A Post-Kyoto Energy and Climate Policy for Switzerland

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JAN O. IMHOF

M. Sc. Ec. University of Berne
B. Sc. Ec. University of Berne

born on November 5, 1982

citizen of Fahrni b. Thun (BE), Switzerland

accepted on the recommendation of

Prof. Thomas F. Rutherford
Prof. Lucas Bretschger

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Jan Imhof, July 2012
“Real knowledge is to know the extent of one’s ignorance.”

Confuzius, 551 BC - 479 BC

“I know one thing, that I know nothing.”

Sokrates, 469 BC - 399 BC

“The important thing is not to stop questioning. Curiosity has its own reason for existing.”

Albert Einstein, 1879 AD - 1955 AD
Summary

This thesis develops energy economic modeling tools that could aid and guide the Swiss energy and climate policy debate by identifying and quantifying existing trade-offs. The first part of the thesis contains a general introduction to the topic and to each of the parts and chapters. Part II discusses the economic impact of carbon mitigation policies in Switzerland in two distinct chapters. The first chapter deals with potential proposals for the CO\textsubscript{2} law, which is currently revised by the Swiss parliament. The chapter compares different proposals as to their cost-effectiveness and their distributional consequences. The second chapter in part II deals with different instruments to reduce carbon emissions and investigates the role of carbon taxes and subsidies and standards for energy efficient equipment. Since the incidence in Fukushima happened, nuclear and renewable electricity generation technologies came into the focus of the debate. Since the top-down model employed in part II is not suitable to study a nuclear phase-out, part III develops a copper-plate bottom-up electricity dispatch and investment model that is capable of analyzing the effects and cost of a nuclear phase-out in Switzerland.

Part II: Revision of the CO\textsubscript{2} Law

Chapter 2: Fuel Exemptions, Revenue Recycling, Equity and Efficiency: Evaluating Post-Kyoto Policies for Switzerland

The Swiss CO\textsubscript{2} law runs out in 2012, together with the first commitment period of the Kyoto Protocol. Currently, the Swiss parliament is deciding on the successor of the law that aims to achieve a 20\% reduction of CO\textsubscript{2} emissions below 1990 levels by 2020. As a means to achieve this ambitious target, the current tax on stationary fuels at 36 CHF/t CO\textsubscript{2} will be maintained, while transportation fuels will still be exempted from the carbon tax. Currently, the tax revenues are fully redistributed as a per-capita lump-sum payment via mandatory health insurance and to the employers proportional to their wage payments. This recycling scheme is likely to be prolonged. However, in the presence of the actual debate on the revision of the CO\textsubscript{2} law, this chapter reexamines the exemption of transportation fuels and the revenue recycling scheme under two points of view. First, I examine the effects on cost-effectiveness and second, I study their impact on equity. Using a static computable general equilibrium model of the Swiss economy incorporating 14 household groups, I find that tax exemptions increase the economy-wide costs of a carbon tax, yet fail to ease the effect on over-proportionally affected households. However, adjusting CO\textsubscript{2} tax rates to correct for pre-existing fuel taxes that do not internalize any external effects may decrease the economy-wide cost of a green tax reform. On the other hand the choice of the recycling scheme has less of an effect on efficiency, but its impact on the distributional
outcome of the tax reform has to be considered. Choosing an optimal, economy-wide tax will decrease overall costs considerably, while a lump-sum per-capita rebate will result in a progressive tax package at reasonable costs.

Chapter III: Subsidies, Standards and Energy Efficiency

Carbon taxes have been shown to be the most cost-effective instrument for carbon abatement in a second-best world characterized by non-energy-related market failures such as pre-existing taxes. I show, however, that both subsidies for energy efficiency improvements and fuel standards can be good policy instruments in a third-best world in which consumers underinvest in energy service capital. In this framework, subsidies and standards can both reduce emissions and increase welfare. I show additionally that still further emission reductions are attainable by combining these instruments with a CO2 tax. Two versions of a CGE model for Switzerland are used to compare five policy proposals. First, I examine the transitional impacts of the different policies using the dynamic CEPE model. The same policies are then implemented within a static representation of the model, which includes an activity analysis of light-duty vehicles and allows a more detailed examination of the role of fuel standards and subsidies for energy-efficient vehicles.

Part III: Nuclear Phase-out in Switzerland

After the nuclear incidence in Fukushima the federal council opted for a nuclear phase-out. No new plants shall be built and existing plants should have a limited life span of 50 years. Thus, Leibstadt, the newest nuclear plant, would be shut down in 2034. Potential substitutes for nuclear electricity are hydro, wind and solar plants, gas-fired plants, large scale geothermal facilities or increased imports. In this chapter I develop a partial equilibrium model of Swiss electricity dispatch and investment to estimate cost and investment decisions optimal to replace nuclear energy. The model represents 1460 load segments of a representative year and can indicate systemic stability of the technology mix, as well as, profitability of hydro storage and pump-and-storage hydro plants. I compute 6 counterfactual phase-out scenarios that differ in the available technologies as well as in the import restriction. I find that even under generous assumptions about the potential of hydro, solar and wind power, those technologies can not guarantee annual self-sufficiency of supply and a small net import is necessary. Such a scenario comes at high cost and the electricity price goes up from 4.3 to 19.1 Rp./kWh. Geothermal or gas-fired plants may keep the cost lower and will secure self-sufficiency. However, geothermal technologies are still immature and natural gas combustion produces CO2 emissions. A carbon tax of 36 CHF per ton of CO2 could half emissions from gas-fired plants and make carbon-capture-and-storage technologies profitable. I find that cost of a nuclear phase-out rely largely on the cost structure of yet immature technologies, but that a phase-out is nevertheless feasible with at present available technologies.
Zusammenfassung


Teil II: Revision of the CO₂ Law

Kapitel 2: Fuel Exemptions, Revenue Recycling, Equity and Efficiency: Evaluating Post-Kyoto Policies for Switzerland


Kapitel 3: Subsidies, Standards and Energy Efficiency


Teil III: Nuclear Phase-out in Switzerland

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“Not everything that counts can be counted, and not everything that can be counted counts.”

Albert Einstein, 1879 AD - 1955 AD
Part I

General Introduction
Chapter 1

Introduction

Switzerland’s modern climate and energy conservation policy started in 1990 with the launch of the Energy 2000 Program as a first effort to reduce energy and fossil fuel consumption. The program, which was approved by the Swiss parliament, promoted and subsidized research and improvements in energy efficiency as well as the use of renewable energy sources. While this program ran until the year 2000, the Federal Council tried to pass a CO$_2$-tax law in 1994 to fulfill Switzerland’s Rio pledge of 1992. The goal was to implement a CO$_2$-tax at 12 CHF per ton of carbon dioxide by 1996 and to raise it to 36 CHF by 2000. Although energy-intensive sectors would have been exempted, the law was withdrawn following heavy criticism by major political parties and other interest groups. In 1997, the Federal Council successfully implemented a carbon abatement policy through the CO$_2$ law, which was meant to ensure that Switzerland’s Kyoto commitments are met. These commitments oblige Switzerland to reach a mean CO$_2$-equivalent emission reduction of 8% between 2008 and 2012 as compared to 1990 levels. While the law aimed at abating carbon emissions through voluntary actions, it also gave the government authority to implement a carbon tax if the Kyoto goals seemed likely to be missed. In subsequent years the Federal Council made several target conventions with important emitting sectors such as the car importers, the cement industry and the oil importers. In 2006 the federal council concluded that these agreements were not going to be sufficient and in 2008 introduced a carbon tax on stationary fuels at a level of 12 CHF/tCO$_2$. In January 2010, the tax was increased to 36 CHF. While stationary fuels are taxed, transportation fuels are not. Instead, the oil industry has to charge a “Climate Cent” of 1.5 Swiss cents per liter of gasoline and diesel, which corresponds to a price of roughly 6 CHF/tCO$_2$. The levy has to be used to offset 9 million tons of CO$_2$ between 2008 and 2012 by subsidizing domestic carbon abatement projects and buying foreign carbon certificates. Nevertheless, the Swiss Carbon Balance has shown that these measures are not likely to fulfill Switzerland’s Kyoto commitments: Even though carbon emissions from stationary fuels were reduced by approximately 15% compared to 1990, transportation fuel consumption has increased substantially, leaving overall carbon emissions at their 1990 levels (see Figure 3.2 on page 33 from (FOEN 2012)). Since the Kyoto protocol and the CO$_2$-Law expire after 2012, the Federal Council announced a revision of the law in August 2009. It is very likely that the parliament will extend measures already in place. Those measures consist of a CO$_2$ tax on stationary fuels of 36 CHF per ton of CO$_2$ and the Climate Cent for transportation fuels. In addition, the parliament is likely to impose a domestic reduction target of 20% below 1990 levels by 2020, in line with current EU proposals. Taking into consideration the official CO$_2$ balance (FOEN 2012) it seems likely that the current policy measures are not strict enough.
to fulfill this ambitious future emission reduction target. Additionally, the Climate Cent scheme - equivalent to an exemption of transportation fuels from the CO$_2$ tax - is controversial, since first, transportation fuels have seen continually increasing use under the policy, and second, a cost-effective carbon policy guaranteeing the equalization of marginal abatement costs is absent. In chapter 2 I analyze equity and efficiency issues of a CO$_2$ tax under the revised law.

The basic literature of optimal environmental taxes goes back to Pigou (1920). The concept of such a Pigouvian tax is shown in Figure 1.1. For the case of fossil fuel consumption there exists an externality. The consumption of fossil fuels harms the environment and, thus, private and social marginal cost differ, as indicated in Figure 1.1. In a *laissez-faire* case, the demand for the harmful good is chosen such that private marginal cost equal marginal benefits. The extensive consumption of the good causes social losses equal to the gray shaded area $\{C, D, E\}$. If the government introduces a tax $T$, the private marginal cost equal the social marginal cost at optimal consumption and a new Pareto optimal equilibrium $C$ with consumption $q_0$ is reached. This pigouvian tax internalizes the external effect and eliminates the distortion caused by wrong price signals. Tullock (1967) proposed to use the tax revenue, equal to the gray shaded rectangular $\{A, B, C, (MC + T)\}$, to reduce pre-existing distortionary taxes. This kicked off a huge literature on the so-called 'double dividend hypothesis' (e.g. Sandmo 1975, Terkla 1984, Bovenberg and De Mooij 1994). Referring to the double dividend literature, the recycling of the revenue matters, and I will compare different revenue recycling schemes in the tradition of this literature.

Exemptions for CO$_2$ taxes are usually granted for sectors rather than fuels. The EU-ETS for example includes only certain sectors. Covered are main carbon emitters as for example the electricity or cement producers. Nevertheless, exemptions are inadequate for both economic and ecological reasons. On the one hand the environmental dividend declines harshly if major polluters are exempted and on the other hand economy-wide cost may increase significantly if the exempted polluters could reduce their emissions at lower marginal costs. The same reasoning may hold true for fuel exemptions. In the Swiss case CO$_2$ reduction targets are not affected
as they are defined economy-wide. Yet the cost for the achievement of the environmental goal may rise considerably since transportation fuels account for almost 40% of Swiss CO₂ emissions from fossil fuel combustion. An efficient carbon policy requires marginal abatement costs to be equalized between different sectors, fuels and even countries. Figure 1.2 demonstrates this fact in a simple context.

Figure 1.2: Equalization of Marginal Abatement Cost and Tax Exemptions

Assume an economy where two types of fuels (heating and transportation fuels) are used for production. Both fuels are emitting carbon dioxide when used. There are carbon free substitutes available for both fuels but their use comes at additional marginal costs $mac_h$ and $mac_t$ for heating and transportation fuels, respectively. We further assume that the substitution of the fuels becomes harder and harder and thus marginal abatement cost increase in the amount of emission reduction and that the marginal abatement cost of transportation fuels increase faster than that of heating fuels. Let us now assume a government plans to reduce emission stemming from those fuels by $\Delta E$ tons. This emission reduction is portrayed in Figure 1.2 by the horizontal width of the graph. If this policy additionally requires both fuels to make the same quantitative contribution we will end up at a reduction level of $\Delta E/2$ tons for both fuels. Since marginal abatement cost increase faster for transportation fuels realized marginal abatement cost in this point are larger for those fuels ($MAC_t > MAC_h$). If the government instead issues free tradable carbon permits or fixes a price for emissions, the firms are free to allocate the necessary reduction in fuel use such that marginal abatement costs are equalized between the two fuels. This situation corresponds to point C in the Figure where heating fuels contribute more to the CO₂ abatement than transportation. Since total abatement costs are represented by the integral under the marginal abatement cost curves the dead weight loss associated with the policy that does not equalize marginal abatement costs is triangle A,B,C. This simple example illustrates the shortcoming of the existing and potential Swiss legislation. Under a pure efficiency oriented point of view there is no reason for a fuel exemption as in the “Climate

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1 This may only hold in theory. Since the Swiss instrument is a tax the effective emission reduction may differ from the targets if the implemented tax is too low.

2 See Böhringer (2002) for a profound discussion of this issue.
CHAPTER 1. INTRODUCTION

Clearly certain sectors or regions could be affected heavily by a carbon tax on transportation fuels, but the associated negative effects on employment and welfare would be more than compensated by the efficiency gains from a uniform tax. Needless to say, efficiency is not the only important dimension when evaluating a policy proposal.

Potential adverse distributional outcomes of environmental taxes have been discussed by both policy makers and researchers. A carbon tax changes relative prices of goods and could thus impact various consumers differently: A household spending relatively more of his income on carbon intensive goods will bear more of the tax burden. Economists who have focused on the expenditure side tend to appraise carbon taxes as being regressive (e.g. Scott and Eakins (2004)). On the other hand carbon taxes create revenue which can be redistributed. If this is taken into account the recycling scheme is crucial to the outcome. Metcalf (1999, 2007) insisted that a green tax reform can lead to almost any desired distributional outcome if the revenue is recycled in the appropriate way. Grainger and Kolstad (2009) show that the recycling of the revenue can offset disproportional effects on households even though carbon taxes are regressive in itself. This domination of the revenue recycling is not surprising, since fuel expenditures are usually only a minor budgetary item.

Additionally I ask the question whether tax exemptions for transportation fuels may affect the distributional outcome of the tax reform. If certain households spend a smaller relative share of their income on transportation fuels, while their expenditures on stationary fuels are disproportionally large, they may be negatively affected by an exemption of transportation fuels. If this holds true for poorer households, the exemption would increase the regressivity of the tax. While for example Poterba (1991) has refused this proposition for a gasoline tax in the USA, Scott and Eakins (2004) finds that poorer households could be badly affected by such an exemption in the case of Ireland. The answer depends on the structure of expenditure patterns, as well as, on the amount of revenue generated and the mode of recycling.

Chapter 3 deals with other policy instruments that should help to abate carbon emissions. As currently discussed, a part of the revenue from the carbon tax shall be used to foster more efficient use of energy in the building sector, while mandates on carbon intensity of imported cars are being discussed in parallel. Such instruments cannot be effective instruments for carbon mitigation in a neoclassic second-best environment. However, regulative measures and subsidies are often advocated in the political process since they are politically easier to sell. Hirst and Brown (1990) state the existence of the efficiency gap and provide a case for subsidies and standards. The energy-efficiency gap theory claims the existence of forgone energy savings potential that would be cost-effective. Recent estimates from McKinsey & CO (McKinsey 2007, McKinsey 2009) gained world-wide popularity under policy makers. Chapter 3 explores the potential role of subsidies and standards in a world where such a gap occurs in the form of distorted choices of private household’s energy-efficiency investments.

Switzerland’s electricity production is virtually carbon neutral. Traditionally, large shares of the Swiss electricity generation were provided by run-of-river and storage hydro plants, while fossil fuel-fired plants were much more expensive and ineffective. As the demand for electricity grew Switzerland built nuclear power plants Beznau I and II and Mühleberg in the early 70ties. Subsequently the plants in Gösgen and Leibstadt followed in 1979 and 1984, respectively. The project for the sixth plant in Kaiseraugst was finally stopped after a decade with massive protests and the nuclear disaster in Chernobyl. In the following decades the nuclear technology in Switzerland faced a de facto moratorium, while two initiatives for a phase-out or a de iure moratorium failed at national ballots in 2003. After those initiatives a nuclear renaissance
seemed to be possible and three projects were launched and submitted to the federal government. A consultative ballot in the canton of Berne in February 2011 was affirmative. On month later, those plans came to an abrupt halt after the disaster in Fukushima Daiichi. The energy political debate in Switzerland has been dominated by carbon emissions targets, which should be mainly achieved by means of electrification. Thus, decarbonization and energy conservation were pillars of the modern Swiss energy policy ever since the “Energy 2000” program has been introduced. Since electricity in Switzerland is produced virtually carbon neutral, mainly through nuclear and hydro power, electrification seemed to push Switzerland towards carbon neutrality. However, after the disaster at Fukushima Daiichi the perception of the whole situation changed drastically in many western countries, including Switzerland. After the shock the Swiss federal council opted for a nuclear phase-out. Existing plants ought to be used until they expire and no new plants will be built. This proposal is equivalent to a gradual nuclear phase-out until 2034 based on a reactor life span of 50 years. This current development has confronted the Swiss energy policy with new challenges. The last chapter will discuss options for a nuclear phase-out in Switzerland. To that end I develop a numeric partial equilibrium model.
“There’s no sense in being precise when you don’t even know what you’re talking about.”

John von Neumann, 1903 AD - 1957 AD
Part II

Revision of the CO$_2$ Law
Chapter 2

Fuel Exemptions, Revenue Recycling, Equity and Efficiency: Evaluating Post-Kyoto Policies for Switzerland

2.1 Introduction

The Swiss parliament is in the process of revising its CO₂ law as its reduction targets are running out in accordance with the first commitment period of the Kyoto Protocol. It is very likely that the parliament will extend measures already in place. Those measures consist of a CO₂ tax on stationary fuels of 36 CHF per ton of CO₂ and the Climate Cent for transportation fuels. In addition, the parliament is likely to impose a domestic reduction target of 20% below 1990 levels by 2020, in line with current EU proposals. Taking into consideration the official CO₂ balance (FOEN 2012) it seems likely that the current policy measures are not strict enough to fulfill this ambitious future emission reduction target. Additionally, the Climate Cent scheme - equivalent to an exemption of transportation fuels from the CO₂ tax - is controversial, since first, transportation fuels have seen continually increasing use under the policy, and second, a cost-effective carbon policy guaranteeing the equalization of marginal abatement costs is absent.

Efficiency and equity issues associated with green taxes are discussed broadly in the literature. One branch of literature focuses specifically on the economic efficiency of green tax reforms. Papers discuss either the double dividend, achievable by reducing distorting pre-existing taxes through revenue recycling (e.g. Bovenberg and De Mooij (1994), Goulder (1995) and Wissema

1 This chapter is based on an article, of a special issue of the Swiss Journal of Economics and Statistics edited by Vielle, M. and Mathys, N. (eds.) about Swiss energy modeling efforts (Imhof 2012). I wish to thank Thomas Rutherford, two anonymous reviewers and participants of the 67th Congress of the IIPF, the 2011 international conference of the IAEE and the YSEM 2011 in Bern for helpful comments and suggestions. All remaining errors are the author’s responsibility.

2 The Climate Cent foundation is financed by a charge of 1.5 Swiss Cents levied on every liter of gasoline and diesel sold at the pump. This corresponds to roughly 6 CHF per ton of CO₂.

3 See Böhringer (2002) for a textbook discussion of the importance of equalizing marginal abatement costs.
CHAPTER 2. EQUITY AND EFFICIENCY

and Dellink (2007)), or the efficiency losses or gains due to tax exemptions (e.g. Böhringer and Rutherford (1997), Paltsev, Jacoby, Reilly, Viguier, and Babiker (2005) or Abrell (2010)). While Böhringer and Rutherford show that sectoral tax exemptions may hurt economic efficiency considerably since marginal abatement cost are not equalized, Abrell (2010) finds that tax exemptions for transportation fuels increase welfare. However, Paltsev, Jacoby, Reilly, Viguier, and Babiker (2005) point out that pre-existing fuel taxes are important, as tax exemptions for transportation fuels may “correct pre-existing distortions and reduce the cost” in Europe, while a uniform taxation in the US can reach a given reduction target at least cost. The explanation for their finding is that a pre-existing petroleum tax may act as a pre-existing CO$_2$ tax on transportation fuels. Equalizing marginal abatement cost over fuels imposes different CO$_2$ tax rates such that pre-existing fuel taxes are equaled out. However, this only holds if it is assumed that the pre-existing fuel tax is useless and does not internalize any external effect. Otherwise, if the pre-existing fuel tax is a perfect Pigouvian tax this argument does not hold and the optimal CO$_2$ taxes should be set at an equal rate regardless of other fuel taxes.

The second branch of literature is concerned with the distributional effects of green tax reforms and with tax incidence. While generally carbon taxes have been shown to be regressive (Poterba (1991), Jorgenson, Slesnick, and Wilcoxen (1992), OECD (1995), Scott and Eakins (2004) or Wier, Birr-Pedersen, Jacobsen, and Klok (2005)), Metcalf ((1999), (2007)) points out that, depending on the mode of revenue recycling, effects on the income side can lead to almost any desired distributional outcome. Grainger and Kolstad (2009) show that revenue recycling can offset disproportional effects on households. This dominating effect of revenue recycling is not surprising, since fuel expenditures are usually only a minor budgetary item. However, the question why undesired distributional outcomes should be approached directly via the green tax reform remains. Atkinson and Stiglitz (1976) show that income taxation should be employed to redistribute income. Jacobs (2011) explicitly shows that in the optimal environmental tax reform distributional issues should be addressed with non-linear income taxes. In Switzerland, however, where direct federal tax rates are rather low, the distributional outcome has to be addressed directly in a green tax reform, since cantonal direct tax rates are not accessible.

Finally there is a branch of studies conducted for Switzerland. Müller and van Nieuwkoop (2009) and Seeia, Thalmann, and Vielle (2010) examine the economic effects of the revised CO$_2$ law. However, they base their scenarios on the original proposals from the Federal Council which have changed significantly since the debate in the federal parliament.

In light of the revision of the CO$_2$ law this paper aims to examine different potential Post-Kyoto policies for Switzerland. First, the paper poses the question of how high carbon tax rates need to be in order to reduce domestic CO$_2$ emissions by 20%. Second, the paper estimates the economy-wide cost of a reduction of CO$_2$ emissions by 20% below 1990 levels and compares different revenue-neutral policy proposals regarding revenue recycling and exemptions for transportation fuels. Third, the paper examines the distributional outcomes of the different tax regimes.

This will be accomplished using the static CEPE model\textsuperscript{5} CEPE is a static computable general equilibrium model of the Swiss economy, suitable for climate and energy policy evaluation. The

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\textsuperscript{4} In developed countries poorer households tend to spend a bigger share of their disposable income on energy. There is strong evidence that this does not hold for developing countries (Boyce, Brenner, and Riddle 2005, Van Heerden, Gerlagh, Blignaut, Horridge, Hess, Mabugu, and Mabugu 2006, Yusuf and Resosudarmo 2007, Corong 2008).

\textsuperscript{5} CEPE stands for Climate and Energy Policy Evaluation Model of the Swiss economy.
2.2. THE CEPE MODEL

The CEPE model portrays Switzerland as a small open economy incorporating 14 household groups, 42 producing sectors and 51 goods of which 9 are energy goods. This paper provides estimates of the economic impact of the CO₂ law revision based on recent developments of the debate in parliament. The paper also reexamines the role of exemptions for equity, something which has not been addressed in other CGE studies.

The remainder of the paper is organized as follows. Section 2.2 describes the static CEPE model. Section 2.3 outlines the scenarios and discusses the results. Section 2.4 examines the stability of the results regarding the parameters of the model. Finally section 2.5 summarizes the results.

2.2 The CEPE model

CEPE is a static computable general equilibrium (CGE) model that represents Switzerland as a small open economy. The static model captures the main structure of the Swiss economy and is calibrated to the input-output table for 2005. The model contains 42 sectors. The technologies in use are constant returns to scale, such that the sectors exhibit zero profits. On the demand side the model incorporates 14 household groups representing retired and working households in different income quantiles. Households maximize utility subject to their budget constraints. Different consumption goods are aggregated with fixed expenditure shares. The consumer then trades off leisure with consumption following the approach favored by Ballard (1999). Households provide labor and capital and receive lump-sum transfers. The government buys a fixed basket of goods in all scenarios. It pays for this by collecting value-added taxes, excise taxes, and direct taxes. The government budget is balanced by transfers to the households. If there is additional revenue from environmental taxes, the government recycles the additional revenue in different schemes specified in the scenarios. Tax reforms are always considered to be revenue-neutral.

2.2.1 Data

CEPE is calibrated to the Swiss 2005 Input-Output table. This table was originally developed by the ETH in collaboration with Ecoplan Bern (Nathani and Wickart 2006, Nathani, Wickart, and van Nieuwkoop 2008). A second important data input are the elasticities of substitution. In the 2005 IO table energy goods are rather rough aggregates. CEPE exploits a database containing data on sectoral energy goods usage in physical units and sectoral energy prices to disaggregate the energy goods further. This allows the representation of sectoral energy use in the model and, thus, sectoral carbon emissions from fossil fuel combustion. Finally I apply the income and expenditure survey of 2001 to disaggregate final demand. CEPE incorporates 14 different household groups in the model. The households are classified into 10 income deciles of working households and 4 income quartiles of retired households, as shown in Table A.3 in Appendix A.4.2.

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6 A list of all sectors in the model can be found in Appendix A.3.
7 The households are denoted by EH1 to EH10 from the poorest to the richest income decile of employed households. The retired households are denoted by RH1 to RH4 from the poorest to the richest income quartile.
8 These transfers represent social security and other payments from the government to households. When the carbon tax is redistributed lump-sum the payments are added to those transfers.
CHAPTER 2. EQUITY AND EFFICIENCY

2.2.2 Tax System

Direct taxes at the federal level are not very important. Total revenue from income taxes, property taxes, and taxes on profits accounted for only 12.2 billion CHF in 2005. On the other hand, direct taxes are responsible for the bulk of community and cantonal tax revenues and account for around 73.3 billion CHF. Therefore I add cantonal and communal direct taxes to the federal income and redistribute the additional fictive income of the federal government via transfers to the households. The direct income tax is then levied on capital and labor earnings, resulting in ad-valorem tax rates of 23.8 and 23.3% respectively. These rates are a much closer representation of the true pre-existing tax distortions than if I had only considered federal charges.

In 2005, a value-added tax with a maximum rate of 7.6% gathered 18.2 billion CHF in revenue. Sectoral value-added tax payments are reported in the input-output table, and I use those to compute average sectoral value-added ad-valorem tax rates on capital and labor inputs such that sectoral tax revenues fit the data. The federal government levies taxes on tobacco, alcohol, and cars and charges import tariffs. A petroleum tax is charged at a rate of 73.1 Swiss cents per liter of gasoline and 75.9 cents per liter of diesel. The tax on heating oil is only 0.3 cents per liter and is thus neglected in the model. Since approximately two third of the petroleum tax revenue is used for road maintenance and building, I do not consider this part of the tax in the model as its benefits (through an increased public good) are not accounted for in the model. This is in line with Paltsev, Jacoby, Reilly, Viguier, and Babiker (2005), who argue that the petroleum tax in the US can be ignored as it is used entirely for transportation purposes. This results in a distorting petroleum tax of 21.6 cents per liter of gasoline and 24.4 cents per liter of diesel, which produced general federal revenue of 1.5 billion CHF in 2005. The extent to which the pre-existing fuel tax is not internalizing any external effect, and, therefore, has to be deducted from a CO\textsubscript{2} tax is debatable and is subject to further research. If the tax rates are computed per ton of carbon this results in pre-existing CO\textsubscript{2} taxes of 92 and 95 CHF per ton of CO\textsubscript{2}, respectively.

2.2.3 Energy Goods and Production

CEPE covers 9 intermediate energy goods: fuel oil, natural gas, coal, electricity, gasoline, diesel, kerosene, uranium and crude oil. Switzerland is not endowed with any primary energy resources and has to import crude oil, coal, natural gas and uranium. While about half of Switzerland’s demand for refined oil products is met by imports, the other half is produced from crude in the oil processing sector. The model includes an electricity sector which produces electricity using

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9 While most goods were taxed with 7.6%, there were tax rates of 3.6% for hotels and 2.4% for certain other goods.

10 30 cents per liter of gasoline and diesel (Mineralölsteuerzuschlag) and half of the ordinary petroleum tax (Mineralölsteuer) are used for financing transportation.

11 To ignore a share of the pre-existing tax is of course awkward since the associated excess burden will not be considered in the model. On the other hand, including the distorting share of the tax without modeling the externalities would distort the model’s results even more.

12 I could as well assume that the remainder of the tax internalizes other externalities as noise, congestion or local air pollution, and, thus, is justified as well. However, the important point I want to make is, that the unjustified share of the tax, however large it may be, has to be deducted from the new CO\textsubscript{2} tax.
2.3 Scenario and Results

### 2.3.1 Policy Scenarios

The model’s BAU scenario is calibrated to 2005 data and I do comparative static analysis using policies that achieve a 20% reduction of CO\textsubscript{2} emissions below 1990 levels in 2005. I consider three tax policies. The first scenario is a uniform tax on carbon dioxide emissions from fossil fuel inputs.
fuel combustion (“Uniform”). The tax applies to all stationary and transportation fuels sold in Switzerland. No border measures apply in any setting. The second policy scenario (“Optimal tax”) is a carbon tax with different rates for emissions produced from different sources. The carbon tax on transportation fuels is 90 CHF less than that for stationary fuels in order to correct for the distorting share of the petroleum tax. The third policy scenario (“Exempt”) is a carbon tax on stationary fuels only. Note, however, that the initial petroleum excise tax remains in place.

I generate results for each of these three tax scenarios using four different revenue recycling schemes. The government is assumed to keep tax changes revenue-neutral by recycling carbon tax income either lump-sum or through a uniform reduction in value-added taxes, labor, or capital taxes.

### 2.3.2 Marginal Costs of Abatement and Carbon Emissions

Table 2.1 shows the carbon tax rates, which range between 289 and 696 CHF per ton of CO₂ for a 20% reduction. Note that only the ordinary tax rates for stationary fuels are reported. Transportation fuels are taxed less than the reported rate in the “optimal tax” and in the “exempt” counterfactuals.

<table>
<thead>
<tr>
<th></th>
<th>Uniform</th>
<th>Optimal tax</th>
<th>Exempt</th>
</tr>
</thead>
<tbody>
<tr>
<td>lump-sum</td>
<td>291</td>
<td>352</td>
<td>646</td>
</tr>
<tr>
<td>vat</td>
<td>306</td>
<td>369</td>
<td>674</td>
</tr>
<tr>
<td>capital</td>
<td>289</td>
<td>350</td>
<td>637</td>
</tr>
<tr>
<td>labor</td>
<td>303</td>
<td>371</td>
<td>696</td>
</tr>
</tbody>
</table>

The influence of the recycling schemes regarding tax rates is slight. Uniform tax rates vary between 289 and 306 CHF/ton CO₂, while tax rates on stationary fuels only range between 637 and 696 CHF. It is not surprising that marginal costs are around doubled in the exemption cases, since the burden of CO₂ reduction is shifted entirely to stationary fuels. As the tax base declines, tax rates have to increase in order to have the same absolute effect on CO₂ emissions. Altering the system of rebate makes no direct effect on emission levels, making only a slight change to tax rates necessary. Their influence is mostly seen in the effects on efficiency. The reduction of very distortionary taxes may increase economic activity and, by propelling energy demand, make higher carbon prices necessary to achieve a given reduction target. Carbon prices reported may seem high but are comparable with those obtained in other studies. Müller and van Nieuwkoop (2009) report CO₂ tax rates as high as 325 CHF/t CO₂. Seeia, Thalmann, and Vielle (2010) obtain prices up to 468 CHF per ton of CO₂ equivalent. However, their scenarios differ from mine with respect to two things. First, they apply less strict abatement targets since the first draft of the revised CO₂ law did not require to achieve all emission reductions domestically. And second, they use more optimistic assumptions on technological change with respect to carbon intensity. While they assume that CO₂ emissions decrease until 2020 under a BAU scenario without any active policy measures in place, I implicitly assume that carbon intensity of production does not improve. Instead, I apply long-term elasticities of substitution.

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15 The same effects could be obtained by implementing a uniform CO₂ tax while the distorting share of the petroleum tax would be abandoned.
to account for increased technological knowledge in 2020.

Table 2.2: CO₂ emission levels in million tons and CO₂ reduction in % w.r.t. 1990 under a lump-sum recycling scheme

<table>
<thead>
<tr>
<th></th>
<th>1990</th>
<th>2005</th>
<th>Uniform</th>
<th>Optimal tax</th>
<th>Exempt</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transportation fuels</td>
<td>15.5</td>
<td>16.7</td>
<td>14.3</td>
<td>14.9</td>
<td>16.9</td>
</tr>
<tr>
<td>Stationary fuels</td>
<td>25.4</td>
<td>23.6</td>
<td>18.5</td>
<td>17.9</td>
<td>15.9</td>
</tr>
<tr>
<td>Total</td>
<td>40.9</td>
<td>40.3</td>
<td>32.8</td>
<td>32.8</td>
<td>32.8</td>
</tr>
</tbody>
</table>

The column headed 1990 reports emission levels in 1990 and column 2005 reports benchmark emission levels.

Source: FOEN (2012) and own computations.

Table 2.2 reports CO₂ emissions from the combustion of stationary fuels, transportation fuels, and total emissions in million tons of CO₂ and as percentage reductions compared to 1990 for the case of lump-sum revenue recycling. In all scenarios a larger fraction of emission reduction comes from reduced demand for stationary fuels. The tax exemption and the optimal tax, which do not alter the overall abatement target, shift the burden of emission reduction even more towards stationary fuels. While transport related emissions are reduced in the uniform and the optimal tax cases, transportation fuel use slightly increases when transportation fuels are exempted from the tax.

2.3.3 Carbon Tax Revenue and Redistribution

Table 2.3 reports the revenue from the carbon tax in billion CHF. While the revenue in all uniform and optimal taxation scenarios lies between nine and ten billion CHF, the revenue is higher in the exempt cases.

Table 2.3: Carbon Tax Revenue in billion CHF

<table>
<thead>
<tr>
<th></th>
<th>Uniform</th>
<th>Optimal tax</th>
<th>Exempt</th>
</tr>
</thead>
<tbody>
<tr>
<td>lump-sum</td>
<td>9.5</td>
<td>9.4</td>
<td>10.2</td>
</tr>
<tr>
<td>vat</td>
<td>10.0</td>
<td>9.9</td>
<td>10.5</td>
</tr>
<tr>
<td>capital</td>
<td>9.5</td>
<td>9.4</td>
<td>10.1</td>
</tr>
<tr>
<td>labor</td>
<td>9.9</td>
<td>9.9</td>
<td>11.0</td>
</tr>
</tbody>
</table>

High revenues reflect high potential cut-backs in existing taxes and high lump-sum payments. As indicated by Table 2.4, the value-added tax can be reduced from 7.6% to 3.3% using the revenue of a uniform tax. The revenue generated by a tax on stationary fuels only can even make a reduction to 3.2% possible.

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16 7.6% is the value-added tax rate for “normal” goods and services. Special rates e.g. for food and the hotel sector are reduced proportionally.
TABLE 2.4: ANNUAL PER CAPITA LUMP-SUM REBATE IN CHF AND REDUCED AD-VALOREM TAX RATES IN %

<table>
<thead>
<tr>
<th></th>
<th>2005</th>
<th>Uniform</th>
<th>Optimal tax</th>
<th>Exempt</th>
</tr>
</thead>
<tbody>
<tr>
<td>lump-sum (CHF/capita)</td>
<td>-</td>
<td>1280</td>
<td>1265</td>
<td>1374</td>
</tr>
<tr>
<td>vat (tax rate in %)</td>
<td>7.6</td>
<td>3.3</td>
<td>3.4</td>
<td>3.2</td>
</tr>
<tr>
<td>capital (tax rate in %)</td>
<td>23.8</td>
<td>16.8</td>
<td>17.0</td>
<td>16.5</td>
</tr>
<tr>
<td>labor (tax rate in %)</td>
<td>23.3</td>
<td>18.6</td>
<td>18.6</td>
<td>18.3</td>
</tr>
</tbody>
</table>

Direct taxes on capital or labor can be reduced significantly as well. As the federal income taxes are already low, it is possible to abandon direct taxes almost completely. If state and communal taxes are taken into account as well, average capital and labor tax rates can be reduced from 23.8 to 16.5% for capital or from 23.3 to 18.3% for labor taxes. In the case of lump-sum revenue recycling, the annual lump-sum payments range between 1265 and 1374 CHF per capita.

2.3.4 Welfare Costs of Exemptions and the Double Dividend

Table 2.5 reports Hicksian equivalent variations as a measure of the welfare effects resulting from different policies. To report societal equivalent variations I use a social welfare function that takes the form:

\[ SWF = \left( \sum_n u_h^{\rho} \right)^{\frac{1}{\rho}} \]  

(2.1)

Where \( u_h \) is the average equivalent per capita utility of a type h household, \( n_h \) is the share of type h household members in the total population, and \( \rho \) is the inequality aversion parameter. If \( \rho = 1 \) there is no inequality aversion and the societal equivalent variation is a weighted sum of equivalent variations over all households. This utilitarian social welfare function is referred to as Bentham’s social welfare function. As \( \rho \) declines, inequality becomes more important, and in the limit \( \rho \to -\infty \) the SWF becomes \( \min_h u_h \) and thus, only the utility of the poorest household enters social welfare. This is called Rawls’ social welfare function. When \( \rho = 0 \), both cost-effectiveness and equality enter social welfare considerations. In this case - in the limit \( \rho \to 0 \) - the function is \( \prod_n u_h^{n_h} \). The function in this case is called Nash’s social welfare function.

Social welfare decreases for all tax reforms when applying Bentham’s social welfare function. It should be noted, however, that this is a cost-side exercise. Benefits of the environmental policies, like increased air quality or less congestion, are not taken into account. There is no evidence for a strong double dividend. As Bovenberg and De Mooij (1994) and Bovenberg and Goulder (1996) have shown, the presence of an environmental tax decreases real return to factors and, thus, factor supply. Carbon abatement comes at a cost, which cannot be compensated for by reducing pre-existing taxes.

The excess burden of a proposal increases as the tax base decreases. Full exemption of transportation fuels raises total cost of emission abatement between 25% and 300% compared to uniform tax rates, depending on the mode of revenue recycling. Tax exemptions for transportation fuels, responsible for about 40% of benchmark emissions, cause fuel consumption for private transportation to decline less and shift the burden of emission reduction to other fuels. As a consequence, higher marginal tax rates and induced welfare losses are required to achieve a
2.3. SCENARIO AND RESULTS

Table 2.5: Hicksian equivalent variation (% of benchmark consumption)

<table>
<thead>
<tr>
<th></th>
<th>Uniform</th>
<th>Optimal tax</th>
<th>Exempt</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Bentham: ( \rho = 1 )</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>lump-sum</td>
<td>-0.28</td>
<td>-0.26</td>
<td>-0.35</td>
</tr>
<tr>
<td>vat</td>
<td>-0.04</td>
<td>-0.04</td>
<td>-0.13</td>
</tr>
<tr>
<td>capital</td>
<td>-0.25</td>
<td>-0.23</td>
<td>-0.31</td>
</tr>
<tr>
<td>wage</td>
<td>-0.14</td>
<td>-0.13</td>
<td>-0.21</td>
</tr>
<tr>
<td><strong>Nash: ( \rho = 0 )</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>lump-sum</td>
<td>-0.01</td>
<td>0.05</td>
<td>0.02</td>
</tr>
<tr>
<td>vat</td>
<td>-0.11</td>
<td>-0.06</td>
<td>-0.05</td>
</tr>
<tr>
<td>capital</td>
<td>-0.56</td>
<td>-0.49</td>
<td>-0.55</td>
</tr>
<tr>
<td>wage</td>
<td>0.05</td>
<td>0.07</td>
<td>0.04</td>
</tr>
<tr>
<td><strong>Rawls: ( \rho = -\infty )</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>lump-sum</td>
<td>3.07</td>
<td>3.00</td>
<td>3.40</td>
</tr>
<tr>
<td>vat</td>
<td>-0.77</td>
<td>-0.75</td>
<td>-0.79</td>
</tr>
<tr>
<td>capital</td>
<td>-1.44</td>
<td>-1.41</td>
<td>-1.37</td>
</tr>
<tr>
<td>wage</td>
<td>-3.11</td>
<td>-3.05</td>
<td>-3.20</td>
</tr>
</tbody>
</table>

Given economy-wide target of emission reduction. The “optimal tax” scenarios are superior to the “uniform” tax scenarios for most social welfare functions.\(^{17}\) Since a share of the pre-existing fuel tax is assumed not to internalize any external effect other than global warming, utility will decrease less with fuel-specific tax rates that equal out the pre-existing fuel tax.

Comparing different rebatement schemes, I find that if the revenue is used to reduce value-added taxes, utilitarian (Bentham) welfare losses are minimized. Although Swiss value-added tax rates are rather small compared to direct taxes on labor and capital, they affect the economy in the same way. On the one hand the value-added tax is charged on labor and capital as well. As such reducing value-added taxes decreases the same distortions as would reduced labor and capital taxes. But the excess burden of taxation on labor and capital falls simultaneously. Since the excess burden of a tax increases with the tax rate, reducing a single tax rate is not the most efficient course of action. Thus a value-added tax reduction is the more cost-effective scheme.

In my analysis a labor tax reduction is superior to a capital tax reduction. The main drivers behind this result are two assumptions. First, economy-wide capital supply is assumed to be inelastic, and, second, impacts on growth are not considered. Both assumptions make capital tax reductions look less favorable. Clearly, lump-sum recycling is the worst from an efficiency point of view, since although lump-sum taxes do not introduce distortions of any sort either.

The Rawlsian equivalent variations equal the equivalent variations of the poorest household.\(^{18}\) Given a Rawlsian social welfare function a social planner would prefer a lump-sum rebate. The poorer the household, the larger is the percentage increase in disposable income. As the poorest household is a retired one, a reduction of labor taxes would be the least effective policy.\(^{19}\) If the tax revenue is redistributed, income effects dominate consumption patterns for evaluating

\(^{17}\) They are superior as long as the inequality parameter is not too important, meaning they are not Pareto-superior.

\(^{18}\) RH1 is the poorest household in all simulations. Using the Rawlsian social welfare function, a modeler has to check whether the income ranking of the household groups changes.

\(^{19}\) Of course, this does not hold if one takes the poorest employed household as a reference. This household would prefer a reduction in labor instead of capital taxes.
distributional concerns, and carbon taxes, although regressive themselves, do not necessarily have a regressive influence if the tax reform is revenue-neutral.

The equivalent variations for a Nash society often lie in between the results of the other functions. It is noteworthy that under this social regime labor tax reductions can be the preferable policy.

2.3.5 Welfare distribution

Figures 2.2 and 2.3 report equivalent variations of all household groups. As discussed in the previous section a value-added tax reduction is the utilitarian cost-effective policy. However, in terms of the distributional outcome, all tax reforms are generally regressive but for a lump-sum recycling scheme. While a reduction in the regressive value-added tax results in an only slightly regressive reform, reductions in progressive taxes, as the labor tax, and to a larger extent, the capital tax, make the reform clearly regressive. However, lump-sum recycling leads to a progressive tax reform, where the poorest employed households and poorer retired households would be even better off. But this equity-improving reform comes at a cost: Regarding the Bentham societal equivalent variation, value-added tax reductions would be less costly.

Figure 2.2 shows the Hicksian equivalent variations graphically for all employed households. As the graphs indicate, partial and full exemptions do not change the distributional outcomes qualitatively but impact efficiency in general. Full exemption is Pareto-dominated by uniform and optimal tax rates, while a partial exemption, as in the “Optimal tax” case, is very close to the outcome of a uniform tax.

Figure 2.3 demonstrates that the same distributional consequences of the different tax reforms arise for retired households. As the environmental tax base changes, the welfare of the household groups change in their absolute values but not relatively to each other. Thus fuel-specific tax exemptions do not alter distributional outcomes but are important for cost-effectiveness.

2.3.6 Income Decomposition

The analysis of the different sources of income sheds light on the role of revenue recycling and relative price changes. Households receive their income from supplying labor and capital and earning transfers. To make the impacts on the income side of the households visible, the Hicksian-equivalent variations are decomposed into shares of income components. Figure 2.4 shows the decomposition of the effect of the optimal CO\textsubscript{2} tax on the income of employed households.

The results for the equivalent variations (EV) are the same as those previously plotted, but the impact of capital (K) and labor (L) income and net taxes and transfers (trn) are added, which sum up to the relative EV impact. If the revenue of an optimal carbon tax is redistributed lump-sum (Figure 2.4a), the main impact on households’ welfare stems from transfers from the government, caused by the lump-sum tax recycling. Income from labor and capital are decreased compared to 2005, since the tax affects the return on factors negatively. The lump-sum transfer more than compensates the poorer 20\% of the households for this effect, making the overall tax reform progressive.

\footnote{The only exemption to this is the lump-sum rebate case, where the increase in revenue from the decreased tax base of an exemption of transportation fuels, allows for high lump-sum payments and is therefore preferred by the poorest households.}
2.4 Sensitivity Analysis

I carried out a number of counterfactual simulations changing various parameter values. I checked the results of the additional counterfactuals regarding marginal cost of abatement, tax revenue, efficiency, and distributional consequences of the tax regimes under study. The sensitivity analysis shows that the model’s results are quite robust with respect to most parameter values. More influential parameters are the elasticity of substitution on the top nest of the production function ($\sigma_s$), the elasticity of substitution between electricity and fossil fuels ($\sigma_e$), the elasticity of substitution between transportation fuels and other inputs in the transportation sector ($\sigma_t$), and the labor endowment of the households. While their impact on efficiency can

---

21 Figures for the retired household groups can be found in Appendix A.1.
be huge quantitatively, they do not alter qualitative results. The ranking of the scenarios with respect to welfare remains unchanged. Distributional results are only changed quantitatively as well. The same households still prefer the same proposals.

While changing the time endowment of the households has only a minor effect on the marginal abatement cost, revenue and thus tax reductions, the energy related elasticities do have strong effects on marginal cost estimates.

Table 2.6 reports necessary tax rates for different rebatement schemes and optimal tax rates for the piecemeal sensitivity analysis of key elasticities of substitution in the production functions. All parameters affect the model in the same way. When elasticities are increased associated tax rates and welfare losses decrease. Optimal tax rates are quite sensitive to the reported parameters, but qualitative results remain unaffected.

Table 2.7 reports the results of the labor supply parameters. $\sigma_l$ is the elasticity of substitution between leisure and aggregate consumption. $E_L$ is the time endowment of the households in excess to what has been supplied in 2005. If $e_L$ is equal to 2 the household consumes double the amount of time as leisure as he sells to firms as work time.

More elastic labor supply works exactly in the opposite direction as increased elasticities of substitution in the production functions do. It decreases the cost of carbon abatement. If the environmental tax revenue is used to reduce labor tax rates, labor supply increases more when labor supply is highly elastic, propelling economic activity and making higher tax rates necessary. This is different to the effect of other elasticities or with other rebatement schemes.
### Table 2.6: Piecemeal sensitivity analysis of key elasticities

<table>
<thead>
<tr>
<th></th>
<th>Welfare</th>
<th></th>
<th>Tax rates</th>
<th></th>
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<td>285</td>
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<td>-0.04</td>
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<td>293</td>
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<tr>
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<td>-0.09</td>
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</table>

The Table shows Hicksian equivalent variations measured in % of the value of 2005 consumption for a Bentham social welfare function and tax rates on stationary fuels measured in CHF/tCO$_2$ for counterfactuals with optimal tax rates.

### Table 2.7: Piecemeal sensitivity analysis of labor supply

<table>
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<th></th>
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<table>
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<td>368</td>
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<tr>
<td>wage</td>
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</table>

<table>
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<th>Hicksian equivalent variation measured in % of 2005 consumption</th>
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<th></th>
<th></th>
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</thead>
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<tr>
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<td>vat</td>
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<tr>
<td>capital</td>
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<td>-0.17</td>
<td>-0.11</td>
</tr>
<tr>
<td>wage</td>
<td>-0.31</td>
<td>-0.22</td>
<td>-0.16</td>
</tr>
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</table>

The Table shows tax rates for stationary fuels and Hicksian equivalent variations measured in % of the value of benchmark consumption for a Bentham social welfare function for counterfactuals with “optimal tax” rates.
2.5 Conclusion

I use a static computable general equilibrium model of the Swiss economy (CEPE) to examine the consequences of 12 different green tax proposals on efficiency and equity. The carbon tax is either levied uniformly on all fossil fuels (“Uniform”), on stationary fuels only (“Exempt”), or less on transportation fuels than stationary fuels (“Optimal tax”) such that the reduced carbon tax rate on transportation fuels accounts for the distorting share of the pre-existing petroleum tax. In either case I choose the tax rates such that the total emission reduction is 20% compared to 1990 levels. I compute equilibria for these three tax regimes using the tax revenue for four different purposes, such that the tax reform is revenue-neutral. The revenue of the tax is redistributed as a per capita lump-sum transfer or through a reduction in value-added, labor, or capital taxes.

I examine how these tax reforms impact on 14 household groups and three social welfare functions. The three social welfare functions differ in their inequality parameters from being utilitarian (Bentham), Rawlsian or moderate (Nash). I can confirm the findings of Metcalf (2007) and Grainger and Kolstad (2009) and show that revenue recycling is the crucial policy parameter when it comes to distributional concerns. I find that equity, however, is not much affected by exemptions. Even though consumption patterns differ from household to household as argued by Scott and Eakins (2004), impacts on households’ welfare are dominated by income effects. Therefore, the tax rates should be chosen solely regarding cost-effectiveness.
I find that tax exemptions for certain fuels are costly as they prevent equalization of marginal abatement costs and thus prevent an efficient allocation of abatement activities as has been found by Böhringer and Rutherford (1997). However, a tax discount on transportation fuels is optimal, if I assume that a part of the pre-existing petroleum tax does not internalize any external effects. While Paltsev, Jacoby, Reilly, Viguier, and Babiker (2005) argue that either uniform taxes or exemptions may be optimal depending on the pre-existence of fuel taxes, I show that a tax exemption is not an either/or question: the optimal tax rates have to be adjusted for pre-existing petroleum taxes. However, the share of the pre-existing tax to be deducted from the CO$_2$ tax depends on which share of the tax is believed to be justified by other external effects. I make the assumption that about one third of the pre-existing tax is not internalizing any externality. I choose this share in accordance to the share of the tax that enters the general federal budget. This assumption is arbitrary and crude but serves as an upper bound for the optimal CO$_2$ tax discount on transportation fuels. To address this concern more accurately, further research could lead to models that portray the public goods and other welfare benefits that are explicitly internalized by those fuel taxes.

While I focus on the distributional effects of carbon taxes on different income groups, it would be interesting for further research to investigate the effects on different geographical regions. The Swiss income and expenditure survey offers the opportunity to do so. However, a regional Swiss CGE model would be necessary for such a task and this has not been done so far since necessary regional data is not available.

I conclude that in terms of cost-effectiveness, the Swiss authorities should prefer uniform carbon taxes such that the tax rates should be corrected for the share of the petroleum tax added to the general federal budget. If the revenue is then used for a reduction of value-added taxes the tax reform would be cost-effective. If distributional equity is considered as well, per-capita lump-sum rebatement leads to a progressive tax reform at moderate cost.
Chapter 3

Subsidies, Standards and Energy Efficiency\textsuperscript{1}

3.1 Introduction

Swiss climate and energy policy faces major obstacles. In fact, carbon abatement and more highly efficient energy use may be very costly. Switzerland’s situation, common in developed countries, is one of being at the global energy efficiency frontier. It can be very costly for a country that already has highly energy-efficient machinery and buildings to increase efficiency further. Second, whereas most countries have the possibility of reducing emissions by decarbonizing their electricity supply, this option is not open to Switzerland. Table 3.1 displays the percentage shares of energy sources used for electricity production in selected OECD countries and demonstrates that Swiss electricity, which is primarily produced from hydropower (around 55%) and nuclear power (40%) is virtually carbon neutral. A carbon-free electrification of energy supply is, however, only possible if Switzerland is able to meet considerable increases in electricity demand. Yet the potential for hydroelectric power plants is almost exhausted and building new nuclear plants is politically difficult. Figure 3.1 shows this as well in its display of per capita emissions and per capita GDP for all OECD countries. Swiss carbon emissions per capita (6 tons of CO\textsubscript{2}) are more than 3 times lower than those of the US (about 19.5 tons per capita). While the US only faces the problem of being at the energy efficiency frontier, Switzerland is also at the “carbon intensity frontier” which may further increase marginal abatement costs.

In general, environmental and energy policy should address two major issues. First, it is widely recognized that CO\textsubscript{2} emissions have likely had and will certainly have future impacts on economies and people worldwide. Therefore the Swiss climate policy should counter the global climate externality. Second, it is argued that a nation’s high energy dependency could

\textsuperscript{1} This chapter is based on an article, which has been published in a special issue of The Energy Journal: \textit{Strategies for Mitigating Climate Change Through Energy Efficiency: A Multi-Model Perspective} edited by Huntington, H. and Smith, E. (eds.) (Imhof 2011) and on work done for the EMF 25 exercise: \textit{EMF 25: Efficiency and the Shape of Future Energy Demand}. I wish to thank Thomas Rutherford, Olga Kiuila, David Goldblatt and an anonymous reviewer for their very helpful comments and suggestions. All remaining errors are the authors responsibility.
harm its energy security. Thus, an adequate energy policy should induce energy conservation for example through increased energy efficiency. However, it is important that each goal be pursued with the right instrument. An externality is best internalized by means of a Pigouvian tax. A carbon tax or carbon permits might be appropriate for the climate change issue. But which policy instrument is best suited to enhancing energy efficiency? A study by McKinsey (2009) argues that Swiss annual CO\textsubscript{2} emissions, currently at about 41 million tons, could be reduced by around 9 million tons at zero or even negative cost. If this is taken to be true, it must be reconciled with economic theory, using assumptions about why agents are not using these cost saving opportunities. The authors of the study suggest that the reason could be capital market imperfections, as energy efficient equipment comes at a higher incremental cost. If agents require shorter pay-back periods or face barriers in capital markets, their choices could be distorted. If that is the case, subsidies or standards for energy-efficient equipment could be the right response.

I will examine the issues surrounding the Swiss debate using five of the seven EMF25 counterfactuals. The carbon tax case will shed light on the role of electrification for reducing emissions and increasing energy efficiency in an environment in which electricity is produced carbon-neutrally. I will then be able to illustrate the contribution of increased efficiency standards or subsidies for energy efficiency improvements with and without an additional carbon tax. As I will see, analyzing the interaction of these instruments with a carbon tax yields interesting insights. These policies are simulated with a dynamic version of the CEPE model which allows the investigation of their transitional impact. This is of interest because timing plays a major role in climate policy. In a second step, I implement a static version of the model that includes a bottom-up representation of the LDV sector to further examine the role of fuel efficiency standards and subsidies for higher efficiency vehicles. I justify the focus on the LDV sector by the fact that it

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**Table 3.1: 2008 Electricity production shares, selected OECD countries [%]**

<table>
<thead>
<tr>
<th>Country</th>
<th>Coal</th>
<th>Oil</th>
<th>Gas</th>
<th>Other CO\textsubscript{2}</th>
<th>Nuclear</th>
<th>Hydro</th>
<th>Other non-CO\textsubscript{2}</th>
<th>Gross production [TWh]</th>
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<td>15</td>
<td>-</td>
<td>-</td>
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<td>257</td>
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<td>2</td>
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<td>0</td>
<td>14</td>
<td>59</td>
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<td>1</td>
<td>76</td>
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<td>1</td>
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<td>1</td>
<td>14</td>
<td>1</td>
<td>23</td>
<td>4</td>
<td>10</td>
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<td>Italy</td>
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<td>10</td>
<td>54</td>
<td>1</td>
<td>-</td>
<td>15</td>
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<td>1</td>
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</table>

*Source: OECD (2010)*

“-” indicate that sources are not used for electricity production, while “0” refers to a production share of less than 0.5 percent.
3.1. INTRODUCTION

Figure 3.1: CO$_2$ emissions and GDP per capita in 2005.


Figure 3.2: Official CO$_2$ statistics of Switzerland with target projections

Source: FOEN (2012, p.4)
accounts for almost 30\% of Swiss CO$_2$ emissions.

I find that while standards and subsidies might help reduce carbon emissions, carbon taxes are still more efficient in general. However, with the further assumption that consumers’ energy-specific investment decisions are distorted, subsidies and standards can become welfare increasing, as they directly help to reduce the market distortion. Interestingly, I find that combining subsidies or standards with carbon taxes can reduce carbon emissions even further than either instrument can alone, while reducing the welfare burden of the carbon tax. However, this finding relies crucially on the assumption of a distortion in energy specific investment decisions: If I am indeed in a second-best world with non-distorted investment decisions rather than a third-best world, subsidies and standards introduce the distortion, rather than reducing it. While the results of the two models are mostly similar, the dynamic model stresses the importance of timing for climate policy. While high standards may reduce CO$_2$ emissions early in the period, associated abatement costs may be rather high.

The remainder of the paper is organized as follows: Section 3.2 describes the specification of the scenarios. Section 3.3 provides an overview of the CEPE-D model and presents its results. Section 3.4 takes a closer look at fuel efficiency standards of light-duty vehicles by implementing a static version of the model with an activity analysis submodel. Section 3.5 concludes.

### 3.2 Scenarios

My business-as-usual scenario is based on Switzerland’s 2005 input-output table and baseline projections of important economic and energy-related variables. I have implemented five counterfactuals. The first counterfactual introduces a uniform carbon tax on all fossil fuels. The second scenario includes energy efficiency standards for vehicles and buildings. The third examines a subsidy for energy-efficient capital. The last two are combinations of the non-tax scenarios with the carbon tax. All scenarios are constructed such that the implemented policy is revenue neutral: Revenue from the carbon tax is redistributed as a lump-sum payment from the government to the consumers, while a subsidy decreases pre-existing lump-sum payments. These scenarios were chosen to reflect my interest in the role of standards and subsidies in climate policy. In fact, the two combination scenarios resemble the current proposals for Switzerland’s post-Kyoto climate policy. Indeed, on top of the current carbon tax, Swiss authorities plan to implement both subsidies for energy efficient building renovations and increased vehicle standards. In particular, I am interested in understanding the interaction of standards and subsidies with the current carbon tax and their impact on emission reductions and abatement costs. The role of the stand-alone policy scenarios is to help isolate the effects of the three instruments and identify their individual advantages and disadvantages. I now define the scenarios in more detail:

**Business-as-usual (BAU)**  The business-as-usual case is a benchmark projection that is in line with current estimates of growth, technological change and other basic variables. I report the basic parameters and projections of important variables in section 3.3 as computed by CEPE-D. The BAU scenario of CEPE-S is defined in the same way but for the year 2005 only. It is noteworthy that no environmental policies are implemented in my BAU case.

**Carbon Tax Case (CT)** A uniform carbon tax on fossil fuel combustion is implemented start-
3.3. DYNAMIC TOP-DOWN APPROACH

ing in 2010 at a level of 30 CHF per ton of carbon dioxide and charged on fossil fuel combustion. The tax subsequently increases by 5% per year, inflation adjusted. In the static model, the tax is implemented at a rate of 30 CHF/tCO₂.

**Sectoral Standards (SS)** This scenario examines the role of increased efficiency standards for buildings and motor vehicles. Between 2012 and 2016, the average energy efficiency of buildings and vehicles is to increase by six percent per year. After that, the required minimum fuel efficiency remains constant. Note that due to technical change, efficiency continues to increase beyond 2016. In the static setup, I implement an increase of 30% in fuel efficiency on light-duty vehicles only.

**Subsidy case (SUB)** In the dynamic model I implement a subsidy on capital that is used to provide heating and transportation services. The 20% subsidy aims to encourage consumers to substitute capital for fuel in the provision of energy services. While the subsidy is applied to all energy-specific capital in the dynamic model, in the static model I applied the subsidy to more efficient vehicles only. The rate of the subsidy is set such that half of the cost increase for more highly efficient vehicles is paid for by the government. Subsidizing energy capital regardless of its qualitative properties vis-à-vis energy efficiency may overestimate potential rebound effects in the dynamic model, since inefficient technologies will benefit as well.

**Standards with Carbon Fee (SST)** This scenario is a combination of the standards case with the carbon tax. Both instruments are introduced in parallel, exactly as they were in the stand-alone cases.

**Subsidy case with Carbon Fee (SUBT)** This scenario couples the subsidy with the carbon tax.

All scenarios, including the business-as-usual case, have been computed with and without a distortion in the representative consumer’s investment in energy efficiency. While I designate a second-best world as the case where pre-existing taxes are the only distortions on the economy, I will call third-best the world that suffers from the additional distortion of consumers’ investment decisions. Because the representative consumer does not choose the optimal amount of energy efficiency by himself, there will be room for a welfare-increasing policy reform. The investment distortion was implemented such that the representative consumer perceives an energy service capital price that is twice as high as the market rate.

### 3.3 Dynamic top-down approach

To analyze the abovementioned issues, I developed an intertemporal computable general equilibrium model of the Swiss economy referred to as CEPE-D. The model is of the classical Ramsey-type with endogenous depreciation and capital adjustment costs. Firms have perfect foresight and maximize their present value profit over the whole model horizon. The model runs until the year 2060 and I control for the finite horizon problem with terminal constraints on investment and capital levels. The current version of the model includes 10 sectors producing 17 goods. The output can be exported or used domestically. Production for domestic use is combined with imports using the Armington assumption (Armington 1969). The Armington composite can be used as an intermediate input in production or in final demand. There are two
3.3.1 Energy supply, demand and substitution possibilities

CEPE-D covers 7 intermediate energy goods: Fuel oil, natural gas, coal, electricity, gasoline, diesel and kerosene. Switzerland is not endowed with any primary energy resources and has to import crude oil, coal, natural gas and uranium. While about half of Switzerland’s demand for refined oil products is met by imports, the other half is produced from crude in the oil processing sector. The model includes an electricity sector, in which electricity is produced using capital, labor and uranium as its major inputs. Other intermediates and small amounts of other energy inputs enter the production function in the same way as in other sectors.

The nested CES production function, common to all sectors, and associated elasticities of substitution are illustrated in Figure 2.4 on page 19. On the top nest less important energy sources such as coal and motor fuels are substituted with a value added composite, intermediate goods and an energy aggregate with an elasticity of substitution of 0.5. The energy aggregate is produced in a Cobb-Douglas nest from electricity and fossil fuels, which combine fuel oil and natural gas inputs, substitutable with a constant elasticity of 2.

While final government demand for energy is fixed, the representative consumer has additional substitution possibilities. His one-period utility function combines consumption of non-energy activities with housing and transport services in the top nest. He can trade-off different activities with an elasticity of substitution of 0.5. Non-energy-related consumption goods are purchased with fixed budget shares.

Figure 3.3 demonstrates the substitution possibilities for the energy consuming activities of the demand-side agents. The representative consumer, who maximizes his discounted utility over the whole model horizon such that his budget constraint holds with equality, and the government, which buys a fixed bundle of goods and adjusts lump-sum transfers such that its budget is balanced period-by-period in all scenarios.
3.3. **DYNAMIC TOP-DOWN APPROACH**

consumer. In the lowest nest of the housing activity, fuel oil (OIL), natural gas (GAS) and electricity (ELE) are substituted with a constant elasticity of 0.5. The energy aggregate then trades-off with capital services representing improvements in furnaces, insolation or appliances. To meet his transportation needs, the consumer purchases gasoline (BEN) and diesel (DIE) in fixed proportions. He can invest in higher fuel efficiency by substituting transport fuels with capital at a rate of 0.5. Finally, he spends fixed shares of his budget for public and private transportation.

### 3.3.2 Business-as-usual projections (BAU)

In this basic scenario no environmental measures are implemented, but there are pre-existing taxes on value added, some excise taxes, import tariffs, a lump-sum transfer from the government to the consumer, and optionally a distortion in the capital-fuel choice of the consumer. I refer to the scenarios with the additional distortion as a third-best world. There, the consumer perceives a price for energy-efficient capital that is double the market rate. The model starts in 2005 and is calibrated to the 2005 input-output table of Switzerland (Nathani, Wickart, and van Nieuwkoop 2008) and parameters as presented in Table 3.2. Table 3.3 presents some basic variables of the business-as-usual projection.

<table>
<thead>
<tr>
<th>Table 3.2: Benchmark parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameter</td>
</tr>
<tr>
<td>$g$</td>
</tr>
<tr>
<td>$r$</td>
</tr>
<tr>
<td>$\delta$</td>
</tr>
<tr>
<td>$\phi$</td>
</tr>
<tr>
<td>$\epsilon$</td>
</tr>
</tbody>
</table>

GDP grows at the calibrated rate of 2% through the whole model horizon. Starting at a value of 455 billion Swiss Francs in 2005, it doubles by the year 2040. In the meantime CO\(_2\) emissions and energy consumption grow at smaller rates. In 2005, CO\(_2\) emissions from fossil fuel combustion are 40 million tons and increase by only 60% until 2040. The overall CO\(_2\)-intensity of GDP therefore declines from 88.5 grams per CHF to 73.8 grams in 2040. The energy intensity of GDP decreases as well. This decline in energy and CO\(_2\) intensity is due to the exogenous technological change assumed in CEPE-D. Whereas the rates of decline of both energy and carbon intensity decrease over time, it is noteworthy that the carbon content of energy slowly declines as well. The share of electricity in total energy consumption increases from 26% in 2005 to 29% in 2040.

### 3.3.3 Subsidies and Standards versus a Carbon Tax

Neoclassical economic theory propounds that a policy maker aiming to reduce carbon emissions does best by implementing a carbon tax. While optimal sectoral standards can enforce the same cost-effective outcome as a tax, they require that the government act under complete information regarding both available technologies and heterogeneity of firms and consumers. Standards not implemented in the optimal way will not be cost-effective, since they will not equalize marginal
CHAPTER 3. SUBSIDIES, STANDARDS AND ENERGY EFFICIENCY

Table 3.3: BAU projections

<table>
<thead>
<tr>
<th></th>
<th>2005</th>
<th>2010</th>
<th>2020</th>
<th>2030</th>
<th>2040</th>
<th>2050</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gross Domestic Product billion CHF&lt;sub&gt;2005&lt;/sub&gt;</td>
<td>455</td>
<td>503</td>
<td>613</td>
<td>747</td>
<td>910</td>
<td>1109</td>
</tr>
<tr>
<td>Consumption billion CHF&lt;sub&gt;2005&lt;/sub&gt;</td>
<td>280</td>
<td>309</td>
<td>376</td>
<td>459</td>
<td>559</td>
<td>682</td>
</tr>
<tr>
<td>CO₂ Emissions million tons</td>
<td>40.3</td>
<td>43.3</td>
<td>50.0</td>
<td>57.9</td>
<td>67.2</td>
<td>78.2</td>
</tr>
<tr>
<td>Delivered Energy PJ</td>
<td>780</td>
<td>841</td>
<td>978</td>
<td>1140</td>
<td>1332</td>
<td>1561</td>
</tr>
<tr>
<td>Electricity PJ</td>
<td>206</td>
<td>225</td>
<td>268</td>
<td>320</td>
<td>382</td>
<td>458</td>
</tr>
<tr>
<td>Electricity share % of delivered energy</td>
<td>26</td>
<td>27</td>
<td>27</td>
<td>28</td>
<td>29</td>
<td>29</td>
</tr>
<tr>
<td>CO₂ intensity of GDP g/CHF</td>
<td>88.5</td>
<td>86.1</td>
<td>81.6</td>
<td>77.5</td>
<td>73.8</td>
<td>70.5</td>
</tr>
<tr>
<td>Energy intensity of GDP MJ/CHF</td>
<td>1.71</td>
<td>1.67</td>
<td>1.60</td>
<td>1.53</td>
<td>1.46</td>
<td>1.41</td>
</tr>
<tr>
<td>CO₂ intensity of energy g/MJ</td>
<td>51.7</td>
<td>51.5</td>
<td>51.1</td>
<td>50.8</td>
<td>50.4</td>
<td>50.1</td>
</tr>
</tbody>
</table>

Notes: Annual growth rate in percent in parenthesis

abatement cost. In some ways subsidies suffer from the same problem. If implemented properly, they adjust relative prices of carbon-abating investments optimally. For that to happen, though, the policy maker has to know exactly which technologies to subsidize and at which rate. On the other hand, a subsidy on energy-efficient capital would decrease the price of energy services and could thus increase their consumption. This rebound effect could have - to some extent adverse effects on emissions and energy use. This section will address these issues in both a second and a third-best world.

Second-best world

I will first examine the counterfactuals in a second-best world without the energy-specific investment distortion. Figures 3.4 to 3.6 display the percentage deviation from BAU levels for selected variables. The results of these counterfactuals emphasize that a uniform carbon tax is the most cost-effective abatement-inducing instrument. Subsidies and standards do not equalize marginal abatement costs between sectors and technologies and thus increase total abatement costs, which negatively impacts consumption.

Figure 3.4 indicates that all policies are costly in terms of consumption, which is expected, as all policy proposals introduce additional distortions to the economy. While sectoral standards and subsidies only slightly decrease consumption levels, the impact of the combined policies is worse, as they distort the economy twofold. They do in fact distort both energy prices and the representative consumer’s energy-specific investment decisions.

As indicated by Figure 3.5, carbon taxes reduce CO₂ emissions more than all other stand-alone policies and, combined with subsidies or standards, can further decrease emissions. Although emissions are reduced by up to 21% in 2050 compared to the BAU level, this reduction is not
3.3. **DYNAMIC TOP-DOWN APPROACH**

**Figure 3.4: Real Consumption: Difference from BAU [%].**

![Graph showing consumption difference from BAU.]

**Figure 3.5: CO₂: Difference from BAU [%].**

![Graph showing CO₂ emissions difference from BAU.]

sufficient to stabilize emissions in absolute terms.

As the standards are not changed after 2016, their impact declines due to technological progress and after 2035 overall emissions even increase relative to BAU levels. This “rebound effect” is due to the larger accumulated energy-specific capital stock. As all proposed policies force substitution from energy to capital inputs, the energy-specific capital stock increases in all scenarios relative to the BAU. But while the other measures persist, the standard becomes less constraining after 2016, and thus the increased capital stock will induce a higher level of energy consumption afterwards. This motivates the need for policy makers to update standards continuously, in order to keep them binding and prevent a rebound in energy use in the regulated sectors.

Figure 3.6: Electricity: Difference from BAU [%]

While total energy demand declines for all binding policy proposals, electricity consumption increases relative to the business-as-usual projections in the three proposals with carbon taxes. In the carbon tax case, as well as in the combined proposals, the share of electricity in total delivered energy increases as the price of electricity relative to other energy inputs declines. This effect is driven by the carbon neutrality of Swiss electricity production: While the price of fossil fuels increases, carbon-neutral energy sources are not directly affected by the tax and thus experience a relative price advantage over fossil fuels. The relative price of electricity drops, since the electricity price is not affected by the carbon tax. In the standards and subsidy scenarios, however, energy use in general is affected. Electricity faces no relative price advantage over fossil fuels and its use declines as well.

Third-best world with distorted investment decisions

I now additionally assume that the representative consumer’s energy-specific investment decisions are distorted, as he overvalues the incremental cost of energy service capital by a factor of two. This distortion would justify the findings of the McKinsey study (McKinsey 2009),
which posits the existence of energy efficiency improvements at negative costs. In the absence of the investment distortion, a carbon tax would optimally internalize the environmental damages caused by emissions, while both subsidies and standards could not guarantee equalization of marginal abatement costs. Carbon taxes are thus the most cost-effective and therefore best instrument to control carbon emissions in the second-best world. An assumed distortion in the fuel-capital choices made by consumers can, however, change the set of suitable instruments. A subsidy on energy service capital could indeed reduce the distortion and move the outcome closer to second-best.

Figure 3.7: Real Consumption: Difference from BAU [%]

Figure 3.7 displays the gains or losses in consumption associated with the five policy proposals. Both non-tax proposals increase welfare, as they correct the investment distortion. A carbon tax still decreases consumption, but since the CO$_2$ tax also reduces the investment distortion by increasing the relative price of energy, its negative impact on welfare is smaller than in the second-best world. Combining taxes with standards has a negative impact on consumption. While a standard in itself increases consumption by reducing the capital price distortion, a combined scenario decreases consumption relative to the tax-only case. While each proposal decreases the investment distortion to some extent when implemented by itself, when implemented together they overcorrect it. Additionally the standard causes emissions to decrease dramatically in an early period at rather high costs. The same effect already causes the large difference between the standards and the subsidy case. While the subsidy causes emissions to drop in a smooth manner, the standard is much more demanding in an earlier period. This specific design of the standard induces additional costs, since on the one hand marginal abatement costs increase with the abatement level, and on the other hand earlier abatement is more costly because of technological progress. The timing of standards as well as their effectiveness may be crucial to the outcome of such a policy. Conversely, if the tax revenue is used to finance a subsidy, consumption levels are increased while emissions are reduced relative to the tax-only case. However, while the proposals impacts on welfare rely crucially on the assumption of the investment distortion, associated emission paths are not affected much.
Considering welfare and emissions, I find that a policy proposal which combines a subsidy and a carbon tax would be most apt at countering carbon emissions in the third-best world. Due to the investment failure, marginal abatement costs are not equalized initially, and thus a carbon tax stand-alone policy would not counter this initial distortion. The subsidy reduces the distortion on private investment and thus helps equate marginal abatement costs. The subsidy and tax scenario has the highest emission reduction rates of all scenarios, while also boosting consumption. Thus, if I believe that consumers invest too little in energy efficiency, I may want to implement a carbon tax and use the revenue partly to subsidize energy-saving investments in buildings, vehicles and equipment.

Comparing the cost-effectiveness of my scenarios is not straightforward. Achieved emission reductions vary widely over the different policy proposals. Since marginal abatement costs increase with the level of abatement, simply computing average cost per ton of CO$_2$ reduced will not do. To deal with this issue I introduced additional scenarios, which are comparable in their impact on emissions. Through analysis of those scenarios, it becomes clear that CO$_2$ taxes are the most effective instrument to reduce carbon emissions in my second-best baseline. If private and corporate agents base their decisions on non-distorted capital-fuel choices, subsidies or standards will add substantial costs for achieving a given environmental target. Losses in consumer welfare may be 4 times as high when achieved with standards and even more expensive when achieved with subsidies. On the other hand, if consumers’ capital-fuel choices are distorted, a subsidy is most suitable for reducing carbon emissions at low costs. I discuss these additional scenarios in greater detail in the appendix.

### 3.4 Integrated static approach

A more detailed analysis of the vehicle-fuel choice in the transportation sector is undertaken with an extension of CEPE-S based on Kiuila and Rutherford (2010). Kiuila and Rutherford nest the static CEPE-S model with a bottom-up representation of the LDV sector. This framework allows examination of consumers’ vehicle-fuel choices at the technology level. Table 3.4 lists the available LDV abatement technologies as indicated by McKinsey’s Swiss GHG abatement cost curve (McKinsey 2009, p.11). Close examination of the transportation sector is justified by the fact that it is responsible for a growing share of around 40% of Swiss carbon emissions, corresponding to almost 17 million tons of carbon dioxide, of which around 13 million tons stem from light-duty vehicles. LDVs thus account for almost 30% of Switzerland’s CO$_2$ emissions in 2005.

The McKinsey study indicates there is potential for abatement at negative costs. In an attempt to justify this finding in an economically relevant manner, Kiuila and Rutherford adjust the technologies’ capital cost such that the technologies not currently in use lie outside the budget set (see Figure 3.8).

As the plain line portrays relative benchmark prices given by the input-output table, the LDV technologies lie within the budget set. In order to rationalize observed consumer choices, I assume a private capital price that is about twice as high as the market rate and excludes the non-chosen technologies from the representative consumer’s budget set, represented by the dashed line. This assumption is identical to the private investment distortion I had introduced in the dynamic model. This distortion leaves room for economically profitable investments, which can subsequently increase welfare.
3.4. INTEGRATED STATIC APPROACH

Figure 3.8: Relative price adjustment of McKinsey’s LDV technologies

3.4.1 Subsidies and standards versus a carbon tax in the LDV sector

I calibrated the static BAU case to the 2005 input-output table and I do comparative-static analysis using the scenarios from section 3.2 focusing on the third-best world with the investment distortion. The scenarios are comparable to those implemented in the dynamic analysis. But in the dynamic model I implemented a subsidy on all energy-specific capital, while the subsidy in the static model applies to more highly efficient technologies only. The effect of this difference is straightforward. A subsidy on highly efficient technologies will have a larger effect on the market penetration of new technologies. Similarly, a subsidy on all energy service capital decreases the relative price of capital and forces the consumers to substitute fuel with capital, but with less pressure for improved technologies. Thus CO$_2$ emissions are reduced by less, but welfare

Table 3.4: GHG Abatement technologies for Switzerland’s transportation sector

<table>
<thead>
<tr>
<th>Technology</th>
<th>Label</th>
<th>Abatement [Mt CO$_2$e/year]</th>
<th>Marginal cost [EUR/t CO$_2$e]</th>
</tr>
</thead>
<tbody>
<tr>
<td>LDV Gasoline Bundle 1</td>
<td>g1</td>
<td>0.82</td>
<td>-82</td>
</tr>
<tr>
<td>LDV Diesel Bundle 1</td>
<td>d1</td>
<td>0.47</td>
<td>-67</td>
</tr>
<tr>
<td>LDV Gasoline Bundle 2</td>
<td>g2</td>
<td>1.12</td>
<td>-52</td>
</tr>
<tr>
<td>LDV Diesel Bundle 2</td>
<td>d2</td>
<td>0.60</td>
<td>-32</td>
</tr>
<tr>
<td>LDV Gasoline Bundle 3</td>
<td>g3</td>
<td>0.76</td>
<td>-29</td>
</tr>
<tr>
<td>LDV Diesel Bundle 3</td>
<td>d3</td>
<td>0.42</td>
<td>-18</td>
</tr>
<tr>
<td>LDV Gasoline Bundle 4</td>
<td>g4</td>
<td>0.45</td>
<td>-13</td>
</tr>
<tr>
<td>LDV Diesel Bundle 4</td>
<td>d4</td>
<td>0.17</td>
<td>-4</td>
</tr>
</tbody>
</table>

increases, since the market barriers on the capital market apply to all energy service capital.

Figure 3.9: CO₂ emission reduction

Figure 3.9 displays total CO₂ reduction as a percentage of BAU emission levels. The carbon tax policy reduces CO₂ emissions by almost 7%. In the standard-only case, CO₂ emissions decrease by little more than 3%, while an emission reduction of almost 5% is achieved by the subsidy on fuel-efficient vehicles. The combined policy of standards and the carbon tax has an exactly identical impact on emissions as the tax itself. The carbon tax makes highly efficient technologies profitable, and since fuel efficiency already increases by more than 30% the standard is no longer binding. A policy combining a subsidy with the carbon tax reduces CO₂ emissions the most.

Since I assume vehicle-fuel choices are distorted, all policies are welfare-increasing as they help reduce a large pre-existing distortion (see Figure 3.10). Standards and subsidies are better in terms of welfare than a carbon tax stand-alone policy, since they address the investment distortion directly. It seems that by comparison subsidies are a better instrument than standards, since they reduce emissions more and increase welfare even further. In fact, the implemented subsidy just refers to a more restrictive standard. It should be noted, however, that differences in welfare are rather small.

Table 3.5: LDV Technologies used, associated expenditures and CO₂ emissions

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Technology in use</th>
<th>LDV transportation expenditures [billion CHF₂₀₀₅]</th>
<th>LDV CO₂ emissions [million tons]</th>
</tr>
</thead>
<tbody>
<tr>
<td>BAU</td>
<td>Reference technology</td>
<td>6.19</td>
<td>13.5</td>
</tr>
<tr>
<td>SS</td>
<td>g₁</td>
<td>6.12</td>
<td>12.2</td>
</tr>
<tr>
<td>SUB</td>
<td>g₁ and d₁</td>
<td>6.08</td>
<td>11.5</td>
</tr>
<tr>
<td>CT</td>
<td>g₁ and d₁</td>
<td>6.00</td>
<td>11.4</td>
</tr>
<tr>
<td>SST</td>
<td>g₁ and d₁</td>
<td>6.00</td>
<td>11.4</td>
</tr>
<tr>
<td>SUBT</td>
<td>g₂ and d₁</td>
<td>5.87</td>
<td>9.7</td>
</tr>
</tbody>
</table>
Table 3.5 reveals which of the LDV technologies are active under each policy and presents the expenditures on LDV transportation and associated CO$_2$ emissions. The proposed policies do not have a huge impact on the set of implemented technologies. However, in all scenarios at least the first technology upgrade for gasoline driven cars (g1) becomes profitable. For all counterfactuals except the standards case, the first diesel upgrade (d1) is also cost-effective. The most restrictive policy is the subsidy and tax proposal, which enforces even the use of the second gasoline bundle (g2). Table 3.5 indicates that the standards are not binding in the combined policy, as the carbon tax is already sufficient to make diesel bundle 1 profitable.

3.5 Conclusion

I introduced a dynamic and a static general equilibrium model for Switzerland with and without a distortion of energy-specific investment decisions. In a world with investment distortions, I find that subsidies and standards are good measures to reduce both carbon emissions and the distortion in investment. Since carbon taxes are more directly targeted at CO$_2$ abatement, combined policies may further improve the outcome: A CO$_2$ tax may efficiently reduce emissions and raise money, while a subsidy may counter the investment distortion. However, if I drop the assumption that consumers are underinvesting in energy-efficient capital, subsidies and standards are revealed to be sub-optimal. Although, in theory, standards and subsidies may be set to reach the same outcome as a uniform tax on carbon emissions, in reality, defining the optimal level of standards or subsidies may be almost impossible. Heterogeneity of consumers and lack of knowledge about technologies and production processes may prevent equalization of marginal abatement costs. Therefore, a carbon tax is the cost-effective instrument to reduce CO$_2$ emissions in this second-best world.

The dynamic model illustrates the importance of timing in climate policy. Restrictive standards
that are introduced early and standards that are not updated subsequently to keep up with technological progress can increase the costs of GHG abatement substantially. Of course my model does not take into account learning-by-doing. Early standards could push technologies up the learning curve and help innovation, which could reduce the negative cost effect.

The static model indicates that subsidies for more highly efficient vehicles and standards are actually similar instruments if I correct a pre-existing market failure in vehicle-fuel choices. Combined with carbon taxes, their impact may be different since standards could become non-binding and therefore negligible. However, the static as well as the dynamic model show that in a world with distorted investment, subsidies and carbon taxes may be good complements.

The EMF scenarios fit the currently discussed policy proposals in Switzerland quite well. While the parliament plans to continue to tax stationary fuels at 36 CHF per ton of CO₂, it is likely to implement subsidies and standards as well. The case of Switzerland and its carbon-neutral electricity is interesting; As carbon taxes are increased, the demand for electricity increases too, since the electricity price falls relative to other energy sources. At the same time, keeping the carbon intensity of electricity at a low level is very important, and thus, increased production from renewables or other low-carbon sources will become essential.

Finally, I conclude that carbon taxes are still the best policy for reducing carbon emissions at low costs. As long as I are not sure about the existence and the nature of energy-specific distortions, finding the right instrument is a troublesome and almost impossible task. Researchers should study the efficiency gap and its causes carefully in order to formulate the efficient policy response.
“Everything should be made as simple as possible, but not simpler.”

“Any intelligent fool can make things bigger, more complex, and more violent. It takes a touch of genius - and a lot of courage - to move in the opposite direction.”

Albert Einstein, 1879 AD - 1955 AD
Part III

Nuclear Phase-out
Chapter 4

Nuclear Phase-out in Switzerland: Systemic Efficiency, Capacity Efficiency and Self-sufficiency

4.1 Introduction

Over the last decade the energy debate in Switzerland has been dominated by climate change. Thus, decarbonization and energy conservation were pillars of the modern Swiss energy policy ever since the “Energy 2000” program has been introduced. Since electricity in Switzerland is produced virtually carbon neutral, electrification seemed to push Switzerland towards carbon neutrality. However, after the disaster at Fukushima Daiichi in March 2011 the perception of the whole situation changed drastically in many western countries, including Switzerland. After the shock the Swiss federal council opted for a nuclear phase-out. Existing plants ought to be used until they expire and no new plants will be built. This proposal is equivalent to a gradual nuclear phase-out until 2034 based on a reactor life span of 50 years. This current development has confronted the Swiss energy policy with new challenges. If nuclear power will be phased-out, short falling capacities will raise prices of electricity. Although this will lead to decreased demand compared to a business-as-usual, increasing electrification will still likely lead to at least stable demand for electricity. This means that abandoned supply capacities have to be replaced in one way or the other. While the simplest way of securing electricity supply would be via increased imports, decreased exports or gas-fired plants, all three options have major disadvantages. Additional imports would stem either from nuclear plants in France or coal-fired plants in Germany. Both options may be viewed as hypocritical: Replacing nuclear plants with foreign nuclear plants is useless since nuclear disasters strike huge regions and many French plants are build close to the Swiss border. Substituting nuclear plants with fossil fuel plants in Germany or Switzerland would put more stress on Swiss climate policy. Finally, decreasing exports may be very costly, since Swiss electricity producers are making huge profits from arbitrage by buying and storing cheap base load electricity and selling expensive peak load electricity. Additionally, having a negative annual net balance on electricity trade may

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1 I wish to thank Thomas Rutherford for very helpful comments and suggestions and Thomas Geissmann for excellent research assistance. All remaining errors are the authors responsibility.
be politically undesirable. Finally, another option for replacing nuclear electricity would be generation from renewables. Often named technologies are solar and wind power. However, they are associated with huge cost via two channels: First, the technologies have high levelized average lifetime cost and second, the huge variance in electricity supply from those sources may use more of the storage capacity of the hydro plants which will hinder their use for trade gains on the European markets. A third renewable technology option is a large-scale geothermal power plant. While engineers think that they could replace nuclear base load power at low cost, hardly calculable risks of earthquakes and their monetary consequences may make this option unattractive for potential investors.

Several papers exist that study nuclear phase-outs. Nakata (2002) studies a nuclear phase-out in Japan using an annual partial equilibrium model. However, an annual model of electricity markets seems to be inadequate since electricity supply and demand have to be balanced in every instant to prevent black-outs and other systemic instabilities. A study for Switzerland (Böhringer, Müller, and Wickart 2003), uses a general equilibrium model with an activity analysis. Such a model is suitable to compute economy-wide cost of a certain policy, but systemic stability and the operation of storage facilities cannot be taken into account properly. Kunz, Hirschhausen, Möst, and Weigt (2011) use a bottom-up partial equilibrium model to compute short-term reactions of the German and the European power market to a German phase-out. They are modeling the dispatch on a single day of winter. However, all those energy economic models have short-comings in their time resolution. Either they compute long-run decisions or short-time dispatch, but no model links the different decisions. Another branch of research focuses on electricity dispatch models with high time resolutions (e.g. Ulbig, Koch, and Andersson 2012) which can represent dispatch and storage decisions sufficiently. However, their focus is on computation of optimal dispatch decisions given available data and given uncertainties. My approach brings the two branches together and provides a copperplate bottom-up electricity dispatch and investment model, that could be linked with a top-down general equilibrium model.

To shed light on the mechanics that drive the cost of Swiss electricity production and to provide an estimate of the additional cost imposed by a nuclear phase-out, this chapter develops a computable partial equilibrium model of the Swiss electricity market. The model seeks to find the cost minimizing generation and trade profiles to meet given demand in 1460 load segments over the year and allows for the installation of new generation capacities. I compute six phase-out scenarios with different sets of technologies. I show, that a nuclear phase-out without gas, geothermal and positive net imports is not feasible and a scenario with a small annual net import comes a at very high cost for domestic consumers. The electricity price increases from 4.1 Rp./kWh in the Benchmark case with nuclear energy up to 19.1 Rp./kWh when all hydro, wind and solar potentials are used. Large scale geothermal plants may decrease total cost of the phase-out policy and gas turbines could decrease the cost even further. But, at present geothermal is still immature and gas-fired plants would produce 9.1 million tons of CO₂.

This chapter is structured as follows. Section 4.2 describes actual Swiss electricity generation and future potentials. Section 4.3 explains the model formulation and the benchmark fit of the

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2 There are several technologies that use solar power to produce energy or energy services. If I am referring to solar power I mean photovoltaic solar cells producing electricity throughout the chapter, since I am interested only in electricity generation. Other solar technologies as for example solar collectors for heating up water, or concentrated solar power in large scale power plants, are not considered.

3 A prominent case is the incident in Basel in 2006, where drillings produced an earthquake and subsequent legal issues.
Table 4.1: Power Generation in Switzerland

<table>
<thead>
<tr>
<th></th>
<th>capacity [MW]</th>
<th>average availability [%]</th>
<th>generation in 2010 [TWh]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nuclear</td>
<td>3253</td>
<td>88.5</td>
<td>25.2</td>
</tr>
<tr>
<td>Run-of-river</td>
<td>3768</td>
<td>48.6</td>
<td>16.0</td>
</tr>
<tr>
<td>Storage hydro</td>
<td>8073</td>
<td>-</td>
<td>(17.4)</td>
</tr>
<tr>
<td>+Pump-and-storage</td>
<td>2139</td>
<td>-</td>
<td>(17.4)</td>
</tr>
<tr>
<td>Conventional thermic</td>
<td>490</td>
<td>81.1</td>
<td>3.5</td>
</tr>
<tr>
<td>Wind</td>
<td>42</td>
<td>(28)</td>
<td>0.04</td>
</tr>
<tr>
<td>Photovoltaic</td>
<td>111</td>
<td>(12)</td>
<td>0.08</td>
</tr>
<tr>
<td>Total generation</td>
<td>15779</td>
<td>47.9</td>
<td>66.3</td>
</tr>
<tr>
<td>Imports</td>
<td></td>
<td></td>
<td>66.8</td>
</tr>
<tr>
<td>Exports</td>
<td></td>
<td></td>
<td>66.3</td>
</tr>
<tr>
<td>Losses &amp; Waste</td>
<td></td>
<td></td>
<td>4.5</td>
</tr>
</tbody>
</table>

Source: SFOE (2011b, 2011c, 2012a)

model. Section 4.4 presents scenarios and discusses the results. Finally section 4.5 summarizes the results.

4.2 Electricity and Nuclear Phase-out

4.2.1 Electricity Generation and Trade in Switzerland

In 2010, Switzerland had a gross domestic electricity consumption of 64.2 TWh. End use net of transmission and other losses had been 59.8 TWh. At the same time generation had been 66.3 TWh, where 37.5 TWh (56.5%) stemmed from hydro power (The two dominating hydro power technologies are run-of-river facilities, which accounted for 16.0 TWh and storage facilities, which had a gross production of 21.5 TWh and a pump demand of 2.6 GWh.), nuclear accounted for 25.2 TWh (38.1%) and conventional thermic and other technologies generated 3.6 TWh (5.4%).

Figure 4.1 shows the load profile of the Swiss electricity network for the whole year as well as for the month of June 2010 based on data provided by Swissgrid for 2010 available for a resolution of 15 minutes time slices. Notably, electricity trade with surrounding countries plays a huge role for Switzerland. In 2010 Switzerland imported electricity of 66.8 TWh and exported 66.3 TWh, resulting in a small net import balance of 0.5 TWh. This trade is due to the geographic location of Switzerland, as well as the economic incentive to do arbitrage on the european markets using the highly flexible hydro storage devices to store energy when prices are low and provide power when prices are high. Third, the generation profile of Switzerland is such that due to the run-of-river hydro plants more electricity is produced during summer months, which can be exported, and less during winter, when demand is higher and Switzerland, thus, relies

---

4 Other technologies include electricity generated from wind (27 GWh) and photovoltaic (80 GWh), while conventional thermic sources account for the major share.

5 Available online at http://www.swissgrid.ch/swissgrid/de/home/experts/topics/energy_data_ch.html
CHAPTER 4. NUCLEAR PHASE-OUT IN SWITZERLAND

Figure 4.1: Load Curves for 2010

(a) 2010 Real Data from Swissgrid

(b) 2010 Real Data for June

Table 4.2: Nuclear power plants in Switzerland

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Beznau I</td>
<td>365</td>
<td>83.1</td>
<td>92.4</td>
<td>2.6</td>
<td>2019</td>
</tr>
<tr>
<td>Beznau II</td>
<td>365</td>
<td>88.6</td>
<td>90.5</td>
<td>2.8</td>
<td>2021</td>
</tr>
<tr>
<td>Mühleberg</td>
<td>373</td>
<td>91.1</td>
<td>91.5</td>
<td>3.0</td>
<td>2022</td>
</tr>
<tr>
<td>Gösgen</td>
<td>985</td>
<td>93.1</td>
<td>93.6</td>
<td>8.0</td>
<td>2029</td>
</tr>
<tr>
<td>Leibstadt</td>
<td>1165</td>
<td>86.1</td>
<td>86.7</td>
<td>8.8</td>
<td>2034</td>
</tr>
<tr>
<td>Total</td>
<td>3253</td>
<td>88.7</td>
<td>90.4</td>
<td>25.2</td>
<td>-</td>
</tr>
</tbody>
</table>

Source: SFOE (2011b) Table 17 and own calculations

4.2.2 Phase-out and New Capacity

The five existing nuclear reactors in Switzerland are Beznau I and II, Mühleberg, Gösgen and Leibstadt. Table 4.2 displays some important facts.

The federal council decided to phase-out electricity gradually until 2034 by not extending expiration dates of existing plants and not building any new ones. This leaves the power sector with a relatively long time to plan a future without nuclear technologies. However, the load to replace is large and sums up to a total of 3253 MW operated at a availability rate of around 90%. If a large fraction of the existing generation capacity is laid idle, the question arises how to substitute for short-falling capacities. Potential means are discussed in the following subsections.

Imports

Imports could provide a simple means of providing electricity. However, there are two important short-comings of this option. First, importing electricity may be viewed as being hypo-
critical, since, imported power would mainly stem from nuclear plants or fossil fuel combusting technologies. Second, it may be politically infeasible to become dependent from net imports on an annual basis. While increased electricity trade over the last decades has helped to increase systemic stability and to raise revenues, politicians and voters may still feel obliged to have a net balanced electricity trade at the end of the year. The exogenously given spot market prices are produced using a rather small data set on average monthly prices from (Zeitreihe_Aussenhandel_Schweiz_nach_Ländern.xls) and real swiss spot market prices in one week to capture weekly and daily price spreads (SWISSIX at EEX (9.1.2010 to 16.1.2010)). The resulting import prices are displayed in Figure 4.3.

Natural Gas

Natural Gas may provide electricity when needed. Short planning and building times may be helpful to overcome temporary leaks in supply and the potential to provide electricity is hardly bounded. However, high marginal cost and associated CO$_2$ emissions may be undesirable. Three different technologies are considered in the model. Gas plants can be built either as conventional or advanced combined cycle plants or as advanced combined cycle with carbon capture and storage (CCS). I take the price structure for natural gas-fired plants from EIA (2012)’s estimates as reported in Table C.1.

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* To use hourly day-ahead spot market prices from EEX is of course a natural and important extension. The model’s dataset is currently under revision.
CHAPTER 4. NUCLEAR PHASE-OUT IN SWITZERLAND

Figure 4.3: Import prices in 2010

Hydro Power

I used Laufer, Grötzinger, Peter, and Schmutz (2004) as a source of potential water power improvements. Later studies used this data source and applied several other issues to it. However, the newest study (SFOE 2012b)\textsuperscript{7} implies that potentials may be much smaller due to several reasons. Instead of a potential increase of 7.57 TWh only increases of 4.56 TWh are reported.

Figure\textsuperscript{4.4} shows the location of existing and potential pump-and-storage plants in Switzerland. Green circles represent existing capacities of 1400 MW, orange facilities are built at the moment and account for 2140 MW, blue spots mark projects for another 1630 MW, which are waiting for a construction license and gray circles denote early project ideas. Table\textsuperscript{4.4} reports main characteristics of the projects.

The existing sites are included in the benchmark replication already and I explicitly model all orange and blue projects as investment possibilities.

Wind and Photovoltaic

Often discussed are new renewables as photovoltaic and wind power. However, the potential for those technologies in Switzerland is limited. Positive estimates on the potential capacities

\textsuperscript{7} Based on SFOE (2011a) and Laufer, Grötzinger, Peter, and Schmutz (2004)

\textsuperscript{8} Despite the fact that new pump-and-storage plants are built, no model run can support profitability of such devices. The prospect of buying future new renewable power from Germany may provide a case, but Hildmann, Ulbig, and Andersson (2011) detect economic risks for storage capacities in those scenarios.
4.2. ELECTRICITY AND NUCLEAR PHASE-OUT

Table 4.3: Capacity Improvement for Hydro Power

<table>
<thead>
<tr>
<th>Type of improvement</th>
<th>Annual Power Investment (GWh)</th>
<th>Power (MW)</th>
<th>Investment CHF/kW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Equipment high-pressure Run-of-river</td>
<td>390</td>
<td>210</td>
<td>318</td>
</tr>
<tr>
<td>Delta Q high-pressure Run-of-river</td>
<td>220</td>
<td>200</td>
<td>1100</td>
</tr>
<tr>
<td>Delta Height low-pressure Run-of-river</td>
<td>200</td>
<td>35</td>
<td>3429</td>
</tr>
<tr>
<td>Retrofit low-pressure Run-of-river</td>
<td>540</td>
<td>150</td>
<td>6480</td>
</tr>
<tr>
<td>New high-pressure Run-of-river</td>
<td>1200</td>
<td>500</td>
<td>4440</td>
</tr>
<tr>
<td>New low-pressure Run-of-river</td>
<td>1900</td>
<td>420</td>
<td>8143</td>
</tr>
<tr>
<td>Total Run-of-River</td>
<td>4450</td>
<td>1515</td>
<td></td>
</tr>
<tr>
<td>Equipment storage hydro</td>
<td>360</td>
<td>120</td>
<td>300</td>
</tr>
<tr>
<td>Retrofit storage hydro</td>
<td>400</td>
<td>230</td>
<td>3130</td>
</tr>
<tr>
<td>New storage hydro</td>
<td>2360</td>
<td>1200</td>
<td>6883</td>
</tr>
<tr>
<td>Total Storage Hydro</td>
<td>3120</td>
<td>1550</td>
<td></td>
</tr>
</tbody>
</table>

Source: Laufer, Grötzinger, Peter, and Schmutz (2004) Table A1-1

Figure 4.4: Pump-and-storage Locations and Capacity of new and existing Facilities

Source: Stettler (2011).
CHAPTER 4. NUCLEAR PHASE-OUT IN SWITZERLAND

Table 4.4: Data of New Pump-and-Storage (Cost in billion CHF)

<table>
<thead>
<tr>
<th>Project</th>
<th>Investment Cost [million CHF]</th>
<th>Increased Storage [GWh]</th>
<th>Generation Year of Completion</th>
</tr>
</thead>
<tbody>
<tr>
<td>hyd-pump</td>
<td>Existing</td>
<td></td>
<td>1400 existing</td>
</tr>
<tr>
<td>PHS1</td>
<td>Hongrin-Leman</td>
<td>330</td>
<td>0</td>
</tr>
<tr>
<td>PHS2</td>
<td>Linth-Limmern</td>
<td>2100</td>
<td>0</td>
</tr>
<tr>
<td>PHS3</td>
<td>Nant de Drance</td>
<td>1800</td>
<td>192</td>
</tr>
<tr>
<td>PHS4</td>
<td>Grimsel 3</td>
<td>700</td>
<td>0</td>
</tr>
<tr>
<td>PHS5</td>
<td>Lago Bianco</td>
<td>1500</td>
<td>0</td>
</tr>
</tbody>
</table>

Source: Own Survey based on project related publications by energy providers.

Table 4.5: Solar and Wind Power Potentials in Switzerland

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind</td>
<td></td>
<td>22.8</td>
<td>4</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>-</td>
<td>9.1 - 22.8</td>
<td>-</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>-</td>
<td>13</td>
<td>-</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Photovoltaic</td>
<td>8000 - 2830</td>
<td>12000</td>
<td>11.4</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td></td>
<td>-</td>
<td>13</td>
<td>-</td>
<td>3</td>
<td></td>
</tr>
</tbody>
</table>


report 12 TWh of photovoltaic and 4 TWh of wind electricity (even though VSE reports up to 13 TWh each.). However, those estimates are very enthusiastic and more conservative numbers may be appropriate.

While annual production of wind and photovoltaic is relatively well predictable, the hourly and daily outputs are uncertain. This causes additional cost as peak load generating units may be activated to cover short-falling generation from new renewables. On the other hand, photovoltaic produces electricity especially during summer, when, traditionally electricity production is high from run-of-river hydro plants and demand is low. This would harden the systemic inefficiency of the annual Swiss electricity production schedule. Wind, which has a much lower potential in Switzerland, would be cheaper and would produce relatively more energy in winter months. This would be desirable and thus wind power seems to be a good complement to run-of-river hydro power. Finally Hildmann, Ulbig, and Andersson (2011) point out, that photovoltaic panels produce their output mainly around noon, when demand is highest during the day. However, evidence suggests that those peak loads have become smaller over the last decade. Both effects may drive price spreads to become smaller and thus may prevent storage technologies from becoming profitable. Table 4.6 shows the photovoltaic and wind technologies in the model. I assume that potential production increase is split over 5 type of sites with different capacity factors.
4.2. ELECTRICITY AND NUCLEAR PHASE-OUT

Table 4.6: Model Input for Wind and Photovoltaic Technologies

<table>
<thead>
<tr>
<th>Site</th>
<th>Average availability [%]</th>
<th>Capacity [MW]</th>
<th>Expected Output [GWh]</th>
<th>Investment cost [CHF/kW]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>existing</td>
<td>28</td>
<td>30</td>
<td>74</td>
<td>0</td>
</tr>
<tr>
<td>wind 1</td>
<td>23</td>
<td>397</td>
<td>800</td>
<td>1700</td>
</tr>
<tr>
<td>wind 2</td>
<td>20</td>
<td>457</td>
<td>800</td>
<td>1700</td>
</tr>
<tr>
<td>wind 3</td>
<td>17</td>
<td>537</td>
<td>800</td>
<td>1700</td>
</tr>
<tr>
<td>wind 4</td>
<td>14</td>
<td>652</td>
<td>800</td>
<td>1700</td>
</tr>
<tr>
<td>wind 5</td>
<td>10</td>
<td>913</td>
<td>800</td>
<td>1700</td>
</tr>
<tr>
<td>Photovoltaic</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>existing</td>
<td>12</td>
<td>152</td>
<td>160</td>
<td>0</td>
</tr>
<tr>
<td>PV 1</td>
<td>10</td>
<td>2740</td>
<td>2400</td>
<td>3000</td>
</tr>
<tr>
<td>PV 2</td>
<td>9</td>
<td>3044</td>
<td>2400</td>
<td>3000</td>
</tr>
<tr>
<td>PV 3</td>
<td>8</td>
<td>3425</td>
<td>2400</td>
<td>3000</td>
</tr>
<tr>
<td>PV 4</td>
<td>7</td>
<td>3914</td>
<td>2400</td>
<td>3000</td>
</tr>
<tr>
<td>PV 5</td>
<td>6</td>
<td>4566</td>
<td>2400</td>
<td>3000</td>
</tr>
</tbody>
</table>

**Geothermal**

The technological potential for electricity generation from geothermal sources is estimated to be 17 TWh (Axpo, 2007). Geothermal is characterized by high upfront investment cost of the drilling, that accounts for about 65-75% of the investment cost with a 10-20% risk of failure. Failure could occur, as after drilling may be discovered that the underground is not ideal for electricity generation or seismic activities and associated damages may occur. Once a plant is built it produces base load electricity at very low marginal cost. Geothermal electricity has thus the potential to replace nuclear plants with a similar production schedule at comparable cost.
Table 4.7: Marginal Cost of Generation

<table>
<thead>
<tr>
<th></th>
<th>variable O&amp;M [CHF/MWh]</th>
<th>fixed O&amp;M [CHF/kW]</th>
<th>Investment Cost [CHF/kW]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nuclear</td>
<td>11.7</td>
<td>43</td>
<td>9500</td>
</tr>
<tr>
<td>Conventional</td>
<td>24.0</td>
<td>40</td>
<td>6181</td>
</tr>
<tr>
<td>Run-of-River Hydro</td>
<td>6.3</td>
<td>17</td>
<td>6710</td>
</tr>
<tr>
<td>Pump-and-Storage</td>
<td>0.0</td>
<td>17</td>
<td>5500</td>
</tr>
<tr>
<td>Storage Hydro</td>
<td>0.0</td>
<td>17</td>
<td>5500</td>
</tr>
<tr>
<td>Gas-ccc</td>
<td>45.6</td>
<td>21</td>
<td>1320</td>
</tr>
<tr>
<td>Gas-acc</td>
<td>42.1</td>
<td>21</td>
<td>1352</td>
</tr>
<tr>
<td>Gas-ccs</td>
<td>49.6</td>
<td>21</td>
<td>2556</td>
</tr>
<tr>
<td>Wind</td>
<td>0.0</td>
<td>9</td>
<td>1700</td>
</tr>
<tr>
<td>Photovoltaic</td>
<td>0.0</td>
<td>9</td>
<td>3000</td>
</tr>
<tr>
<td>Geothermal</td>
<td>9.5</td>
<td>13</td>
<td>8800</td>
</tr>
</tbody>
</table>


4.2.3 Marginal Cost of Production

Table 4.7 reports marginal cost of production, fixed operation and maintenance cost and investment cost.
Our model of electricity dispatch maximizes the total surplus in the electricity market given some physical, economic and political conditions. As I assume domestic consumption to be given exogenously this is not different from minimizing total cost of electricity provision minus the surplus on the export market. Compared to other electricity dispatch models, an important feature of my model is the handling of trade in electricity. While most dispatch models do not pay major attention to trade issues, for Switzerland foreign electricity trade is very important, and thus a Swiss electricity model has to take foreign trade into account. While imports are modeled to be perfectly elastic, I model export demand using a linear demand function calibrated to an elasticity of demand of 0.5 at 2010 prices and quantities.

\[
\begin{align*}
\text{min} & \quad \sum_s \theta_s \left( \sum_j v c_j G_{j,s} + p_s^w I_s - p x r e f E_s \left( 1 + 1/\epsilon \left( 1 - \frac{E_s}{2 e r e f} \right) \right) \right) \\
& \quad + \sum_j (\delta_j + r_j) k c_j G_j^N + \sum_p (\delta_p + r_p) d c_p H_p^N + \sum_d (\delta_d + r_d) d c_d Q_d^N \\
\text{s.t.} & \quad I_s + \sum_j G_{j,s} = c_s + E_s + \sum P_{p,s} \quad \forall s \\
& \quad H_{s+1} = H_s + \theta_s \sum_p (\beta_p \cdot P_{p,s} - G_{p,s}) + \phi_s - R H_s \quad \forall s \\
& \quad Q_{d,m+1} = Q_{d,m} - \sum_{s \in m} \theta_s \cdot G_{d,s} + \phi_{d,m} - R Q_{d,m} \quad \forall d, m \\
& \quad 0 \leq H_s \leq \text{reservoir}^H + \sum_p H_p^N \quad \forall p, s \\
& \quad 0 \leq Q_{d,m} \leq \text{reservoir}^Q_d + Q_d^N \quad \forall m \\
& \quad 0 \leq G_{j,s} \leq \alpha_{j,s} \cdot (\text{cap}_j + G_j^N) \quad \forall j, s \\
& \quad \sum_s \theta_s \cdot E_s \geq \sum_s \theta_s \cdot I_s \\
& \quad 0 \leq E_s \quad \forall s, \quad 0 \leq I_s \quad \forall s, \quad 0 \leq P_{p,s} \quad \forall s \\
& \quad 0 \leq R H_s \quad \forall s, \quad 0 \leq R Q_{d,m} \quad \forall s, m \\
& \quad 0 \leq G_j^N \quad \forall j, \quad 0 \leq H_p^N \quad \forall p, \quad 0 \leq H_d^N \quad \forall d 
\end{align*}
\]
CHAPTER 4. NUCLEAR PHASE-OUT IN SWITZERLAND

Variables

\[ G_{j,s} \] Power generated by technology \( j \) in segment \( s \) [MW]
\[ G_N^j \] New vintage generation capacity [MW]
\[ I_s \] Imports in segment \( s \) [MW]
\[ E_s \] Exports in segment \( s \) [MW]
\[ P_s \] Pumping activity in segment \( s \) [MW]
\[ H_{p,s} \] Head in pump-and-storage reservoirs [MWh]
\[ H_N^p \] New vintage PHS reservoir capacity [MWh]
\[ RH_s \] Spill of water in pump-and-storage reservoirs [MWh]
\[ Q_m \] Head in storage reservoirs [MWh]
\[ Q_N^p \] New vintage seasonal reservoir capacity [MWh]
\[ RQ_m \] Spill of water in storage reservoirs [MWh]

Parameters

\[ \theta_s \] Hours in load segment \( s \) [h]
\[ v_{c,j} \] Variable cost [CHF/MWh]
\[ \delta_j \] Linear depreciation rate of technology \( j \)
\[ r_j \] Return to investment including risk premium
\[ p^w_s \] Import price of electricity [CHF/MWh]
\[ c_s \] Consumption in load segment \( s \) [MW]
\[ \beta_p \] Efficiency of pumping [MW/MW]
\[ \phi_{p,s}^H \] Natural inflow to pump-and-storage reservoirs [MWh]
\[ \phi_{d,m}^Q \] Natural inflow to storage reservoirs [MWh]
\[ \text{cap}_j \] Installed capacity of technology \( j \) [MW]
\[ \alpha_{j,s} \] Availability of technology \( j \) in segment \( s \)
\[ reservoir^H \] Pump-and-storage reservoir capacity in [MWh]
\[ reservoir^Q_d \] Storage reservoir capacity in [MWh]
\[ e_{ref} \] Average export load in 2010 year [MW]
\[ px_{ref} \] Annual average export price [CHF/MWh]

The objective of the model (4.1) is to minimize total cost of electricity production net total export surplus subject to the market clearing condition (4.2) for every segment \( s \) of the year. Imports are assumed to be perfectly elastic, while export demand is represented by a linear demand curve calibrated to an elasticity of demand of 0.5 at benchmark prices and quantities. Equations (4.3) and (4.4) are updating the storage head of the short-term and the seasonal storage, respectively. Since I am optimizing over a year I also assume that the storage heads at the beginning of the year have to be equal to the heads at the end of the year and equations (4.5) and (4.6) make sure that storage heads stay non-negative. While I have a separate storage equation for all new hydro storage technologies, I assume, that the pump-and-storage hydro facilities use the same reservoir. All those projects are built on existing lakes and dams and no new independent reservoirs are being built. Constraint (4.7) restricts generation from all technologies to be non-negative and below the capacity limits taking into account availability in every specific segment. Equation (4.8) is a political constraint that requires annual imports to be balanced with annual exports. Of course this self-sufficiency policy is costly and the stability of the system hinges critically on the ability of the system to trade electricity. However, in the political debate it seems to be important to maintain annual autarky of electricity supply. Dropping this constraint allows for an assessment of the additional cost implied by this virtual autarky. Finally, all other
4.4 Scenarios and Results

Figure 4.5 displays load curves and generation profiles for 2010 and for the month of June produced by the dispatch model. The load curves of the model look realistic when compared to the observed load curves in Figure 4.1. Table 4.9 displays some results for the benchmark scenario and the year 2010 as well. The average electricity price in 2010 has been 16 Rp./kWh (SFOE 2011b) from which about 7 Rp./kWh accounted for energy cost, while the rest was due to taxes and transmission cost. In our benchmark scenario we compute a price of 4.3 Rp./kWh. In this price no depreciation of existing capacities is considered. Existing capital cost would account for 18.1 cents which is extremely high. In reality only the share of not yet amortized facilities will enter the electricity price. To compare electricity prices in the model we will not consider the amortization of existing capacity.

In all scenarios I assume that the nuclear power production is discontinued. Thus I compute scenarios where the power sector has to deal with a short-fall of a capacity of 3253 MW, which...
has been operated at a high and stable availability of around 90%. I compare counterfactuals which differ with respect of the technologies allowed. The scenarios are summarized in Table 4.8.

I compute counterfactuals with or without the assumption that annual domestic electricity generation has to be at least as large as domestic consumption. This self-sufficiency constraint does not mean that the system is autonomous in every instant. But in the political discussion this form of annual autarky is very prominent.

### 4.4.1 New Renewables

The first scenario I introduce is one where I allow only new hydro facilities and new renewables as wind and photovoltaic power to be built. Figure 4.6 shows load curves and generation load curves for this scenario.

In this scenario all hydro capacity is built, as well as all potential wind and photovoltaic capacities. Still the production is not enough to serve demand and thus the import restriction has to be relaxed by 703 GWh. High import cost together with high investment cost will drive the electricity price up to 19.1 Rp./kWh and new capacities will have to be built for 67.5 billion CHF.

In the second scenario I allow geothermal plants to be built as well. No new capacities will be fossil fuel-fired and thus carbon emissions will not be affected directly.

Figure 4.7 shows a counterfactual where annual electricity production has to meet at least domestic consumption. The technologies being built to substitute for nuclear electricity are geothermal for 2394 MW, storage hydro power facilities and wind power for 1391 MW. Short falling annual nuclear production of 25.2 TWh are compensated by 19.3 TWh from geothermal, an increase of 3 TWh from hydro power and 2.4 TWh of wind power. Photovoltaic and wind power do not become profitable and also no new pump-and-storage plants are being built. The electricity price increases due to higher marginal cost of production as well as high investment cost for the geothermal technology to 10.7 Rp./kWh.

---

9 The Federal Council states in his energy perspectives 2050 that Switzerland should aim at an independent electricity production.

10 However, higher electricity prices may cause substitution towards fossil fuels and may thus have a second order effect on domestic carbon emissions. A top-down bottom-up hybrid model could estimate such second-order general equilibrium effects. Coupling this dispatch-investment electricity model with the CEPE model could be an interesting extension.
4.4. SCENARIOS AND RESULTS

Figure 4.6: STANDARD TECHNOLOGIES WITH SELF-SUFFICIENT GENERATION

(a) Load Curve 'StandardSS'

(b) Generation 'StandardSS'

(c) Load Curve 'standardSS' June

(d) Generation 'StandardSS' June
CHAPTER 4. NUCLEAR PHASE-OUT IN SWITZERLAND

Figure 4.7: Geothermal-plants allowed

(a) Load Curve 'GeoSS'

(b) Generation 'GeoSS'

(c) Load Curve 'GeoSS’ June

(d) Generation 'GeoSS’ June
### Table 4.9: Results for Technology Cases

<table>
<thead>
<tr>
<th>Technology</th>
<th>Built capacity [MW]</th>
<th>2010</th>
<th>BM</th>
<th>StandardSS</th>
<th>GeoSS</th>
<th>AllSS</th>
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<tr>
<td>Run-of-River Hydro</td>
<td></td>
<td>0</td>
<td>1046</td>
<td>0</td>
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<td>0</td>
</tr>
<tr>
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<td></td>
<td>0</td>
<td>442</td>
<td>382</td>
<td>108</td>
<td></td>
</tr>
<tr>
<td>Pump-and-storage Hydro</td>
<td></td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
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<td>Gas (CCC, ACC)</td>
<td></td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>3354</td>
<td></td>
</tr>
<tr>
<td>Gas (CCS)</td>
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<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Sol</td>
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<td>0</td>
<td>17688</td>
<td>0</td>
<td>0</td>
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<td></td>
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<td>1391</td>
<td>0</td>
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<td>10598</td>
<td></td>
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<td>477</td>
<td>210</td>
<td>366</td>
<td>1291</td>
<td></td>
</tr>
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<td>309</td>
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<td></td>
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<td>3426</td>
<td>3391</td>
<td>3245</td>
<td></td>
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<tr>
<td>Export Cost</td>
<td></td>
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<td>-3602</td>
<td>-3608</td>
<td>-3600</td>
<td></td>
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<td>Total New Investment</td>
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<td>0</td>
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<td>25425</td>
<td>4649</td>
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<td>New annual Capital Cost</td>
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<td>3051</td>
<td>558</td>
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<td>Million CHF</td>
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<td>12442</td>
<td>17380</td>
<td>12283</td>
<td>10598</td>
<td></td>
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<tr>
<td>Rp./kWh</td>
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<td>3.8</td>
<td>5.7</td>
<td>5.7</td>
<td>5.9</td>
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<td>Average Marginal Cost</td>
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<td>0.7</td>
<td>0.5</td>
<td>0.5</td>
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</tr>
<tr>
<td>Average fixed O&amp;M Cost</td>
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<td>12.7</td>
<td>4.6</td>
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<td></td>
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<td>13.8</td>
<td>13.2</td>
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</tr>
<tr>
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<td>4.3</td>
<td>19.1</td>
<td>10.7</td>
<td>7.1</td>
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</tbody>
</table>
4.4.2 Gas-fired plants and Carbon emissions

If natural gas-fired plants are allowed, they replace the expensive geothermal technology. Since I allow only for a capacity up to 2000 MW per specific plant-type, also the slightly more expensive conventional combined cycle plants are built up to a capacity of 1354 MW. On the other hand, the most expensive storage hydro projects are no longer profitable and are thus not realized. Both type of gas plants run at almost full capacity in all load segments to produce a total of 25.4 TWh of electricity. Due to the high marginal cost and low capital cost of gas-fired plants, average marginal cost of production increase to 5.9 Rp./kWh, while the price share due to investment cost decreases. The total production price of electricity goes up to only 7.1 Rp./kWh.

Producing 25.2 TWh of electricity from gas combustion causes 9.1 million tons of CO$_2$. This would seriously harm climate policy since total Swiss CO$_2$ emission from fossil fuel combustion have been 40.8 million tons of CO$_2$ in 2010. It is very likely that potential gas plants would have to compensate their emissions by buying certificates from the EU-ETS market.

I now introduce a carbon tax of 36 CHF per ton of CO$_2$. This is the rate that natural gas is taxed under the CO$_2$ law. Figure 4.9 displays the results.

If a CO$_2$ tax applies to the power sector, marginal cost of production of fossil-fuel fired tech-
FIGURE 4.9: ALL TECHNOLOGIES ALLOWED WITH A CO$_2$ TAX OF 36 CHF/t OF CO$_2$

(a) Load Curve 'tax36ss'

(b) Generation 'tax36ss'

(c) Load Curve 'tax36ss' June

(d) Generation 'tax36ss' June
Technologies increases proportional to the technologies carbon content. A tax of 36 CHF per ton of CO$_2$ corresponds to a rate of 12.9 CHF/MWh and thus marginal cost of production increase from 45.6 CHF/MWh to 58.5 CHF/MWh for the conventional gas technology. The tax is enough to make the CCS technology cheaper than the advanced combustion cycle. The carbon tax on natural gas increases the electricity price from 7.1 to 8.6 Rp./kWh.

Finally, I run a scenario with a high carbon tax of 205 CHF/t CO$_2$ which is just enough to make all emitting technologies uninteresting. However, this result hinges critically on the assumption of available carbon capture and storage technologies. As the carbon tax increases from 36 to 205 CHF per ton of carbon dioxide, the power companies switch from gas-fired plants back to geothermal and wind power. This tax increases the electricity price substantially to 22.2 Rp./kWh.

4.4.3 Self-sufficiency

I want to take a look on the effect of the annual self-sufficiency constraint. This constraint can prevent the economy from importing when very expensive technologies have to be used. When I let go of the self-sufficiency constraint, only a few storage hydro facilities are built. But not even gas plants could compete with imports.

\footnote{I assume, that the conventional and the advanced gas technologies have a carbon content of 358 g CO$_2$/kWh.}
## 4.4. SCENARIOS AND RESULTS

### Table 4.10: Results for Carbon Cases

<table>
<thead>
<tr>
<th>Built capacity [MW]</th>
<th>2010</th>
<th>BM</th>
<th>AllSS</th>
<th>36 CHF</th>
<th>205 CHF</th>
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<tr>
<td>Storage Hydro</td>
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<td>108</td>
<td>112</td>
<td>382</td>
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<td>Pump-and-storage Hydro</td>
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CHAPTER 4. NUCLEAR PHASE-OUT IN SWITZERLAND

Figure 4.11: All Technologies allowed

(a) Load Curve ‘AllNoSS’

(b) Generation ‘AllNoSS’

(c) Load Curve ‘AllNoSS’ June

(d) Generation ‘AllNoSS’ June
4.5. CONCLUSION

Table 4.11: Results for Import Cases

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<th>Built capacity [MW]</th>
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</tr>
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<td>Storage Hydro</td>
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<td>Pump-and-storage Hydro</td>
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</tr>
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<td>Wind</td>
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<tr>
<td>Geothermal</td>
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<tr>
<td>Million CHF</td>
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<td>Rp./kWh</td>
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Increased imports may be the cheapest means of substituting for short falling nuclear capacities. Total annual cost of electricity production would go down to 10.3 billion CHF and an electricity price of 6.3 Rp./kWh.

4.5 Conclusion

This chapter discusses potential scenarios for a nuclear phase-out and their partial equilibrium economic impact. By developing a copperplate bottom-up electricity dispatch, investment and trade model, I show that substituting nuclear electricity with new renewables comes at high cost and may increase electricity prices substantially. Moreover, hydro, wind and photovoltaic potentials may likely not be large enough to replace short-falling nuclear production. A slight negative annual electricity trade balance could balance demand and supply. If I assume that large scale geothermal plants are allowed, cost of a nuclear phase-out may decrease considerably. Building gas-fired plants may be even a cheaper option. However, gas combustion technologies are emitting CO$_2$ and may, thus, harm climate policy goals. CO$_2$ taxes have to be as high as 205 CHF per ton of CO$_2$ to make the electricity sector carbon neutral again. Finally I compute a scenario where imports are no longer restricted. Electric self-sufficiency increases the cost of a nuclear phase-out substantially and, thus, letting go of this constraint may decline total cost of the policy. However, imported electricity will stem mainly from nuclear power in France or
coal-fired plants in Germany, which harms the goals of Switzerland’s energy and climate policy. This chapter builds a starting point for analyzing various policies concerning the Swiss power sector. To that end different extensions of the model may lead to fruitful results. Possible extensions include:

- Endogenous domestic demand
- Integration into a hybrid model
- Endogenous import prices through a representation of foreign electricity production and demand
- Multi-year dynamics
- Stochastics (stochastic demand and supply, political uncertainty)

Endogenous domestic demand may be a first step to integrate the model into a bottom-up top-down hybrid framework. Elastic demand may prevent prices from increasing too much. A hybrid model would be suitable to compute the role of gas-fired plants for CO$_2$ abatement policies and to estimate economy-wide and sectoral implications of a phase-out policy. Endogenizing international markets may help to make more realistic statements towards future development. The structural change in the German power sector may change price spreads considerably. The integration of high shares of renewable generation technologies as wind and solar may drive prices down considerably during high wind and/or high solar radiation. On the other hand the nuclear phase-out and climate policies in Germany may increases average import prices. All those developments affect investment decisions of the Swiss power sector. Higher price spreads may make pump-and-storage devices profitable, which do not generate profits at the moment. Going from comparative-static to a multi-year dynamic time-frame may increase the models power to analyze investment decisions under changing demand, changing environmental and political constraints.
Bibliography


IV Appendices
Appendix A

Chapter 2
A.1 Figures for retired household groups

**Figure A.1:** HICKSIAN EQUIVALENT VARIATION DECOMPOSITION OF RETIRED HOUSEHOLDS IN % IN THE OPTIMAL TAX CASES.

(a) lump-sum

(b) value added

(c) labor

(d) capital

A.2 Sectoral Impacts

Figure A.2 shows some aspects of the sectoral impacts of the “Optimal tax” case with lump-sum recycling. Figure A.2a shows the 10 largest CO\textsubscript{2} emitting sectors and their respective CO\textsubscript{2} emissions measured in million tons. Figure A.2b shows the change in real production in percent of 2005 production for the 5 most growing and the five most declining sectors under the policy proposal. Figures A.2c and A.2d show CO\textsubscript{2} reductions for the 10 sectors with the largest absolute and relative reductions, respectively.

Sectoral impacts do not change much in different tax scenarios. If transportation fuels are taxed more, the transport sector, and sectors that use a lot of transportation, are affected more.
A.3  SECTORS, GOODS AND FINAL DEMAND CATEGORIES

Figure A.2: Sectorial impacts of a 20% reduction of CO₂ emissions with lump-sum recycling and optimal taxes.

(a) CO₂ emissions
(b) Sectoral Activity
(c) Abatement (absolute)
(d) Abatement (relative)

A.3  Sectors, Goods and Final Demand Categories

Table A.1: Sectors in the model

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<tr>
<th>Standard NOGA Sectors in 2001 IOT</th>
<th>Description</th>
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<tbody>
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<td>S01-S05 Agriculture, hunting and related service activities; Forestry, logging and related service activities; Fishing, fish farming and related service activities</td>
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<tr>
<td>S10-S14 Mining and quarrying (includes also NOGA 10-13)</td>
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</tr>
<tr>
<td>S15-S16 Manufacture of food products and beverages; Manufacture of tobacco products</td>
<td></td>
</tr>
<tr>
<td>S17 Manufacture of textile</td>
<td></td>
</tr>
<tr>
<td>S18 Manufacture of wearing apparel; dressing and dyeing of fur</td>
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</tr>
<tr>
<td>S19 Tanning and dressing of leather; manufacture of luggage, handbags, saddlery, harness and footwear</td>
<td></td>
</tr>
<tr>
<td>S20 Manufacture of wood and of products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials</td>
<td></td>
</tr>
<tr>
<td>S21 Manufacture of pulp, paper and paper products</td>
<td></td>
</tr>
<tr>
<td>S22 Publishing, printing and reproduction of recorded media</td>
<td></td>
</tr>
<tr>
<td>S25 Manufacture of rubber and plastic products</td>
<td></td>
</tr>
<tr>
<td>S26 Manufacture of other non-metallic mineral products</td>
<td></td>
</tr>
<tr>
<td>S27 Manufacture of basic metals</td>
<td></td>
</tr>
<tr>
<td>S28 Manufacture of fabricated metal products, except machinery and equipment</td>
<td></td>
</tr>
<tr>
<td>S29 Manufacture of machinery and equipment n.e.c.</td>
<td></td>
</tr>
<tr>
<td>S30-S31 Manufacture of office machinery and computers; Manufacture of electrical machinery and apparatus n.e.c.</td>
<td></td>
</tr>
<tr>
<td>S32 Manufacture of radio, television and communication equipment and apparatus</td>
<td></td>
</tr>
</tbody>
</table>
### Table A.1: Sectors in the model (continued)

<table>
<thead>
<tr>
<th>Sector</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>S33</td>
<td>Manufacture of medical, precision and optical instruments, watches and clocks</td>
</tr>
<tr>
<td>S34</td>
<td>Manufacture of motor vehicles, trailers and semi-trailers</td>
</tr>
<tr>
<td>S35</td>
<td>Manufacture of other transport equipment</td>
</tr>
<tr>
<td>S36</td>
<td>Manufacture of furniture; manufacturing n.e.c.</td>
</tr>
<tr>
<td>S37</td>
<td>Recycling</td>
</tr>
<tr>
<td>S45</td>
<td>Construction</td>
</tr>
<tr>
<td>S50</td>
<td>Sale, maintenance and repair of motor vehicles and motorcycles; retail sale of automotive fuel</td>
</tr>
<tr>
<td>S51-S52</td>
<td>Wholesale trade and commission trade, except of motor vehicles and motorcycles; Retail trade, except of motor vehicles and motorcycles; repair of personal goods</td>
</tr>
<tr>
<td>S55</td>
<td>Hotels and restaurants</td>
</tr>
<tr>
<td>S60-S62</td>
<td>Land transport; transport via pipelines; Water transport; Air transport</td>
</tr>
<tr>
<td>S63</td>
<td>Supporting and auxiliary transport activities; activities of travel agencies</td>
</tr>
<tr>
<td>S64</td>
<td>Post and telecommunications</td>
</tr>
<tr>
<td>S65</td>
<td>Financial intermediation, except insurance and pension funding (includes also part of NOGA 67)</td>
</tr>
<tr>
<td>S66</td>
<td>Insurance and pension funding, except compulsory social security (includes also part of NOGA 67)</td>
</tr>
<tr>
<td>S70+S96/97</td>
<td>Real estate activities (incl. private households)</td>
</tr>
<tr>
<td>S71+S74</td>
<td>Renting of machinery and equipment without operator and of personal and household goods; Other business activities</td>
</tr>
<tr>
<td>S72</td>
<td>Computer and related activities</td>
</tr>
<tr>
<td>S73</td>
<td>Research and development</td>
</tr>
<tr>
<td>S75</td>
<td>Public administration and defence; compulsory social security</td>
</tr>
<tr>
<td>S80</td>
<td>Education</td>
</tr>
<tr>
<td>S85</td>
<td>Health and social work</td>
</tr>
<tr>
<td>S90</td>
<td>Sewage and refuse disposal, sanitation and similar activities</td>
</tr>
<tr>
<td>S91-S92</td>
<td>Activities of membership organizations n.e.c.; Recreational, cultural and sporting activities</td>
</tr>
<tr>
<td>S93-S95</td>
<td>Other service activities; Activities of households as employers of domestic staff</td>
</tr>
</tbody>
</table>

#### Disaggregated sectors

<table>
<thead>
<tr>
<th>Sector</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ELEC</td>
<td>Electricity production (namely Nuclear power, water power and other public power plants from S40)</td>
</tr>
<tr>
<td>S40-S41</td>
<td>Rest of S40-S41: Electricity, gas, steam and hot water supply; Collection, purification and distribution of water (Without Electricity)</td>
</tr>
<tr>
<td>OIL</td>
<td>Oil refining from crude (taken from sector S23)</td>
</tr>
<tr>
<td>S23-S24</td>
<td>Rest of S23-S24: Manufacture of coke, refined petroleum products and nuclear fuel; Manufacture of chemicals and chemical products (Without refined petroleum products)</td>
</tr>
</tbody>
</table>

Source: NOGA classification as in the 2001 Swiss IOT and own computations.

### Table A.2: Goods in the model

<table>
<thead>
<tr>
<th>Standard NOGA Goods in 2001 IOT</th>
</tr>
</thead>
<tbody>
<tr>
<td>G01-G05</td>
</tr>
<tr>
<td>G10-G14</td>
</tr>
<tr>
<td>G15-G16</td>
</tr>
<tr>
<td>G17</td>
</tr>
<tr>
<td>G18</td>
</tr>
<tr>
<td>G19</td>
</tr>
<tr>
<td>G20</td>
</tr>
<tr>
<td>G21</td>
</tr>
<tr>
<td>G22</td>
</tr>
<tr>
<td>G25</td>
</tr>
</tbody>
</table>
### Table A.2: Goods in the model (continued)

<table>
<thead>
<tr>
<th>Code</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>G26</td>
<td>Manufacture of other non-metallic mineral products</td>
</tr>
<tr>
<td>G27</td>
<td>Manufacture of basic metals</td>
</tr>
<tr>
<td>G28</td>
<td>Manufacture of fabricated metal products, except machinery and equipment</td>
</tr>
<tr>
<td>G29</td>
<td>Manufacture of machinery and equipment n.e.c.</td>
</tr>
<tr>
<td>G30-G31</td>
<td>Manufacture of office machinery and computers; Manufacture of electrical machinery and apparatus n.e.c.</td>
</tr>
<tr>
<td>G32</td>
<td>Manufacture of radio, television and communication equipment and apparatus</td>
</tr>
<tr>
<td>G33</td>
<td>Manufacture of medical, precision and optical instruments, watches and clocks</td>
</tr>
<tr>
<td>G34</td>
<td>Manufacture of motor vehicles, trailers and semi-trailers</td>
</tr>
<tr>
<td>G35</td>
<td>Manufacture of other transport equipment</td>
</tr>
<tr>
<td>G36</td>
<td>Manufacture of furniture; manufacturing n.e.c.</td>
</tr>
<tr>
<td>G37</td>
<td>Recycling</td>
</tr>
<tr>
<td>G38</td>
<td>Construction</td>
</tr>
<tr>
<td>G50-G52</td>
<td>Sale, maintenance and repair of motor vehicles and motorcycles; retail sale of automotive fuel</td>
</tr>
<tr>
<td>G55</td>
<td>Hotels and restaurants</td>
</tr>
<tr>
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<td>Land transport; transport via pipelines; Water transport; Air transport</td>
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<td>G65</td>
<td>Financial intermediation, except insurance and pension funding (includes also part of NOGA 67)</td>
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<td>Insurance and pension funding, except compulsory social security (includes also part of NOGA 67)</td>
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<tr>
<td>G70-G96/97</td>
<td>Real estate activities (incl. private households)</td>
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<td>G73</td>
<td>Research and development</td>
</tr>
<tr>
<td>G75</td>
<td>Public administration and defence; compulsory social security</td>
</tr>
<tr>
<td>G80</td>
<td>Education</td>
</tr>
<tr>
<td>G85</td>
<td>Health and social work</td>
</tr>
<tr>
<td>G90</td>
<td>Sewage and refuse disposal, sanitation and similar activities</td>
</tr>
<tr>
<td>G91-G92</td>
<td>Activities of membership organizations n.e.c.; Recreational, cultural and sporting activities</td>
</tr>
<tr>
<td>G93-G95</td>
<td>Other service activities; Activities of households as employers of domestic staff</td>
</tr>
</tbody>
</table>

#### Disaggregated sectors

- **BEN**: Gasoline
- **DIE**: Diesel
- **KER**: Kerosene
- **OIL**: Fuel oil
- **CRU**: Crude oil
- **COL**: Coal
- **URA**: Uranium
- **GAS**: Natural gas
- **ELE**: Electricity

#### Final demand categories

- **C01**: Food and non-alcoholic beverages (COICOP 1)
- **C02**: Alcoholic beverages, tobacco and narcotics (COICOP 2)
- **C03**: Clothing and footwear (COICOP 3)
- **C04**: Housing, water, electricity, gas and other fuels (COICOP 4)
- **C05**: Furnishings, household equipment and routine household maintenance (COICOP 5)
- **C06**: Health (COICOP 6)
- **C07**: Transport (COICOP 7)
- **C08**: Communication (COICOP 8)
- **C09**: Recreation and culture (COICOP 9)
### A.4 CO₂ emissions and Equity

#### A.4.1 CO₂ Emissions

To monitor CO₂ emission reductions, the Federal Office for the Environment (FOEN) provides an official CO₂ balance. Figure A.3 displays carbon emissions from fossil fuel combustion since 1990. The CO₂-Law does not only define a reduction target for overall CO₂ emissions but specific targets for stationary and transport fuels as well. While the overall reduction of 10% should be achieved by a 15% reduction in emissions from stationary fuels, transport fuels have to contribute an 8% decrease, only. But as the figure shows, overall emissions are only stabilized and while emissions from stationary fuels are on the targeted path, transport fuels are still increasingly used.

![Figure A.3: Official CO₂ statistics of Switzerland with target projections](source: FOEN (2012, p.4))

However, the gap between realized and targeted emissions is large and it may be doubted.
whether the actual legislation is able to achieve the targets of the CO$_2$-Law and the Kyoto-protocol. Under those circumstances the dynamics of the debate in the Swiss parliament are even more questionable. For the revision of the CO$_2$-Law it is likely that the new target will be a CO$_2$ emission reduction of 20% by 2020 in line with the EU proposals. While this goal is rather ambitious the intended measures are not. The carbon tax on stationary fuels will be continued at a rate of 36 CHF/t CO$_2$, and the exemption of transport fuels will be maintained as well.

A.4.2 Equity

For Switzerland the Statistical Office (SFSO) gathers data on expenditure and income patterns of Swiss households since 1912. I use the income and expenditure survey from 2001 (EVE 2001).

Table A.3 illustrates that the biggest difference in relative consumption of fuels results from differences in income. While expenditure shares for fossil fuels by language group range from 3.1% for the german area to 5.8% for the Italian-speaking area, the expenditure shares if classified by differences in income range from 5.8% for poor households to 2.7% for the richest working households. Clearly regional characteristics of households are important: In rural areas, where less public transport is available, the consumption of fossil fuels is larger than in urban areas. But the data set shows that the main variable that effects differences is income. Ideally I could use a household classification that would be multidimensional. Unfortunately, the EVE consists of only 3000 observations per year and thus a multidimensional classification would be statistically doubtful. Therefore I use the dimension that seems to have the largest impact on fuel expenditures.

A.5 The CEPE model

CEPE is a small open economy representation of Switzerland. The static model captures the main structure of the Swiss economy being calibrated to the most recent input-output table for 2005. The model contains 42 sectors. The technologies in use are constant returns to scale, such that the sectors exhibit zero profits. On the demand side the model incorporates 14 different household representing retired and working households in different income quantiles. Households are maximizing their utility such that their budget constraint holds with equality. Households generate income by providing labor and capital and receive lump-sum transfers. The government is buying a fixed basket of goods in all scenarios. It pays for this by collecting value-added taxes, excise taxes and direct taxes. The government budget is balanced by transfers to the households. If there is additional revenue from environmental taxes in the scenarios, the government is recycling the additional revenue in different schemes depending on the scenario. Tax reforms are always considered to be revenue-neutral. Basic flows in the model are illustrated by Figure A.4.

In Figure A.4 Y$_j$ portrays sectors $j$ which produces a goods $i$ that are either exported or used domestically. $A_i$ stands for an Armington aggregator which combines imports and domestic produced goods for the usage as intermediates in the domestic production or in final demand. $C_{q,r}$ and $G$ stand for the production of consumption goods and the government demand, respectively. The government $G$ consumes a fixed basket of goods which it pays for by taxes and transfers collected from households, firms and consumption (dotted arrows). The trade balance $TB$ is
### Table A.3: Household Expenditures on Energy

<table>
<thead>
<tr>
<th></th>
<th>Total Consumption per month</th>
<th>Fossil Fuels</th>
<th>Transport Fuels</th>
<th>Stationary Fuels</th>
<th>% of Consumption</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Average Household</strong></td>
<td>4853</td>
<td>3.6</td>
<td>3.0</td>
<td>0.6</td>
<td></td>
</tr>
<tr>
<td><strong>Language</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>German speaking*</td>
<td>4939</td>
<td>3.1</td>
<td>2.7</td>
<td>0.4</td>
<td></td>
</tr>
<tr>
<td>French speaking</td>
<td>4707</td>
<td>4.7</td>
<td>3.7</td>
<td>1.0</td>
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<tr>
<td>Italian speaking</td>
<td>4303</td>
<td>5.8</td>
<td>4.3</td>
<td>1.5</td>
<td></td>
</tr>
<tr>
<td><strong>Housing: Renters/Owners</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Renters</td>
<td>4553</td>
<td>3.1</td>
<td>2.8</td>
<td>0.3</td>
<td></td>
</tr>
<tr>
<td>House owners</td>
<td>5360</td>
<td>4.4</td>
<td>3.2</td>
<td>1.2</td>
<td></td>
</tr>
<tr>
<td><strong>Geographic: Greater Regions</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lake Geneva</td>
<td>4797</td>
<td>4.4</td>
<td>3.5</td>
<td>0.9</td>
<td></td>
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<tr>
<td>Espace Mittelland</td>
<td>4663</td>
<td>3.8</td>
<td>3.1</td>
<td>0.7</td>
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<tr>
<td>Northwest</td>
<td>5213</td>
<td>3.0</td>
<td>2.4</td>
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<tr>
<td>Zurich</td>
<td>5260</td>
<td>2.6</td>
<td>2.1</td>
<td>0.5</td>
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<tr>
<td>East</td>
<td>4430</td>
<td>3.8</td>
<td>3.2</td>
<td>0.6</td>
<td></td>
</tr>
<tr>
<td>Central</td>
<td>4873</td>
<td>3.0</td>
<td>2.8</td>
<td>0.2</td>
<td></td>
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<tr>
<td>Ticino</td>
<td>4363</td>
<td>5.7</td>
<td>4.3</td>
<td>1.5</td>
<td></td>
</tr>
<tr>
<td><strong>Working: Income Deciles of Working Households</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>EH1 (1st income decile)</td>
<td>2868</td>
<td>5.8</td>
<td>4.2</td>
<td>1.5</td>
<td></td>
</tr>
<tr>
<td>EH2</td>
<td>3781</td>
<td>4.8</td>
<td>3.4</td>
<td>1.4</td>
<td></td>
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<tr>
<td>EH3</td>
<td>4184</td>
<td>4.5</td>
<td>3.1</td>
<td>1.4</td>
<td></td>
</tr>
<tr>
<td>EH4</td>
<td>4865</td>
<td>3.9</td>
<td>2.7</td>
<td>1.2</td>
<td></td>
</tr>
<tr>
<td>EH5</td>
<td>4977</td>
<td>3.8</td>
<td>2.6</td>
<td>1.2</td>
<td></td>
</tr>
<tr>
<td>EH6</td>
<td>5029</td>
<td>3.8</td>
<td>2.6</td>
<td>1.2</td>
<td></td>
</tr>
<tr>
<td>EH7</td>
<td>5397</td>
<td>3.6</td>
<td>2.5</td>
<td>1.2</td>
<td></td>
</tr>
<tr>
<td>EH8</td>
<td>6025</td>
<td>3.3</td>
<td>2.2</td>
<td>1.1</td>
<td></td>
</tr>
<tr>
<td>EH9</td>
<td>6529</td>
<td>3.1</td>
<td>2.0</td>
<td>1.1</td>
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</tr>
<tr>
<td>EH10 (10th income decile)</td>
<td>8830</td>
<td>2.7</td>
<td>1.5</td>
<td>1.1</td>
<td></td>
</tr>
<tr>
<td><strong>Retired: Income Quartiles of Retired Households</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RH1 (1st income quartile)</td>
<td>1781</td>
<td>5.8</td>
<td>4.4</td>
<td>1.4</td>
<td></td>
</tr>
<tr>
<td>RH2</td>
<td>2634</td>
<td>4.7</td>
<td>3.5</td>
<td>1.3</td>
<td></td>
</tr>
<tr>
<td>RH3</td>
<td>3533</td>
<td>4.3</td>
<td>3.2</td>
<td>1.1</td>
<td></td>
</tr>
<tr>
<td>RH4 (4th income quartile)</td>
<td>5946</td>
<td>3.0</td>
<td>2.0</td>
<td>1.0</td>
<td></td>
</tr>
</tbody>
</table>

*Source: EVE 2001 and Ecoplan.*

*: German speaking households includes rhaeto-romanic households

fixed and part of the governmental budget. Private households $HH_r$ maximize their utility by consuming goods $c_{g,r}$ with respect to their budget constraint. They earn money by selling their capital and labor endowments ($K_r, L_r$) to the firms.

### A.5.1 Production

All sectoral production functions are nested CES functions with a common nesting structure, but different coefficients, as indicated by figure 2.1. If a sector has a coupled production its output is in fixed proportions. On the top nest enters value added, which contains labor and capital inputs
A.5. THE CEPE MODEL

Figure A.4: Diagrammatic Overview of the Model Structure

nested in a Cobb-Douglas function, non-energy intermediate inputs, coal\(^1\), transportation fuel\(^2\) and an energy aggregate which are substituted with an elasticity of substitution of 0.5. The energy-aggregate is an energy service produced with electricity and a liquids aggregate combined in a Cobb-Douglas nest. An elasticity of substitution of 2 is applied to the aggregation of gas and oil inputs.

A.5.2 Consumption

Instead of consuming intermediate goods directly, the consumers’ utility stems from 12 different consumption goods. This representation follows the idea of Lancaster (1966). I use this feature of the model to represent demand and production of energy services. Obviously the consumer does not consume natural gas because he draws utility from it directly. He rather draws utility from having a warm house. Thus he consumes an energy service called heating which can be produced by gas, electricity or oil and capital. The households’ derive income from wages and capital earnings. Additionally they have to pay direct taxes and receive a transfer rebate of the environmental taxes levied in certain scenarios.

---

1 Coal accounts for less than one percent of total physical energy use.
2 Transportation fuels are gasoline, diesel for light and heavy vehicles, and kerosene for domestic flights. Where kerosene is only used in the air transport sector. Industrial demand for transportation fuels is not that important, as most transportation fuels are covered in the transport sector.
A.5.3 Government

The government purchases a fixed basket of goods in all scenarios. It pays its bills with direct tax income (from labor and capital taxes), a value-added tax and excise taxes. The tax system in the model is just a rough representation of the Swiss tax system but should reflect its main structure. This is important, as pre-existing distortional taxes may alter the outcome of a green tax reform substantially\[3\]. The government is setting transfers such that it reaches budget balance.

A.5.4 Labor-leisure choice

In order to focus on the reduction of distorting taxes, it is important to have an elastic labor supply. I calibrated the labor-leisure choice with an elasticity of substitution between leisure and consumption of 0.65 and a total labor endowment of twice the benchmark labor supply. This parameter values are chosen such that the labor supply elasticity equals 0.3, as proposed by Ballard (1999).

A.5.5 Small open economy

Switzerland is modeled as a small open economy. As Switzerland is treated small compared to the world, world market prices are not affected by Swiss tax reforms. The export surplus is exogenously fixed at the benchmark value and is part of the government’s budget. The sectors decide whether to sell their products on foreign or domestic markets. Imports are determined using the Armington assumption. At the end of the day the import and export mix is aloud to change, but the overall trade surplus is kept constant.

A.5.6 Data

The model is calibrated to the Swiss 2005 Input-output table. This table was originally developed by ETH in collaboration with Ecoplan Bern (Nathani and Wickart 2006, Nathani, Wickart, and van Nieuwkoop 2008). An input-output table contains all relevant flows, measured in monetary units, for a certain sectoral aggregation, covering an entire economy. A second important data input are elasticities of substitution. These two data sources are enough to calibrate a static computable general equilibrium model. Third CEPE takes advantage of a database containing data on sectoral energy goods usage in physical units. Using this data allows for representing sectoral energy use in the model and thus sectoral carbon emissions from fossil fuel combustion. Benchmark data determine parameters of the functional forms from a given set of benchmark quantities, prices, and elasticities. Table [A.4] shows the key elasticity values employed in the model.

---

\[3\] Switzerland is a country that is organized in a federal kind similar to the US. Most taxes are levied on state level and can thus not easily be reformed in a federal tax reform. This also constrains the ability of achieving a second dividend by a cut back of existing taxes.
A.6 CEPE MODEL SPECIFICATION

A general equilibrium with constant returns to scale production functions is characterized by a system of nonlinear inequalities. Those inequalities belong to one of three groups. First, the activity levels of the production functions (sectors) are linked to a zero profit condition. Second, price levels are determined via market clearance conditions for every good and factor. And, third, every consumer’s budget has to be balanced. In the following subsections I am explaining the structure of the model in MPSGE (Rutherford 1999) and GAMS (Brooke, Kendrick, and Meeraus 1996) and I am presenting the associated inequalities in algebraic formulation. The model formulated in GAMS/MPSGE is solved using the PATH solver (Dirkse and Ferris 1995).

A.6.1 Model Structure

The model covers the following sectors. All those sectors have associated zero profit conditions which I will state in following subsections.

\[
\text{sectors:}
\begin{align*}
Y(s) & \quad \text{! Sectoral activity} \\
X(g) & \quad \text{! Export decision} \\
A(g) & \quad \text{! Armington aggregation} \\
W(hh) & \quad \text{! Welfare} \\
CG(fd) & \quad \text{! Consumption of final goods} \\
CT(hh) & \quad \text{! Transportation services} \\
I & \quad \text{! Investment}
\end{align*}
\]

\(Y(s)\) is the activity level of the sectors \(s\). \(X(g)\) is the activity level of exports of good \(g\). \(A(g)\) denotes the Armington aggregate of good \(g\). \(W(hh)\) is the welfare level of household \(hh\). \(CG(fd)\) is the consumption level of COICOP good \(fd\). \(CT(hh)\) denotes the level of transportation. While all other COICOP goods are produced using the same production function for all households, we
disaggregate the input shares for transportation services by households to account for different fuel/capital shares in transportation decisions. Sector I produces the investment good, which is produced in a fixed amount in the static model. Finally K(s) is the capital input to sector s.

The next piece of code shows the price variables in the model. Of course all prices are related to associated goods and have to be accompanied with market clearing conditions.

\begin{verbatim}
$commodities:
  PW(hh) ! Price index of utility
  PY(g) ! Price of domestic production
  PA(g) ! Price of armington supply
  PD(g) ! Price of domestic supply
  PC(fd) ! Price of consumption commodities
  PT(hh) ! Transport services
  PCARB ! Price of carbon
  RK ! Return to capital
  PL ! Wage rate
  PINV ! Investment
  PFX ! Foreign exchange
\end{verbatim}

PW(hh) is the price level of utility of household hh. PY(g) denotes the price for domestically produced good g. PA(g) is the price of the armington aggregate of good g and PD(g) is the price of the domestically produce good g for domestic consumption. PC(fd) is the price of consumption good fd, while PT(hh) is the household specific price index of transportation. PCARB is the price for carbon permits if issued in a scenario. RK is the rental price of capital and PL is the wage rate. PINV is the price index of investment and PFX denotes the foreign exchange rate.

The model features two types of agents. Representative households and a government. Both consumers have to fulfill their budget balance.

\begin{verbatim}
$consumers:
  RH(hh) ! Representative household
  GOVT ! Government
\end{verbatim}

Finally the model features additional constraint which assure that the green tax reform will be kept revenue neutral. Every auxiliary variable is linked to a constraint and in every scenario only one of those constraints will be active, determining the mode of revenue recycling.

\begin{verbatim}
$auxiliary:
  LUMPSUM ! Equal yield multiplier for lumpsum return
  VAT ! Equal yield multiplier for VAT
  CAP ! Equal yield multiplier for capital tax
  LAB ! Equal yield multiplier for labor tax
\end{verbatim}

A.6.2 Zero profit conditions

Y: Domestic Production

The first set of zero profit conditions are related to domestic production of goods Y(s). The firms in the model produce their output by combining various inputs in a nested CES function
and are minimizing cost. Since production is characterized by constant returns to scale (CRS) we can compute a unit cost function and use Shepard’s lemma to compute compensated demand and supply functions. The zero profit conditions in prices read:

\[
\Pi_s = \sum_g \varphi_g s(1 + \theta^e_s) p^Y_s - \left[ (\theta^{VA}_s)^{\sigma_s} ((1 + \theta^{VA}_s) p^{VA}_s)^{1-\sigma_s} + (\theta^M_s)^{\sigma_s} (p^M_s)^{1-\sigma_s} + (\theta^{ENE}_s)^{\sigma_s} (p^{ENE}_s)^{1-\sigma_s} \right]^{1-\sigma_s} = 0 \quad (A.1)
\]

\[
\Pi_{VA}^s = p^{VA}_s - \left( \frac{(1 + t^L_w) w}{\alpha^L_s} \right)^{1-\alpha^L_s} = 0 \quad (A.2)
\]

\[
\Pi_{M}^s = p^{M}_s - \sum_{g \notin ENE} \left( \theta^A_{g} p^A_{g} \right)^{1-\alpha^A_s} = 0 \quad (A.3)
\]

\[
\Pi_{ENE}^s = p^{ENE}_s - \left( \frac{p^{LQ}_s}{\theta^{LQ}_s} \right)^{1-\theta^{LQ}_s} = 0 \quad (A.4)
\]

\[
\Pi_{LQ}^s = p^{LQ}_s - \left( (\theta^{OIL}_s)^{\sigma_{IJ}} (p^{A}_{OIL} + \psi_{OILPCO_2})^{1-\sigma_{IJ}} + (1 - \theta^{OIL}_s)^{\sigma_{IJ}} \right) = 0 \quad (A.5)
\]

**X: Export Decision**

Sectors X(g) represent the export decision of good g.
\[
\Pi^X_g = \left[ \left( \varphi^X_g \right)^{\eta_X} (p_F X)^{1-\eta_X} + \left( 1 - \varphi^X_g \right)^{\eta_X} (p_D^g)^{1-\eta_X} \right]^{\frac{1}{1-\eta_X}} - \left. \left[ \left( \theta^X_g \right)^{\sigma_{DM}^X} (p_F X)^{1-\sigma_{DM}^X} + \left( 1 - \theta^X_g \right)^{\sigma_{DM}^X} (p_Y)^{1-\sigma_{DM}^X} \right]^{\frac{1}{1-\sigma_{DM}^X}} \right] = 0 \quad (A.6)
\]

A: Armington Aggregation

Sectors A(g) represent the armington aggregator of good g.

\[
\Pi^A_g = p^A_g - \left( \left( \theta^A_g \right)^{\sigma_{DM}^A} (p^A_g)^{1-\sigma_{DM}^A} + \left( 1 - \theta^A_g \right)^{\sigma_{DM}^A} (p_F X)^{1-\sigma_{DM}^A} \right)^{\frac{1}{1-\sigma_{DM}^A}} \quad (A.7)
\]

I: Investment good

\[
\Pi^{INV} = (1 + t^{INV}_{INV}) p^{INV} - \sum_g \left( \theta^A_g^{INV} \left( p^A_g + \psi_g P_{CO2} \right) \right) = 0 \quad (A.8)
\]

W: Welfare good / Utility
A.6. CEPE MODEL SPECIFICATION

\begin{align}
\Pi^W_{hh} &= p^W_{hh} - \left( \left( \theta^{INV}_{hh} \right)^{\sigma_t} (p^{INV}_{hh})^{1-\sigma_t} + \left( 1 - \theta^{INV}_{hh} \right)^{\sigma_t} \right)^{\frac{1}{1-\sigma_t}} \\
\Pi^U_{hh} &= p^U_{hh} - \left( \left( \theta^{LEI}_{hh} \right)^{\sigma_t} (w)^{1-\sigma_t} + \left( 1 - \theta^{LEI}_{hh} \right)^{\sigma_t} \right)^{\frac{1}{1-\sigma_t}} \\
\Pi^C_{hh} &= p^C_{hh} - \left( \prod_{hfd} \frac{p^{CG}_{hfd}}{\alpha_{hh,hfd}} \right)^{\frac{1}{1-\sigmaCT}} \cdot \left( 1 - \sum_{hfd} \alpha_{hh,hfd} \right)^{1-\sigmaCT} \\
\Pi^D_{fd} &= (1 + \theta^{VA}_{fd} p^{CG}_{fd}) - \sum_g \left( \theta^{CG}_{fd,g} (p^A_g + \psi_g p^{CO2}_g) \right) = 0 \\
\Pi^{CT}_{hh} &= (1 + \theta^{VA}_{CT} p^{CT}_{hh}) - \left( \left( \theta^{CT}_{hh} \right)^{\sigmaCT} \sum_{g} \left( \theta^{CT}_{ghhh} p^A_g \right) \right)^{1-\sigmaCT} \\
&+ \left( 1 - \theta^{CT}_{hh} \right)^{\sigmaCT} \left( \sum_e \left( \theta^{CT}_{e,hh} \left( p^A_e + \psi_e (1 - s_e) p^{CO2}_e \right) \right) \right)^{1-\sigmaCT} \cdot \left( 1 - \sum_{hfd} \alpha_{hh,hfd} \right)^{1-\sigmaCT}
\end{align}

A.6.3 Market Clearance Conditions

All goods have to fulfill a market clearance condition. The market clearance conditions are defined such that total endowment and production has to be at least equal to total intermediate demand and final demand of a certain good. The compensated demand functions are found by taking the derivatives of the expenditure functions with respect to the respective price of the good.

Intermediate goods

\begin{align}
\sum_s Y_s \frac{\partial \Pi^Y_g}{\partial p^g_s} &= X^g \frac{\partial \Pi^X_g}{\partial p^g_s} \quad \forall g \\
X^g \frac{\partial \Pi^X_g}{\partial p^D_g} &= A^g \frac{\partial \Pi^A_g}{\partial p^D_g} \quad \forall g
\end{align}
Armington goods

\[ A_g = \sum_s Y_s \partial \Pi_s^Y \partial p_g^A + \sum_{fd} CG_{fd} \frac{\partial \Pi_{fd}^G}{\partial p_g^A} + \sum_{hh} CT_{hh} \frac{\partial \Pi_{hh}^T}{\partial p_g^A} + I \frac{\partial \Pi_{INV}^I}{\partial p_g^A} \quad \forall g \]  

(A.16)

Foreign exchange

\[ X_g \frac{\partial \Pi_g^X}{\partial p_{FX}} + \pi B = A_g \frac{\partial \Pi_g^A}{\partial p_{FX}} \quad \forall g \]  

(A.17)

Welfare

\[ W_{hh} = \frac{R H_{hh}^W}{P_{hh}^W} \quad \forall hh \]  

(A.18)

Investment

\[ I = \sum_{hh} W_{hh} \frac{\partial \Pi_{hh}^W}{\partial p_{INV}} \]  

(A.19)

Consumption Goods

\[ CG_{hfd} = \sum_{hh} W_{hh} \frac{\partial \Pi_{hh}^W}{\partial p_{hfd}^{CG}} \quad \forall hfd \]  

(A.20)

\[ CT_{hh} = W_{hh} \frac{\partial \Pi_{hh}^W}{\partial p_{hh}^{T}} \quad \forall hh \]  

(A.21)

\[ CG_{gfd} = \frac{GOVT}{P_{gfd}^{CG}} \quad \forall gfd \]  

(A.22)
A.6. CEPE MODEL SPECIFICATION

Factor markets

\[ \sum_{hh} T_{hh} = \sum_s Y_s \frac{\partial \Pi_Y}{\partial w} + \sum_{hh} W_{hh} \frac{\partial \Pi_W}{\partial w} \]  \hspace{1cm} (A.23)

\[ \sum_{hh} K_{hh} = \sum_s Y_s \frac{\partial \Pi_Y}{\partial r} \]  \hspace{1cm} (A.24)

Carbon Price

The carbon tax is actually modeled as carbon permits. This is absolutely equivalent. The market clearance condition for the permits is:

\[ \overline{CARB} = \sum_s Y_s \frac{\partial \Pi_Y}{\partial p_{CO_2}} + \sum_{hfd} CG_{hfd} \frac{\partial \Pi^{CG}_{hfd}}{\partial p_{CO_2}} + \sum_{hh} CT_{hh} \frac{\partial \Pi^{CT}_{hh}}{\partial p_{CO_2}} \]  \hspace{1cm} (A.25)

A.6.4 Budget Balance Constraints

We have two versions of budget balance conditions. The first one belongs to the representative household groups. The second one to the government.

\$demand:RH(hh)
  e:PFX q:dtshr(hh) r:lumpsum
  e:PL q:le0(hh)
  e:PL q:(le0(hh)*leishr(hh))
  e:RKT q:(sum(s,ke0(hh,s))) R:KS
  e:PA(g) q:(-invt0(hh,g)) R:KS
  e:PFX q:trn0(hh)
  d:PW(hh)

\[ RH_{hh} = L_{hh} w + K_{hh} r + (\overline{dtax}_{hh} + \overline{trans}_{hh})pFX \]  \hspace{1cm} (A.26)

\$demand:GOVT
  e:PFX q:(-sum(hh,dtshr(hh))) r:lumpsum
  e:PFX q:b0
  e:PFX q:(-sum(hh,trn0(hh)))
  e:pcarb q:carblim r:ctax
  d:pc(gfd) q:c0(gfd)
\[
\text{GOVT} = TBpFX + CARBP_{CO_2} \\
- \sum_{hh} (\text{tax}_{hh} + \text{trans}_{hh}) pFX + \sum \varphi_{os} Y_p \\
+ \sum_s t^Y_s p^Y_s \frac{\partial \Pi^Y_s}{\partial p^Y_s} + \sum_s t^w_s w \frac{\partial \Pi^Y_s}{\partial w} + \sum_s t^K_s r \frac{\partial \Pi^Y_s}{\partial r} \tag{A.27}
\]

### A.6.5 Variables, Indices and Parameters

<table>
<thead>
<tr>
<th>Identifier</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>s</td>
<td>sectors</td>
</tr>
<tr>
<td>g</td>
<td>goods</td>
</tr>
<tr>
<td>e</td>
<td>energy goods (subset of g)</td>
</tr>
<tr>
<td>hh</td>
<td>household identifier</td>
</tr>
<tr>
<td>fd</td>
<td>final demand categories COICOP</td>
</tr>
<tr>
<td>hfd</td>
<td>consumption goods (subset of fd)</td>
</tr>
<tr>
<td>gfd</td>
<td>government consumption (subset of fd)</td>
</tr>
</tbody>
</table>

**Activity Variable**

| \(Y_s\) | output level of sector \(Y\) |
| \(X_g\) | output level of sector \(X\) |
| \(A_g\) | output level of armington good \(g\) |
| \(CG_{f_d}\) | output level of final demand category \(f_d\) |
| \(CT_{hh}\) | output level of household \(hh\)’s transportation |
| \(I\) | output level of investment sector |
| \(RH_{hh}\) | Household \(hh\)’s expenditures |
| \(W_{hh}\) | Household \(hh\)’s welfare |

**Profits**

| \(\Pi^Y_s\) | per unit profit of sector \(s\) |
| \(\Pi^{VA}_s\) | per unit profit of sector \(s\)’s VA composite |
| \(\Pi^M_s\) | per unit profit of sector \(s\)’s intermediate good aggregate |
| \(\Pi^{LQ}_s\) | per unit profit of sector \(s\)’s liquid fuel |
| \(\Pi^g\) | per unit profit of export arbitrage decision for good \(g\) |
| \(\Pi^A_g\) | per unit profit of armington aggregation sector \(g\) |
| \(\Pi^{INV}\) | per unit profit of the investment sector |
| \(\Pi^W_{hh}\) | per unit profit of household \(hh\)’s welfare sector |
| \(\Pi^U_{hh}\) | per unit profit of household \(hh\)’s instant utility sector |
| \(\Pi^C_{hh}\) | per unit profit of household \(hh\)’s consumption sector |
| \(\Pi^{CG}_{f_d}\) | per unit profit of sector final demand sector \(f_d\) |
| \(\Pi^{CT}_{hh}\) | per unit profit of household \(hh\)’s transportation sector |

**Endowments**

| \(L_{hh}\) | Household \(hh\)’s labor endowment |
| \(K_{hh}\) | Household \(hh\)’s capital endowment |
\( dtax_{hh} \) \text{ imputed lumpsum tax to balance federal and households budgets} \\
\( trans_{hh} \) \text{ social transfer payments to households} \\
\( TB \) \text{ Net foreign trade balance} \\
\( CARB \) \text{ Carbon cap} \\

**Prices** \\
\( p_Y \) \text{ price of domestically produced good } g \\
\( p_g \) \text{ price of domestic production for domestic use of good } g \\
\( p_{VA} \) \text{ price of sector } s’s VA composite \\
\( p_M \) \text{ price of sector } s’s intermediate good aggregate \\
\( p_{ENE} \) \text{ price of sector } s’s energy composite \\
\( p_{CO2} \) \text{ carbon price} \\
\( p_{FX} \) \text{ real foreign exchange rate} \\
\( p_W \) \text{ price index of welfare of household } hh \\
\( p_{INV} \) \text{ price of investment good} \\
\( p_U \) \text{ price index of household } hh’sinstantaneously utility \\
\( p_{C} \) \text{ price index of household } hh’s consumption \\
\( p_{CG} \) \text{ price index of final demand category } fd \\
\( p_{CT} \) \text{ price index of household } hh’s transportation good \\
\( w \) \text{ wage rate} \\
\( r \) \text{ rental rate of capital} \\

**Shares** \\
\( \varphi_{gs} \) \text{ output share of good } g \text{ of sector } s’s output \\
\( X \) \text{ share of good } g \text{ that is exported} \\
\( \theta_{VA} \) \text{ input share of value-added in sector } s \\
\( \theta_M \) \text{ input share of non-energy intermediates in sector } s \\
\( \theta_{ENE} \) \text{ input share of energy in sector } s \\
\( \theta_{ENE}^{s} \) \text{ input shares of less important energy sources in } s \\
\( \theta_{g}^{A} \) \text{ share domestically produced in total demand of good } g \\
\( \theta_{g}^{g} \) \text{ shares of good } g \text{ in sector } s \text{ intermediate inputs} \\
\( \theta_{INV}^{g} \) \text{ input share of good } g \\
\( \theta_{INV}^{hh} \) \text{ benchmark savings rate of household } hh \\
\( \alpha_{hh,hfd} \) \text{ share of final demand good } hfd \text{ in household } hh’s consumption \\
\( \theta_{fd,g}^{CG} \) \text{ input share of good } g \text{ in consumption good } fd \\
\( \theta_{gh}^{cg} \) \text{ share of non-energy inputs in household } hh’s transportation \\
\( \theta_{e,hh}^{C} \) \text{ share of energy good } e \text{ in household } hh’s energy input to transportation \\
\( \alpha_{h}^{L} \) \text{ labor share in sector } s \text{ value-added composite} \\

**Elasticities** \\
\( \eta_X \) \text{ Elasticity of transformation between exports and domestic use} \\
\( \sigma_{s} \) \text{ Top level elasticity of substitution}
\( \sigma_{ff} \) Elasticity of substitution between fossil fuels
\( \sigma_{X}^{DM} \) Elasticity of substitution between imports for reexport and domestic goods
\( \sigma_{A}^{DM} \) Armington elasticity of substitution
\( \sigma_{t} \) Top-level elasticity of substitution in welfare generation
\( \sigma_{ls} \) Elasticity of substitution between consumption and leisure inputs in transportation

**Parameters**

- \( \psi_{c} \) carbon content of energy good \( e \)
- \( t_{s}^{s} \) sectoral excise taxes in ad-valorem terms
- \( s^{e} \) carbon tax exemption
- \( t_{VA}^{s} \) sectoral value-added taxes
- \( t_{L}^{L} \) income tax on labor
- \( t_{K} \) income tax on capital
- \( t_{VA}^{VA} \) value-added tax on consumption good \( f d \)
- \( t_{VA}^{fd} \) value-added tax on transportation services
Appendix B

Chapter 3
B.1 Welfare comparison of instruments

Comparing the cost-effectiveness of different policy measures as defined in our scenarios in section 3.2 is not a simple exercise. Our scenarios differ in their effects on consumer welfare as well as on energy usage. Since marginal CO$_2$ abatement costs usually increase with the abatement level, direct comparisons of the welfare effects are not possible by simply taking average costs per ton of CO$_2$ reduced. To deal with this problem, we defined four new scenarios that are alike in terms of emission reduction:

**Comparable Standard Case (SS2)** This scenario implements the same standards as in our basic standards case (SS) but includes an additional cap-and-trade permits system with a quantity of allowances following the BAU emission path. This feature prevents an overshooting of the BAU emissions path.

**Carbon Fee with Emission Path of SS2 (CT$_{SS}$)** This scenario features a carbon tax which is implemented such that the emission path follows the one of the SS2 scenario.

**Comparable Subsidy case (SUB2)** In this scenario we implement a subsidy with a constant rate such that the cumulative emissions until 2050 equal that of the comparable standards case.

**Carbon Fee with Emission Path of SUB2 (CT$_{SUB}$)** A carbon tax is implemented such that the realized emission path equals the one under the comparable subsidy case.

The emission paths in Figure B.1 portray the effect on CO$_2$ emissions in a model without the investment distortion. The introduction of the distortion hardly affects emissions. In all scenarios, cumulative CO$_2$ emissions are reduced by 55 million tons in the second-best world and 53 million tons in the third-best world, respectively.

Table B.1 lists results for all four scenarios with and without the additional distortion. In a world without the additional distortion, the cost-effective measure is a carbon tax that follows a smooth abatement path (CT$_{SUB}$). The difference in the realized equivalence variation between this case and a carbon tax that follows the emission path of the standards case (CT$_{SS}$) demonstrates the cost advantage of balanced emission reductions. Second, the loss from not equalizing marginal abatement costs becomes visible when comparing the carbon tax to the standards case.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>EV in 2nd best world [billion CHF]</th>
<th>EV in 3rd best world [billion CHF]</th>
</tr>
</thead>
<tbody>
<tr>
<td>SS2</td>
<td>-7.8</td>
<td>6.9</td>
</tr>
<tr>
<td>CT$_{SS}$</td>
<td>-1.5</td>
<td>1.7</td>
</tr>
<tr>
<td>SUB2</td>
<td>-62.7</td>
<td>266.7</td>
</tr>
<tr>
<td>CT$_{SUB}$</td>
<td>-0.5</td>
<td>2.3</td>
</tr>
</tbody>
</table>

The right column of Table B.1 shows the same results for a model where investment in energy capital is distorted. Although a carbon tax can reduce emissions at negative costs, it is no longer the cost-effective instrument. A subsidy on energy capital addresses the investment distortion directly and increases welfare the most.
B.2 Capital Adjustment Costs and Endogenous Depreciation

In the standard neoclassical growth model capital can be adjusted by every desirable amount period-by-period. This fast respondence to shocks seems to be unrealistic. Further on it reduces the importance of forward-looking behavior of agents. To overcome this problem Uzawa (1969) proposed the implementation of capital adjustment costs which are quadratic in investment but negative proportional to the existing aggregated capital stock. Additionally the model has an endogenous depreciation rate. The investors can pay for maintenance which decreases the depreciation rate.

So the capital accumulation constraint can be written as:

$$K_{t+1} = (1 - \delta_t)K_t + J_t$$ (B.1)

Where $J_t$ is net investment and $\delta_t$ is the endogenous depreciation rate. The depreciation rate has an isoelastic relation to the level of maintenance $M_t$ relative to the aggregate capital stock $K_t$:

$$\delta_t = \psi \left( \frac{K_t}{M_t} \right)^\epsilon$$ (B.2)

Now we have a closer look on how gross investment $I_t$ and net investment $J_t$ are related. As stated above installation cost of capital (gross investment) decreases when the capital stock increases and vice versa given a certain target level of net investment. Additionally the cost increases quadratically in net investment:
We can still see the classical Ramsey model as a special case of our formulation. If we set \( \epsilon = 0 \) the depreciation rate is constant and equals \( \psi \). If we set \( \phi = 0 \) then net and gross investment are equal and adjustment costs are zero.

### B.3 Household energy service consumption

#### B.3.1 Addressing energy-efficiency

Addressing the issue of energy demand we have to distinguish two independent choices of an energy demanding agent. On one side he can always choose to consume less of the energy abundant good and on the other hand he can invest in more energy intensive technologies. In our example the representative agent consumes 12 different goods. He can spend his budget on 10 non-energy related goods and on heating and transportation. On the top level of his one period utility function he substitutes his non-energy intensive consumption with the two energy consuming activities with an elasticity of substitution of 0.5. If energy prices rise the two energy abundant goods become relatively more expensive and he can choose to travel less or to turn down the thermostat, respectively. The second stage in his choice problem is represented in the production of the energy abundant consumption goods. Figures [B.3] and [B.4] indicate the nesting of the CES function. On the bottom level of both production functions he can substitute between different fuel types. If for example a carbon tax makes oil and gas relatively more expensive to electricity the consumer will be willing to invest in heat pumps or even in electric heating. He also makes a decision about the specific furnace to put in place which is represented by the possibility to substitute energy inputs with capital. A more energy efficient installation is supposed to be more costly.

#### B.3.2 Technological change in energy technologies

In our business-as-usual case we assume that the average energy efficiency of heating and transport services increases by 1% annually. On the same time this exogenous technological change
B.3. HOUSEHOLD ENERGY SERVICE CONSUMPTION

Figure B.3: Production function for heating services

\[ C_H \]

\[ M \quad ES \quad K \]

\[ \sigma_b = 0 \]

\[ \sigma_f = 0.5 \]

\[ E \]

\[ \text{OIL} \quad \text{ELE} \quad \text{GAS} \]

Figure B.4: Production function for transport services

\[ C_T \]

\[ M \]

\[ \sigma_r = 1 \]

\[ \text{Public Transport} \quad \text{Private Transport} \quad K \]

\[ \sigma_v = 0.5 \]

\[ \sigma_f = 0 \]

\[ E \]

\[ \text{BEN} \quad \text{DIE} \]
is cost neutral meaning that the capital expenditures increase such that the same amount of heating service provided will cost the same as with the old technology. Figure B.5 illustrates the mode of operation.

The curve printed is the isoquant for one unit of energy service provided in period 1. At given capital and energy prices $\bar{p}$ the consumer chooses technology $P0$ and produces one unit of output with $\bar{K}$ capital and $\bar{E}$ units of energy. In the next period technological change will allow to produce the same output with only $\hat{E}$ units of energy. At the same time the capital necessary to produce one unit with this amount of energy will go down from $T_2$ to $T_1$. So the new technology becomes effective at the same prices. As the consumer will have the same substitution possibilities in the new point he will face a new isoquant which will be tangential to the price $\bar{p}$ in point $T_1$. If we want to modify the cost effectiveness of the new technology we can introduce the amount of capital needed somewhere between $T_0$ and $T_2$. Cost neutrality is given as explained above at point $T_1$. If we want to introduce new technologies that are cheaper absolutely to the initial technologies we will introduce a point somewhere between $T_1$ and $T_0$. This is exactly how we are implementing the reduced cost scenario.

---

1 Lets assume for the moment that there is only one type of fuel
Appendix C

Chapter 4
C.1 Technologies

Table C.1: Estimated levelized cost of new generation resources, 2016 in $\text{2009/MWh}$

<table>
<thead>
<tr>
<th>Technology</th>
<th>Capacity Factor (%)</th>
<th>Levelized Capital Cost</th>
<th>Fixed O&amp;M (including fuel)</th>
<th>Variable O&amp;M</th>
<th>Transmission Investment</th>
<th>Total System Levelized Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conventional Coal</td>
<td>85</td>
<td>65.3</td>
<td>3.9</td>
<td>24.3</td>
<td>1.2</td>
<td>94.8</td>
</tr>
<tr>
<td>Advanced Coal</td>
<td>85</td>
<td>74.6</td>
<td>7.9</td>
<td>25.7</td>
<td>1.2</td>
<td>109.4</td>
</tr>
<tr>
<td>Advanced Coal with CCS</td>
<td>85</td>
<td>92.7</td>
<td>9.2</td>
<td>33.1</td>
<td>1.2</td>
<td>136.2</td>
</tr>
<tr>
<td>Natural Gas Fired</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Conventional Combined Cycle</td>
<td>87</td>
<td>17.5</td>
<td>1.9</td>
<td>45.6</td>
<td>1.2</td>
<td>66.1</td>
</tr>
<tr>
<td>- Advanced Combined Cycle</td>
<td>87</td>
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Source: EIA (2012)

C.2 Scenario Results
### Table C.2: Results for Benchmark

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## C.2. Scenario Results

Table C.6: Results for All Technologies allowed with a CO₂ tax of 36 CHF/t of CO₂

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C.2. **SCENARIO RESULTS**

### Table C.8: Results for All Technologies allowed without self-sufficiency

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