of our model imply that it is important to account for network externalities between EVs and EVCSs when designing EV promoting policies. The resulting feedback loops might exacerbate shocks to either side of the market and thus generate effects which are greater than any single market study suggests. Ignoring the interdependence of EVs and EVCSs could therefore lead to an underestimation of the impact of policy measures. Finally, the presence of a strong double dividend implies that a lower number of ICEVs can be economically-improving while reducing the negative impact of pollution.

Future research should focus on introducing non-linearities in the demand functions and on a more in-depth study of alternative market structures. Moreover, our economic setting might be studied in a dynamic framework so that the adoption of new technologies (EVs and EVCSs) follows from non-simultaneous decisions of consumers and retailers. In addition, the pricing decision by the platform might be affected by the production costs of suppliers (for instance, battery production). A more realistic model might therefore also allow for vertical integration of production.

Chapter 4

Economic Impacts of Decarbonizing the Swiss Passenger Transport Sector*†

Abstract

Switzerland committed to reaching net-zero emissions in 2050. This goal is particularly ambitious for the Swiss passenger transport system, which emits more than one third of Swiss CO_2 emissions, and is not yet on a clear emission reduction path. The chapter investigates the economic impact and the emission-saving potential of a decarbonization pathway for the Swiss transport sector based on three edge case scenarios and on a combination of them: (1) improved fuel/engine technology and fostered diffusion of battery electric vehicle, (2) increased capacity use of passenger cars, and (3) enhanced modal shift towards public transport. Our analysis is conducted using a multi-model framework, which interlinks a computational general equilibrium model with two external transportation models. This approach allows

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[*] This work is a joint effort with Vanessa Angst (Infras), Chiara Colesanti Senni (CEP), Markus Maibach (Infras), Martin Peter (Infras) and Renger van Nieuwkoop (BFS).

[†] This research was financially supported by the Swiss National Science Foundation (SNSF) within the framework of NFP 73.

us to incorporate a highly disaggregated passenger transport system into the economic analysis. The framework is calibrated to Swiss data to assess the optimal scenario mix in terms of emissions and economic impact. The optimal decarbonization pathway mix slightly increases welfare and lowers CO_2 emissions of passenger transport in 2050 from 6 to 1.7 million tons CO_2 compared to the reference scenario. Despite the sharp reduction in emissions, a decarbonization pathway based on the considered scenarios is insufficient to reach the net-zero emission target.

4.1 Introduction

By adhering to the Paris Agreement, Switzerland has set the goal of net-zero emission by 2050 in order to limit global warming below 1.5°C. Achieving this goal requires a substantial transformation of the whole Swiss economy and its energy system towards a massive reduction of energy demand and CO_2 emissions. Accounting for 40% of the Swiss CO_2 emissions in 2018, the transport sector plays a prominent role in the transition to a net-zero economy. Contrary to other sectors, the transportation sector is not yet on an emissions reduction path: While CO_2 emissions have been significantly reduced in most other sectors since 1990, they have increased by 3% in the transport sector (BAFU 2020).[1] It is striking that, despite its great relevance, the political discussion started to shift towards specific measures and transformation paths for the transport sector in Switzerland only recently (see Bundesrat (2021) and BFE (2021)). Also, there has been surprisingly little research about the overall impacts of decarbonization scenarios on the transportation sector and the Swiss economy as a whole. This chapter aims at filling this gap by analyzing different decarbonization scenarios for the Swiss passenger transport sector in terms of emission-savings potential and economic impact.

The decarbonization of the passenger transport sector depends, among others, on technological development and behavioral changes, as well as transportation

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[1] As an example, according to BAFU (2020), the CO_2 emissions of the industry sector decreased by 18% in the same period.

policies. In this study, we focus on “ongoing” decarbonization scenarios, that induce gradual change in the economy over time until 2050.[2] For Switzerland, three ongoing scenarios of how to pursue decarbonization of the Swiss passenger transport system came into focus (see Zimmer et al. (2016)): (1) The technology and battery electric vehicle (BEV) diffusion scenario (TECHS), where increased fuel efficiency, motor vehicle efficiency and transport efficiency towards carbonless and carbon-free technologies, as well as a policy scheme favoring BEVs lead to a future with a majority of BEVs in the car stock, (2) the capacity use scenario (CAPU), where a behavioral change or low-cost governmental policies incentivize car- and ride-sharing, leading to a higher capacity use of passenger cars and (3) the modal shift scenario (SHIFTP), where a policy scheme fosters a modal shift towards public transport. Each scenario contributes differently to a green and sustainable transport system in a “non-transport” industrial country, such as Switzerland.[3] In accordance with the literature and experts, we set the values of the parameters in the scenarios to their upper limit reasonable for Switzerland, making them edge case scenarios. That allows us to perform a “potential analysis” of each scenario, meaning that we can evaluate their economic impact and emission-savings potential, to investigate whether Switzerland can rely on them to achieve net-zero emissions in 2050.

Analyzing the impact of these edge case scenarios requires a framework that combines the overall economy with the transport system in a disaggregated form. To account for that, we develop a multi-model approach, which relies on three different models: (1) a recursive dynamic CGE model for Switzerland capturing the economy as a whole; (2) a cohort model, which we use to compute the survival rate of specific passenger car categories (i.e. cars characterized by a given

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[2] We call them “ongoing” scenarios as they utilize market-based mechanisms, gradual technological improvements and behavioral changes following an “ongoing” approach over time. In contrast, measures such as bans for internal combustion engine vehicles have an abrupt impact.

[3] Switzerland has no strong production sector in the passenger car industry and is dependent on passenger car and fuel imports. The value-added chain of the railway industry (electricity production, rolling stock production), however, is relevant for Switzerland.

registration year, fuel type and power), as well as the demand for new passenger cars and (3) a choice model, that classifies the specific passenger car types (i.e. cars characterized by a given fuel type and power) entering the market in a given year. Interlinking the economic model (1) with the two external transport models (2 and 3) allows us to incorporate a highly disaggregated transport system into the economic analysis. Hence, our framework is suitable to compare alternative transport policies and rank them according to their impact on the economy, energy use, and CO_2 emissions. We calibrate our framework to Switzerland to evaluate the economic and emission-savings potential of a decarbonization pathway based on the three edge case scenarios. We first investigate the impact of the edge case scenarios separately. Our results show that, despite having a slightly positive impact on welfare and lowering emissions, none of the edge case scenarios can reach the net-zero target. Under TECHS, boosting BEVs decreases the CO_2 emissions from passenger transport by 45.7% relative to the business-as-usual scenario (BAU) in 2050 to 3.2 million tons. An increase in the capacity use of cars in CAPU reduces the CO_2 emissions from passenger transport by 25.7% to 4.4 million tons. Incentivizing people to rely more on public transport as in SHIFTP results in a decrease by 22.7% to 4.6 million tons CO_2 in 2050. That makes TECHS the most promising edge case scenario in reducing the CO_2 emissions. The reductions of the individual edge case scenarios are, however, not sufficient to achieve the net-zero target. Thus, we use our framework to analyze different combinations of all measures used in the scenarios and to evaluate their optimal mix in terms of reducing emissions. In that case, CO_2 emissions of passenger transport can be decreased substantially by 71.3% relative to BAU in 2050 to 1.7 million tons CO_2, which is, however, not sufficient to reach the net-zero target of Switzerland. Therefore, we conclude that an ongoing decarbonization pathway with realistic assumptions on gradual technological change, policy measures, and behavioral changes can not be relied on to achieve this target. An explanation for that is that a passenger vehicle stays in the market for more than ten years on average, and its specific vehicle type can survive up to 28 years. Thus, pursuing the net-zero emissions target might require immediate action having an abrupt impact in the short term. This time pressure prevents Switzerland to successfully follow a smooth decarbonization pathway of the passenger transport system.

4.1.1 Relation to the literature

Existing CGE models including the transport sector vary significantly in model structure, regional and sector aggregation, and in the representation of transport. In most cases, transport costs are calculated using an external transport model considering one, or perhaps two modes of transport. Different to that and closer to our framework are bottom-up models with specific transport technologies. In these type of modeling structure the transport costs are calculated within the model, as in the MIT-EPPA model developed by Schaefer and Jacoby (2005) and Schaefer and Jacoby (2006). These models have, however, the disadvantage of being highly aggregated (the EPPA model, for example, contains only 11 production sectors).

Another strand of the literature analyzing the transport sector uses spatial network models, which allow to study important issues like congestion, but are not very tractable with regard to transport impacts because of the high-dimensionality of the network (Kim et al. 2004, Venables 2004, Kim et al. 2011, Bröcker and Korzhenevych 2013). Moreover, most of them have a highly aggregated transport sector. All the studies mentioned above deal with infrastructure proposals or optimal pricing scenarios (Wickart et al. 2002).

A recent paper by Thalmann and Vielle (2019) also looked at the decarbonization of the transport sector in Switzerland. They use a CGE model to study the impact of different tax strategies regarding transportation fuel on emissions and the economy. The model introduced here differs in two key aspects. First, Thalmann and Vielle (2019) implement the transport system directly in a CGE model, whereas we interlink a CGE model with an external transport bottom-up model for passenger cars. Our approach allows us to disaggregate the transport system into greater detail, which is essential to capture the full impact of transport policies. Second, the model of Thalmann and Vielle (2019) contains 11 sectors, of which five are energy- and three are transport sectors. In contrast to them, we include 78 sectors in our model. This enables us to analyze the impact of transport policies more comprehensively, considering their sectoral effects.

The chapter is organized as follows: Section 4.2 describes the theoretical framework adopted and details the various sub-models. In Section 4.3 we calibrate the model with data for Switzerland. Section 4.4 introduces three edge case scenarios and 4.5 presents the simulation results. Lastly, Section 4.6 concludes.

4.2 Theoretical framework

Our framework combines three different models, as outlined in Figure 4.1: (1) A recursive-dynamic, single-country CGE model for Switzerland calibrated on the energy- and transport-specific input-output table (IOT) for the year 2014 (CGE model); (2) A cohort model that categorizes all available passenger cars according to their category, i.e. registration year, fuel type and power (Cohort model); (3) A choice model, which is used to compute the demand for new passenger cars, that is, cars sold in a specific year, for the different passenger car type, i.e. fuel type and power (Choice Model). The model is solved using two loops. The inner loop is necessary to account for the non-simultaneous solution of the three models ("1"). Specifically, it allows us to incorporate the feedback effects between the demand for passenger cars and its composition derived in the bottom-up models and the economic variables in the CGE model. We use the outer loop to account for time in the model ("2").

The overall functioning of the model is as follows: We first use a regression model including population growth to obtain the total number of passenger cars for the current year. Next, we make an assumption about the number of passenger

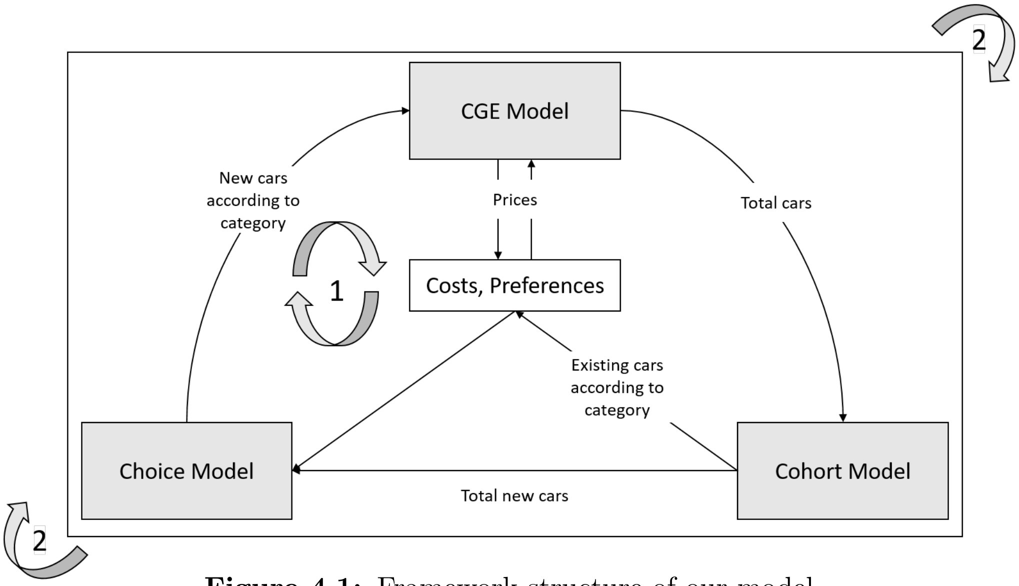

Figure 4.1: Framework structure of our model

cars of each type (i.e. fuel type and power) entering the market. This information allows us to solve the CGE model completely and thus to derive the prices that realize in the economy, including the prices for new passenger cars.

The total number of passenger cars obtained from the regression model then serves as an input for the cohort model, where we use an age-function for passenger cars to compute the stock of surviving cars that were already in the market in the previous year. Subtracting the surviving cars from the total number of passenger cars allows us to calculate the total demand for new passenger cars.

The demand for new passenger cars together with the prices obtained from the CGE model enter then the choice model, which allows to derive the number of new passenger cars according to fuel type and power. Next, we check whether the output of the choice model coincide with the initial assumption on passenger cars type entering the market in the CGE model. If not, we re-calibrate the CGE model accordingly and execute the first loop again. This inner loop is repeated until the model converges, i.e. the difference in the number of new cars for each type is less than ten cars. Once convergence is achieved, we update the stock of passenger cars using the regression model, and move to the outer loop, where the model is re-calibrated for the next time period. We use the savings/investments of the consumers from the previous year to calculate the new capital stock. Moreover, we update the values for the working force and use the projected autonomous energy efficiency increase to re-calibrate the energy demand and use. After these adjustments, we move back to the inner loop and solve the CGE model for the next year. In what follows, we describe in greater detail the three models of our framework.

4.2.1 CGE model

The first building block of our framework is a CGE model for Switzerland, which follows an Arrow-Debreu type of framework and captures the behavior of supply, demand and prices in the whole economy, allowing for several interacting agents and markets. Moreover, the model depicts the interaction with the rest of the world through import and export. The driving factors for an equilibrium are the following three assumptions on the behavior of the producers and consumers, together with the requirement of non-negative prices: First, each consumer maximizes utility taking prices as given and under the assumption of a balanced budget. Second, producers maximize their profits (or minimize their costs), given their production technology. Third, supply at least covers demand in each market.

Consumers and government

Consumers in our model are a representative household and the government. They maximize welfare in the form of a hierarchical CES utility function as shown in Figure 4.2.

For each nest of the utility function, the elasticity of substitution captures the responsiveness of demand for the good in each nest to relative price changes.[4]

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[4] The goods are perfect substitutes when the substitution elasticity approaches infinity and perfect complements when it approaches zero.

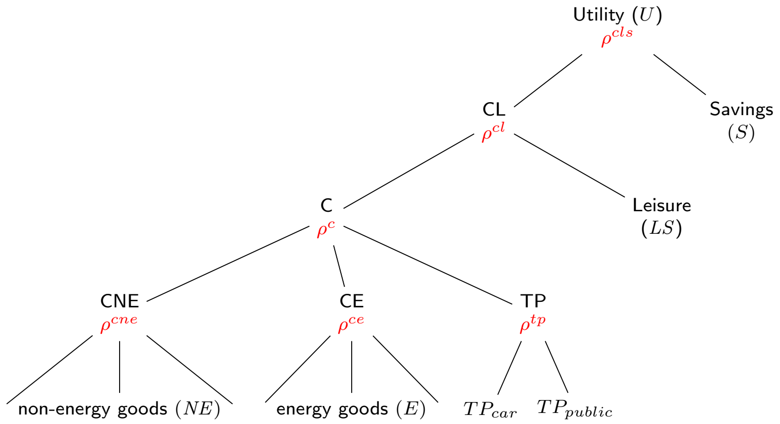

Figure 4.2: Utility function with substitution parameters (ρ) for each nest

At the lowest level of the hierarchy, the consumer decides on the composition of a bundle of non-energy CNE, energy goods NE and private transport TP. The parameters ρ^{cne}, ρ^{ne} and ρ^{tp} capture the substitution parameters within the various energy, non-energy and transport goods, respectively.[5] These three bundles build a composite consumption good C, according to the substitution parameter ρ^{c} that, at the next level, is combined with leisure LS. At the top level, the composite of consumption and leisure is combined with savings S, providing overall welfare. The parameters ρ^{cl} and ρ^{cls} capture the substitution between consumption and leisure, and between the consumption-leisure bundle and savings, respectively. The utility function of the government does not contain leisure and savings. Moreover, the saving share of the government is fixed.

Assumption 1 (Utility function)**.** *The utility function of consumers is given by*

$$U = \left\{ \theta^{cls} \left[\left(\theta^{cl} C^{\rho^{cl}} + (1-\theta^{cl}) LS^{\rho^{cl}} \right)^{\frac{1}{\rho^{cl}}} \right]^{\rho^{cls}} + (1-\theta^{cls}) S^{\rho^{cls}} \right\}^{\frac{1}{\rho^{cls}}}, \tag{4.1}$$

where θ^{cls} captures the value shares of the consumption-leisure composite and of

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[5] The elasticity of substitution σ is given by $\frac{1}{1-\rho}$.

savings in total utility and θ^{cl} *the relative importance of consumption and leisure in the consumption-leisure bundle.*

Composite consumption of non-energy, energy and transport goods C is also assumed to follow a CES aggregation.

Assumption 2 (Composite consumption)**.** *Composite consumption is given by*

$$C = \left[\theta^{c} CNE^{\rho^{c}} + \theta^{ce} CE^{\rho^{c}} + (1 - \theta^{c} - \theta^{ce}) TP^{\rho^{c}}\right]^{\frac{1}{\rho^{c}}}, \tag{4.2}$$

where θ^{c} *represents the value shares of non-energy consumption and* θ^{ce} *the value share of energy consumption.*

Consumption of non-energy good is obtained as

$$CNE = \left(\sum_{ne} \theta^{ne}_{ne} (X^{c}_{ne})^{\rho_{cne}}\right)^{\frac{1}{\rho^{cne}}}, \tag{4.3}$$

where X^{c}_{ne} are non-energy goods and θ^{ne}_{ne} is the value share of each individual good in non-energy good consumption. Similarly, consumption of energy goods reads

$$CE = \left(\sum_{e} \theta^{e}_{e} (E^{c}_{e})^{\rho_{ce}}\right)^{\frac{1}{\rho^{ce}}}, \tag{4.4}$$

where E^{c}_{e} are energy goods and θ^{e}_{e} is the value share of each individual good in energy good consumption. We consider the transportation good TP as the distance an individual wants to travel with passenger cars given its endowments. In our framework, we separate the cost of private transport into variable costs, PC_{vc}, and fixed costs, PC_{fc}. The fixed costs, which are the annualized cost of having a car, enter the CGE model as negative endowments. Total transport is given by

$$TP = \left[\theta^{pr}\, {TP_{car}}^{\rho^{tp}} + (1 - \theta^{pr})\, {TP_{public}}^{\rho^{tp}}\right]^{\frac{1}{\rho^{tp}}}, \tag{4.5}$$

where TP_{car} is the distance covered with the passenger car at the expense of PC_{vc}

per kilometer and TP_{public} the distance covered with public transport. The parameter θ^{pr} captures the share value of private transportation and ρ^{tp} represents the substitution parameter between private and public transport. In this framework, the variable costs appear in the utility function and reflect the decision of the consumer to drive fewer or more kilometers with the car. In addition to that, the number of passenger cars influences the total number of kilometers driven by passenger cars in the economy. To calculate the number of passenger cars, we use a regression model regressing them on the population projection for Switzerland (see Appendix 5.3.1). In Section 4.2.2 and 4.2.3, we derive the number of new passenger cars, their type, and the variable and fixed costs.

The income for the representative agent is defined by

$$I^{RA} = w(\overline{L} - LS) + rK + TR - T^{RA} - PR_{fc}, \tag{4.6}$$

where $\overline{L}$ is the time endowment, LS the demand for leisure, r the rental price of capital endowment K, T^{RA} represents tax expenditures and TR are transfers. The income for the government is given by

$$I^{Gov} = T^{RA} + T^{CP} - TR, \tag{4.7}$$

where T^{CP} are the taxes on consumption and production. The labor endowment of the government (and therefore its leisure demand in the utility function) is zero.[6] The behaviour of the representative consumer and the government in the model is now explicitly described by the maximization of the utility function (Equations (4.1) and (4.2)) subject to their respective income constraints (Equations (4.6) and (4.7)).

Besides the income constraint, the government is also not allowed to change its growth- and population adjusted deficit ("equal-yield constraint"). A lump-sum

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[6] Note, that people working for the government in sectors like public transport are private persons and their labor endowment is part of the endowment of the representative agent.

tax/transfer is used to keep the adjusted deficit unchanged.

Producers

Each producer maximizes profits, for each good $j \in N$. Under perfect competition, the producer takes the prices of outputs and inputs as given. We formulate the production technology as a nested CES function as shown in Figure 4.3. We make a distinction between non-energy (indexed over i) and energy sectors (indexed over e). In the non-energy sectors, substitution between energy E and value-added VA (capital and labor bundle) is allowed. Energy producing sectors can not substitute the energy input with other inputs to keep the link between the quantity of energy input and output constant.[7]

We follow van der Werf (2008) in the choice of the substitution possibilities between capital K, labor L, energy E and intermediate demand M. The author estimates and compares the substitution elasticities of six industrial sectors for several nesting structures KE-L, KL-E, KLE and finds the highest statistical significance for the elasticities of the KL-E structure. The substitution elasticity in the intermediate nest, σ^m, is set to 0, which is common practice in applied CGE work.[8]

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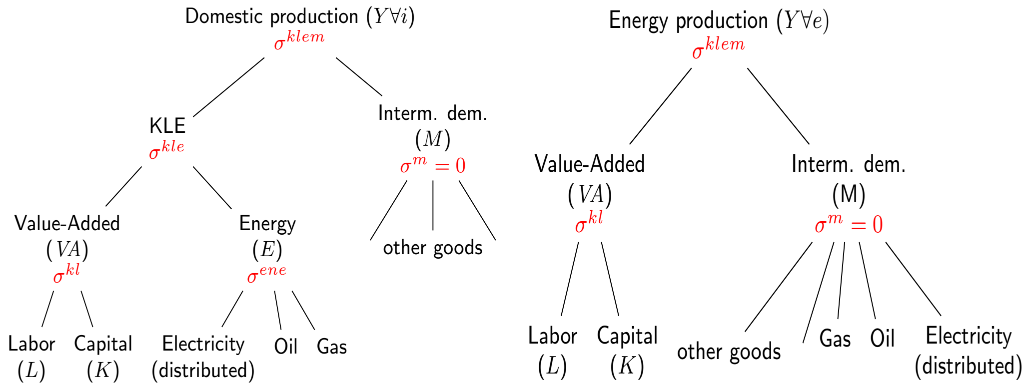
[7] This formulation excludes that, for example, the input of nuclear fuels can be reduced to a minimum by substituting it for capital.

[8] A substitution elasticity of zero implies complementary goods: cars need four wheels. However, one reason for setting this value to zero, was the reduction of the complexity of the model in times when computer power was an issue.



(a) Production sector (not energy sector) (b) Energy production sector

Figure 4.3: Domestic production function

Assumption 3 (Production of non-energy sectors)**.** *The production function for the non-energy sector i can be written as*

$$Y_i = \left\{ \theta_i^{kle} \left[\left(\theta_i^{va}\, VA^{\rho_i^{kle}} + (1-\theta_i^{va}) E_i^{\rho_i^{kle}} \right)^{\frac{1}{\rho_i^{kle}}} \right]^{\rho_i^{klem}} + (1-\theta_i^{kle}) \left(\min_j M_{ji} \right)^{\rho_i^{klem}} \right\}^{\frac{1}{\rho_i^{klem}}}, \tag{4.8}$$

where M_{ji} is the intermediate demand of sector i. The parameter θ_i^{kle} represents the value share of the composite KLE in non-energy production and θ_i^{va} the value share of value-added in the KLE composite. ρ_i^{kle} is the substitution parameter for the KLE nest and ρ_i^{klem} the substitution parameter of the top nest.

The value-added subnest of the production function is given by

$$VA_i = \left[\theta_i^{k} K_i^{\rho_i^{kl}} + (1-\theta_i^{k}) L_i^{\rho_i^{kl}} \right]^{\frac{1}{\rho_i^{kl}}}, \tag{4.9}$$

where K_i represents capital services and L_i is labor. The parameter θ_i^{k} captures the value share of capital and ρ_i^{kl} is the substitution parameter for the KL nest.

The composite good of energy inputs E is, in turn, defined as

$$E_i = \left[\sum_e \theta_{ei}^{ene} E_{ei}^{\rho^{ene_i}} \right]^{\frac{1}{\rho^{ene_i}}}, \tag{4.10}$$

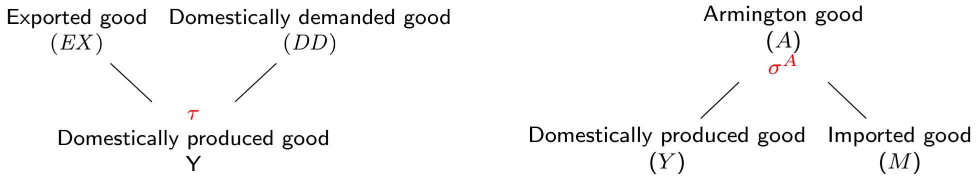
where E_{ei} is the specific energy good input (like gas, oil, etc) in sector i and θ_{ei}^{ene} is its share value. The parameter ρ^{ene_i} is the substitution parameter of the energy nest. In our model, energy can be produced using several technologies (nuclear, hydro, etc.). Each technology s is modeled as a Leontief-function

$$ELE_s = \min \left(L_s, K_s, E_{es}, X_{is} \right), \tag{4.11}$$

where ELE_s is the technology s producing energy and E_{es} is the energy good input used by technology s. The relative costs of the technologies and the available capacity determine the production mix. The producer behavior can explicitly be described as the maximization of profits given the production function as defined in Equations (4.8), (4.9), (4.10) and (4.11).

International trade

In our model, sectoral output is transformed into goods produced for the domestic market and exports (see Panel (a) in Figure 4.4). Goods for the domestic market are a composite of imports and domestically produced goods, the so-called Armington good (see Panel (b) in Figure 4.4). The producer uses the domestically



(a) Exports (b) Imports

Figure 4.4: Illustration of the treatment of imports (Armington) and exports.

produced goods for domestic supply and exports to maximize its profits given the transformation function

$$\max \Pi_i = P_i^E EX_i + P_i^D DD_i - P_i^A A_i, \tag{4.12}$$

where P_i^E is the price of exported goods EX_i, P_i^D is the price for domestically demanded goods DD_i and P_i^A is the price of the Armington good A_i. The transformation technology for domestically produced goods follows a CES structure.

Assumption 4 (Domestically produced goods)**.** *Domestically produced goods follow the transformation function*

$$Y_i = \left[\theta_i^E EX_i^{\psi_i} + (1-\theta_i^E) DD_i^{\psi_i}\right]^{\frac{1}{\psi_i}}, \tag{4.13}$$

where θ^E capture the value shares of exported good and ψ_i is the transformation parameter (with $\psi = (\tau - 1)/\tau$ where tau is transformation elasticity).

We consider imports as imperfect substitutes for similar domestically produced goods to allow for cross hauling (importing and exporting the same kind of good). Hence, we replace the domestic consumption by an (Armington) function which converts imported and domestically produced goods into a composite good (Armington 1969).

Assumption 5 (Imported goods)**.** *Imported goods are defined by the transformation function*

$$A_i = \left[\theta_i^D Y_i^{\rho_i^a} + (1-\theta_i^D) IM_i^{\rho_i^a}\right]^{\frac{1}{\rho^{a_i}}}, \tag{4.14}$$

where IM_i is the import good, θ^D capture the value shares of domestically produced and ρ_i^a is the transformation parameter (with $\rho^A = (\sigma^A - \sigma^A)/\tau$ where σ^A is the substitution elasticity).

We treat Switzerland as a small, open economy; hence, the world market prices for goods and services are taken as given. The domestic prices P_i^E (P^{IM_i}) for exports EX_i (imports IM_i) are given by

$$P_i^E = PFX\overline{P}_i^{E_w} \quad \text{and} \quad P_i^{IM} = PFX\overline{P}_i^{IM_w}, \tag{4.15}$$

where PFX is the exchange rate, and $P_i^{E_w}$ ($P_i^{IM_w}$) the world market price for exported (imported) goods in foreign currencies.

Market clearing

The third set of conditions for a general equilibrium demands that supply should cover demand in each market (note that this also includes the case of excess supply resulting in a zero price). The CGE model contains market clearing conditions for the factors (labor, capital), and produced goods (Armington goods, domestically produced goods and an investment good, i.e. a composite of the demand in the IOT for investments).

The market-clearing conditions for the factor markets (labor L and capital K) are given by

$$\sum_i L_i = \overline{L} - LS \text{ and } \sum_i K_i = \overline{K}, \tag{4.16}$$

while the market-clearing conditions for the domestically produced and the Armington goods are given by:

$$Y_i = DD_i + EX_i, \text{ and } A_i = \sum_j M_{ij} + X_i^c + X_i^g + X_i^{inv}, \tag{4.17}$$

for the non-energy goods and

$$Y_e^E = DD_e + EX_e, \text{ and } A_e = \sum_j M_{ej} + E_e^c + E_e^g + X_e^{inv}, \tag{4.18}$$

where $X_i^{c/g}$ is the household/governmental demand for good i (non-energy goods),

$E_e^{c/g}$ the demand for energy goods, and X_i^{inv} is the demand for good i in the investment function. In the last forty years, except for 1981 and 2008, Switzerland faced a current account surplus.[9] We assume that the surplus is fixed leading to the additional market clearing constraint

$$\sum_i \overline{P}_i^{E_w} EX_i + \overline{CA} = \sum_i \overline{P}_i^{M_w} M_i, \tag{4.19}$$

where $\overline{CA}$ is the level of the current account surplus. Additionally, the investment good INV is linked to the investment demand for sectoral goods by introducing a Leontief production function

$$INV_t = \min_i \left(X_i^{inv} \right), \tag{4.20}$$

where the market clearing for the investment good is given by the savings-investment equality

$$\frac{S}{P^{inv}} = INV. \tag{4.21}$$

Lastly, the market clearing function for the utility goods of the representative agent (RA) and the government (Gov) is given by

$$U = \frac{I^{RA}}{PU}, \text{ and } UG = \frac{I^{Gov}}{PUG}, \tag{4.22}$$

where PU and PUG are the prices of the utility good for the consumer and the government, respectively. The CGE model is set up and solved as a mixed-complementarity problem (MCP), as described in Appendix 5.3.1.

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[9] See `https://tradingeconomics.com/switzerland/current-account`, visited March 9, 2018.

Dynamics in the CGE model

There are several approaches to incorporate time in a CGE model. The prevalent methods are either Ramsey-type or recursive dynamics.[10] In the Ramsey setting, agents are assumed to have perfect foresight and decide at the beginning of the time horizon for all the following years. This approach is not feasible for this study due to the complexity of the solving process of our model. Therefore, we implement the recursive dynamic approach in which the agents do not form consistent expectations of future prices as their decisions are based on the actual information. Using a recursive dynamic framework, the CGE model and the bottom-up models can be solved and updated for the next year.

A key input variable for the implementation of recursive dynamics is the gross investment in the previous period. This variable is used to update the available capital stock with the capital movement equation

$$K_{t+1} = (1-\delta)K_t + I_t, \tag{4.23}$$

where the capital in the next period, K_{t+1}, is defined as the depreciated capital in the current period, K_t, plus the actual investments, I_t, where δ is the depreciation rate. Based on that, we can set up the maximization problem as

$$\begin{aligned} \max \mathcal{L}(K_t, I_t) = p_t\left(F_t(K_t) - I_t\right) - \lambda_t\left(K_t - (1-\delta)K_{t-1} - I_{t-1}\right) \\ - \lambda_{t+1}\left(K_{t+1} - (1-\delta)K_t - I_t\right), \end{aligned} \tag{4.24}$$

where $F_t(K_t)$ is the production function, p_t the price of the selling good, r the exogenous interest rate and λ can be interpreted as the marginal value or price of

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[10] A third approach would be to endogenize growth using a Romer-type model (see for example Bretschger et al. (2011)).

one capital unit. Solving Equation (4.24) gives us

$$\frac{\partial \mathcal{L}}{\partial K_t} = p_t \frac{\partial F_t}{\partial K_t} - \lambda_t + (1-\delta)\lambda_{t+1} = 0 \tag{4.25}$$

$$\frac{\partial \mathcal{L}}{\partial \lambda_t} = K_{t+1} - (1-\delta)K_t - I_t = 0 \tag{4.26}$$

$$\frac{\partial \mathcal{L}}{\partial I_t} = -p_t + \lambda_{t+1} = 0. \tag{4.27}$$

Equation (4.25) tells us that the additional value in production of one additional unit of capital is equal to the additional cost of capital. This additional cost is equal to the cost of the investment of one unit of capital in the previous period minus the value of the remaining capital in the actual period.

Assuming a steady state, all the quantities grow at the rate γ and, as the interest rate is constant, the future price is given by

$$K_{t+1} = (1+\gamma)K_t \tag{4.28}$$

$$p_{t+1} = \frac{p_t}{1+r}. \tag{4.29}$$

Using Equations (4.27) and (4.28), the steady state condition for investment is given by

$$I_t = (\gamma + \delta)K_t. \tag{4.30}$$

4.2.2 Cohort model

The cohort model is used to simulate the number of passenger cars surviving each year. This is necessary to evaluate the inflow of passenger cars and the change in the composition of the stock. As the age of a passenger car is particularly relevant to determine its survival rate in the market, we estimate an age function for passenger cars, which tells us how passenger car presence in the market evolves depending on age.

To estimate the age-function for Switzerland, we use data from BFS (2019b) on the composition of the stock of passenger cars from 1990-2018. We obtain the share of passenger cars registered in a given year which are present in the stock of passenger cars at a particular year (e.g. we have the share of cars registered in 2011, which are present in the stock of 2012). The dataset provides the registration year aggregated into ranges of five years (cars registered in 2000-2004) for the period 1990-2010. From 2010 onwards, registrations are yearly. To get the best fit for our age-function, we apply a stepwise OLS estimation combined with a machine learning algorithm. We first use an OLS estimation of the original aggregated dataset. Next, we take the outcome of that estimation and apply it to the original dataset, which allows us to disaggregate the stock of passenger cars into yearly registration years for the entire time. Then, we take this manipulated dataset as input for another OLS estimation, which, applied to the manipulated dataset, updates the data again. We continue that approach until we reach convergence between the input and the output, meaning that we find the OLS estimation that does not change the manipulated data anymore. With this method, we compute the best fit for the age structure of passenger cars using a fourth-order polynomic function of age.

The results of our estimation are shown in Figure 4.5, which plots the passenger cars for each registration year against the age of the car. Notice that age equal to zero implies that the registration year is equal to the year in which the stock is computed.[11]

Our basic assumption is that the age function is the same for all the registration years and thus identical across time. This function combined with the total passenger cars estimation allows us to compute the demand for new passenger cars,

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[11] The bump in the age function can be explained by measurement issues and imports of passenger cars. First, data on registration are from January to December, whereas the stock is measured from September to September. This explains why in the subsequent year the number of passenger cars registered in a given year might be larger than in the registration year. Second, the stock can increase because of passenger cars registered in other countries, which enter the Swiss stock either because they are bought by Swiss residents or because of people moving to Switzerland together with their passenger cars. In both cases, passenger cars enter the stock in a given year but the registration year remains the original one. Supposedly, this happens for relatively young passenger cars as older passenger cars are less likely to be imported.

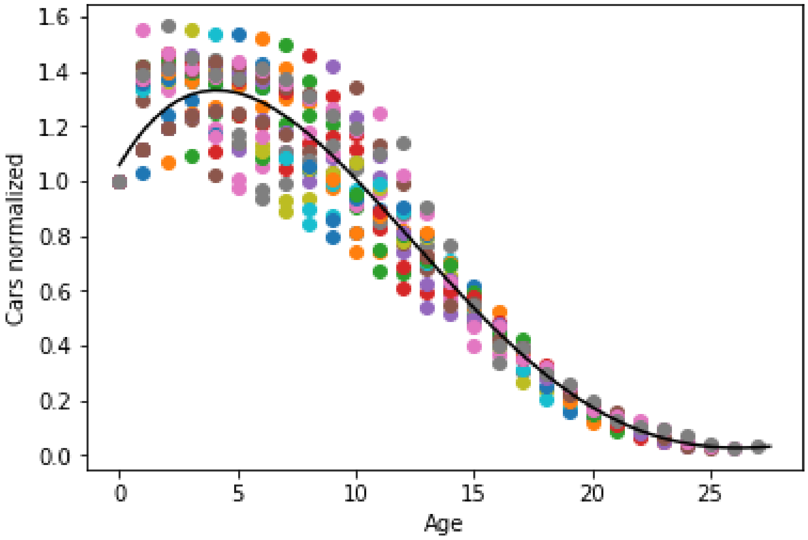

Figure 4.5: Age-function

$Cars^{new}_{ay}$, according to

$$Cars^{new}_{ay} = Cars^{est}_{ay} - \sum_{y<ay,t} Cars^{old}_{y,ti}, \tag{4.31}$$

where $Cars^{est}_{ay}$ are the estimated total passenger cars in the actual year ay and $Cars^{old}_{y,t}$ are the passenger cars from type ti in year y.

4.2.3 The choice model

Finally, the choice model is used to obtain the number of new passenger cars disaggregated according to 20 types in terms of fuel type and power. We include six fuel types: “Gasoline”, “Diesel”, “Gasoline-Electric”, “Gas”, “Electric”, and “Fuel cell”.[12] Each fuel type is further specified according to the power of the engine (“$< 60kW$”, “60-100kW”, “100-140kW”, “$> 140kW$”). In order to compute the

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[12] “Gasoline-electric” vehicles refer to the technology plug-in hybrid (PHEV) and “electric” vehicles to BEV.

endogenous shares of different passenger car types, we use a multi logit model. Our specification follows Rivers and Jaccard (2006), Jaccard (2009), and Mulholland et al. (2017). The market share algorithm uses capital costs CC, maintenance and operating costs MC, energy (fuel) costs EC, intangible costs perceived by consumers, ic, and the weighted time preference ω to calculate the market share θ_j of a passenger car type j in a given year when competing against Z passenger car types. Hence, we can write

$$\theta_j = \frac{\left(\frac{\omega}{1-(1+\omega)^{-n_j}} CC_j + MC_j + EC_j + ic_j\right)^{\nu}}{\sum_{z=1}^{Z}\left(\frac{\omega}{1-(1+\omega)^{-n_z}} CC_z + MC_z + EC_z + ic_z\right)^{\nu}}, \tag{4.32}$$

where n is the average life span of a passenger car type. The parameter ν captures the heterogeneity in the market and determines the shape of the inverse power function that allocates market share to technology. A low value results in an even distribution even if the life cycle costs of the different technologies differ widely. An infinite value (and ic equal to zero) leads to the cheapest technology capturing the whole market. Of particular interest for our analysis are intangible costs, which can explain the adoption of BEV and PHECV although being more expensive than ICEV. These costs capture general preferences of consumers, including, amongst others, hesitation toward new technologies (alternative-fueled vehicles), range anxiety due to uncertainty about the battery performance, or peer effects.

We solve for the intangible costs by calibrating the logit function to the known shares obtained from the data of passenger car technologies in the base year (2014). The choice model is a crucial element of the inner loop of our general framework: after being initialized, it uses the output of the two models solved beforehand to calculate the market shares per specific passenger car type. Then, we use this information as input for the CGE model to check whether its output differs from the CGE output in the previous iteration. If the difference is significant, we perform another run based on the updated market share information until we reach convergence.

4.3 Calibration

The models for the business-as-usual scenario (BAU) are calibrated to projections and actual data taken from several sources. The idea is to reproduce this data by adjusting parameters of the model (substitution elasticities, shares in the production and demand functions, etc.). Table 4.1 summarizes the most important input data and the sources required to calibrate the model.

In Table 4.2, we list the periodic output of the framework serving as input for the calibration of the next period (outer loop). Those data that are input from or sent to another model through an interface are noted with an asterisk (*) (inner loop). Inputs and outputs are all yearly and for Switzerland.

Inputs	**Unit**	**Source**
Input-Output-Table 2014	CHF	Nathani et al. (2019)
Macroeconomic data like GDP, etc.	CHF	BFS (2019a)
Elasticities		Various Sources
Energy inputs	Joules, kWh	Swiss Federal Office of Energy (2019) and Prognos (2012)
CO2-Emissions	Tonnes	Federal Office for the Environment (2019)
Population and employment	Full-time equivalents	BFS (2015)
Passenger car fleet according to registration year		BFS (2019b)
Passenger car costs	Total cost of ownership in CHF	Touring Club Switzerland (2019)
Kilometers per passenger car, capacity use per passenger car, motor efficiency		Various Sources

Table 4.1: Data inputs

Output	**Unit**
GDP, exports, imports, sectoral production	CHF
Consumption, investments/savings, tax revenue	CHF
Capital and labor input	CHF
Welfare	percentage change
Sectoral prices and production, cost indices*	indexed CHF
CO_2 price of permits and CO2 tax*	CHF
Fuel demand overall and car specific	TWh
CO2-Emissions	tonnes
Passenger car fleet	number of cars
Vehicle kilometers	km
Person kilometers	km
Public transport kilometers	km

Table 4.2: Periodic output

In what follows, the data used for the calibration of the individual building block of the CGE model is described.

4.3.1 Consumption

The composite consumption good is defined over the available consumer goods categorized according to the divisions of the Classification of the Purposes of Non-Profit Institutions Serving Households (United Nations 1999). These goods are listed in Table 5.2 in Appendix 5.3.2.

In empirical work with CGE models, the elasticities for the nested utility function of consumers are mostly taken from econometric studies. Table 4.3 shows the values for the substitution elasticities adopted in this chapter as well as the studies they are taken from.

Parameter	**Value**	**Source**
σ^{cls}	0.28	Havránek (2015)
σ^{cl}	0.7	Own calculations based on Jäntti et al. (2015)
σ^{c}	0.9	Own assumption
σ^{ce}	0.5	Papageorgiou et al. (2017)
σ^{cne}	0.9	Own assumption
σ^{tp}	0.8	Own calculation based on ARE (2016)

Table 4.3: Utility function: values for the substitution elasticities and their sources

4.3.2 Production

Our CGE model contains over 70 sectors (see Table 5.3 in Appendix 5.3.2) taken from the Swiss IOT. For each sector we focus on a representative producer. The electricity sector in the Swiss IOT is disaggregated in distribution and several generation technologies (CPA 40a-40d3 in Table 5.3 in Appendix 5.3.2). The generated electricity serves as input in the distribution sector (CPA 40e). The relative costs of the technologies and the available capacity (taken from Swiss Energy Modelling Platform (2018) and Prognos (2012)) determine the production mix. Table 4.4 contains the values or range of the chosen sectoral elasticities for production and Table 4.5 for international trade.

Parameter	**Value or range**	**Source**
σ_i^{klem}	0.11 - 1.15	Koesler and Schymura (2015)
σ_i^{kle}	0.09 - 1.27	Koesler and Schymura (2015)
σ_i^{kl}	0.06 - 3.36	Koesler and Schymura (2015)
σ^{ene}	0.5	Papageorgiou et al. (2017)
σ^{m}	0	Common practice in CGE modelling

Table 4.4: Production: values for the substitution elasticities and their source

Parameter	**Value or range**	**Source**
σ^{A}	1.2 - 8.0	Own calculations based on Imbs and Méjean (2010) and Lofgren and Cicowiez (2018)
τ	1.3 - 8.0	Own calculations based on Imbs and Méjean (2010) and Lofgren and Cicowiez (2018)

Table 4.5: International trade and Armington elasticities

4.3.3 Private transport

Calibration of total passenger cars and car shares

Private transport is calibrated according to projections developed in Infras (2019) until 2050. The main calibrated variables are the total passenger cars, the new passenger cars purchased, and the share of passenger cars according to fuel. Table 5.4 in Appendix 5.3.2 presents the passenger car costs for the benchmark year.[13]

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[13] Taken from https://www.tcs.ch/de/testberichte-ratgeber/ratgeber/fahrzeug-kaufen-verkaufen/autosuche-vergleich.php. The costs were slightly adjusted after discussions with experts.

Moreover, Table 5.5 and 5.6 in Appendix 5.3.2 show the yearly change in these costs and the change in fuel efficiency per fuel type taken from Infras (2019). Using this information and the projection of the fleet mix in 2050 displayed in Table 4.6, the choice function (Equation (4.32)) is calibrated by solving for the intangible costs.[14] The procedure adopted to harmonize the cost information on passenger cars with the data from the IOT is described in Appendix 5.3.2.

Fleet mix (stock)	**2014**	**2050**
Gas	0.21%	2%
Gasoline	72.5%	33%
Gasoline-Electric	0.9%	6%
Diesel	26.28%	21%
Electric	0.11%	35%
Fuel cell	0%	3%

Table 4.6: Projection of passenger car stock and fuel efficiency

4.3.4 Dynamics

We calibrate the recursive model to a steady-state baseline equilibrium growth path. To do so, we use the fact that on a steady-state growth path, all quantities grow at the same steady-state rate γ. Thus, capital also grows according to

$$K_{t+1} = (1+\gamma)K_t. \tag{4.33}$$

We can now use Equations (4.23) and (4.33) and information from the IOT to calibrate the model to the given growth path. For Switzerland, we assume a steady-state growth rate of 1.5% (see Table 4.7 for the growth projections until

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[14] As our model does not follow a forecasting approach, we set the projections of the fleet mix close to the one of Infras (2019) and BFE (2021) in 2050. Some minor differences, however, exist due to the complexity of the model. We are aware of the difficulty predicting the development of the fast-changing BEV technology until 2050. Some projections expect a higher share of BEVs than we do in 2050, which, if they are moderate, do not substantially change our qualitative result.

2050). The depreciation rate is calibrated in such a way that the investments reflect the investments according to the IOT.

This steady-state growth path does not consider the changes in the working population. Therefore, we use the projections on the working population to calculate the yearly percentage change γ_t^{WP}. The total GDP growth rate γ^{GDP} is now given by

$$\gamma_t^{GDP} = (1 + \gamma^{GDP/Cap})(1 + \gamma_t^{WP}) - 1. \tag{4.34}$$

We assume that government expenditure and the current account grow at the same growth rate as GDP. If governmental income falls below this level, a per-capita tax is raised (and a per-capita subsidy is paid in the opposite case). This ensures that the welfare effects of the implemented policies are not influenced by changes in the governmental budget.

The energy demand projections (electricity and fossil fuels) are shown in Table 4.7. The projection for electricity demand is growing at a slower rate than GDP. Total energy demand is falling and total employment remains almost the same for the next 35 years. To reach the given levels in the model, we adjust the technical progress for the energy goods to calibrate demand to the projections from Prognos (2012) using the technique developed in Böhringer et al. (2009).

Parameter	2010	2020	2035	2050	Reference
Population (million)	7.79	8.68	9.8	10.3	Scenario A-00-2015 from BFS (2015)
Working population (million full time equivalents)	3.853	4.31	4.58	4.63	Scenario A-00-2015 from BFS (2015)
GDP potential (relative to 2010)	1	1.18	1.43	1.66	Projections from BFS (2019a)
Energy demand (relative to 2010)	1	0.937	0.839	0.782	BAU (WWB) scenario from Prognos (2012) (p. 96)
Electricity demand (relative to 2010)	1	1.05	1.097	1.175	BAU (WWB) scenario from Prognos (2012) (p. 97)
Fossil energy demand by ETS sectors (relative to 2010)	1	0.858	0.621	0.388	Swiss Energy Modelling Platform (2018)

Table 4.7: Assumed projections for Swiss population, GDP and energy demand

4.4 Edge case scenarios

In addition to the BAU, we study the impact on economic variables, energy usage and emissions under three edge case scenarios. Each scenario focuses on an alternative approach towards a decarbonization of the passenger transport system. Specifically, we include the following three scenarios: (1) The technology and BEV diffusion scenario (TECHS); (2) The capacity use scenario (CAPU); (3) The modal shift scenario (SHIFTP). For each scenario, we define the key parameters that differ from the BAU. In TECHS, we vary the fuel/engine efficiency of passenger cars and the share of BEVs in 2050. The latter is achieved thanks to subsidies designed such that they favor the diffusion of BEVs, as, for example, subsidies that improve the private and public charging infrastructure of Switzerland or decrease the costs of BEVs.[15] Those subsidies are financed by taxes on fossil fuel for passenger

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[15] In what follows, I refer to those subsidies as “subsidy for BEVs”.

cars. CAPU includes behavioral changes towards a more prominent role of car- and ride-sharing, which increases the capacity use of passenger cars. In SHIFTP, we incorporate a policy scheme including subsidies for public transport, which leads to a change in the modal split towards this mean of transport. We set the parameters for the different scenarios to the upper bound of their range for Switzerland, in accordance with the literature and based on discussions with experts. Thus, we analyze edge case scenarios and draw results on their emission-savings potential and economic impact. Table 4.8 displays the underlying assumptions for the three edge case scenarios, where personal kilometers are denoted by pkm and the asterisk means model output. In what follows, we describe the three edge case scenarios more in detail.

	BAU			**TECHS**		**CAPU**		**SHIFTP**		
Parameter	2014	2030	2050	2030	2050	2030	2050	2030	2050	Main Sources
Fleet mix (stock)										
Share of BEV	0%	17.83%*	35%	34.13%*	65%					Infras (2019)
Share of gas	0%	1.98%*	2%	1.36%*	1%					BFE (2021)
Share of gasoline and diesel	99%	68.77%*	54%	54.68%*	29%					
Share of PHEV and FCEV	1%	11.42%*	9%	9.83%*	5%					
Change in fuel efficiency										
BEV, FCEV	0%	0%	0%	0%	0%					Infras (2019)
PHEV	0%	+3%	+10%	+5%	+10%					Öko-Institut et al. (2016)
ICEV	0%	+30%	+50%	+40%	+50%					
Occupancy rate										
Number of persons per vehicle	1.56	1.56	1.56			1.84	2.2			BFS and ARE (2015) Hörl et al. (2019)
Modal split pkm										
Share of motorized private transport	79%	77%	75%					72%	59%	ARE (2016) Öko-Institut et al. (2016)
Share of public transport	21%	23%	25%					28%	41%	

Table 4.8: Edge case scenarios

4.4.1 Technology and BEV diffusion scenario (TECHS)

TECHS describes a future where the majority of passenger cars are BEVs. The government is assumed to use subsidies for BEVs to foster their diffusion and to finance these subsidies through taxes on fossil fuels for passenger cars. Moreover, we assume that the technological progress in fuel efficiency takes place earlier compared to BAU. The maximum improvement possible in fuel efficiency up to 2050 is derived based on Öko-Institut et al. (2016), BFE (2021) and experts know-how. Öko-Institut et al. (2016) assume in their "Efficiency Scenario" that the efficiency of passenger cars increases by 40% (90%) until 2030 (2050) relative to 2010. However, according to the validation of experts and the underlying assumptions in BFE (2021), the value for 2050 should not differ from BAU (50% according to BFE (2021)). Thus, we assume that the fuel efficiency increases by 40% (30%) until 2030 in TECHS (BAU), but is the same in 2050.

In TECHS, 65% of the passenger cars are BEVs in 2050. These assumptions are based on the BFE (2021) and discussions with experts, who estimate the maximal possible share of BEVs in 2050 considering the efficiency gain and reasonable subsidies for BEVs financed by taxes on fossil fuels for passenger cars.

4.4.2 Capacity use scenario (CAPU)

In CAPU, we focus on a future where individuals use their vehicles more efficiently. The government can impose measures such as mobility pricing focusing on capacity use, reserved parking spaces, or lanes for passenger cars used by more than 3 persons to increase the average number of persons per passenger car. Implementing these measures is not cost-intensive, and their success relies on the willingness to intensify car- and ride-sharing. Thus, this scenario assumes a change in the occupancy rate, which is not caused by costly measures but by behavioral changes. Our assumptions on increasing the occupancy rate from 1.56 in BAU to 2.2 in CAPU are based on Mühlethaler et al. (2011) and Hörl et al. (2019).

4.4.3 Modal shift scenario (SHIFTP)

SHIFTP depicts a future with a shift towards less carbon-intensive transport. We thereby focus on a shift of passengers traveling by passenger car towards traveling by public transport. We assume that the government implements a subsidy for public transport, which is financed by taxes on fossil fuels for passenger cars. The subsidy is set such that the target share of 28% (41%) of public transport in 2030 (2050) is reached. Our assumptions are based on Öko-Institut et al. (2016) and interviews with experts.

4.5 Simulation results

In this section, we first conduct an economic impact analysis to understand how each of the three edge case scenarios contribute to the decarbonization of the Swiss passenger transport system. Then, we combine these scenarios to evaluate the optimal policy mix.

4.5.1 Economic impact analysis

The economic impact analysis allows us to derive results in terms of the passenger transport system, energy use and emissions, as well as macroeconomic variables.

Results on the passenger transport system

This section presents the result related to the passenger transport system. Figure 4.6 shows the development of the passenger car stock in terms of fuel mix until 2050 for all edge case scenarios. We see that in TECHS, the stock of passenger cars develops similar to BAU.[16] In CAPU, fewer passenger cars carry more individuals

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[16] We calculate the stock of passenger cars for BAU until 2050 with the regression model described in Appendix 5.3.1. In the scenarios CAPU and SHIFTP we adjust the demand for new passenger cars in line with the change in capacity and increasing demand for public transport respectively. As the occupancy rate and modal split remain untouched in TECHS, we have the same level of passenger cars in BAU and TECHS.

due to a higher occupancy rate. That leads to a decrease in the stock of passenger cars. In SHIFTP, a subsidy scheme towards public transport makes passenger car transport relatively more expensive. Thus, more individuals switch to public transport, resulting in a lower passenger car stock relative to BAU.

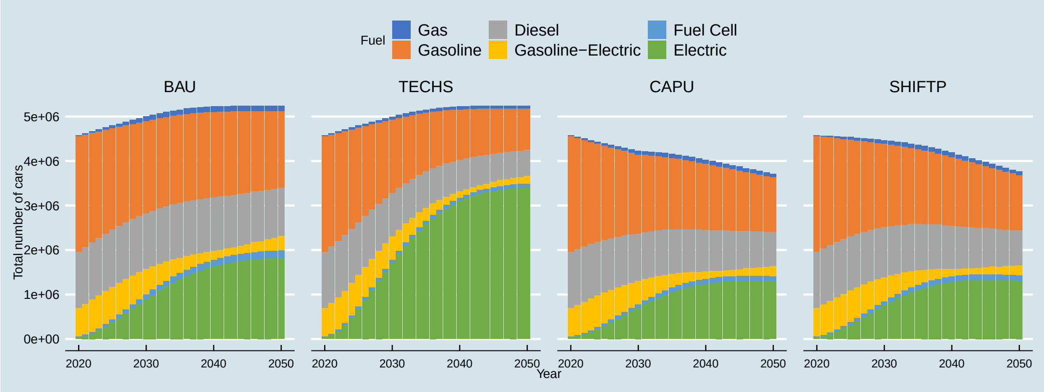

Figure 4.6: Passenger car stock and fuel mix

Figure 4.7 shows the percentage change of transport performance of the three edge case scenarios for the transport sector relative to BAU. In TECHS, the development of pkm in private transport is based on the following effects. First, improving the fuel efficiency in TECHS sets an incentive to drive more. Second, switching from ICEVs to BEVs induces a decrease in pkm in private transport as a BEV is driven less on average than ICEV (see Infras (2019)). The latter effect prevails, which leads to a decrease in pkm in private transport until 2050 relative to BAU, but in a slight increase in pkm in public transport. In addition, from 2040 onwards, increasing electricity prices lower the incentives to drive BEVs, which fosters the decline of pkm in private transport in TECHS relative to BAU due to the high share of BEVs in TECHS (see Figure 5.16 in Appendix 5.3.3). In CAPU, the improved efficiency of using passenger cars leads to a sharp decrease in the accumulated amount of vehicle kilometers (vkm). A higher number of persons per passenger car decreases their stock (see Figure 4.6) and, thus, also the total vkm traveled. The total pkm in public transport is more or less the same as in BAU as the relative prices between the two modes of transport hardly change. In SHIFTP, the subsidies for public transport decrease its price in relative terms to private transportation. That leads to a shift from private to public traveling. Moreover, the tax on fossil fuels increases the cost of using passenger cars in relative terms resulting in lower vkm.

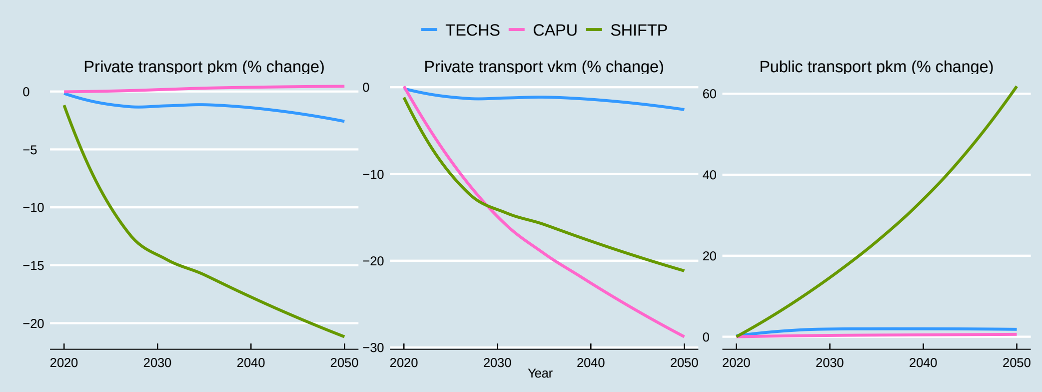

Figure 4.7: Transport performance relative to BAU

Results on energy use and emissions

We now turn to the results in terms of energy use and emissions. Figure 4.8 shows the development of gasoline, diesel, and electricity consumption for passenger cars in Terawatthour (TWh). In TECHS, the consumption of gasoline and diesel for passenger cars is decreasing, whereas electricity is increasing. This is due to the improved fuel efficiency and the larger share of BEVs. In CAPU and SHIFTP, the consumption of fossil fuels decreases heavily because of lower vkm. In all scenarios, the demand for electricity for passenger cars grows compared to 2020 due to the increasing share of BEVs. The stabilizing electricity demand after 2040 is mainly caused by increasing electricity prices, which decreases the incentive to drive with BEVs (see Figure 5.16 in Appendix 5.3.3). In Figure 4.9, we see that TECHS has

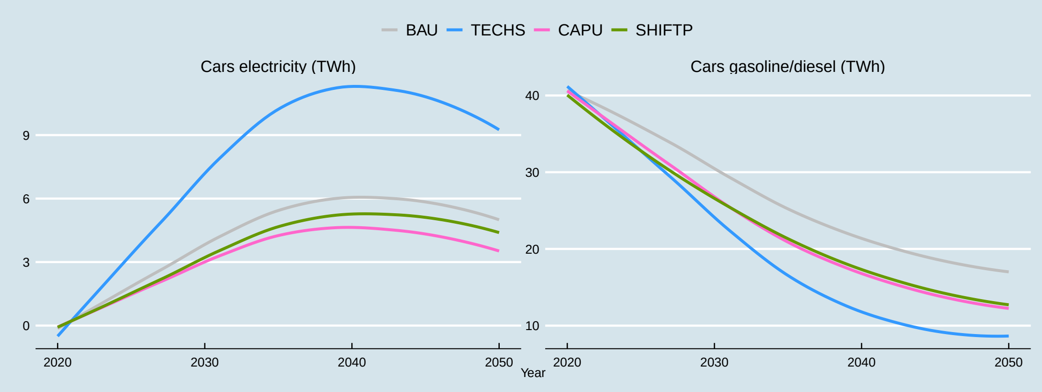

Figure 4.8: Development of disaggregated energy use of passenger cars

the highest energy demand for passenger cars comparing to CAPU and SHIFT, which is due to its higher stock of passenger cars.

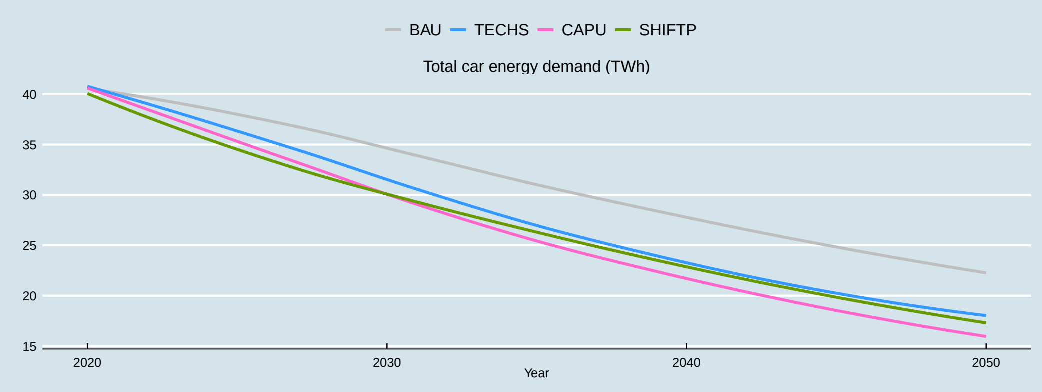

Figure 4.9: Total energy use for passenger cars

To analyze the impact on CO_2 emissions, we need to incorporate the electricity production mix for Switzerland. In accordance with the findings of Swiss Energy Modelling Platform (2018) and Prognos (2012), we derive the mix by setting the electricity production of each technology to its capacity limit (see Figure 5.17 in Appendix 5.3.3). The sequential drops in the picture are the nuclear phase-outs which decrease domestic electricity production. Consequently, Switzerland has to partly rely on importing electricity to meet its demand in the future (see Figure 5.18 in Appendix 5.3.3). In TECHS, import of electricity is higher compared to the other scenarios due to the large share of BEVs. In CAPU and SHIFTP, the smaller stock of passenger cars comes with a smaller amount of BEVs relative to the BAU, which results in relatively low electricity import.

The CO_2 emissions of passenger transport in each scenario are displayed in Figure 4.10.

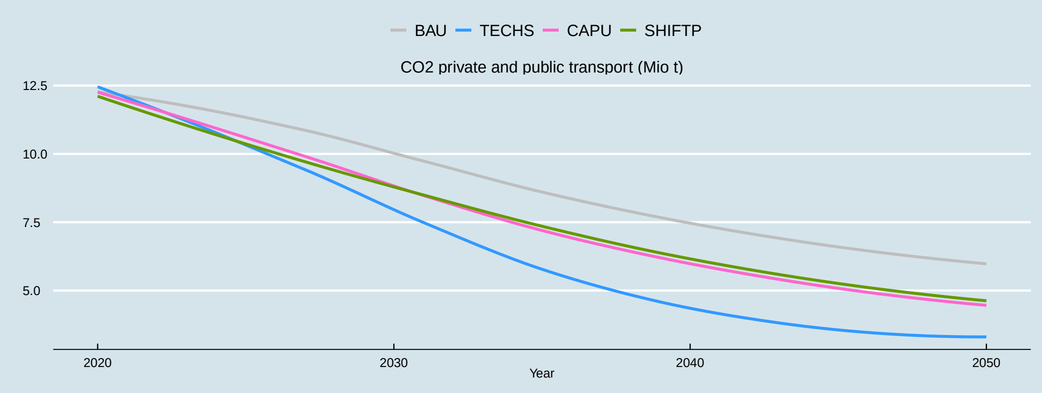

Figure 4.10: CO_2 emissions of passenger transport

TECHS is the most promising edge case scenario considering the reduction of CO_2 emissions from passenger cars. The boost of BEVs decreases the CO_2 emissions from passenger transport by 45.7% relative to BAU to 3.2 million tons in 2050. An increase in the capacity use of cars in CAPU reduces the CO_2 emissions from passenger transport by 25.7% to 4.4 million tons. Incentivizing people to rely more on public transport as in SHIFTP results in a decrease by 22.7% to 4.6 million tons CO_2 in 2050. Although each edge case scenario decreases the emissions substantially, none of them allows to achieve the net-zero emissions target of Switzerland.

Economic results

This section discusses the effects of the three edge case scenarios on different macroeconomic indicators. Figure 4.11 displays the change of per capita consumption, leisure, and savings in the three edge case scenarios relative to BAU.

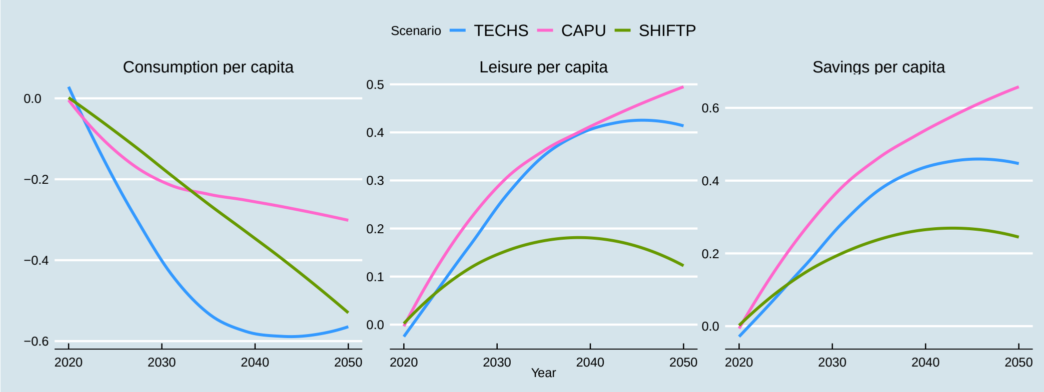

Figure 4.11: Household's choices relative to BAU

All edge case scenarios increase the efficiency of passenger transportation. That, in turn, decreases the cost of transport for households, which leads to an increase in real income per hour. In the calibrated version of the model, the income effect outweighs the substitution effect in the labor choice. Thus, an increase in real income results in a lower labor supply. Moreover, increasing income incentivizes to save. We identify three main drivers for our outcome: the cost-saving effect, the policy-cost effect, and the fleet-mix effect. In TECHS, all three effects are present. First, increasing fuel efficiency leads to a cost-saving effect. Initially, that effect is marginal because only the new passenger cars are affected by increasing fuel efficiency. Over time, however, the new composition of the stock with more efficient passenger cars results in a significant decline in transport costs. Second, TECHS embeds a policy-cost effect as the subsidy for BEVs is financed by the households through taxes on fossil fuels for passenger cars (see Figure 5.19 in Appendix 5.3.3), which increases the relative price of consumption. That mitigates the incentive for more leisure and savings. Moreover, it amplifies the negative response in consumption. Last, considering that BEVs are cheaper after 2030, increasing the share of BEVs leads to a fuel-mix effect that positively affects real income. In CAPU, the economic gains are based on the cost-saving effect: fewer passenger cars are needed to meet the demand for transport. Thus, the representative households spends less on transportation resulting in a decrease in consumption, whereas leisure and savings increase.[17] SHIFTP, instead, incorporates a cost-saving and policy-cost effect. On the one hand, the subsidies for public transport in SHIFTP incentivize households to change to a cheaper means of transport. That increases their real income and thus leisure and investment. On the other hand, the subsidy for public transport is financed by the households through taxes on fossil fuels for passenger cars (see Figure 5.19 in Appendix 5.3.3), which increases the relative price of consumption. Thus, the policy-cost effect negatively affects leisure, savings, and consumption.

From the firm perspective, increasing leisure and savings means that labor is becoming relatively more expensive compared to capital. Thus, in all edge case scenarios, the economy gets more capital-intensive relative to BAU (see Figure 5.20 in Appendix 5.3.3). On a sectoral level, the results indicate that the edge case scenarios particularly favor the capital-intensive sectors.

Figure 4.12 displays the resulting change in GDP per capita and welfare relative to BAU. While GDP per capita slightly decreases due to a lower consumption level and labor supply, all edge case scenarios result in higher welfare mainly due to increasing leisure.

Summarising the transportation, energy, emission, and welfare effects, we see that while welfare is slightly positively affected in the edge case scenarios, the passenger transport system and the CO_2 emissions change substantially. However,

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[17] In our model, passenger cars are included as negative endowment necessary to be able to drive them. Thus, buying fewer passenger cars (without lowering their ability to drive them) increases their “income” by decreasing the cost of passenger cars.

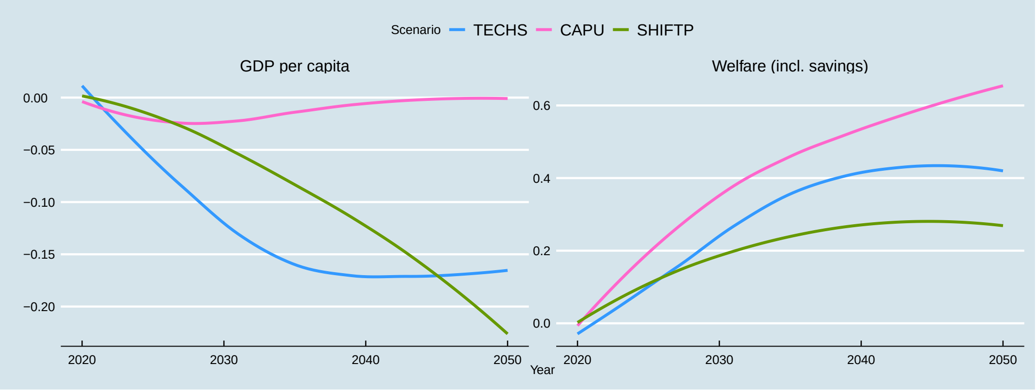

Figure 4.12: Change in GDP per capita and welfare relative to BAU

in Section 4.5.1 we showed that none of the edge case scenarios result in complete decarbonization of the Swiss passenger transport system. Thus, in the next section, we analyze whether an optimal combination of all measures used in the scenarios is sufficient to reach the net-zero emissions target.

4.5.2 Optimal combination of scenarios

In this section, we analyze the emission-saving potential and the economic impact of combining the scenario measures optimally. We assume that technology develops favorably as in TECHS and behavioral changes increase the capacity use like in CAPU.[18] To evaluate the optimal combination of scenario measures, we use a Monte-Carlo simulation varying the subsidies for BEVs and public transport up to the level assumed in TECHS and SHIFTP, respectively. Figure 4.13 displays the resulting CO_2 emissions from passenger transport on the Y-axis and relative welfare on the X-axis for the year 2050.[19] The numbers depict the outcome of different combinations of the subsidies (see Table 5.10 in Appendix 5.3.3). The

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[18] Enhancing the fuel efficiency and the capacity use results in a better outcome, as shown in Section 4.5.1 and 4.5.1. Thus, it is straightforward to set them to the maximum value when evaluating the optimal scenario measure mix.

[19] The X-axis indicates the welfare in relative terms to the mix with maximum welfare (which has 100%).

scenario labelled “10” is the optimal combination considering the welfare and CO_2 emissions. In this mix, we set the subsidies for BEVs and public transport to the upper bound, which results, in combination with the technical improvement and increasing capacity use of passenger cars, in a sharp decline of CO2 emissions to 1.7 million tons in 2050. This is, however, not sufficient to reach the net-zero emissions target of Switzerland. In other words, the gradual effect until 2050 of our scenarios and their combination represent an ongoing decarbonization pathway, with which the Swiss passenger transport system can not be completely decarbonize until 2050. An explanation for that is that the lifespan of a vehicle is on average around 10 years, some of them surviving up to 28 years in the market.

Figure 4.13: Monte-Carlo simulation

4.6 Conclusion

Switzerland has embarked on the ambitious challenge to decarbonize its transport sector until 2050, as a part of the net-zero emissions target. This requires a profound restructuring of the transport sector to reduce its emissions drastically. Decarbonization of the passenger transport sector depends, amongst others, on the development of new and better technologies and behavioral changes, as well as transportation policies. This chapter studies the economic impact and the emission-saving potential of three decarbonization scenarios and a combination of them. In the first scenario, an improvement in technology and a widespread diffusion of electric vehicles is envisioned. In this scenario, the fuel efficiency of passenger cars develops favorably. In addition, subsidies favor the diffusion of BEVs. These subsidies are financed by taxes on fossil fuels for passenger cars. In the second scenario, behavioral changes lead to an increase in the capacity usage of passenger cars. This shift is incentivized by policies supporting car- and ride-sharing. Third, Switzerland could adopt policies inducing a modal shift by favoring public compared to private transport. In accordance with the literature and experts, we set the values of the parameters in the scenarios to the upper limit reasonable for Switzerland, making them edge case scenarios. We evaluate the impact of these edge case scenarios using a multi-model framework, where we interlink a CGE model capturing the economy of Switzerland with two external transport models. That allows us to incorporate a highly disaggregated passenger transport system into the economic analysis. We show that all edge case scenarios lead to a substantial reduction in CO_2 emissions and slight welfare improvements. TECHS is most promising in reducing emissions: it results in a decrease by 45.7% relative to BAU in 2050, followed by 25.7% in CAPU and by 22.7% in SHIFTP. None of them, if implemented alone, however, allow achieving complete decarbonization of the passenger transport system. The same holds for the optimal combination of all measures used in the three scenarios, which reduces emissions even further by 71.3% relative to BAU in 2050 to 1.7 million tons CO_2, but still not sufficiently to achieve the net zero. An explanation for that is that the considered scenarios have an ongoing impact until 2050, meaning that they gradually influence the passenger transport system with reasonable technical improvements, market-based instruments, and behavioral changes for Switzerland over time. Considering that a specific vehicle type can survive up to 28 years in the market, that is not enough to completely decarbonize the sector until 2050. We, therefore, conclude that Switzerland should consider additional actions to reach its commitment. These might include abrupt policies, such as the ban for buying new internal combustion engine vehicles or excluding emitting vehicles that exceed a specific age. The analysis of such alternative policies is left to future research.

Chapter 5

Appendices

5.1 Appendix for Chapter 2

5.1.1 Wage mechanism

$$
\begin{aligned}
w_F^* =& (H_I(m_I^F + m_S^F)P_F((-1+Q)(1+Q(-1+\beta_F+\delta_S^F)) + Q^3\beta_F(-\delta_I^F+\delta_S^F)\delta_S^I) \\
& (-1+\eta_F)\eta_I\lambda_F(-1+\tau_{p,F})(1+\chi)\frac{\partial X_F}{\partial L_F} - H_F\eta_F(1+\tau_{p,F})(H_I(m_I^F+m_S^F)Q \\
& \eta_I(c_F pc(1+Q(-1+Q(\delta_I^F-\delta_S^F)\delta_S^I))\lambda_F(1+\chi) + h_F^{1+\chi}(1+Q(-1+Q(\delta_I^F \\
& -\delta_S^F)\delta_S^I))\psi + (-1+Q)((c_S pc - h_S w_S)\lambda_S(1+\chi) + h_S^{1+\chi}\psi) - (1+Q(-1 \\
& +Q(\delta_I^F-\delta_S^F)\delta_S^I))(1+\chi)Log[1+c_F] - (-1+Q)(1+\chi)Log[1+c_S]) + P_I \\
& (m_I^F(-1+Q)(1+Q(-1+\beta_F+\delta_S^F)) + m_S^F(-1+Q)Q\delta_S^I + m_I^F Q(-1+Q \\
& +Q^2\beta_F(-\delta_I^F+\delta_S^F))\delta_S^I)(-1+\eta_I)\lambda_I(1+\chi)\frac{\partial X_I}{\partial L_I}))/(h_F H_F H_I(m_I^F+m_S^F)Q \\
& (1+Q(-1+Q(\delta_I^F-\delta_S^F)\delta_S^I))\eta_F\eta_I\lambda_F(-1+\tau_{p,F}^2)(1+\chi))
\end{aligned}
$$

$$
\begin{aligned}
w_I^* = &-((-H_I\eta_I(h_S w_S\lambda_S - h_S Q w_S\lambda_S + h_S Q^2 w_S\delta_I^F\lambda_S - h_S Q^2 w_S\beta_I\delta_I^F\lambda_S - h_S \\
&Q^2 w_S(\delta_I^F)^2\lambda_S - h_S Q^2 w_S\delta_S^F\lambda_S + h_S Q^2 w_S\beta_I\delta_S^F\lambda_S + h_S Q^2 w_S\delta_I^F\delta_S^F\lambda_S + h_S \\
&w_S\lambda_S\chi - h_S Q w_S\lambda_S\chi + h_S Q^2 w_S\delta_I^F\lambda_S\chi - h_S Q^2 w_S\beta_I\delta_I^F\lambda_S\chi - h_S Q^2 w_S(\delta_I^F)^2 \\
&\lambda_S\chi - h_S Q^2 w_S\delta_S^F\lambda_S\chi + h_S Q^2 w_S\beta_I\delta_S^F\lambda_S\chi + h_S Q^2 w_S\delta_I^F\delta_S^F\lambda_S\chi + c_I pc(1+Q \\
&(-1+Q(\delta_I^F-\delta_S^F)\delta_S^I))\lambda_I(1+\chi) + c_S pc(-1+Q+Q^2(-1+\beta_I+\delta_I^F)(\delta_I^F \\
&-\delta_S^F))\lambda_S(1+\chi) - h_S^{1+\chi}\psi + h_S^{1+\chi}Q\psi - h_S^{1+\chi}Q^2\delta_I^F\psi + h_S^{1+\chi}Q^2\beta_I\delta_I^F\psi + h_S^{1+\chi} \\
&Q^2(\delta_I^F)^2\psi + h_S^{1+\chi}Q^2\delta_S^F\psi - h_S^{1+\chi}Q^2\beta_I\delta_S^F\psi - h_S^{1+\chi}Q^2\delta_I^F\delta_S^F\psi + h_I^{1+\chi}(1+Q(-1 \\
&+Q(\delta_I^F-\delta_S^F)\delta_S^I))\psi - (1+Q(-1+Q(\delta_I^F-\delta_S^F)\delta_S^I))(1+\chi)Log[1+c_I] \\
&+Log[1+c_S] - (-\chi+Q(1+Q(-1+\beta_I+\delta_I^F)(\delta_I^F-\delta_S^F))(1+\chi))Log[1 \\
&+c_S]) + 1/(H_F\eta_F(1+\tau_{p,F}))H_I P_F(\delta_I^F-\delta_S^F)(1+Q(-2+\beta_I+\delta_I^F+Q(-1 \\
&+\beta_I+\delta_I^F)(-1+\delta_S^F)+\delta_S^I+Q(-1+\delta_I^F)\delta_S^I))(-1+\eta_F)\eta_I\lambda_F(-1+\tau_{p,F}) \\
&(1+\chi)\frac{\partial X_F}{\partial L_F} - 1/((m_I^F+m_S^F)Q)P_I(m_S^F(-1+Q)(1+Q(-1+\beta_I+\delta_I^F)) \\
&+m_S^F Q(-1+Q(1-\delta_I^F+\delta_S^F))\delta_S^I + m_I^F(-1-Q(-2+\beta_I+\delta_S^F+\delta_S^I)+Q^2 \\
&(-1+\beta_I-\delta_I^F+\beta_I\delta_I^F+(\delta_I^F)^2+2\delta_S^F-(\beta_I+\delta_I^F)\delta_S^F+\delta_S^I)+Q^3(\delta_I^F-\delta_S^F) \\
&((-1+\beta_I+\delta_I^F)(-1+\delta_S^F)+(-1+\delta_I^F)\delta_S^I)))(-1+\eta_I)\lambda_I(1+\chi)\frac{\partial X_I}{\partial L_I}) \\
&/(h_I H_I(1+Q(-1+Q(\delta_I^F-\delta_S^F)\delta_S^I))\eta_I\lambda_I(1+\chi)))
\end{aligned}
$$

5.1.2 Calibration

Parameter	**Value**	**Source**
δ	0.75	Hafstead and Williams (2018)
ϕ_X	1.5	Anand and Khera (2016)
ϕ_Q	0.75	Own assumption
σ	1.15	Anand and Khera (2016)
ρ_{EX}	4.5	Anand and Khera (2016)
ϵ_S^{Agr}	0.998	Okagawa and Ban (2008)
ϵ_{FI}^{Ind}	0.9	Okagawa and Ban (2008)
ϵ_{FI}^{Ser}	0.94	Okagawa and Ban (2008)
ω_S^{Agr}	0.55	Okagawa and Ban (2008)
ω_k^{Ind}	0.4	Okagawa and Ban (2008)
ω_k^{Ser}	0.49	Okagawa and Ban (2008)
ζ_k^{Ind}	0.2	Okagawa and Ban (2008)
ζ_k^{Ser}	0.41	Okagawa and Ban (2008)
ξ	0.9	Peter et al. (2018)

Table 5.1: Elasticities of Substitution and Sources

I assume that $\phi_Q < \phi_X$ holds. Therefore, I implement a lower EoS between own-and firm produced goods than between formal and informal firm goods in my model. A reason for that is that own-produced goods often end-up in the rural market while firm-produced goods in the urban one. Consequently, own-and firm goods are less substitutable.

5.1.3 Results

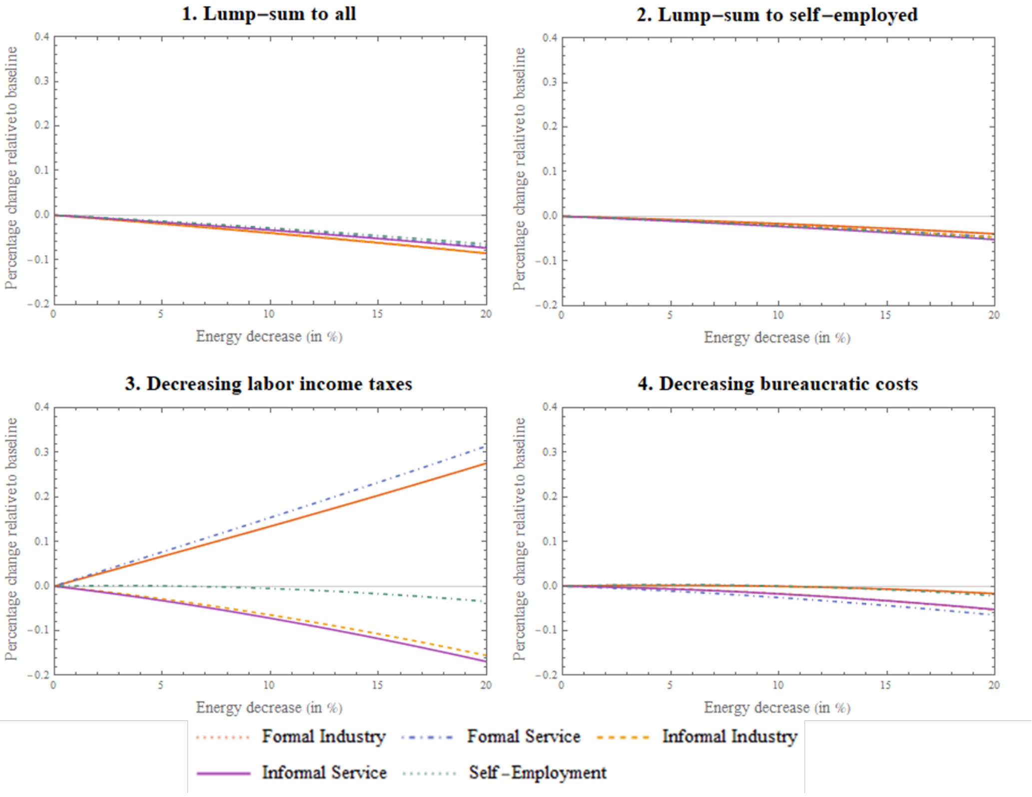

Figure 5.1: Effect on real income per day

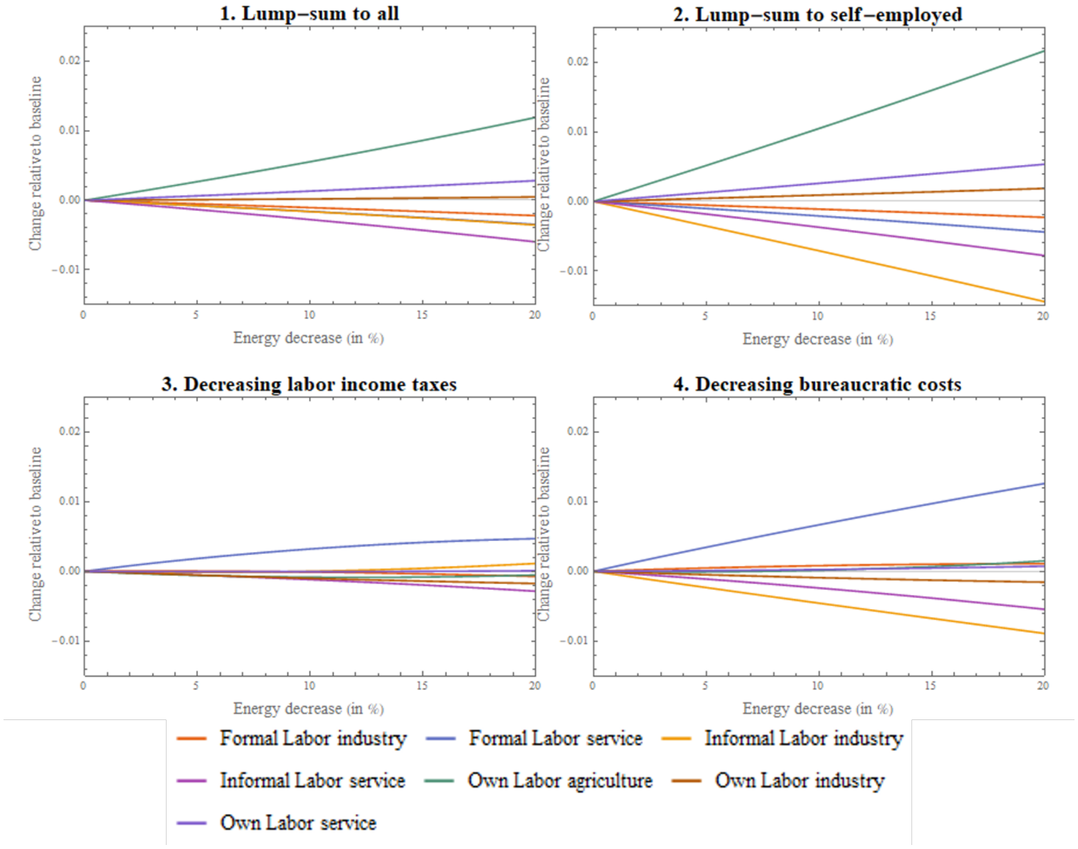

Figure 5.2: Sectoral labor effect

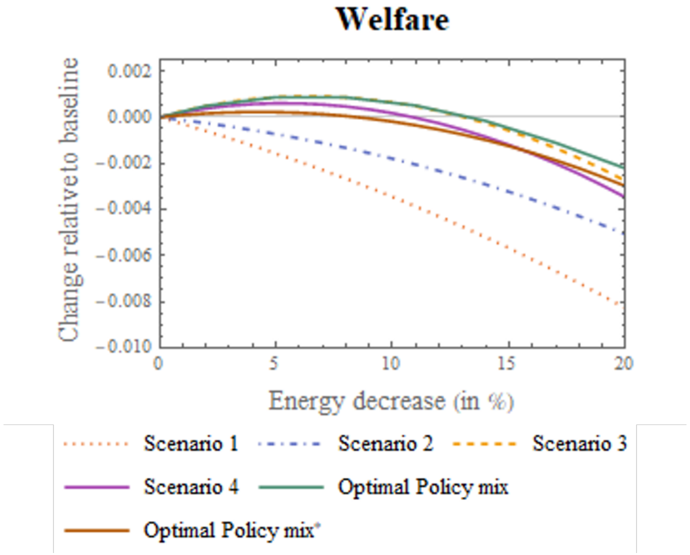

Figure 5.3: Optimal welfare with fixed Gini coefficient

5.2 Appendix for Chapter 3

5.2.1 The *monopoly condition*

In Figure 5.4 we show the combination of parameters so that the condition $X = 4(1 - \gamma_1^2) - (\gamma_2 + \gamma_4)^2 > 0$ is satisfied. Note that the degree of substitutability ($\gamma_1 \in [0, 1]$) imposes an upper bound for the network effects, i.e. $\gamma_2, \gamma_4 \in [0, 1)$. The set of network effects (γ_2, γ_4) so that the *monopoly condition* is satisfied decreases with a higher substitution between EVs and ICEVs. We also observe that the effect of the substitution parameter is non-linear.

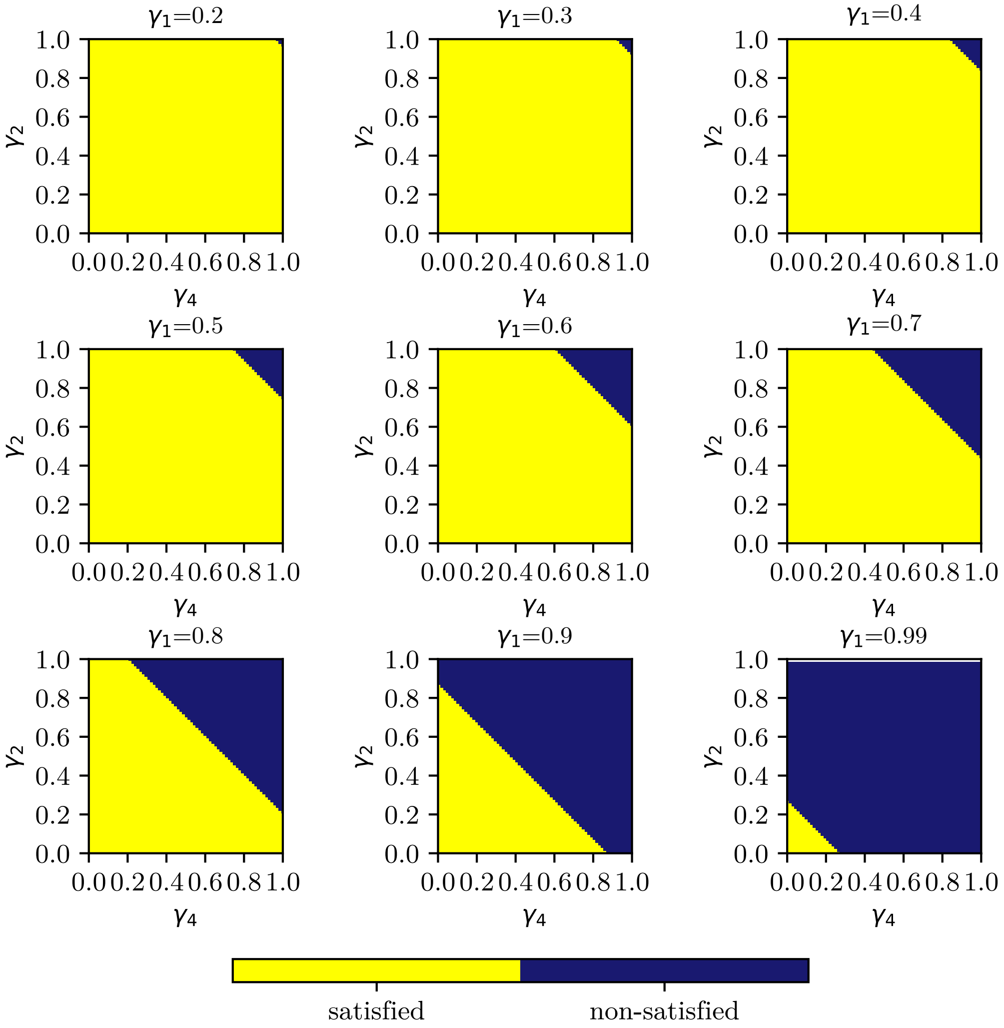

Figure 5.4: Graphical representation of the parameter space (γ_1, γ_2 and γ_4) satisfying the *monopoly condition* (that is, $X > 0$)

5.2.2 Policies

We analytically derive the impacts of policies in the form of subsidies and taxes on quantities and prices, and provide simulations of the effects, for different policy choices. In our framework, the policies take the form of subsidies to EVs and EVCSs (s_c and s_f) as well as a tax on ICEVs (t_d). The policy parameters are chosen so that they take values between zero (no policy intervention) and a maximum value for which the demand for ICEVs vanishes ($q_d = 0$). The latter are given by

$$s_c^{max} = \frac{q_d^* X}{2\gamma_1}, \tag{5.1}$$

$$t_d^{max} = \frac{q_d^* X}{2 - \frac{1}{2}(\gamma_2 + \gamma_4)^2}, \tag{5.2}$$

$$s_f^{max} = \frac{q_d^* X}{\gamma_1(\gamma_2 + \gamma_4)}, \tag{5.3}$$

where q_d^* represents the demand for ICEVs in the monopoly case without policy intervention.

***Subsidy to EVs* ($\mathbf{s_c}$)**

When a subsidy is provided to the purchase of EVs, the optimal quantities are

$$q_c^{s_c} = q_c^* + \frac{2}{X} s_c, \tag{5.4}$$

$$q_d^{s_c} = q_d^* - \frac{2\gamma_1}{X} s_c, \tag{5.5}$$

$$q_f^{s_c} = q_f^* + \frac{\gamma_2 + \gamma_4}{X} s_c. \tag{5.6}$$

Recalling that $X = 4(1 - \gamma_1^2) - (\gamma_2 + \gamma_4)^2$, larger substitution and network effects increase the magnitude of the change in all the quantities. In the absence of substitution possibilities between EVs and ICEVs ($\gamma_1 = 0$), the subsidy to EVs does not affect the quantity of ICEVs; similarly, q_f is not affected if there are no network effects ($\gamma_2 + \gamma_4 = 0$). Figure 5.5 illustrates the behavior of quantities for different values of the subsidy to EVs.

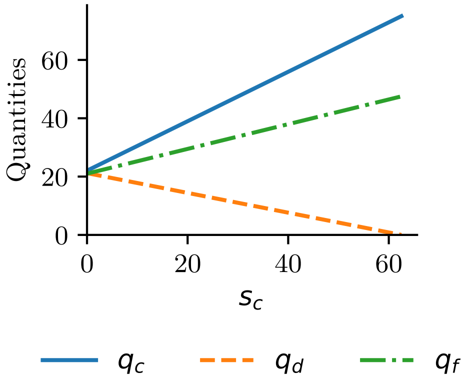

Figure 5.5: Effect on the quantities when a subsidy to EVs is applied, with the model parameters $\gamma_1 = 0.4, \gamma_2 + \gamma_4 = 1, \alpha_c = 40, \alpha_d = 60, \alpha_f = 20, c_c = 0, c_d = 0$ and $c_f = 0$. In general, the impacts are independent of network effects

The optimal prices when the subsidy is in place are

$$p_c^{s_c} = p_c^* + \frac{2(1-\gamma_1^2) - \gamma_4(\gamma_2+\gamma_4)}{X} s_c, \tag{5.7}$$

$$p_d^{s_c} = p_d^*, \tag{5.8}$$

$$p_f^{s_c} = p_f^* - \frac{(\gamma_2 - \gamma_4)}{X} s_c, \tag{5.9}$$

showing that if substitution is perfect ($\gamma_1 = 1$) and the network effect is not existing for retailers ($\gamma_4 = 0$), the price of EVs is not affected by the presence of the subsidy to EVs. Moreover, there is no effect on p_f if the network intensities are the same on the two sides of the market ($\gamma_2 = \gamma_4$). Figure 5.6 shows the conditions on the network effects γ_2 and γ_4 for a positive impact of s_c on p_c using different values of the substitution parameter γ_1, focusing on the set of parameters satisfying the *monopoly condition*. High substitutability reduces the parameter space so that s_c has a positive impact on p_c.

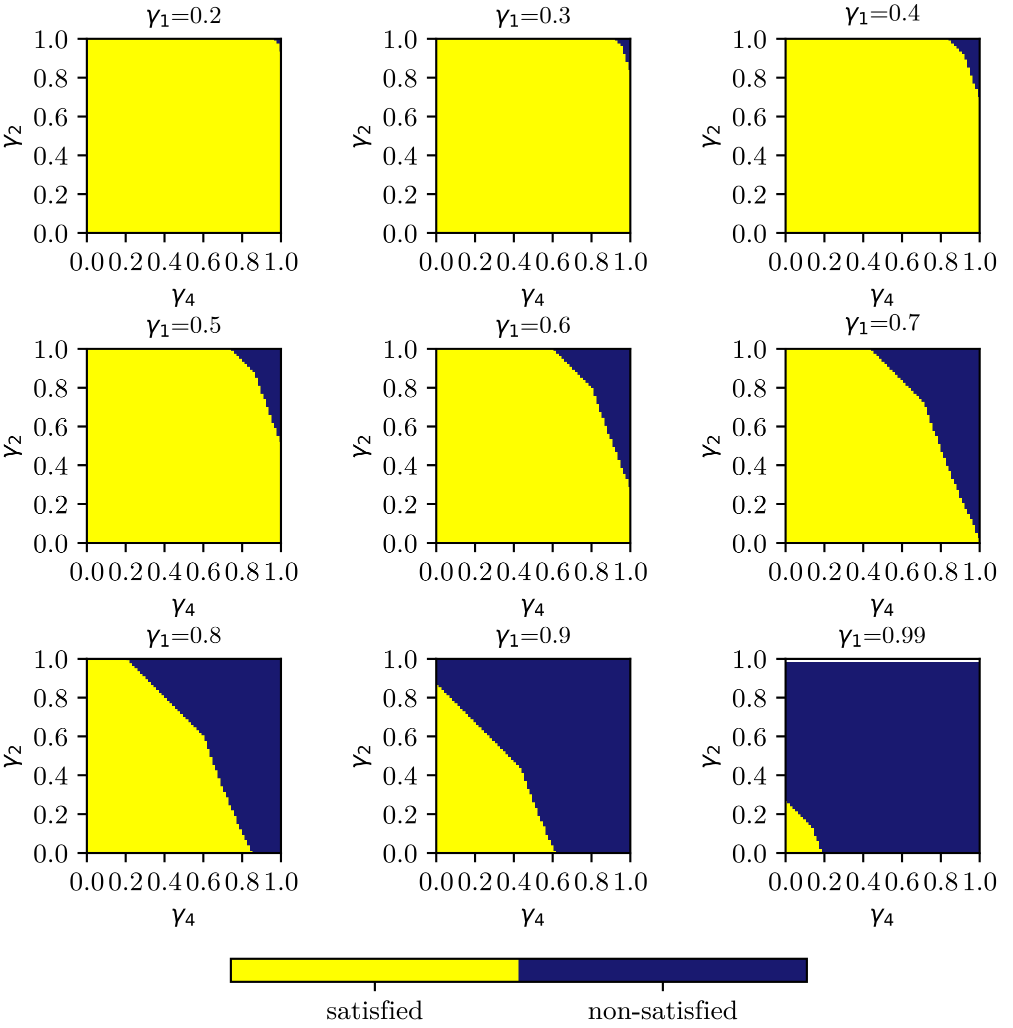

Figure 5.6: Graphical representation of the parameter space $(\gamma_1, \gamma_2, \gamma_4)$ satisfying the *monopoly condition* and leading to a positive impact of an EV subsidy on the price of EVs, that is, $X > 0$ and $2(1 - \gamma_1^2) - \gamma_4(\gamma_2 + \gamma_4) > 0$

Taxes on ICEVs ($\mathbf{t_d}$)

If a tax is imposed on the demand for polluting cars only, the optimal quantities are

$$q_c^{t_d} = q_c^* + \frac{2\gamma_1}{X} t_d, \tag{5.10}$$

$$q_d^{t_d} = q_d^* - \frac{2 - \frac{1}{2}(\gamma_2 + \gamma_4)^2}{X} t_d, \tag{5.11}$$

$$q_f^{t_d} = q_f^* + \frac{\gamma_1(\gamma_2 + \gamma_4)}{X} t_d. \tag{5.12}$$

The tax on ICEVs affects quantities of EVs and EVCSs, and ICEVs. The impact on the quantity of EVs is higher the stronger the substitution effect. Note that if there is no substitutability between EVs and ICEVs ($\gamma_1 = 0$), nor q_c neither q_f are affected by the tax. Moreover, the quantity of EVCSs is not affected if the network effects are zero ($\gamma_2 + \gamma_4 = 0$). Figure 5.7 illustrates the behavior of quantities for different values of the tax on ICEVs.

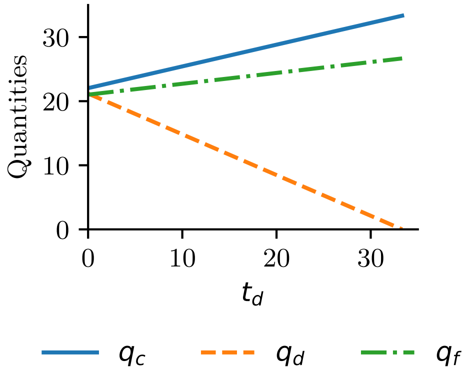

Figure 5.7: Effect on the quantities when a tax to ICEVs is applied, with the model parameters $\gamma_1 = 0.4, \gamma_2 + \gamma_4 = 1, \alpha_c = 40, \alpha_d = 60, \alpha_f = 20, c_c = 0, c_d = 0$ and $c_f = 0$. In general, the impacts are independent of network effects

The optimal prices are

$$p_c^{t_d} = p_c^* + \frac{\gamma_1(\gamma_2^2 - \gamma_4^2)}{X} t_d, \tag{5.13}$$

$$p_d^{t_d} = p_d^* - \frac{1}{2} t_d, \tag{5.14}$$

$$p_f^{t_d} = p_f^* - \frac{\gamma_1(\gamma_2 - \gamma_4)}{X} t_d, \tag{5.15}$$

showing that in case of no substitutability or identical network effects, p_c and p_f are not affected by the tax. As discussed in the main text, the effect of the tax on p_c and p_f depends on the relative intensity of network effects.

Subsidy to EVCSs $(\mathbf{s_f})$

When a subsidy is provided to EVCSs, the optimal quantities are

$$q_c^{s_f} = q_c^* + \frac{\gamma_2 + \gamma_4}{X} s_f, \tag{5.16}$$

$$q_d^{s_f} = q_d^* - \frac{\gamma_1(\gamma_2 + \gamma_4)}{X} s_f, \tag{5.17}$$

$$q_f^{s_f} = q_f^* + \frac{2(1 - \gamma_1^2)}{X} s_f. \tag{5.18}$$

When the subsidy is applied, EV, EVCS and ICEV purchases are affected. In the absence of network effects ($\gamma_2 + \gamma_4 = 0$) such subsidy has no effect on q_c and q_d. Also, no substitution ($\gamma_1 = 0$) implies that q_d is not affected, whereas perfect substitution ($\gamma_1 = 1$) rules out any effect of the subsidy on q_f. Figure 5.8 illustrates the behavior of quantities for different values of the subsidy to EVCSs.

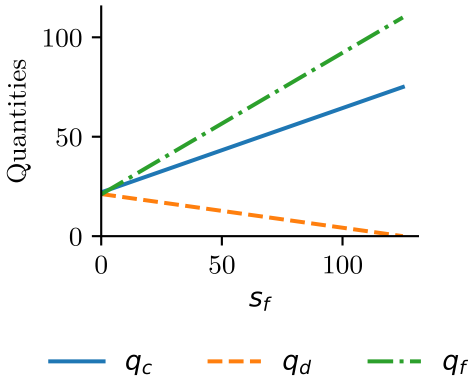

Figure 5.8: Effect on the quantities when a subsidy to EVCSs is applied, with the model parameters $\gamma_1 = 0.4, \gamma_2 + \gamma_4 = 1, \alpha_c = 40, \alpha_d = 60, \alpha_f = 20, c_c = 0, c_d = 0$ and $c_f = 0$. In general, the impacts are independent of network effects

The optimal prices when a subsidy to EVCSs is in place are

$$p_c^* = p_c^* + \frac{(1-\gamma_1^2)(\gamma_2 - \gamma_4)}{X} s_f, \tag{5.19}$$

$$p_d^* = p_d^*, \tag{5.20}$$

$$p_f^* = p_f^* + \frac{2(1-\gamma_1^2) - \gamma_2(\gamma_2 + \gamma_4)}{X} s_f, \tag{5.21}$$

showing that p_c is not affected by the policy if there is perfect substitution or the network effects equal. Any effect on p_f is eliminated when EVs and ICEVs are perfect substitutes and if the network effect on the consumers' side is zero. Figure 5.9 shows the conditions on the network effects γ_2 and γ_4 for a positive impact of s_f on p_f using different values of the substitution parameter γ_1, focusing on the set of parameters satisfying the *monopoly condition*.

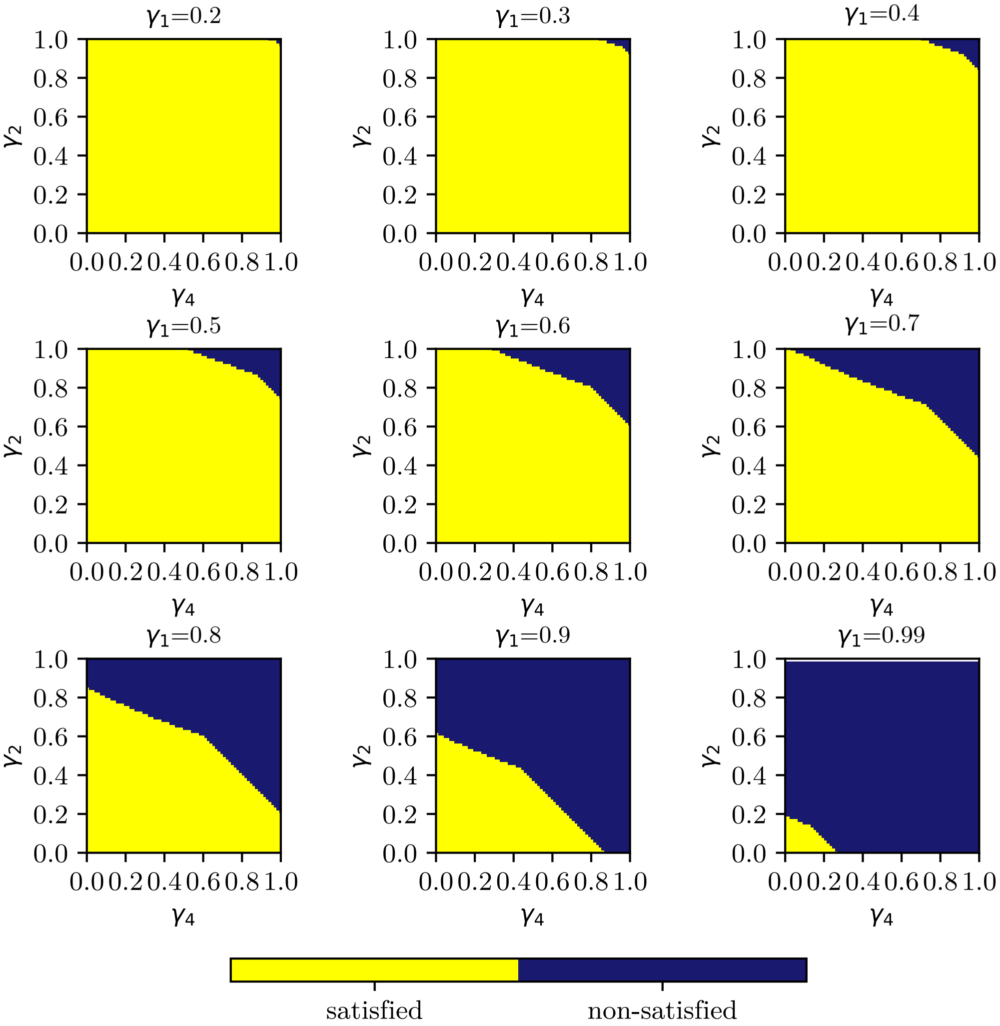

Figure 5.9: Graphical representation of the parameter space $(\gamma_1, \gamma_2, \gamma_4)$ satisfying the *monopoly condition* and leading to a positive impact of a subsidy to EVCSs on the price of EVCSs, that is, $X > 0$ and $2(1 - \gamma_1^2) - \gamma_2(\gamma_2 + \gamma_4) > 0$

Effect of policies on prices

The dependence of prices on the relative intensity of network effects is illustrated in Figures 5.10, 5.11 and 5.12. The graphs show that the price of ICEVs represents an exception thereof as it is solely affected by its own demand parameters (α_d and c_d) and the tax on ICEVs. In contrast, the prices of EVs and EVCSs are generally influenced, both in terms of magnitude and sign by the relative intensity of network effects. Figure 5.10 shows that for the chosen parameters, the price of EVs is always increasing with the subsidy to EVs, whereas the price of EVCSs is increasing for $\gamma_2 > \gamma_4$ and decreasing otherwise. As expected, in Figure 5.11, where a tax is applied, the signs of the impacts are reversed depending on the relative intensities of network effects. For $\gamma_2 > \gamma_4$ the price of EVs is increasing and the price of EVCSs is decreasing. For $\gamma_4 > \gamma_2$, the outcome is reversed. Finally, Figure 5.12 shows that, for the chosen parameters, the price of EVs is increasing with a subsidy to EVCSs for $\gamma_4 > \gamma_2$ and decreasing otherwise, whereas the price of EVCSs is always increasing.

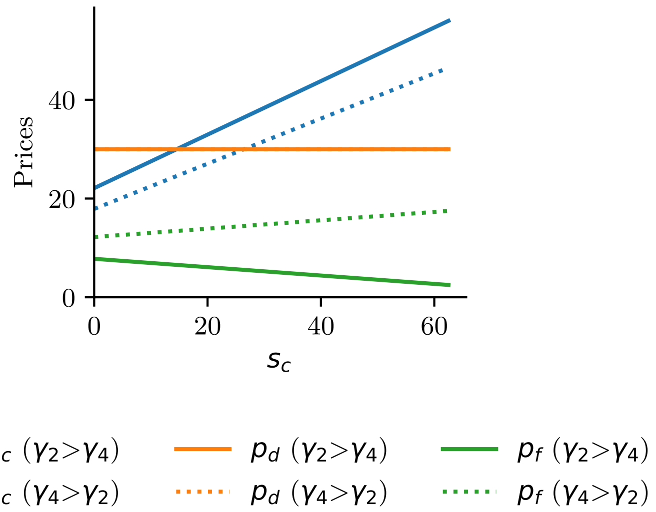

Figure 5.10: Effect on the prices when a subsidy to EVs is applied, with the model parameters $\gamma_1 = 0.4, \gamma_2, \gamma_4 \in \{0.4, 0.6\}, \alpha_c = 40, \alpha_d = 60, \alpha_f = 20, c_c = 0, c_d = 0$ and $c_f = 0$

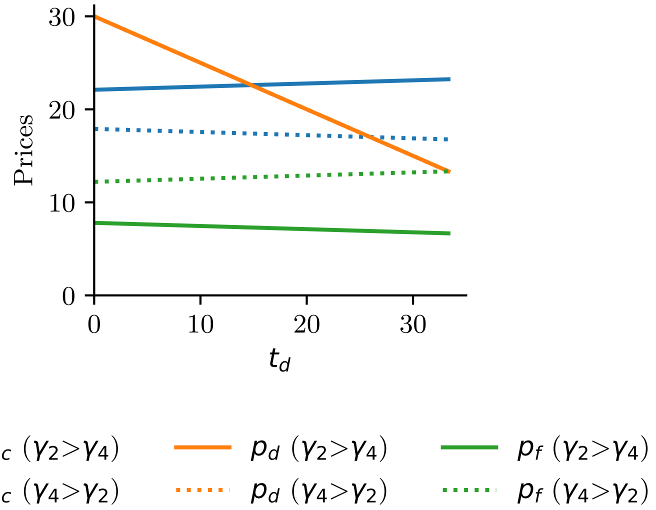

Figure 5.11: Effect on the prices when a tax on ICEVs is applied, with the model parameters $\gamma_1 = 0.4, \gamma_2, \gamma_4 \in \{0.4, 0.6\}, \alpha_c = 40, \alpha_d = 60, \alpha_f = 20, c_c = 0, c_d = 0$ and $c_f = 0$

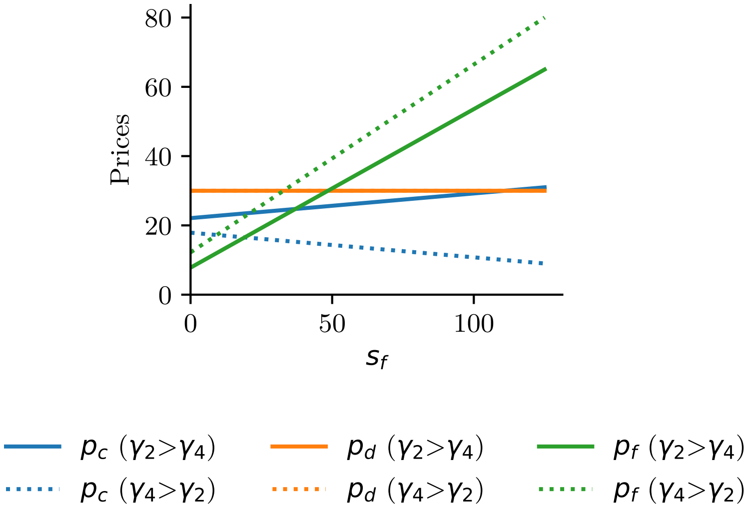

Figure 5.12: Effect on the prices when a subsidy to EVCSs is applied, with the model parameters $\gamma_1 = 0.4, \gamma_2, \gamma_4 \in \{0.4, 0.6\}, \alpha_c = 40, \alpha_d = 60, \alpha_f = 20, c_c = 0, c_d = 0$ and $c_f = 0$.

Subsidies to EVs $(\mathbf{s_c})$ ***and EVCSs*** $(\mathbf{s_f})$

In the following, we study the parameter space of substitution and network effects, $(\gamma_1, \gamma_2, \gamma_4)$, with respect to the price effect of both subsidies s_c and s_f. To simplify the notation we use $\partial p_c/\partial s_c = ds_c > 0$ to denote a positive impact of the subsidy to EVs on the price of EVs and $\partial p_f/\partial s_f = ds_f > 0$ to denote a positive impact of the subsidy to EVCSs on the price of EVCSs. Figure 5.13 provides a graphical illustration of this study separating the parameter space based on the different price effects, taking the *monopoly condition* into account. We can distinguish five different sets: (1) both subsidies have a positive effect on the respective prices ($ds_c > 0$ and $ds_f > 0$); (2) negative effect of the subsidy to EVs on their price and positive effect of the subsidy to EVCSs on their price ($ds_c < 0$ and $ds_f > 0$); (3) positive effect of the subsidy to EVs on their price and negative effect of the subsidy to EVCSs on their price ($ds_c > 0$ and $ds_f < 0$); (4) both subsidies have a negative effect on the respective prices ($ds_c < 0$ and $ds_f < 0$); (5) the monopoly condition not satisfied ($X < 0$). Figure 5.13 shows that the set of parameters so that both subsidies have a negative effect on respective prices is empty, that is ds_c and ds_f can never be jointly negative. This follows from our assumption $X > 0$ and the fact that $ds_c + ds_f = X$. The economic interpretation of this finding follows from the two-sided market structure: as consumers and retailers represent two different sides of the market, the platform will never reduce the price on both sides.

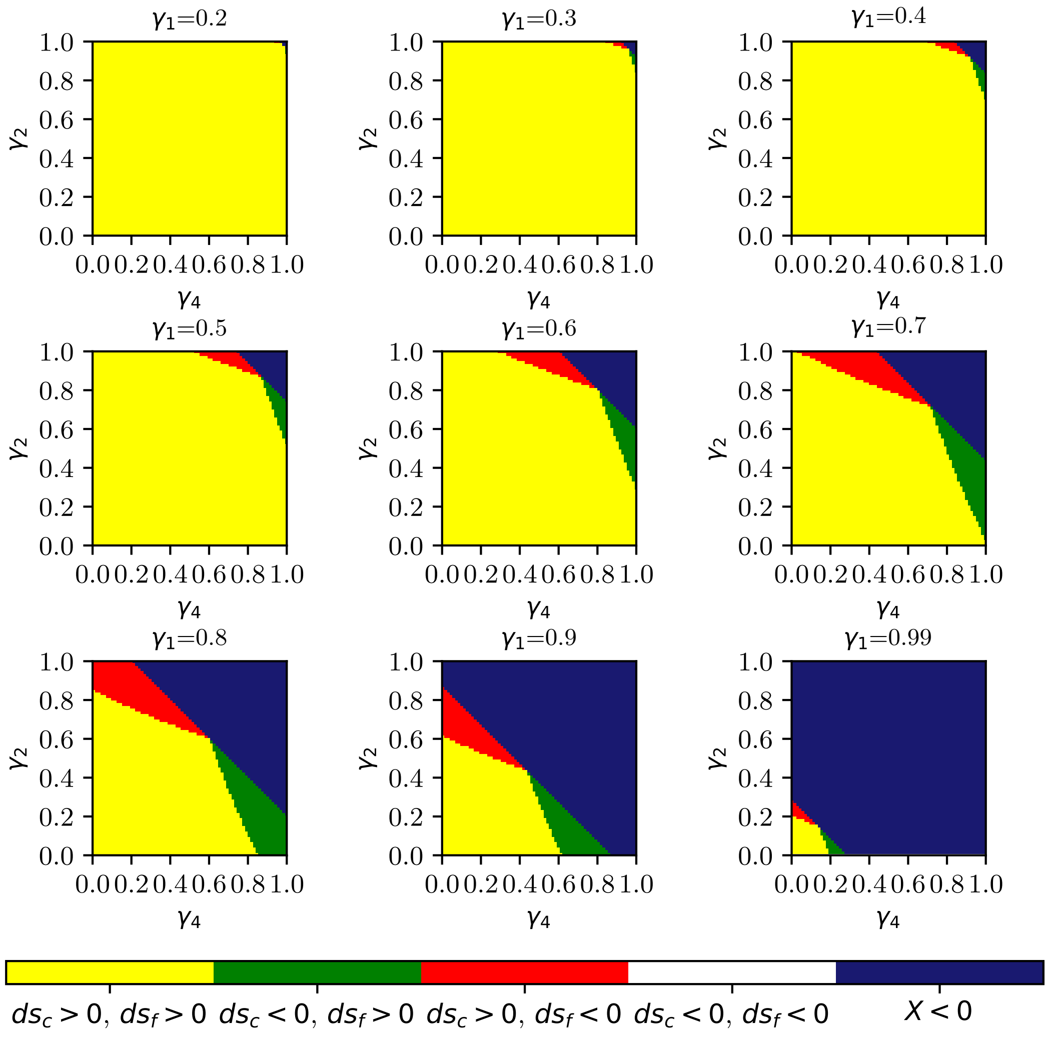

Figure 5.13: Graphical representation of the parameter space $(\gamma_1, \gamma_2, \gamma_4)$ satisfying the *monopoly condition* and determining the sign of the impact of the subsidy on the respective price, provided that $X > 0$

5.2.3 First-best solution

The social planner takes into account the negative externality due to pollution and solves

$$\max_{q_{0,h},q_{0,a},q_c,q_d,q_f} \quad W^P \quad s.t. \quad q_{0,h}+q_{0,a}=m_h+m_a-p_cq_c-p_dq_d-p_fq_f,$$

where $W^P = U + F + \pi - \phi q_d$. The first-order conditions of the social planner problem are

$$\begin{aligned} \alpha_c - q_c - \gamma_1 q_d + (\gamma_2+\gamma_4)q_f - c_c &= 0, \\ \alpha_d - q_d - \gamma_1 q_c - c_d^P &= 0, \\ \alpha_f - q_f + (\gamma_2+\gamma_4)q_c - c_f &= 0, \end{aligned} \tag{5.22}$$

where $c_d^P = c_d + \phi$ is the cost of producing ICEVs when pollution is taken into account. For an interior solution, the welfare-maximizing quantities are

$$q_c^{fb} = \frac{1}{\tilde{X}}\left[\alpha_c - c_c - \gamma_1(\alpha_d - c_d^P) + (\gamma_2+\gamma_4)(\alpha_f - c_f)\right], \tag{5.23}$$

$$q_d^{fb} = \frac{1}{\tilde{X}}\left[-\gamma_1(\alpha_c - c_c) + \left[1-(\gamma_2+\gamma_4)^2\right](\alpha_d - c_d^P) - \gamma_1(\gamma_2+\gamma_4)(\alpha_f - c_f)\right], \tag{5.24}$$

$$q_f^{fb} = \frac{1}{\tilde{X}}\left[(\gamma_2+\gamma_4)(\alpha_c - c_c) - \gamma_1(\gamma_2+\gamma_4)(\alpha_d - c_d^P) + (1-\gamma_1^2)(\alpha_f - c_f)\right], \tag{5.25}$$

where $\tilde{X} = 1 - \gamma_1^2 - (\gamma_2+\gamma_4)^2$. The condition $\tilde{X} > 0$ is stricter than $X > 0$ in the monopoly case and will be referred to as the *first-best condition.* The set of parameters satisfying the *monopoly condition* includes the one satisfying the *first-best condition* as

$$X = \tilde{X} + 3(1-\gamma_1^2), \tag{5.26}$$

where the second term can only be non-negative due to $\gamma_1 \in [0,1]$. In Figure 5.14, we plot all the combinations of parameters satisfying the *first-best condition*. The set of γ_2 and γ_4 such that the condition holds shrinks with the substitution parameter γ_1. The economic intuition is that if two goods are good substitutes it is more likely that one of the two disappears.

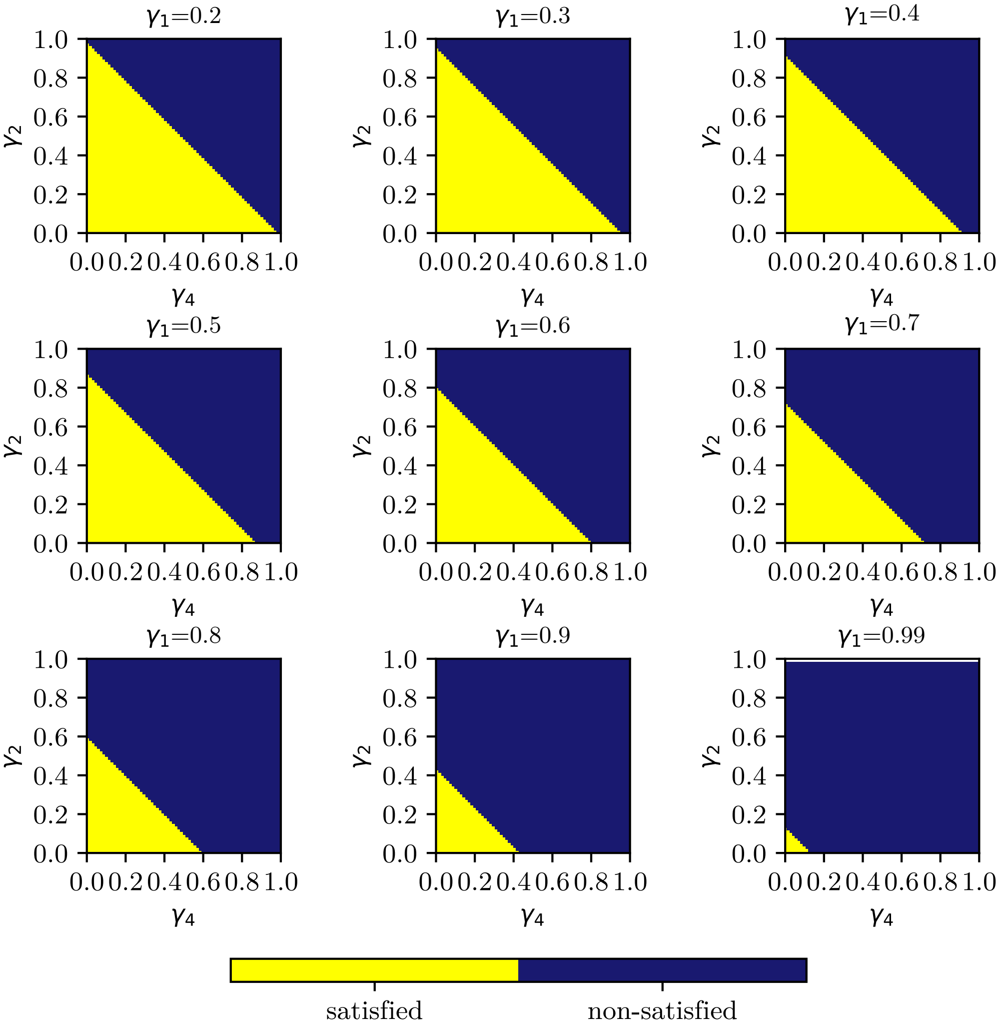

Figure 5.14: Graphical representation of the parameter space (γ_1, γ_2 and γ_4) satisfying the *first-best condition* (that is, $\tilde{X} > 0$)

In what follows, we show that in the presence of network effects and pollution externality, the ratio of EVs to ICEVs in the first-best is always higher compared to the monopoly outcome; this result does not depend on the actual values of the demand parameters and network externalities. We define $\zeta_{fb} = \zeta_{fb}^N/\zeta_{fb}^D$, and $\zeta_m = \zeta_m^N/\zeta_m^D$. Using the ratios of EVs to EVCSs in the in the firs-best and decentralized economy, we can write

$$\begin{aligned}
\zeta_m &= \frac{2\zeta_{fb}^N - (\gamma_2+\gamma_4)(\alpha_f - c_f)}{2\zeta_{fb}^D + \gamma_1(\gamma_2+\gamma_4)(\alpha_f - c_f) + \frac{3}{2}(\gamma_2+\gamma_4)^2(\alpha_d - c_d)}, \\
&= \frac{\zeta_{fb}^N - \frac{1}{2}(\gamma_2+\gamma_4)(\alpha_f - c_f)}{\zeta_{fb}^D + \frac{1}{2}\gamma_1(\gamma_2+\gamma_4)(\alpha_f - c_f) + \frac{3}{4}(\gamma_2+\gamma_4)^2(\alpha_d - c_d^D)},
\end{aligned} \tag{5.27}$$

which implies $\zeta_m^N \leq \zeta_{fb}^N$ and $\zeta_m^D \geq \zeta_{fb}^D$. Hence, for any parameter values $\zeta_m \leq \zeta_{fb}$.

5.2.4 Oligopoly

In an oligopolistic market structure, the inverse demand functions faced by firms become

$$\begin{aligned}
p_c &= \alpha_c - Q_c - \gamma_1 Q_d + \gamma_2 Q_f, && (5.28)\\
p_d &= \alpha_d - Q_d - \gamma_1 Q_c, && (5.29)\\
p_f &= \alpha_f - Q_f + \gamma_4 Q_c, && (5.30)
\end{aligned}$$

where $Q_j = \sum_{i=1}^{N} q_{i,j}$, with $j = \{c, d, f\}$, is the total quantity of each good produced in the economy and $q_{i,j}$ denotes the quantity of each good produced by firm i. Each firm maximizes individual profits taking into account the quantities produced by the other firms

$$\begin{aligned}
\pi_i &= (p_c - c_c)q_{i,c} + (p_d - c_d)q_{i,d} + (p_f - c_f)q_{i,f} \qquad (5.31)\\
&= (\alpha_c - Q_c - \gamma_1 Q_d + \gamma_2 Q_f - c_c)q_{i,c} + (\alpha_d - Q_d - \gamma_1 Q_c - c_d)q_{i,d}\\
&+ (\alpha_f - Q_f + \gamma_4 Q_c - c_f)q_{i,f}.
\end{aligned}$$

Profit maximization yields

$$\begin{aligned}
\alpha_c - (Q_c + q_{i,c}) - \gamma_1(Q_d + q_{i,d}) + \gamma_2 Q_f + \gamma_4 q_{i,f} - c_c &= 0,\\
\alpha_d - (Q_d + q_{i,d}) - \gamma_1(Q_c + q_{i,c}) - c_d &= 0, \qquad (5.32)\\
\alpha_f - (Q_f + q_{i,f}) + \gamma_2 q_{i,c} + \gamma_4 Q_c - c_f &= 0.
\end{aligned}$$

From the first-order conditions we can derive the reaction functions of firm i, that is, the optimal quantities of the EVs, ICEVs and EVCSs produced by each firm given production of the three goods by the other firms. The reaction functions are linear because of the assumption of linear demand and cost functions. Moreover, the quantity of each good produced by firm i depends on the quantity of the other two goods produced by the firm itself because of the presence of substitution and network effects. Firms are identical, hence they all produce the same quantities of EVs, ICEVs and EVCSs, that is, $q_{i,j} = q_{-i,j} = q_j$, for all the goods in the economy. For an interior solution, optimal quantities produced by each firm i are

$$q_c^* = \frac{1}{X_{olig}}[(n+1)(\alpha_c - c_c) - \gamma_1(n+1)(\alpha_d - c_d) + (n\gamma_2 + \gamma_4)(\alpha_f - c_f)], \tag{5.33}$$

$$q_d^* = \frac{1}{X_{olig}}[-\gamma_1(n+1)(\alpha_c - c_c) + \left[n + 1 - \frac{(n\gamma_2 + \gamma_4)(\gamma_2 + n\gamma_4)}{n+1}\right](\alpha_d - c_d) \tag{5.34}$$

$$- \gamma_1(n\gamma_2 + \gamma_4)(\alpha_f - c_f)],$$

$$q_f^* = \frac{1}{X_{olig}}[(\gamma_2 + n\gamma_4)(\alpha_c - c_c) - \gamma_1(\gamma_2 + n\gamma_4)(\alpha_d - c_d) \tag{5.35}$$

$$+ (n+1)(1 - \gamma_1^2)(\alpha_f - c_f)],$$

where $X_{olig} = (n+1)^2(1 - \gamma_1^2) - (n\gamma_2 + \gamma_4)(\gamma_2 + n\gamma_4) > 0$ is defined as the *oligopoly condition.* For $n = 1$, the *oligopoly condition* coincides with the *monopoly condition*; in general, for $n > 1$, we can write

$$X_{olig} = X + 2(n-1)(1 - \gamma_1 - \gamma_2\gamma_4), \tag{5.36}$$

meaning that for $1 - \gamma_1 - \gamma_2\gamma_4 > (<)0$, the set of parameter satisfying the *oligopoly condition* (*monopoly condition*) is larger than the one satisfying the *monopoly condition* (*oligopoly condition*). Since prices do not affect welfare as in the baseline model, we do not report them in the oligopolistic case. When the optimal policies apply, the optimal quantities become

$$q_c^{pol} = q_c^* + \frac{1+n}{X_{olig}} s_c + \frac{\gamma_1(1+n)}{X_{olig}} t_d + \frac{n\gamma_2 + \gamma_4}{X_{olig}} s_f, \tag{5.37}$$

$$q_d^{pol} = q_d^* - \frac{\gamma_1(1+n)}{X_{olig}} s_c - \frac{(n+1) - \frac{1}{n+1}(n\gamma_2+\gamma_4)(\gamma_2+n\gamma_4)}{X_{olig}} t_d - \frac{\gamma_1(n\gamma_2+\gamma_4)}{X_{olig}} s_f, \tag{5.38}$$

$$q_f^{pol} = q_f^* + \frac{\gamma_2 + n\gamma_4}{X_{olig}} s_c + \frac{\gamma_1(\gamma_2 + n\gamma_4)}{X_{olig}} t_d + \frac{(1+n)(1-\gamma_1^2)}{X_{olig}} s_f. \tag{5.39}$$

Notice that welfare now includes profits from all the n firms in the economy and damage is given by the total amount of ICEVs produced, that is

$$W = U + F + n\pi_i - \phi Q_d, \tag{5.40}$$

where $Q_d = nq_d$. As in the monopoly case, however, profits are simply redistributed within the economy and they do not matter in the welfare determination.

5.3 Appendix for Chapter 4

5.3.1 CGE Model

Regression Model

We use a regression model to calculate the total number of passenger cars in the economy. In the last twenty years, the number of passenger cars in Switzerland follows the development of the population; growing income does not play a role anymore. The total number of passenger cars followed the growth of GDP from 1995 until 2000 (see the left part of Figure 6 which shows the indexed values for GDP, population, and total passenger cars). Starting in 2000 the passenger cars grow much slower than GDP. However, over the whole period of 1995 until 2014, the passenger cars grow more or less with the population. We, therefore, assume that in the CGE model, passenger cars are not depending on income (the type of car, however, is). We used a simple Ordinary-Least-Squares (OLS) procedure to estimate the relation between total passenger cars and population for the period 2014 - 2050.

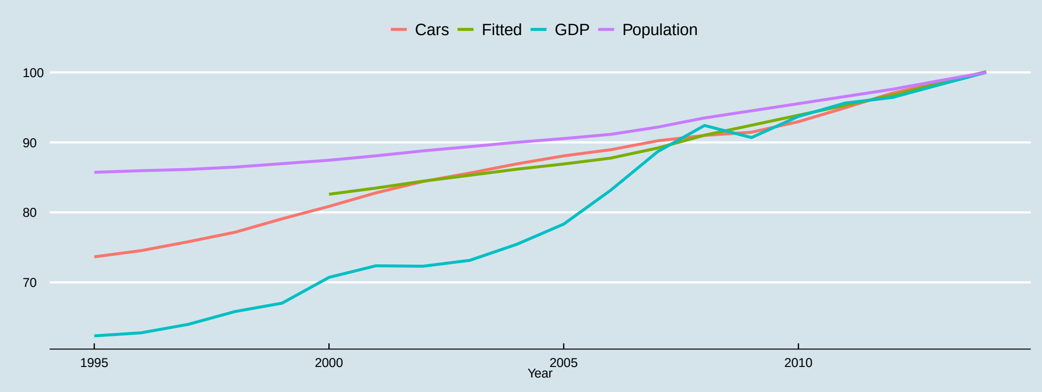

Figure 5.15: Estimation of passenger cars using data from 1995-2014

MCP-format

Mathiesen (1985) showed that the three Arrow-Debreu conditions for a general equilibrium as discussed above can be cast as a (mixed) complementarity problem (MCP). The MCP format is a special case of a variational inequality problem in which all the variables lie in the positive orthant (see Facchinei and Pang (2003)). The MCP format suits itself for solving general equilibrium models. As Mathiesen (1985) writes, although the first-order optimality conditions of a mathematical programming model also satisfy a CP problem, there may be no optimization problem for a general equilibrium model that leads to this CP problem (the so-called "integrability-problem" (see Samuelson (1950)). This can happen if, for example, the model contains several households with distinct endowments and preferences, or if there are ad-valorem taxes or constraints on prices.

A complementary problem can be described as a system of (non-)linear constraints where the system variables are linked to the constraints with complementarity conditions (Ferris and Munson 2014). More formally, given a function $F : \mathbb{R}^n \to \mathbb{R}^n$, lower bounds $l \in \{\mathbb{R} \cup -\infty\}^n$ and upper bounds $u \in \{\mathbb{R} \cup \infty\}^n$, we try to find $x \in \mathbb{R}^n$ such that precisely one of the following holds for each $i \in 1, \ldots, n$:

$$\begin{aligned} F_i(x_i) &= l_i \quad \text{and} \quad F_i(x_i) \geq 0, \quad \text{or} \\ F_i(x_i) &= u_i \quad \text{and} \quad F_i(x_i) \leq 0, \quad \text{or} \\ l_i < x_i &< u_i \quad \text{and} \quad F_i(x_i) = 0 \end{aligned}$$

This means that the variable x_i is at one of its bounds or the linked function is equal to zero.

In the mixed complementarity problem (MCP), we not only have inequalities with complementary nonnegative variables but also equations where the associated variables are free. The complementarity conditions can then be written as:

$$\begin{aligned} &F_i(x_i, x_j) \geq 0, \quad x_i \geq 0, \quad x_i F_i(x) = 0, \\ &F_j(x_i, x_j) = 0, \quad x_j \text{ free}, \end{aligned}$$

where we partition the set n in the sets i and j.

Often the following shorthand notation is used, where the perpendicular symbol ($\perp$) indicates the complementarity slackness between the constraint and the variable:

$$0 \geq F(x) \perp x \geq 0. \tag{5.41}$$

Complementarity models can be used for solving linear, quadratic and nonlinear programs by writing the Karush-Kuhn-Tucker optimality conditions. In the case of minimizing a function $f(x)$, where $x \in \mathbb{R}^+$, the first-order condition is given by:

$$\frac{\partial f}{\partial x} \geq 0, \quad x \geq 0. \tag{5.42}$$

If x is at its lower bound, we must must have that the function is increasing in x. If we have an interior solution, the derivative must be equal to zero. Combining these two pieces of information, we get the mixed complementarity formulation:

$$\frac{\partial f}{\partial x} \leq 0, \quad x \geq 0, \quad x\frac{\partial f}{\partial x}. = 0 \tag{5.43}$$

As the complementarity problem can often be formulated using the optimality conditions of the original problem, it is easy to write down the model equations. However, there is not always an optimization problem that corresponds to the complementarity conditions. This means that a MCP formulation allows us to solve a wider class of problems.

Complementary models have been used for expressing a variety of economic equilibrium models for both markets and games, where the underlying problem cannot be written down as a single optimization problem or if no equivalent optimization problem exists, for example, due to non-integrability conditions.[1] Many examples in MCP format can be found in Ferris and Munson (2014), Rutherford (1995) and Dirkse and Ferris (1995). The development of the complementarity modeling format was motivated by theoretical and practical developments in algorithms for nonlinear complementarity problems and variational inequalities. The most recent techniques are based on ideas from interior-point algorithms for linear programming (Kojima et al. 1991). Computational evidence suggests that algorithms for solving MCPs are relatively reliable and efficient, particularly for models that are not natural optimization problems. A survey of developments in the theory and applications of these methods is provided by Harker and Pang (1990).

Mathiesen (1985)'s MCP version of the CGE model is formulated as a nonlinear system of (weak) inequalities and equalities corresponding to the three classes of equilibrium conditions associated with the Arrow-Debreu general equilibrium. The fundamental unknowns of the system are three vectors consisting of non-negative prices (for commodities and factors), activity levels (production and utility) and household incomes. In equilibrium, each of these variables is linked to one of the inequalities or equalities. The three classes are:

1. The **zero-profit conditions** (more precise, the non-positive profit conditions). In this class the variable complementary to the equation is the activity level: If a sector in equilibrium makes a negative profit, the activity level will be zero; if the profit is zero, the activity level will be positive. Note, that because of the assumption of perfect competition in equilibrium no (excess) profits will exist: Positive profits would lead to new entrants driving the price and, therefore, the profits to zero. The zero-profit functions can be derived from the maximization or, in case of the producers of the dual cost minimization problems.

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[1] See the paper on this topic by Samuelson (1950).

We use the calibrated share form of the CES function (see Rutherford (1998)) to write down the zero-profit condition for the utility function

$$
\begin{aligned}
P^U \leq & \left[\theta^{cls}\left(\frac{P^{inv}}{\overline{P}^{inv}}\right)^{1-\sigma^{cls}} + (1-\theta^{cls})\left[\left(\frac{P^{cls}}{\overline{P}^{cls}}\right)^{\frac{1}{1-\sigma^{cl}}}\right]^{1-\sigma^{cls}}\right]^{\frac{1}{1-\sigma^{cls}}} \perp U \\
& \text{where } P^z = \left[\theta^{cl}\left(\frac{P^{ls}}{\overline{P}^{ls}}\right)^{1-\sigma^{cl}} + (1-\theta^{cl})\left(\frac{P^{C}}{\overline{P}^{c}}\right)^{1-\sigma^{cl}}\right] \\
& \text{and } P^c = \left[\theta^{c}\left(\frac{P^{ne}}{\overline{P}^{ne}}\right)^{1-\sigma^{c}} + (1-\theta^{c})\left(\frac{P^{e}}{\overline{P}^{e}}\right)^{1-\sigma^{c}}\right]^{\frac{1}{1-\sigma^{c}}} \\
& \text{where } P^{ne} = \left[\sum_{sne}\theta^{cne}_{sne}\left(\frac{P^A_{sne}}{\overline{P}^A_{sne}}\right)^{1-\sigma^{cne}}\right]^{\frac{1}{1-\sigma^{cne}}} \\
& \text{and } P^e = \left[\sum_{e}\theta^{ce}_{e}\left(\frac{P^A_{e}}{\overline{P}^A_{e}}\right)^{1-\sigma^{ce}}\right]^{1/1-\sigma^{ce}}
\end{aligned}
\tag{5.44}
$$

Using the calibrated share form, it is straightforward to write down the other zero-profit conditions. We refrain from writing down these equations in the extensive form and use a condensed form. The zero-profit function for the government utility, the domestic non-energy and energy sectors, the Armington sectors as well as the investment sector is given by:

Government utility: $$-\Pi^G \geq 0 \perp UG \tag{5.45}$$

Non-energy domestic production: $$-\Pi^D_{ne} \geq 0 \perp Y_{ne} \tag{5.46}$$

Energy domestic production: $$-\Pi^D_{e} \geq 0 \perp Y_{e} \tag{5.47}$$

Armington sector: $$-\Pi^A_{i} \geq 0 \perp A_{i} \tag{5.48}$$

Investment sector: $$-\Pi^{inv}_{i} \geq 0 \perp INV_{i}. \tag{5.49}$$

2. The **market clearing conditions**. These equations are complementary with the prices: Supply minus demand for every commodity should be non-negative. In equilibrium, a positive supply means that the complementary price is zero (the case of a free good); if supply is equal to demand, a positive equilibrium price will be the result. The market clearing conditions can be derived using Shephard's lemma. This lemma states that that the conditional demand for an input in production is equal to the derivative of the cost function with respect to the price of the input (Varian 1992).

   $$A_i = \sum_j \frac{\partial C_i^D}{\partial P_i^A} + \frac{\partial C_i^U}{\partial P_i^A} \tag{5.50}$$

   All other market clearing functions can be derived in the same way differentiation the cost functions in the respective production functions.

3. **Income balance or definition**: This class of equations simplifies the market clearing conditions as the expression for income in the consumer or government consumption demand functions can be replaced by a single variable (I^{RA} and I^G).

5.3.2 Calibration

Consumers

COICOP	**Description**	**HABE**
C01	Food and non-alcoholic beverages	A51
C02	Alcoholic beverages, tobacco, and narcotics	A52
C03	Clothing and footwear	A56
C04	Housing, water, gas, electricity, and other fuels	A57
C05	Furnishings, household equipment and routine maintenance of the house	A58
C06	Health	A61
C07	Transport	A62
C08	Communication	A63
C09	Recreation and culture	A66
C10	Education	A67
C11	Restaurants and hotels	A53
C12	Miscellaneous goods and services	A68

Table 5.2: Consumer goods in the model.

Producers

CPA-Code	Names	CPA-Code	Names
01	Agriculture, hunting and related service activities	40g	Gas supply
02	Forestry, logging and related service activities	41	Collection, purification and distribution of water
05	Fishing, fish farming and related service activities	45	Construction
10-14	Mining and quarrying	50	Sale, maintenance and repair of motor vehicles
15-16	Manufacture of food products, beverages and tobacco	51-52	Wholesale and retail trade
17	Manufacture of textiles	55	Hotels and restaurants
18	Manufacture of wearing apparel, dressing and dyeing of fur	60a	Passenger rail transport
19	Leather and footwear	60b	Goods rail transport
20	Manufacture of wood	60c	Rail infrastructure
21	Manufacture of pulp and paper	60d	Other scheduled passenger land transport
22	Publishing, printing	60e	Taxi operation, Other land passenger transport
23a	Manufacture of coke, refined petroleum products	60f	Freight transport by road
23b	Manufacture of nuclear fuel	60g	Transport via pipelines
24	Chemical industry	61	Water transport
25	Manufacture of rubber and plastic products	62	Air transport
26	Manufacture of other non-metallic mineral products	63a	Water transport infrastructure
27	Manufacture of basics metal	63	Air transport infrastructure / Airports
28	Manufacture of fabricated metal products	63c	Other supporting and auxiliary transport activities; activities of travel agencies

CPA-Code	Names	CPA-Code	Names
29	Manufacture of machinery and equipment	64	Post and telecommunications
30-31	Manufacture of office and electrical machinery and computers	65	Financial intermediation, except insurance and pension funding (includes also part of NOGA 67)
32	Manufacture of communication equipment	66	Insurance and pension funding, except compulsory social security (includes also part of NOGA 67)
33	Manufacture of medical and optical instruments, watches	70, 97	Real estate (incl. renting by private households)
34	Manufacture of motor vehicles	71, 74	Other business activities
35	Manufacture of other transport equipment	72	Informatics
36	Manufacture of furniture, manufacturing	73	Research and development
37	Recycling	75a	Road infrastructure
40a	Running hydro power plants	75b	Other public administration and defence; compulsory social security
40b	Storage hydro power plants	80	Education
40c	Nuclear power plants	85	Health and social work
40d1	Public power plants (incl. CHP) based on fossil fuels	90a	Electricity generation in MSW incineration plants
40d2	Wood based power plants (incl. CHP)	90	Heat generation in MSW incineration plants
40d3	Wind power and PV plants	90c	Other waste treatment
40e	Electricity distribution and trade	91-92	Recreational, cultural and sporting activities
40f	Public heat supply	93-95	Private households with employed persons, other service act.

Table 5.3: Sectors in the CGE model

Passenger transport cost

	lstkw	**fixcosts**	**varcosts**	**fuelcosts**
Gas	<60kW	4’710	1’314	752
Gas	60-100kW	6’273	2’106	640
Gas	100-140kW	8’533	2’796	889
Gas	>140kW	9’519	3’054	1’962
Gasoline	<60kW	4’188	960	735
Gasoline	60-100kW	5’223	1’365	897
Gasoline	100-140kW	6’223	1’676	933
Gasoline	>140kW	7’824	2’240	1’201
Gasoline-Electric	<60kW	9’173	1’741	611
Gasoline-Electric	60-100kW	7’928	2’517	578
Gasoline-Electric	100-140kW	7’592	2’349	522
Gasoline-Electric	>140kW	10’600	3’477	684
Diesel	<60kW	4’770	2’502	535
Diesel	60-100kW	5’751	2’587	1’055
Diesel	100-140kW	6’389	2’989	1’144
Diesel	>140kW	8’269	3’801	1’349
Electric	<60kW	6’021	669	532
Electric	60-100kW	7’750	1’160	535
Electric	100-140kW	7’843	1’313	456
Electric	>140kW	10’102	1’762	512
Diesel-Electric	<60kW	7’320	1’098	809
Diesel-Electric	60-100kW	9’422	1’904	987
Diesel-Electric	100-140kW	9’535	2’155	1’026
Diesel-Electric	>140kW	11’673	3’876	1’321

Table 5.4: Assumptions on costs in benchmark year

	FixCosts	**VarCosts**
Gas	0.2%	0.2%
Gasoline	0.2%	0.2%
Gasoline-Electric	0.2%	0.2%
Diesel	0.2%	0.2%
Electric	-0.9%	0.2%
Fuel cell	-0.6%	0.2%

Table 5.5: Yearly change in costs

Change in fuel efficiency	**2030**	**2050**
BEV, FCEV	0%	0%
PHEV	+3%	+10%
ICEV	+30%	+50%

Table 5.6: Projection of passenger car stock and fuel efficiency

Reconciliation of cost information on passenger cars with the IOT

We need to reconcile the cost information on passenger cars in Section 4.3.3 with the data of the IOT. The demand of the Swiss households in the IOT classifies individual consumption expenditures incurred by households, non-profit institutions serving households and general government according to their purpose. The COICOP division C7 contains the overall costs for private transport. Table 5.7 in Appendix 5.3.2 shows the groups (three-digit) and classes (four-digit) of this division.

In the IOT these costs are mapped to the sectors. The published Swiss IOT only shows the division and not the groups and classes. However, we can use the raw, disaggregated information (see Table 5.8 in Appendix 5.3.2) to infer the costs for the use of passenger cars which can be found in the class 7.1.1 (Purchase of vehicles) and group 7.2 (Operation of personal transport equipment) (see Table 5.9 in Appendix 5.3.2). The latter group contains also costs for other vehicles. Using the shares of newly bought passenger cars and other transport equipment we split these costs accordingly.

These costs are compared with the costs we get from multiplying the costs from Table 5.4 with the number of passenger cars in 2014. There, total use of electricity for the vehicles using batteries contains also the loss of load (15%). As these costs differ by a factor two from the costs in the IOT, we scale the fixed costs in such a way that they are equal.

Code	**Description**
C07.1.1	**Purchase of motor cars**
C07.1.2	Purchase of motorcycles
C07.1.3	Purchase of bicycles
C07.1.4	Purchase of animal drawn vehicles
C07.2.1	**Spare parts and accessories for personal transport equipment**
C07.2.2	**Fuels and lubricants for personal transport equipment**
C07.2.3	**Maintenance and repair of personal transport equipment**
C07.2.4	**Other services in respect of personal transport equipment**
C07.3.1	Passenger transport by railway
C07.3.2	Passenger transport by road
C07.3.3	Passenger transport by air
C07.3.4	Passenger transport by sea and inland waterway
C07.3.5	Combined passenger transport
C07.3.6	Other purchased transport services

Table 5.7: COICOP classes in transport demand

Code	**Description**	**C07_1_1**	**C07_2_1**	**C07_2_2**	**C07_2_3**	**C07_2_4**	**Total**
S23a	Manufacture of coke, refined petroleum products and nuclear fuel			3’668			3’668
S24	Manufacture of chemicals and chemical products			23			23
S25	Manufacture of rubber and plastic products		117				117
S31	Manufacture of electrical machinery and apparatus n.e.c.		65				65
S34	Manufacture of motor vehicles, trailers and semi-trailers	6’159	219				6’378
S40g	Gas supply			2			2
S50	Sale, maintenance and repair of motor vehicles and motorcycles; retail sale of automotive fuel	1’832	104	367	1’732		4’034
S71	Renting of machinery and equipment without operator and of personal and household goods					1’035	1’035
S75b	Other public administration and defence; compulsory social security					285	285
	Total	7’990	504	4’060	1’732	1’320	15’606

Table 5.8: Expenditure of households for private transport in million CHF

Coicop	**Description**	**Cost category**
C07.1.1	Purchase of motor cars	Fixed cost
C07.2.1	Spare parts and accessories for personal transport equipment	Operation and maintenance cost
C07.2.2	Fuels and lubricants for personal transport equipment	Fuel cost
C07.2.3	Maintenance and repair of personal transport equipment	Operation and maintenance cost
C07.2.4	Other services in respect of personal transport equipment	Operation and maintenance cost

Table 5.9: Demand for transport in the household budget survey

5.3.3 Simulation Results

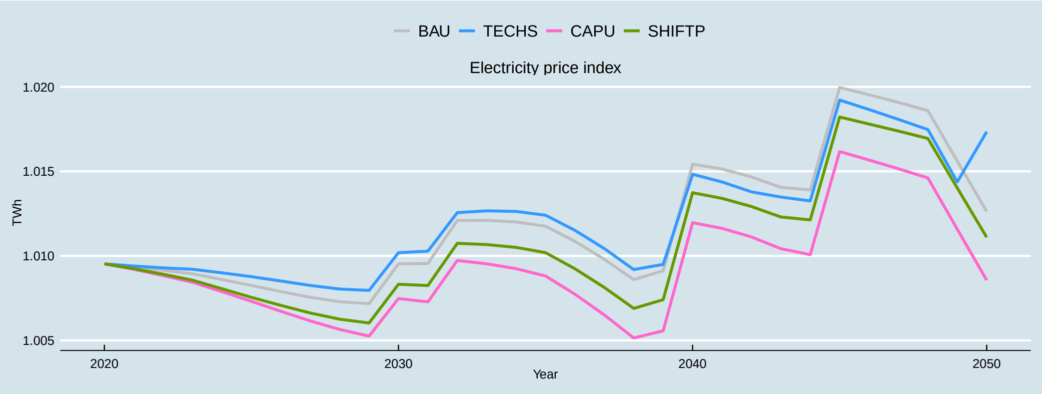

Figure 5.16: Development of electricity prices

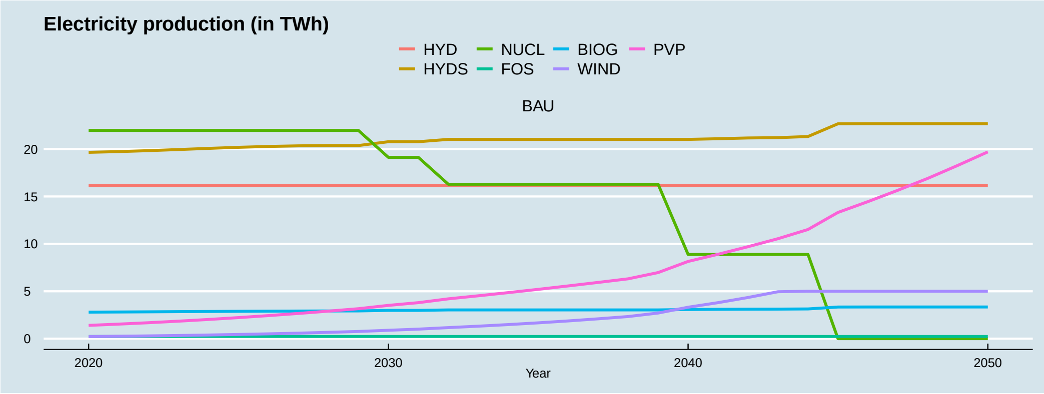

Figure 5.17: Production capacity of electricity

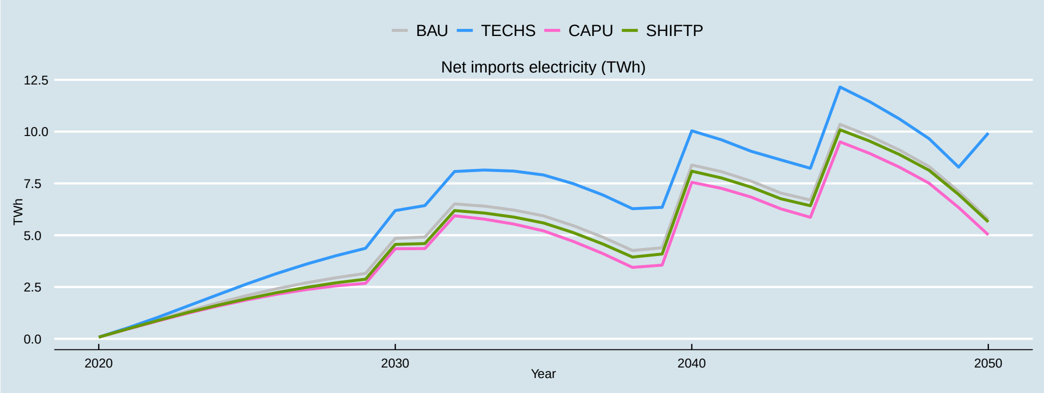

Figure 5.18: Net imports of electricity

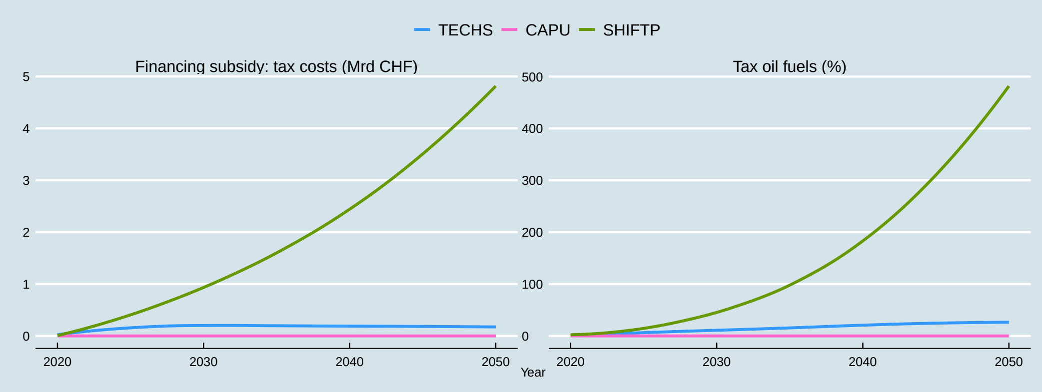

Figure 5.19: Policy-cost effect

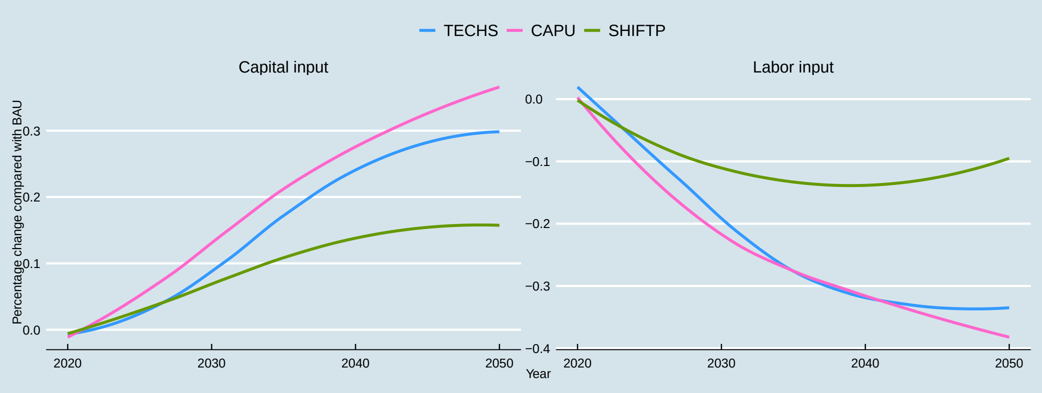

Figure 5.20: Labor and capital Input relative to BAU

Scenario	**Subsidy for BEVs relative to TECHS**	**Subsidy to public transport relative to SHIFTP**
TECHS	1	0
CAPU	0	0
SHIFTP	0	1
1	1	1
2	0.636363636	1
3	0	1
4	0	1
5	0.887272727	0.817505212
6	0.672727273	0.814896189
7	0.723636364	0.93414739
8	0.945454545	0.748050089
9	0.774545455	0.847347338
10	1	1
11	0.734545455	0.850168654
12	0.934545455	0.756920133
13	0.701818182	0.797089126
14	0.76	0.87343404
15	0.887272727	0.904369834
16	0.883636364	0.836246877
18	1	0.87343404
19	0.650909091	0.907584369
20	0.650909091	0.907584369
21	0.883636364	0.914082485
22	0.996363636	0.772959602
23	0.84	0.941032887
24	0.985454545	0.804624529
25	0.701818182	0.739385525
26	0.858181818	0.87343404
27	0.785454545	0.748050089
28	0.76	0.825433492
29	0.869090909	0.828110535
30	0.887272727	0.743692571
31	0.814545455	0.861644328
32	0.952727273	0.820130995
33	0.974545455	0.984576094
34	0.818181818	0.75917061
35	0.978181818	0.996098896
36	0.832727273	0.973316834
37	0.807272727	0.720605503
38	0.96	0.841760513
39	0.810909091	0.917366562
40	0.68	0.973316834

Table 5.10: Subsidies in the optimal scenarios in 2050

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Curriculum Vitae

Born on October 16, 1992 in Chur, Switzerland

2017 – 2021	Ph.D. in Economics - ETH Zurich
2014 – 2016	MA Economics - University of Zurich
2011 – 2014	BA Economics - University of Zurich