Enhancing PV systems adoption by Swiss households, a system dynamics policy analysis

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Enhancing PV systems adoption by Swiss households, a system dynamics policy analysis

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Abstract

The Swiss Federal Government faces the challenge of ensuring a reliable and affordable electricity supply while fulfilling the nuclear phase-out and strengthening its commitment to a sustainable future. Swiss households are becoming the largest consumers of electricity, while displaying a large potential of substantially contributing to the energy model shift by the investing in solar photovoltaic technologies. What are the key drivers moving households to invest in PV systems, and how and to what extent political measures can enhance the adoption of the technology, are studied by modelling and simulating a system dynamics representation of the Swiss energy system.

The main factors determining the level of private investment by households in the photovoltaic technology are found to be: economic advantages, environmental concerns and social pressure, with a critical importance of complexity barriers in the decision-making process. A model is built featuring a decision-making, an adoption accountancy, and a subsidy accountancy sections. Three demand projections are combined with policy design variations regarding the level of investment subsidy, pursued goals, and financing schemes so as to simulate 42 scenarios. Decreasing subsidies and gradually growing goals are found best to achieve high penetrations of the technology, especially under fast growing electricity demand. The diffusion of PV systems is brought forward by a decade, though the diminishing costs of the technology generalizes its adoption in the long-term, making the scenarios convergent.

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List of abbreviations, symbols and units

AES	Association of Swiss Electrical enterprises
BS	Base scenario
C	Constant electricity demand scenario
CG	Constant goal scenario
CHF	Swiss francs
CS	Constant subsidy scenario
FD	Fast decline of electricity demand scenario (-0.3% yearly)
FG	Fast growth of electricity demand scenario (+0.6% yearly)
FIT	Feed-in tariff
FT	Free taxation scenario
GIC	Grid integration costs
GW	Gigawatt, power measure equal to 10^9 Watts.
IEA	International Energy Agency
kW	Kilowatt, power measure equal to 10^3 Watts
kWh	Kilowatt hour, energy measure equal to $3.6 \bullet 10^9$ Jules
LT	Limited taxation scenario
Mk	Market driven goal scenario
NPV	Net Present Value
OFEN	Federal Office of Energy (the same as SFOE, BFE)
OFS	Federal Office of Statistics (the same as BFS)
PV	Photovoltaic
SD	System dynamics
SG	Stepwise goal scenario
SME	Small and medium size enterprises
SS	Stepwise subsidy scenario
TIS	Technology Innovation System
TWh	Terawatt hour, energy measure equal to 10^9 kWh
WTI	Willingness to invest

1. Introduction

In 2011, after the nuclear accident in Fukushima, the Swiss Federal Council adopted the decision of phasing out nuclear energy (Swiss Federal Government 2011). This decision heavily influences the future of the Swiss electricity generation since nuclear power plants have been consistently contributing to nearly 40% of total electricity production (OFEN 2014). This shift off nuclear energy takes place in a context where environmental concerns are increasingly conditioning not only the power generation industry, but all the aspects of today's life. The risks lying ahead are well documented (IPCC 2014), and should be avoided directing our societies into a sustainable path. The Swiss government has, then, to balance its self-imposed imperative to leave nuclear energy by 2034, ensuring a reliable and affordable electricity supply, and keeping and widening its commitment to a sustainable future. A challenging task to which this work humbly contributes.

Renewable sources are expected to play a main role in the definition of the next Swiss energy model, particularly solar energy due its large potential (Rufer 2014; Swiss Energy Scope 2015). Photovoltaic technologies are well known in Switzerland since the very start of the technology, pioneering some of its applications (Hächler, R.Nordmann 1991) and use in residential contexts (Real 1991). In the recent years, the adoption of PV systems have rapidly grown (OFEN 2014). The Swiss government implemented in 2008 an incentivizing framework for the deployment of the technology (OFEN 2012), though it has proved unable of attending the large demand (Mombelli 2014). It is, therefore, necessary to envisage new strategies, not only to overcome the issues of the current policies, but to further encourage the adoption of the technology.

The engagement of private investors is essential if a high penetration of the technology is wanted. However, private investors are a colorful group with very different priorities. Hence, aligned with the development of the Swiss solar market and the fact that households are becoming the biggest electricity final consumer (OFEN 2014), this study focuses on policies to encourage Swiss households to invest in PV systems.

Public policy research has a fundamental limitation when compared to natural sciences research: the possibilities of direct experimentation are, at best, limited. The potential costs and the difficult translation of local-basis results to a national system, have pushed researchers into cheaper, easier-to-manage alternatives. Among the tools employed, system dynamics (SD) reveals itself as a powerful tool for virtual experimentation, where designing and testing public policies with no risk (Pruyt 2013). Its adoption is framed in the shifting from purely inductive analysis, to studying socio-technological transitions through simulation (Papachristos 2014), where SD suitably fits our needs (Papachristos 2011). Hence, a model is built based on SD, and simulated.

This report begins with a contextualizing chapter 2 on the background in which the research is framed, as well as the research questions. Chapter 3 consists of a quick literature review on similar previous works. Chapter 4 explains the methodology followed to build and simulate the model, introducing SD, to continue with chapter 5 on the conceptualization of the system. The chapter 6 explains the scenarios simulated, discussing their results in chapter 8, with a short chapter 7 dealing with the validation of the system. Then, the chapter 9 concludes the report with the conclusions, limitations and future works identified during this project. Finally, the references are listed and the appendices containing the figures with the results from the simulations are attached.

2. Background information and research questions

The unparalleled challenge faced by the Swiss government to direct the energy transition motivated a preliminary exploration of relevant research questions on the governance of the process that could meaningfully contribute to its success. *"What are the key factors defining the level of private investment in photovoltaic technologies?"* and *"How political measures can, and to what extent, influence those factors?"* were the interrogations fruit of that exploration. A deeper review of the surroundings led to a refined version of these questions. This chapter briefly introduces the key elements of that environment, allowing us to retake these questions and refine them at the end of this section.

2.1.Solar photovoltaic technologies

Solar energy has, by far, the largest potential to supply the growing, global energy needs. 21,840 TW is the estimated irradiation reaching the solid surface of the Earth (where between 2 to 50 TW would be technically, sustainably and economically exploitable (de Castro et al. 2013)). Looking at the total final energy consumption of the whole planet, around 12 TW (IEA 2014), the potential of solar energy becomes evident. In the Swiss case, if we assume an average electricity production of 185 kWh/m^2 in the Swiss plateau (Rufer 2014) the potential of employing only the roofs suitable for it (around 140 km^2 (Swiss Energy Scope 2015)), the production could reach around 25.9 TWh/year, more than 40% of current electricity consumption or 1.38 times what households consumed in 2013 (OFEN 2014). These numbers bluntly show why solar photovoltaics needs to be seriously consider to solve the challenged presented.

The technology is based on the photovoltaic effect first observed by Becquerel in 1839 (Becquerel 1839). It produces the promotion of an electron, in a material exposed to solar light, which could be later used to generate an electric current. This phenomena occurs in different materials composing the solar panels, being silicon-based solar cells the most widely extended and used, reaching efficiencies of conversion around 20% (slightly lower in commercial applications) (Green et al. 2015).

Since the electricity generated by this effect is direct current, it needs a converter to transform it into alternating current. This latter device (and, thus the whole installation) can be connected to the electrical grid (on-grid) or can be isolated (off-grid), where it would likely be necessary an energy storage device (i.e. batteries). Additionally, it is to be differentiated among large-scale installations (in the order of MW) typically called "centralized" and often ground-based, with those of small-scale usually associated with residential and small commercial applications (in the order of kW) named "distributed" and -often encountered in rooftops or integrated in the buildings.

The technology has experienced an unprecedented growth in the last years mostly due to a dramatic drop in costs fruit of economies of scale and expertise development on its production and use, as well as technical progresses. Without leaving Switzerland, the price per kW installed has fallen from more than 13.00 CHF in 1992 to less than 5.00 CHF by 2013 (more than 60% price decrease) (Husser et al. 2013). In the same period, the world has passed from less than 1,300 MW to nearly 140,000 MW, with 81,500 MW in Europe (EPIA 2014), demonstrating the interest in the technology.

The development of the technology should be attributed mostly to the wide spread availability of solar irradiation in the globe, a free and sustainable resource accessible to everyone. This latter aspect, its environmentally friendly features, was the initial driver for its growth, but now several other advantages, ranging from economic savings to local production, have taken over. Notwithstanding it, caution needs to be present when promoting its development since its intermittency and extremely low operation costs can seriously distort the electricity market (Haas et al. 2013), requiring a carefully thought approach combining technical, economic and social criteria (Haas et al. 2004).

2.2. Technology innovations systems and energy transitions

Despite the discovery of its physical principles in the XIX century, the photovoltaic technology is yet considered an innovative technology. In many places it is just entering the power market showing a vast potential for penetration, what is the case in Switzerland. The introduction of this new technology triggers large, complex socio-technological changes requiring a theoretically solid framework to better study them. This conceptual frame, in our work, comes from the Technology Innovation Systems (TIS) approach. It is used since it allows to better study the dynamics of innovation systems (Hekkert & Negro 2009), and has been previously applied to similar cases.

A TIS is defined as a "networks of institutions, public or private, whose activities and interactions initiate, import, modify, and diffuse new technologies" (Freeman 1987, p1) or, more completely, as "a network of networks of agents interacting in a specific technology area under a particular institutional infrastructure to generate, diffuse, and utilize technology" (Carlsson & Stankiewicz 1991, p94).

To effectively diffuse the technological innovation, the TIS carries out a set of functions, according to (Hekkert & Negro 2009): (1) entrepreneurial activities, (2) knowledge development, (3) knowledge diffusion, (4) guidance of search, (5) market formation, (6) resource mobilization, and (7) creation of legitimacy/counteract resistance to change. The object of this study, analysis of policy measures to encourage household investment in PV systems, despite potentially contributing to all the functions of the TIS, is mostly centered in: (5) market formation, creating a temporary competitive advantage in price, and thus trying to stimulate demand and create a pulling market formation context. In second order of importance it also addresses the functions: (3) knowledge diffusion, and (7) creation of legitimacy. The policy measures suggested later on, directly enhance these functions so as to increase the TIS effectiveness by government-led (or promoted) initiatives.

Our key assumption is that if domestic demand is created for photovoltaic technologies, the supply-side will follow. Hence, assuming an adequate entrepreneurial environment, what arguably is the case in Switzerland, the more households demanding PV systems, the bigger the market will grow, reinforcing further diffusion of the technology. In this sense, this work is not only related with the studies of other students in the MIR laboratory (on the Swiss energy transition), but also with past works, mostly with Margelou's (Margelou 2015), in a coherent effort to shed light into the introduction of renewable technologies in Switzerland.

2.3.Swiss energy transition

The shock caused by the Fukushima nuclear accident in 2011 ignited popular opposition to nuclear energy, determining the Swiss Federal Council to abandon the technology once the active power plants in the country reach the end of their lifetimes (Swiss Federal Government 2011). This increased the pressure to define a new energy model for Switzerland substantially different from the current one.

Focusing on the electricity system, Switzerland, with a population of around 8 million inhabitants, produced in 2013 a bit more than 68 TWh of electricity that came almost exclusively from nuclear power plants and hydropower (see Table 1). The consumption was little more than 59 TWh, divided mostly into households, industry and services (see Table 1). The consumption has grown consistently in the last decades, however not equally among the different sectors. There is an ongoing shift where the large end-consumers, services and households, are close to dethrone the industry as the biggest end-consumer sector (see Table 1). Despite efficiency measures being encouraged by the Swiss administrations, the progressive electrification of the domestic consumption will most likely continue this trend in the future.

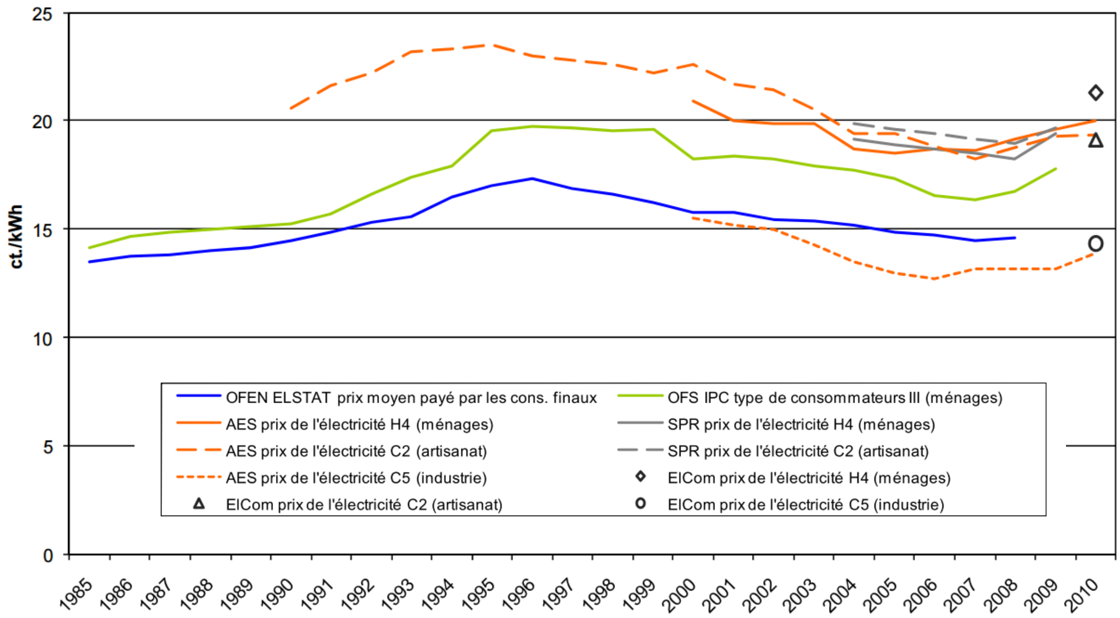
Table 1. Overview of recent Swiss electricity system evolution.

Own elaboration, (OFEN 2014) data.

	Technology / sector	2008 [TWh]	2008 [%]	2013 [TWh]	2013 [%]	$\Delta_{2008/2013}$ [%]
Generation	*Hydropower*	37.559	56.09%	39.572	57.93%	5.36%
	Nuclear	26.132	39.02%	24.871	36.41%	-4.83%
	Cogeneration & Other	3.276	4.89%	3.869	5.66%	18.10%
Consumption	*Households*	17.897	30.47%	18.768	31.64%	4.87%
	Agriculture	1.013	1.72%	0.993	1.67%	-1.97%
	Industry	19.280	32.83%	18.768	31.64%	-2.66%
	Services	15.730	26.78%	16.009	26.99%	1.77%
	Transport	4.809	8.19%	4.785	8.07%	-0.50%

The challenge is crystal clear: replacing the around 25 TWh that annually nuclear power plants have been producing in the best way, what includes ensuring an affordable, secure and sustainable electricity supply (Grätz 2012). This report argues that, in a future system where domestic consumption becomes the top consuming sector, enhancing distributed photovoltaic systems that locally produce most of the energy needed by these consumers should be considered as a key part of the solution. In order to encourage adoption of the technology, the creation of the temporary competitive advantage is indispensable in Switzerland.

The average electricity price paid by Swiss households is among the lowest in the European area (OFEN 2011) (also see its recent evolution in Figure 1), what added to a modest irradiation levels compared to its southern neighbors, had kept the economics of photovoltaics unattractive for investors during decades. The current low prices of PV systems have improved the situation, though the payback time of the technology remains fairly high (for a typical household in 2013, as much as 24 years [own estimation]). If PV systems adoption is a priority, an incentivizing policy is unavoidable.



Adapted from (OFEN 2011).

Figure 1. Nominal prices of electricity evolution in Switzerland.

Indeed, renewable technologies promotion is a key aspect of the Federal government strategy for the long-term (BFE 2012), though it started only some years ago. Despite its pioneering role in the development of photovoltaic systems (Nordmann 1995; Perlin 2013), its incentivizing schemes were very timid until 2008 with the introduction of a feed-in tariff system. Previous to that year, green certificates allowed consumers to pay a premium for buying renewably produced electricity (Weibel 2011; Husser et al. 2013), and in 2005 a prelude of the FIT scheme was put in place, where utilities had to buy independent producers electricity at a fixed price around 0.15 CHF/kWh (SFOE 2007).

In March 2008, the Swiss Federal Parliament approved the current feed-in tariff policy, which entered into action in May of the same year (Weibel 2011). Producers employing renewable technologies (included photovoltaic) below 10 MW can benefit from the measure by registering the installation in the offices of the Swiss grid operator Swissgrid (SFOE 2011). After approval, the local utilities are forced to buy the electricity produced at fixed prices defined from reference case installations during 25 years (in the case of PV) (Weibel 2011; Husser et al. 2013). In the case of domestic installations (roof mounted under 10 kW), the retribution would be 0.483 CHF/kWh that additionally decreases around 8% (but the drop can be higher if technology gets cheaper than expected, what happened in 2010) (SFOE 2010; SFOE 2011). This subsidy is financed by an increase in the electricity bill of consumers that is capped at CHF 247 million[1], around 10% of the electricity cost per kWh paid by domestic consumers (Weibel 2011).

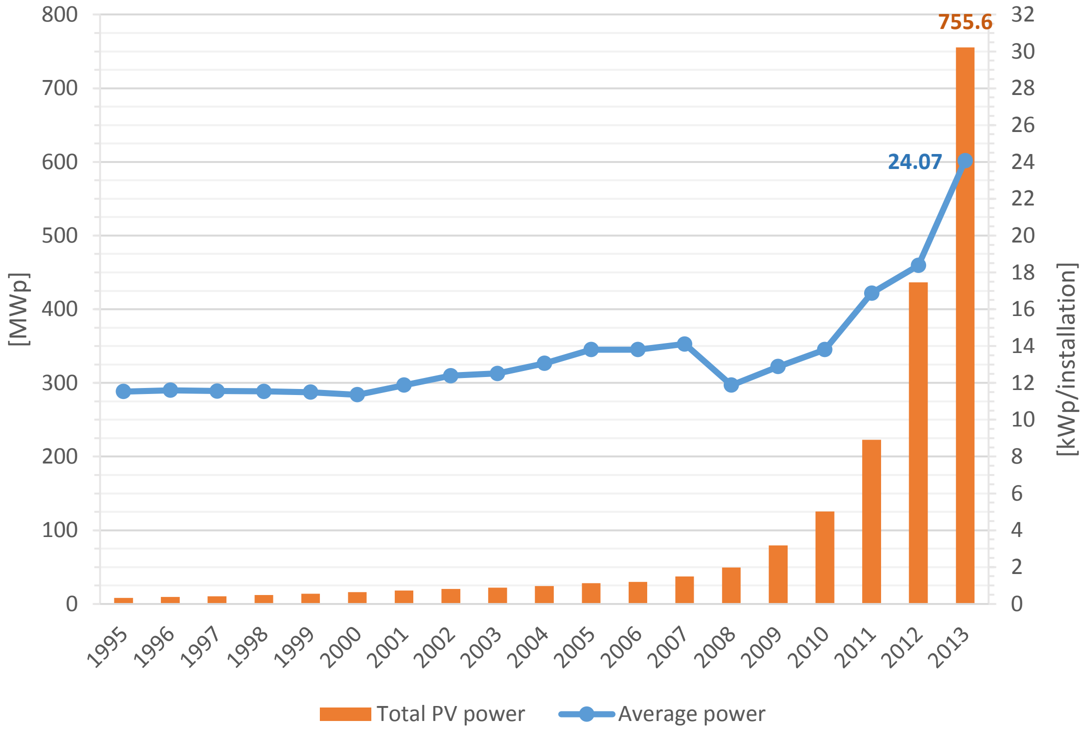
Without entering into further details, it is necessary to highlight that this system allocates insufficient resources to satisfy the high demand generated, being recriminated by several agents in the solar market (Weibel 2011). In fact, a waiting list (for subsidization approval) of more than 30,000 systems has been growing in the latest years (Mombelli 2014), clearly showing the willingness to invest in photovoltaic systems and the limits of the policy. On April 2014, the Federal Council approved a reform affecting small-scale producers. It left out of the FIT scheme the systems below 10 kW,

[1] This figure will be later used as the maximum annual budget of our model (see section 5.2.3).

being substituted by a rebate of 30% of the total investment costs, aiming at reducing the waiting list by around 10,000 installations (Mombelli 2014; Woods 2014). Studying the effect of this policy, as well as its variations, is a key motivation for this project.

Notwithstanding its limitations, the FIT scheme succeeded in accelerating the adoption of solar photovoltaics, which has experienced a drastic boom in the latest years (see Figure 2). Besides, the introduction of this policy has attracted larger small producers that have increased the average size of the systems, from a typical domestic size to around the double of it (see Figure 2). The study of this niche of consumers is proposed as an interesting expansion of the scope of this project in future works.

Either way, the vast majority of systems are yet on-grid, distributed systems with virtually no ground-based system (Husser et al. 2013). This latter feature clearly identify the existing PV installations as domestic or small scale commercial rooftop or building integrated systems. As long as the incentives remains for <10 MW systems (and with the new ones focused on small installations <30 kW), this trend is not likely to change, but to increase (Woods 2014), reinforcing the interest for better approaching domestic investors.



Own elaboration. IEA-PVPS CH 2013 data.

Figure 2. Accumulated photovoltaic capacity installed in Switzerland and average size of the installation.

2.4. Research questions

The brief introduction of the background in which this report takes place undoubtedly justifies the interest in exploring the research questions mentioned at the beginning of the chapter. However, in their original form, they are found too broad to be clearly answered. Therefore, based on the knowledge of the context developed in the previous sections, the research questions were detailed as follows:

- *What are the key factors defining the level of private investment in photovoltaic technologies?*
    - *What private investors?* – Households. Domestic consumers are becoming the most important electricity consumers in Switzerland, showing its own set of priorities regarding investment in new technologies, and experiencing the highest PV system costs[2]. Studying how will they react to different policies encouraging them to adopt PV systems, and exploring possible evolutions of the newly available scheme is then of the highest interest for policy makers.
    - *What kind of investment?* – Installing a PV system in their property. Other kind of investments are not considered.

- *How political measures can, and to what extent, influence those factors?*
    - *What is the goal?* – Swiss government goal for renewables (excluding big hydropower) was of at least 5.4 TWh by 2030 (Swiss Federal Government 2013), though it was raised to around 20% of electricity production by 2035 (BFE 2012; Mombelli 2014). To explore the effect of the different goals, it is included as a policy variable.
    - *What are the constraints?* – The annual budget and the deadlines.
    - *What defines success?* – The amount of installed capacity of PV systems.

Once defined more precisely the research questions and presented the background in which this work takes place, we are ready to start trying to answer them.

[2] The specific cost of PV systems (CHF/kW) has always been substantially higher than for larger applications (Husser et al. 2013), what also translates into a biggest economic support needed from the subsidizing scheme. Hence, it becomes vital a deep understanding of the dynamic of domestic investors to ensure the maximum effectiveness of the efforts for diffusing the technology (Wand & Leuthold 2011).

3. Literature overview

The extensive literature regarding energy policy on renewable technologies, and particularly on photovoltaic technologies, forced us to narrow down the scope of this literature overview so as to only present the most relevant studies matching our perspective. Hence, exclusively the most relevant works on PV systems incentivizing, technology innovation systems concerning sustainable transitions (or directly PV), as well as renewable energy policy-design articles are included. Additionally, attempts to analyze the Swiss electricity system by using system dynamics or works on PV diffusion in neighboring countries are quoted.

The concept of technology innovation system (TIS) emerged in the 1980s as a part of a broader school of the so-called innovation system approach, where Lundvall was one of its pioneers (Lundvall 1985). This approach acknowledged that firms and technologies are embedded in social and economic systems (Rip & Kemp 1998), shifting the focus from firms and industries to socio-technical regimes. The current challenge is to turn them sustainable (Berkhout 2002), and it is nothing but a governance challenge (Smith et al. 2005).

This report is framed in this approach, applying it to the study of photovoltaic diffusion among Swiss households. Among the literature on the use of the TIS concept to analyze energy and sustainable transitions we highlight the works of Jacobsson and others (Jacobsson & Johnson 2000; Jacobsson & Lauber 2006; Jacobsson & Bergek 2011). In their studies, they combine the proposal of an analytical framework based on the TIS approach, while directly applying it to the case of photovoltaic technologies and suggesting fields of future research. Additionally, the studies of Dewald and Truffer concerning market formation for photovoltaic technologies, with a look on the dynamics occurred in Germany, shed light of the mechanisms underlying the systemic changes needed (Dewald & Truffer 2011; Dewald & Truffer 2012). Further contributions to understanding PV market formation, again with particular examples on the German case, can be found in (Möllering 2009).

The different national policy measures available and often used in the promotion of renewable energies are reviewed in (Sawin 2006), which is complemented by the more recent works of (Abolhosseini & Heshmati 2014) and (Couture et al. 2015). Despite the variety of policy instruments that could be implemented, most analysis have focused on FIT schemes (see (Couture & Gagnon 2010; Ayompe & Duffy 2013; Polo & Haas 2014) among others), often from a comparative perspective (see (Muñoz et al. 2007; Lüthi 2010; Varma et al. 2011; Kitzing et al. 2012; Avril et al. 2012; Jenner et al. 2013; Sarasa-Maestro et al. 2013) among others). An analysis of the feed-in tariff scheme in Switzerland can be found in (Weibel 2011), with a quick summary also found in the reports to the IEA's program: photovoltaic power systems (Husser et al. 2013).

In the study of policy instruments for encouraging photovoltaic adoption, the employment of system dynamics has been gaining terrain. It has been used to optimize the subsidy level of FIT schemes (Jeon et al. 2015) and study its influence (Ahmad et al. 2015). SD also has been applied to whole photovoltaic market simulations (Drury et al. 2010; Movilla et al. 2013; Yaquob et al. 2014) or predict the behavior of policy measures such as the Massachusetts SREC market (Flynn et al. 2010) and the PV industry in Massachusetts (Jones 2007; Jones 2009). Finally, a few studies have worked directly on our topic, simulating the diffusion of PV technologies under investment subsidies schemes (Yan 2009; Hsu 2012).

Nonetheless, none of the previously mentioned studies was focused on the Swiss case (neither they address the key factors moving households to invest). The studies regarding the energy transition in Switzerland are yet few and not focused on photovoltaic technologies. The work carried out by Prof. Van Ackere and collaborators focuses on the electricity market and its capacity expansion (Ochoa 2005; Ochoa & van Ackere 2009), and also in the security of supply of the Swiss system (Osorio & Van Ackere 2014). Complementing the work on the Swiss market, the work of (Noembrini 2009) with emphasis put on the interconnection between transportation and energy conversion. Other works are relatively less related, tackling with policy governance of the shift towards more efficient buildings in Switzerland (Muller & Ulli-Beer 2012; Muller et al. 2013).

Despite the different objects of study, the SD studies of the Swiss case have served as primary inspirations for this work. Additionally, the comparison of two paradigmatic cases in Europe, the German and the Spanish models, was found in the roots of the motivations for this work.

A closer look to these two very different examples, one of success and one of failure, with similar policy designs, is left for future works due to time limitations. The main reason for highlighting these two cases is that they remark the importance of keeping a holistic perspective when studying the governance of socio-technical transformations. A narrow comparison among the two countries' incentivizing policies can lead to misleading conclusions, unable to explain the wide difference in their final outcomes (Dewald & Truffer 2011).

The interested reader can know more of the Spanish case in the work of (del Río & Mir-Artigues 2012), the analysis of (Prieto & Hall 2013) and the SD model of (Movilla et al. 2013). More extensive is the literature on the German case, where the reader is left to consider the analysis of its experience from the TIS approach in (Jacobsson & Lauber 2006; Dewald & Truffer 2011; Dewald & Truffer 2012), as well as the relevant work of (Karakaya et al. 2015) on the motivators for domestic diffusion of the technology.

4. Methodology

Reviewed the context in which this report is developed and the available literature on the topic, this chapter introduces the concept of system dynamics and justifies its use for policy-design research projects. Finally, the procedure followed in this report to conceptualize the project and simulate the Swiss energy system is detailed.

4.1.System dynamics and policy analysis

Following the definition given by Pruyt, system dynamics (SD) can be described as "a method to describe, model, simulate and analyze dynamically complex issues and/or systems" (Pruyt 2013, p1). System dynamics' assumption is that the behavior of a system is fundamentally determined by its own structure (Pruyt 2013), where structure is conformed of physical and informational features as well as the policies and traditions relevant for the decision-making process in the system (Roberts 1988). The dynamic analysis of complex systems considering social, economic, technical and other criteria, SD allows to identify potential system behaviors, trends and particular sensitivities to certain elements of the system.

System dynamics are models based on the use of systems, model boundaries, variables, causal linkages and feedback loops. Systems are understood in SD as causally closed structures that generates its behavior endogenously over time, based on the results from previous actions (Forrester 1968; Pruyt 2013). Given this conception of the systems, it is straight forward to realize the critical importance of the system boundaries. Too narrow model boundaries could lead to incomplete representations of the issues modeled, while too broad can increase the complexity of the model over what is necessary to achieve the goals of the research. Hence, following the description of Pruyt, "all (potentially) important elements which influence other parts of the system and are also significantly influenced by elements of the systems should be modeled as endogenous variables, all elements that (could) seriously impact the system – but that are not sufficiently influenced by the system – become exogenous variables, and all other elements are omitted." (Pruyt 2013, p33-34).

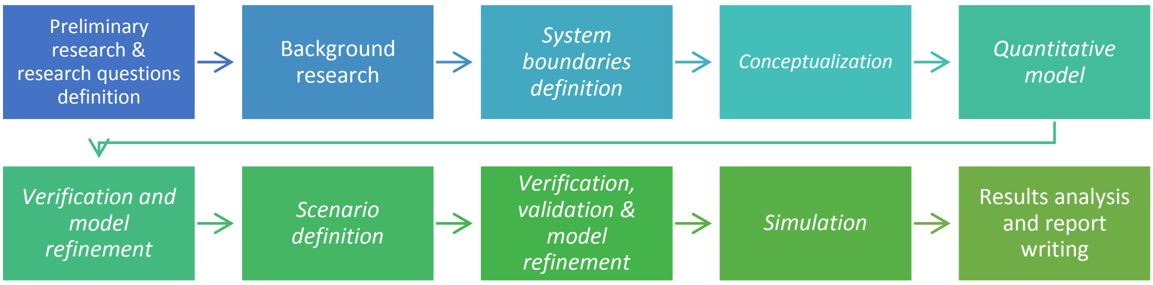
Defined the limits of the system, its elements are then put in place in the form of variables and links. There could be stock variables, flows, auxiliary variables, constants and parameters, representing material or informational processes. The links between these elements constitute direct causal relations that, jointly, configure the structures of the model. Therefore, it is necessary to clearly identify the justification of each link within the system. Links (i.e. from A to B) can be generally be described as positive (+) (i.e. if an increase in A leads to an increase of B), or negative (-) (i.e. if an increase in A leads to a decrease in B). Finally, the links between several elements of the model can compose feedback loops. A feedback loop is a path of links starting in one element of the system that, if followed, leads to it after passing through at least another system element. Two kinds of feedback loops can exist: (+) positive or reinforcing loops, where an initial increase in the first element of the loop leads up to a further increase of that element; (-) negative or balancing, where an initial increase in the first element of the loop leads up to a decrease of it. Quantitative SD would later require the translation of this elements into equations to create a mathematical model.

The system dynamic approach was first developed by Jay W. Forrester, professor at the Sloan School of Management of the MIT, in the late 1950s and 1960s (Forrester 1958; Forrester 1961; Forrester 1968). Forrester first began developing this methodology in the field of firm management and industry analysis, to scale it up afterwards until formally describing the system dynamics tool (Forrester 1995). Since then, SD has been applied to a growing variety of topics hugely surpassing its original domains. Among them, policy analysis in numerous fields have adopted this approach in which this report is framed, particularly among those trying to better understand energy transitions.

System dynamics has empowered political researchers with a tool that helps them overcoming the extreme difficulty, when not impossibility, of direct policy experimentation, understood as the deployment of public policies in a limited scale under controlled conditions so as to test its effectiveness before adopting them in a larger scale. In other words, SD enable virtual experimentation to gain insights from the response of the models to the different policy designs and extract policy recommendations from them (Hsu 2012; Pruyt 2013). This feature allows political researches to exploit their creativity to configure different policy alternatives and simulate their effects under controlled conditions, easily capturing the effects of the adjustments. Its use is then completely justified in this work, particularly when regarding the arguments in favor of applying this approach on energy transitions research (Papachristos 2011; Papachristos 2014).

4.2.Procedure and tools

This report is the final outcome of a whole process centered in the construction of the model and its simulation in the attempt to shed light into the research questions stated before (see chapter 2). The process followed was based on continuous feedback on the progresses made and ongoing search of references to expand the basis for the study development, its key stages are summarized in Figure 3, with SD steps *highlighted*.



Own elaboration.

Figure 3. Project development stages and system dynamics steps.

The system dynamics model was built using the Vensim® PLE 6.3 version for Windows from Ventana Systems Inc. Additional analysis, figures and redaction was made with the Microsoft Office 2013 suite, with the help of Mendeley for reference handling.

5. Model description

Once introduced the conceptual tools of system dynamics, in this chapter the model developed for the exploration of the research questions (see chapter 2) is thoroughly described. Additionally, the equations determining the relations among its components are highlighted and the assumptions underlying its construction are made explicit.

5.1.Overview

The research questions of this project were the guiding lines for the design and definition of the model to explore them. Identifying the key factors encouraging private investors, households in our case (see chapter 2), to invest in photovoltaic systems and simulating how different policy measures can affect its proneness to invest required modelling the decision making process of households. It constitutes the main section of the model and can be briefly summarized in the interrelation between the key factors that have found to be the most relevant in the household decision making: (1) economic, (2) compatibility, and (3) complexity factors. In the same section, the underlying drivers defining the strength of these factors are modelled and the different policy measures studied to influence them are included.

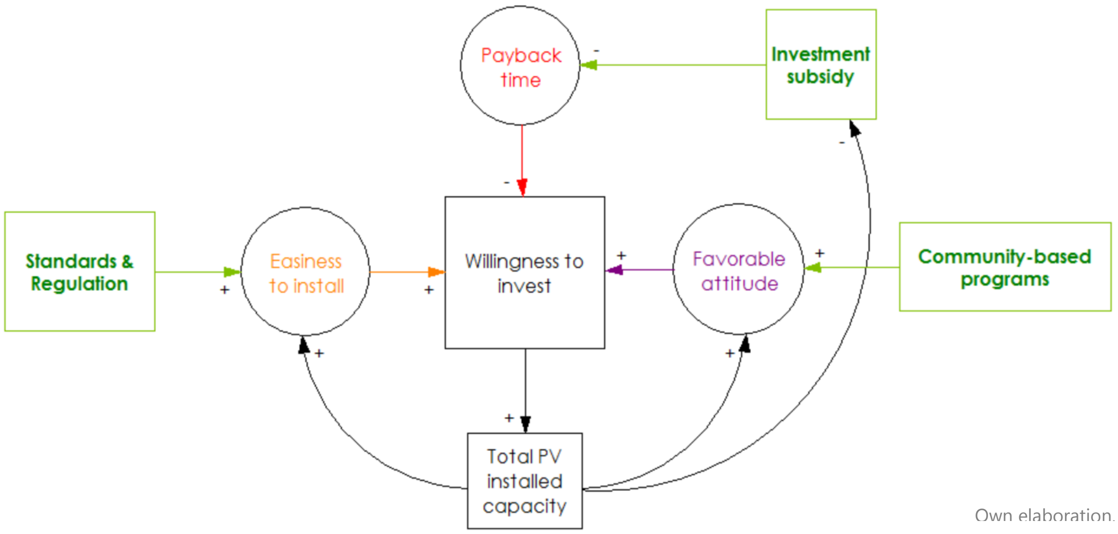


Figure 4. Simplified conceptual model.

Besides the decision-making modelling section, a second part is employed for the accountancy of the installations and another additional section modelling the financing scheme for the economic incentives management. Except this latter section that is explored in the following section (see section 5.2), a global overview of the system is provided in Figure 4.

The core element of the system is the "Willingness to invest" of households that determines whether they would invest in a photovoltaic system for their own use or not. It is shaped by the combination of the aforementioned factors modelled by the "Payback time", in the case of economic factors; "Easiness to install", in the case of complexity factors; and by "Favorable attitude" towards the photovoltaic technology, in the case of compatibility factors.

The “Willingness to invest” of households defines the rate of adoption of photovoltaic systems thus determining the “Total PV installed capacity” that in the model limits to grid-connected, domestic photovoltaic systems. The amount of installed systems directly influence some of the key factors (the “easiness to install” and the “favorable attitude”), while acting on the economic factors indirectly through the policy instruments put in place to encourage investment. To enhance the adoption of the technology, three policy instruments are used so as to tackle each one of the three key factors modelled: (1) “investment subsidy” to reduce the total costs of the system when it is installed by the household, (2) “standards & regulation” to simplify the decision-making of the investors and ensure a minimum quality in the deployment of the technology, and (3) “community-based programs” to catalyze the formation of local communities supporting the diffusion of the technology and the spread of it via information and experience exchange.

The dynamic of the system is relatively simple and can be regarded as an attempt of creating a market-pull diffusion process, since it is the demand of photovoltaic systems by households what the whole scheme is trying to increase. The policy instruments in place pursues to easing the adoption of PV systems, increasing the financial benefits of it and favoring a societal support of it, creating two virtuous circles (i.e. reinforcing loops) and one vicious circle (i.e. negative or balancing loop).

Easier installation of photovoltaic systems reduces the barriers customers (i.e. households) have to overcome to purchase them and start using them, thus it increases their willingness to invest in PV systems, what eventually rises the total photovoltaic installed capacity. A further spread of the photovoltaic technology requires the solar PV market to grow (i.e. higher number or larger companies with a wider presence), contributing to the easing of the barriers to installation (see Figure 4).

Similarly, a more favorable attitude towards the technology loosens the resistances to its adoption, mainly by making it easier for households to accept the innovating concept of becoming energy producers. Hence, their willingness to invest rises leading to an increase in the installed PV capacity. The more neighbors installing PV systems, the more social pressure on households without solar systems to install them and start benefiting from them, configuring the second reinforcing loop (see Figure 4).

Slightly more complex is the balancing loop formed by the investment subsidy policy. Subsidizing partly the cost of the photovoltaic systems considerably reduces the payback time for households and thus it boosts the adoption of the technology. However, a limitation in the budget available for subsidizing the systems is put in place to avoid facing large costs in a short time period. Hence, the more installed capacity, the less remaining resources available for future adopters, thus reducing the incentive to invest in the technology.

The model hosts reinforcing and balancing loops that make the understanding of its response not straight-forward. What’s more, the details of how each factor is defined and interrelates with others are indispensable for correctly evaluate the results from the simulations. They are reviewed in the following section, as well as the information on which the model is based, highlighting as well the main assumptions present in it.

5.2.Conceptualization of the system

Building a system dynamics model is a highly iterative process that is usually started with a small and simple model that is subsequently developed into a more complex one, until achieving the final version of it (Pruyt 2013). In this case, the key outcome of the system is the total installed capacity of photovoltaic systems by Swiss households, and thus it is the very beginning of our model.

5.2.1. Installation accountancy section

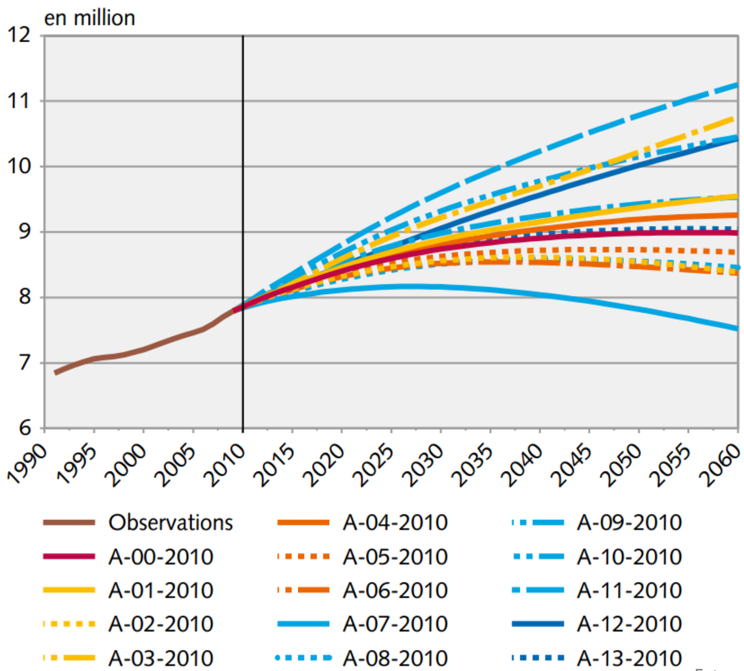
It is modeled as a stock variable named "Total PV installed capacity" (see chapter 4) whose inflow is defined by the "Adoption rate" and its outflow by the "Decommissioning rate". At the initial date of the simulation, 2013, domestic photovoltaic systems in Switzerland accounted 752 MW (Husser et al. 2013), thus it is set the initial value of the stock.

The decommissioning rate depends on the lifetime of the system and of the annual installed capacity. Hence it equals the adoption rate with a time delay that is the average lifetime of the system, which has been taken as constant at 25 years.

Since increasing the adoption rate is the final goal of the policy measures put in place, it deserves a little more attention, intervening in its definition several variables, what forces us to enlarge the system. First of all, the active actors in the definition of the adoption rate, the Swiss households, should be modeled and discriminated between those already having a solar PV system (who are assumed not to install another one) and those yet to install it. It gives birth to two new stock variables: "Households" and "Households with PV". The share of households willing to install a photovoltaic system is determined by the other core variable of the system: the "Willingness to invest". Additionally, to account the capacity installed, not only the number of households that decided to buy a solar system, the auxiliary variable "Average system size" is put in place.

This latter variable, the "Average system size" is modeled by applying one strong assumption: households would install solar photovoltaic systems capable of producing as much energy as they consume on average. Hence, to define it dynamically, the electricity demand of Swiss households and the average production per photovoltaic kW installed in Switzerland needs to be modeled. Including the efficiency of the system and the irradiation in Switzerland, that varies widely between its regions, the "Specific annual production" of each kW of solar power ranges between 950 and 1100 kWh (Husser et al. 2013). Given most of Swiss population concentrates in the northern part of the country, a relatively conservative specific production of 1000 kWh/kW was taken for our simulations.

Before reviewing how the electricity demand has been modeled, let's briefly discussed the definition of the household's stock variables. The number of "Households with PV" accounted for a little less than 128,000 households initially. It comes from the evenly distribution of the 752 MW of solar capacity installed at the end of 2013 in systems of the average system size for 2013 (around 5.9 kW). The growth or decline of this number is determined by the "Adoption rate" and "Decommissioning rate", and by simple division by the "Average system size". However, the total number of Swiss households is not static, it is modeled as continuously growing by a "Population net growth" rate. The initial number of households (3,532,650 in 2013 (OFS 2013)), as well as the estimated growth of it in the future has been taken from or based on official reports from the Federal government.



Extracted from (OFS 2010).

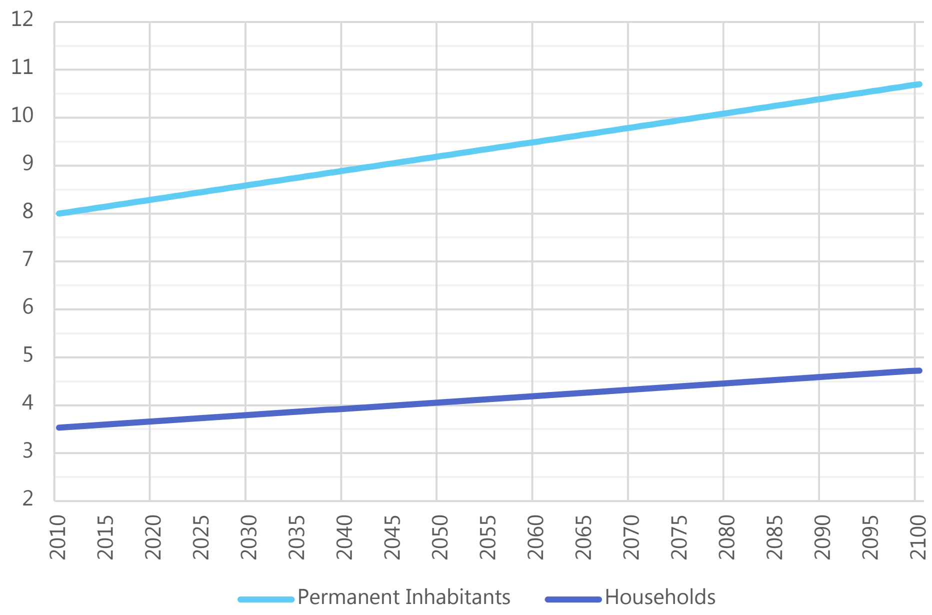
Figure 5. Permanent Swiss population evolution scenarios, in million inhabitants.

In the latest available report on the future evolution of the Swiss population (OFS 2010), several scenarios are analyzed (see Figure 5) with most of them suggesting a plateau around the nine million inhabitants that would be reached approximately by 2040. However, in the recent years, the real evolution of the population has followed the fastest growing pace foreseen in the previous report, what can occur again in the coming years.

Given the complexity of the subject, particularly if taken into account the growing political noise in the question, we decided to assume a simple linear behavior of the population that would be slightly above the median scenarios by the OFS (see FIGURE 02), that would be similar to their own scenarios A-09-2010 and A-01-2010 (see Figure 5). This strong assumption is complemented by the distribution of the growing population in evenly occupied households with an average number of components equals to the present structure (around 2.26 people per households (OFS 2013)). It is another strong assumption given the relatively heavy trend towards households occupied by one or two persons (currently near 70% of Swiss households (OFS 2013)).

The final outcome is a linear growth that adds 13,250 households to the total number of them in Switzerland every year. This variable (the "Households") is the main limitation of the adoption of photovoltaic systems by the logic rule that there could be installed no more domestic solar systems than households exist.

Returning to the electricity demand, its prediction is at least equally complex to the foresight of the population evolution and, as shown by this work, determinant of the adoption of photovoltaic technologies. Given the complexity of its modelling and the many drivers influencing its evolution (including the policies of the Swiss Federal Government), we decided to take three different scenarios for the evolution of the electricity demand, constituting the only external variable for our simulations.

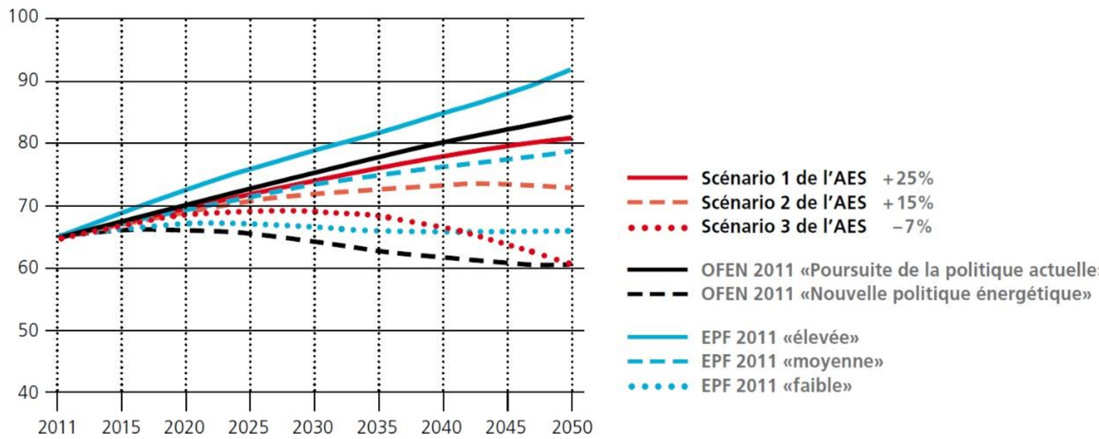


Own elaboration.

Figure 6. Household number and population evolution estimation, in millions.

The association of Swiss electrical companies (AES) recently published a report concerning the future of the electricity demand in Switzerland (AES 2012). In this report, the different drivers of changes in consumption are discussed, as well as the efforts to contain and reduce electrical consumption.

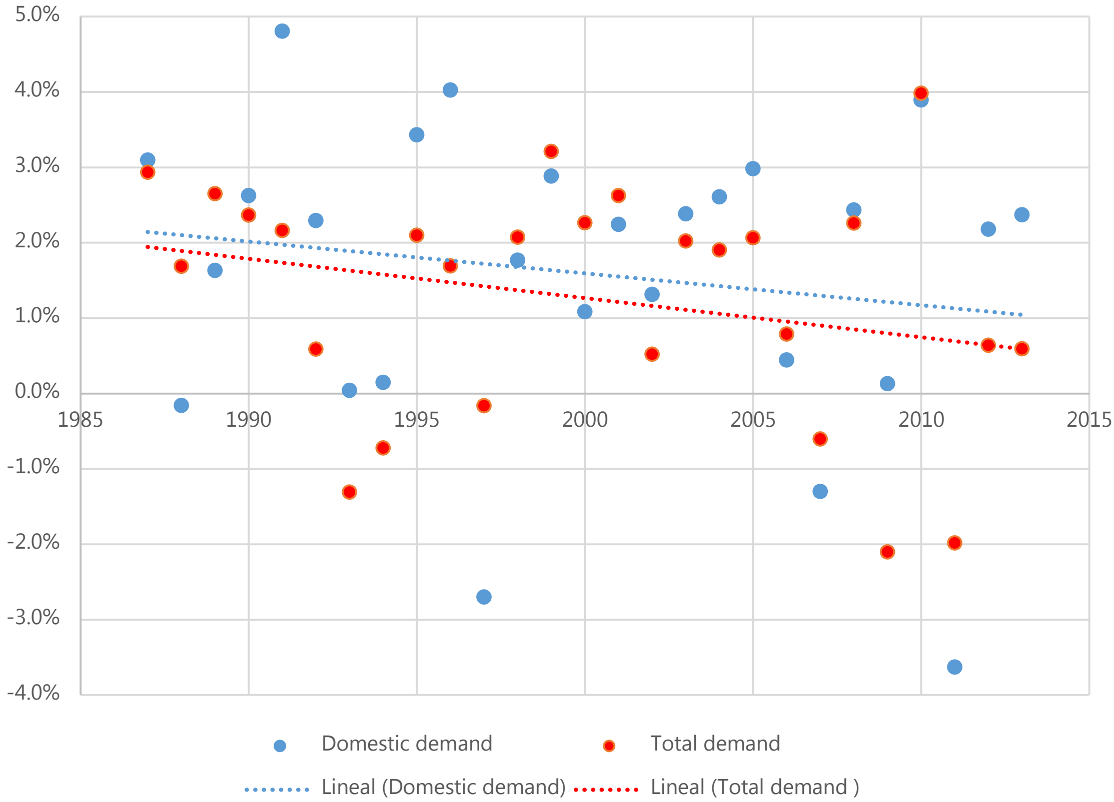
The outcome is composed of three different scenarios for the electricity demand that are studied by the final destiny of it (domestic, agriculture, industry or tertiary sector). The scenarios feature a rapid growth of consumption (scenario AES 1, see Figure 7), a relatively constant one (scenario AES 2, see Figure 7) and a rapid decreasing one (scenario AES 3, see Figure 7). When compared with other estimations by the Federal Office of Energy (OFEN) and by professors of the ETH Zurich (Boulouchos et al. 2011) appear to be relatively moderated and thus are taken are considered most appropriate for our simulations.



Extracted from (AES 2012).

Figure 7. Electricity demand consumption in Switzerland evolution estimations, in TWh.

Additionally, when the electricity statistics of the later decades are analyzed, the high volatility in its annual changes (see Figure 8). Despite most of the values of the annual changes locates around 2%, being in most cases higher the increase of domestic consumption than the total demand (see Figure 8), there is a clear trend towards a moderation in the growth of consumption that is aligned with the scenarios suggested by the different sources (see Figure 7).



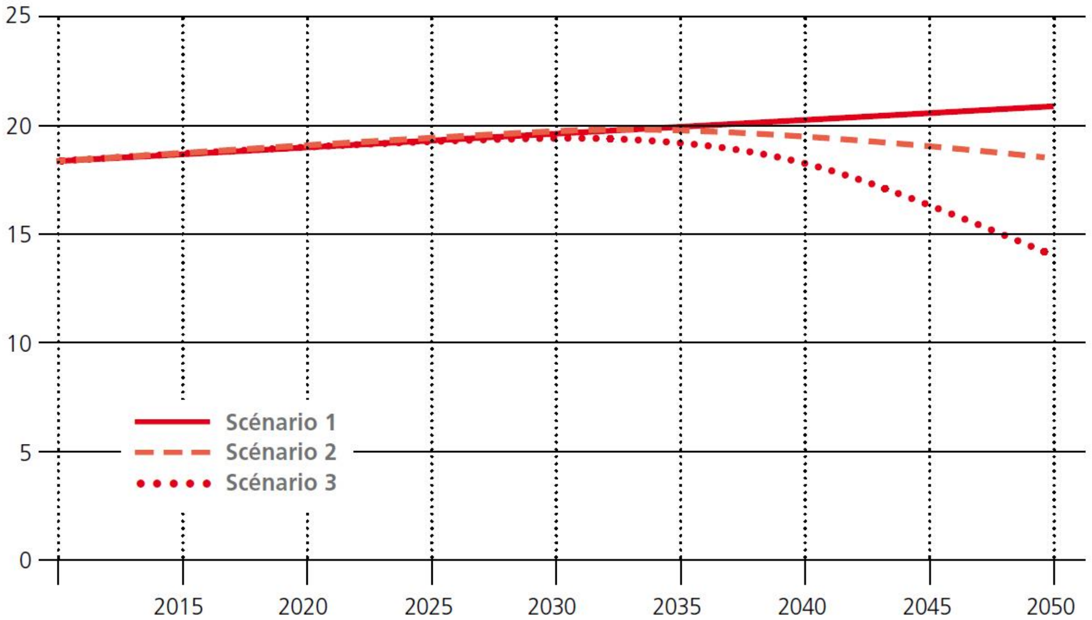
Own elaboration. (OFEN 2014) data.

Figure 8. Annual growth of total and domestic electricity demand in Switzerland.

Therefore, the three scenarios employed in the different simulations for modeling the evolution of the total electricity demand are:

- FG – Fast growth: +0.6% annually
- C – Constant electricity consumption
- FD - Fast decline: -0.3% annually

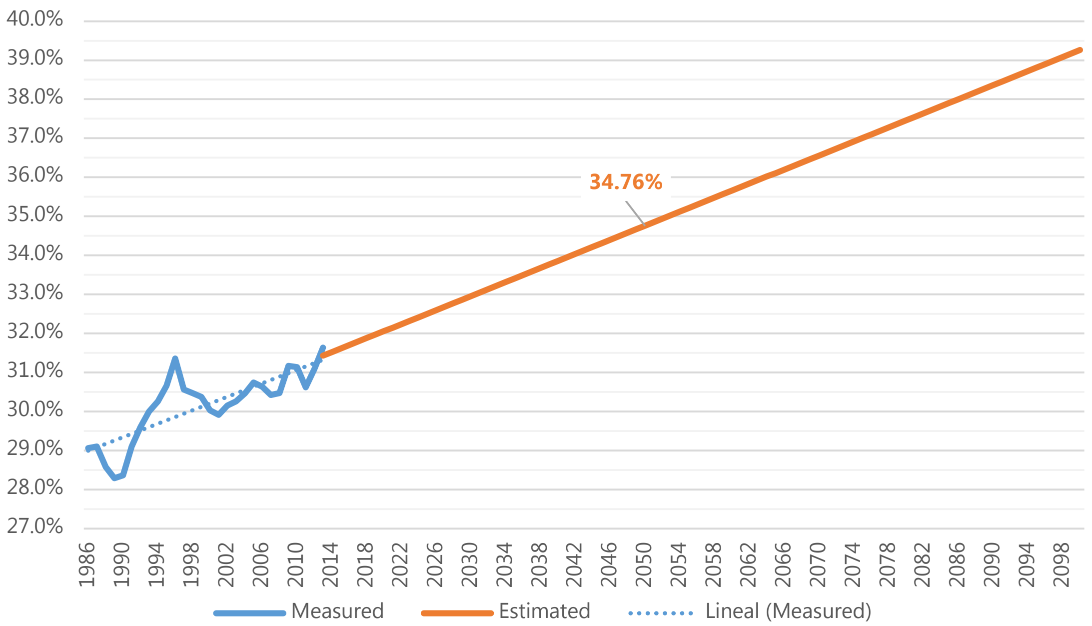
Additionally, the evolution of the domestic consumption is needed in the model given that the financing of the subsidizing scheme will be realized through taxes on domestic consumption. The share of domestic consumption has slowly grown in Switzerland for the last three decades since 29.06% in 1986 to a maximum of 31.64% in 2013 (OFEN 2014), and its evolution is foreseen by the AES as potentially different of the total demand (see Figure 10). According to the scenarios drawn by the AES, the share of the domestic consumption would be reduced to around 25% in all scenarios.



Adapted from (AES 2012).

Figure 10. Domestic electricity demand consumption in Switzerland evolution estimation, in TWh.

Notwithstanding it, analyzing the electricity demand statistics of the last decades in Switzerland, the overall trend in the share of domestic consumption seems to be very much otherwise (see section 2.3). A linear estimation of its evolution in the future based on the data from the last three decades suggest a strong increase up to above 39% (see Figure 9), which seems rather unlikely.

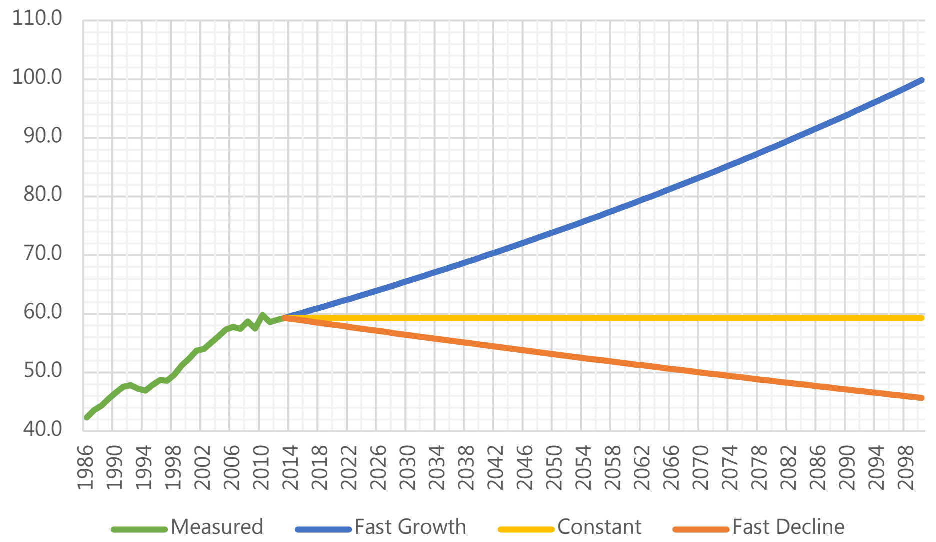


Own elaboration. (OFEN 2014) data.

Figure 9. Domestic electricity consumption evolution estimation.

To balance the contrasting estimations about the domestic consumption, we took a second look at the annual growth rates of both the total and the domestic electricity demand in Switzerland. The average annual growth of the domestic demand almost doubles the total demand growth rate in the last ten years (average for domestic consumption is 1.21% while for the total demand is only 0.75%, own calculations from (OFEN 2014) data).

Therefore, it does not seem probable that the domestic consumption share will decrease in Switzerland, but it is not convincing either that it will reach almost 40% in the future years. Given the complexity of modeling its evolution, a more simplistic approach was taken and the share was fixed at 35% for all simulations, which is the level it would reach around 2050 if it follows a linear evolution (see Figure 9). The final evolution of the total demand of electricity in Switzerland then depends on the scenarios defined, with a constant share devoted to consumption by households (see Figure 11).



Own elaboration. (OFEN 2014) data.

Figure 11. Measured and estimated evolution of total electricity consumption in Switzerland.

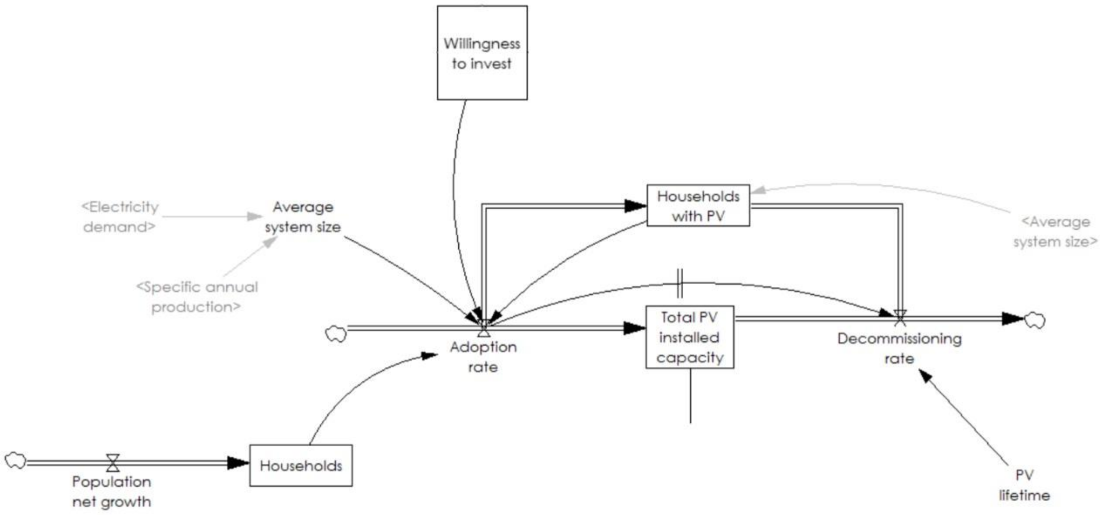
Once the “Electricity demand” is defined, we have now configured one of the main sections of the system that models the installations of PV systems (see Figure 12). One last additional caution has to be said before moving to the next sections. The definition of the “Willingness to invest” of households refers to the percentage of total households that are decided to invest in photovoltaic technologies. Hence, the adoption rate has to refer exclusively to the number of households that have not yet installed a PV system. In order to do so, only the number of willing households exceeding the number of “Households with PV” are accounted as adopting the technology (see Equation (1)).

$$\text{Adoption rate} = (\text{Households} \cdot \text{WTI} - \text{Households with PV}) \cdot \text{Average system size} \tag{1}$$

The following section of the model to develop is the one influencing the “Willingness to invest” of Swiss households that will determine the “Adoption rate” of photovoltaic systems. In order to do it, the combination of logical assumptions and literature references have been necessary.

5.2.2. Decision-making section

The decision of investing in solar photovoltaic technologies has some implications for households that are not present in the decision-making of other private investors, more focused on the balance between risk and return (Masini & Menichetti 2010; Masini & Menichetti 2013). From a behavioral perspective, the decision of purchasing a photovoltaic system is "a high involvement decision people usually make once in their lives" (Jager 2006). In understanding how rapid and to what extent a technological innovation such as photovoltaic system diffuses, five attributes account the most for explaining it: (1) relative advantage, (2) compatibility, (3) complexity, (4) trialability, and (5) observability (Rogers 1995). This five aspects relate to economic advantages of the innovation, compatibility with the current values, social norms and needs (besides other more obvious such as technical compatibility), complexity of adopting the innovation, possibility of trying the innovation without committing with its adoption and the degree to what the results of adopting an innovation are visible to others (Rogers 1995).



Own elaboration.

Figure 12. Photovoltaic system installation model.

In accordance with the work of Jager, the domestic photovoltaic systems are increasingly advantageous in economic terms thanks to the drop of its costs, and their compatibility with current values, particularly regarding to the rising environmental awareness, is high. However, the complexity of its adoption is considerable. Not only have the many different configurations available had to be considered and evaluated by the customer, but also their integration in its domestic electrical system and its connection to the grid. The latter requirement has usually to undergo official approval by the municipality, creating a bureaucratic barrier on top of the expertise barrier to determine the most suitable configuration (Jager 2006).

Photovoltaic systems also present a limited trialability since it is not usual to be able to install a reduce scale system in your house to try the innovation without directly investing in it. On the other hand, the installation of a solar system is clearly visible for the surrounding neighbors and the information technologies applied to the management of the production by the system from mobile devices (i.e. smartphones) have improved dramatically the visibility of the benefits for the final user.

In the case of households investing in photovoltaic technologies, the relevance of the time distance between the initial expenditure and the economic benefits of the innovation have to be considered. When it comes to decision-making, economic revenues in the distant future are applied a large discount rate, immediacy being highly rewarded by people (Loewestein & Elster 1992; Roelofsma 1996; Chapman 1998). The case of photovoltaic systems is then unfavorable since in most cases it renders negative cash flows in the early years until the largest part of the investment has been paid[3]. Again in accordance with Jager, reducing the "time discounting framing of the decision problem would stimulate consumers to install PV systems" (Jager 2006).

Dealing with the complexity of the decision is also crucial to enhance the adoption of this technology, which can be addressed in several ways. Perhaps, one of the most effective paths is the diffusion of the technology itself, since the information received from friends and neighbors will greatly reduce the uncertainty about the features of the innovation. What's more, when a customer interacts with someone who has successfully installed a PV system, "social comparison processes" emerge facilitating the exchange of information and putting social pressure on the non-adopter to gain access to the benefits delivered by the adoption of the PV system (Jager 2006). If the information exchange is further formalized into local associations or movements, the observability of the innovation and the peer-effect favoring the adoption of the solar technology are much strengthened (Seyfang & Haxeltine 2012; Dewald & Truffer 2012). Other strategies, such as local meetings and demonstration sites have proved to be effective tools to palliate the principal cause of the perceived complexity: lack of information and knowledge (Jager 2006; Brown & Hendry 2009; Balcombe et al. 2014). In the case of Switzerland, actions taken by the public organisms and municipalities could see greater relevance than in other places thanks to the high influence and reliability Swiss households put in them (Kaenzig & Wüstenhagen 2008).

Although the discussion on the motivators of photovoltaic adoption could be much longer, the prominence of some aspects of the technology influencing its adoption could be easily spotted at this stage: (1) economic barriers, (2) favorable attitude towards the technology, and (3) easiness to install the systems. In order to corroborate the justification of summing up the varied factors into this three hubs, quantitative data from surveys on adopters of PV systems was searched in the literature, with little success. No quantitative information was found for Swiss adopters of PV systems, and thus it was necessary to use different international sources studying the motivations behind the adoption of the technology by American, British and Dutch citizens (see Table 2).

As it can be read in Table 2, decision-making factors cited as most influencing by domestic adopters of photovoltaic systems usually comprise a mixture of economic benefits, environmental awareness and social pressure from acquaintances. It is relevant to highlight that the absence of complexity barriers is not present as a motivator, but its existence can lead to demotivation of consumers in a similar fashion that Herzberg discriminated between hygienic and motivating factors (Herzberg 1968). However, commercial advertising campaigns launched by private companies can improve diminishing the complexity of the decision and simultaneously moving consumers to adopt the innovation (Sigrin & Drury 2014).

[3] It has to be said that the introduction of financing mechanisms such as "project finance" or other schemes such as buying the electricity generated by the system installed in one's rooftop without being its owner until long time after the installation, are becoming the solutions to this problem devised by the industry with good examples of it in the United States. Nevertheless, due to time constrains, in this report a more simplistic approach is followed where the customer has to buy the system in order to benefit from the electricity production of it.

Table 2. Decision-making factors relevance for adopters of domestic PV systems.

Decision-making factor	(Jager 2006)[a]	(Rai & McAndrews 2012)[a]	(Sigrin & Drury 2014)[b]	(Balcombe et al. 2014)[c]	(Korcaj et al. 2015)[a]
Contribution to a better environment	4.22	3.94	-	16.6	3.67
Economic benefits (i.e. grant, FIT)	4.21	3.94	-	-	2.94
Protection against future higher electricity costs	-	-	32	24.1	
Increase value of the household	2.97	-	-	-	
Independence from the grid and utility companies	2.49	-	-	23.6	3.96
Neighbors or friends have installed PV systems	2.07	1.53	21	-	2.41
Alternative way of investment	-	-	24	-	3.15

[a] In an scale from 1 (Not important at all) to 5 (Very important), in the case of (Korcaj et al. 2015) it has to be converted from a 0-6 scale.
[b] The values reflect the relative importance of the factors, where all motivators and barriers sum 100. The values for adopters are shown in here, with the main difference with rejecters and considerers is a higher environmental awareness by the formers and higher attention to economic criteria by the latter. In the evolution over time of these factors' importance, it is clear how the environmental commitment of first adopters leave place to more practical (mainly economical) considerations of later adopters (see Figure 1 in (Sigrin & Drury 2014)).

Aggregating the factors gathered in the literature, the three variables mentioned before are introduced into the system as the determinants of the "Willingness to invest" of households. In order to review the configuration of each of them, we will start with the "Easiness to install".

Based on the barriers mentioned by photovoltaic system adopters (mainly economy and complexity related), as well as the experience gained from the diffusion processes in other countries (Balcombe et al. 2014; Karakaya et al. 2015), three variables were set to be influencing the "Easiness to install": "Capital access", "Solar PV market size", and "Standards & Regulation", which is the first policy-dependent variable introduced in the model so far (see Figure 13).

An average photovoltaic system of 4.5 kW could easily surpass the 15,000 CHF cost (own estimation based on (Husser et al. 2013)), therefore, the easiness to access credit can heavily influence the adoption of the technology. An easier access to credit will then increase the easiness to install the systems, making it more likely for considerers to finally adopt the technology.

Switzerland has been consistently ranked among the easiest countries to get credit and it is not expected to change in the foreseeable future (Barth et al. 2010). However, there is not a standardized metric to measure the easiness to get credit despite some efforts into that direction, however mostly oriented for businesses (Barth et al. 2010; World Bank 2014). In our own attempt to do it while keeping the system simplicity, a scale from 0 (very difficult) to 0.5 (very easy) was chosen to represent this factor. Despite the attempts to make this factor dynamic, since it is understand that a wider diffusion of the technology could ease the barriers of private institutions to approve private consumption credits to Swiss households, the lack of information (and time) determined us to keep it static. The value of this variable was then taken as constant at 0.4 in accordance to the good results of Switzerland shown in the Milken

Institute reports (Barth et al. 2010) and the not so favorable performance in the survey of the World Bank (World Bank 2014).

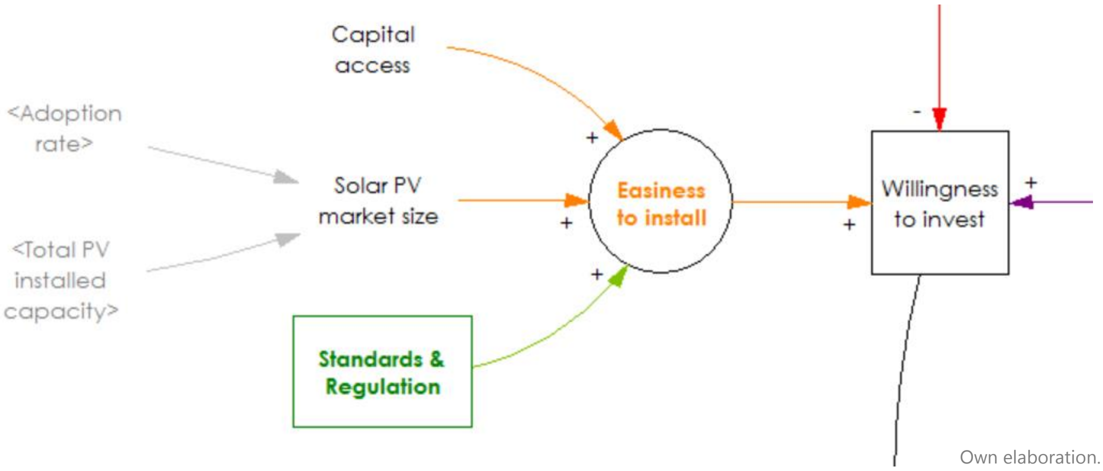


Figure 13. Easiness to install model section.

Similar problems arose when trying to model the influence of standardization and regulation of the market in the decision making of consumers, with the additional complexity of a political measure that has to be time framed as well as its consequences. Again, the lack of relevant information, despite some articles defending its relevance (Oliva H. et al. 2014), moved us to fix it at a constant value of 0.5 once introduced in the system by 2020 (five years afterwards the subsidizing scheme enters into action).

The "Solar PV market size" was set to reflect the annual power that the Swiss market is able to install. It is considered to be a critical influencer of the "Easiness to install" the technology given it can actively encourage consumers to become adopters and a widespread presence of installers can significantly reduce the complexity barriers for consumers. However, both its formation and growth as well as it influence are complex and hard to model.

To overcome the limited insights into the factors defining the "Solar PV market size" variable and its impact downstream it was set to have a minimum constant size of 300 MW (in agreement to what the sector installed yearly in 2012 and 2013 in Switzerland (Husser et al. 2013)) and a variable additional capacity based on the "Adoption rate" of the technology and the "Total PV installed capacity".

The size of the solar market is then decided to perceive a smoother version of the adoption rate and to forecast its growth in the next two years by taking into account the values of it in the latest three exercises[4]. Additionally, to model the influence of a growing installed capacity that will require maintenance services and occasional replacement, the size of the market is influence by the total capacity present, corrected by a factor of 1/100 no to over-dimension the market (see Equation (2)). In order to ensure the market is able to fulfill the needs of the households, it is assume that the private companies are always exceeding the forecasted needs of consumers by a 25%.

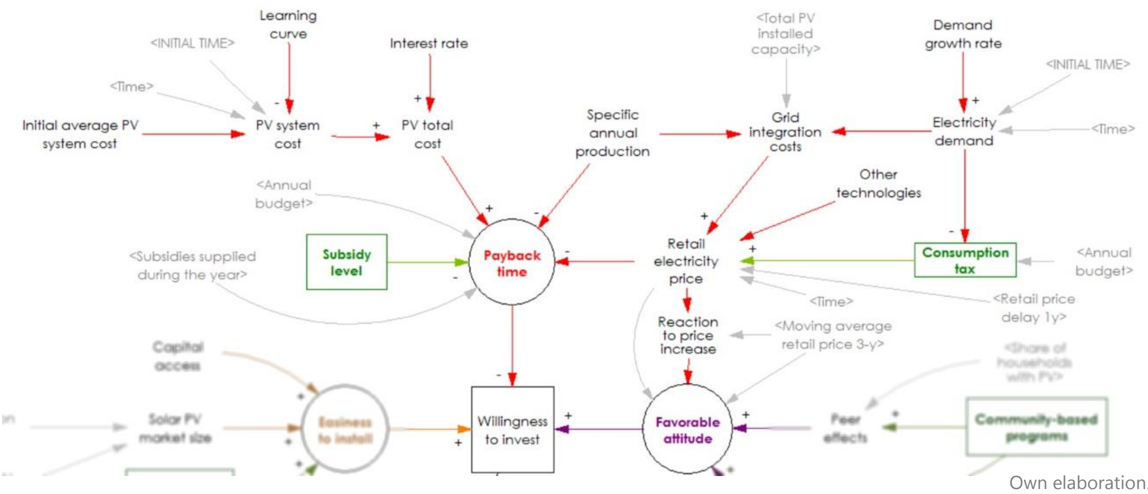
$$\text{Solar PV market size [kW]} = 300{,}000 + 1.25 \cdot \text{FORECAST(Adoption rate} + 0.01 \cdot \text{Total PV installed capacity)} \tag{2}$$

[4] This is done by employing the function FORECAST(input, average time, time horizon) available in the software Vensim (Ventana Systems Inc. 2012).

The influence of this three factors is gathered at the "Easiness to install" where they are weighted following the logical assumption that hygienic factors (such as the access to credit or the regulation of the market) are much less noticeable motivators for innovation adoption. Hence, the market size is weighted with 80% relevance, while the other factors are attributed only 10% each. Additionally, and in order to keep units coherence, the size of the solar market is divided by a factor 1/8e6 so that the values of the "Easiness to install" remain between 0 (extremely difficult to install) and 1 (extremely easy to install).

Once complete this part of the system, the second and most relevant factor defining the "Willingness to invest" of Swiss households in photovoltaic systems is then build: the economic criteria. Among the varied metrics to determine the economic benefits of an investment alternative (i.e. NPV, rate of return), the payback time of the technology (i.e. the time needed to overcome the costs of the investment and start receiving net positive capital flows) is usually ranked as the most used in close competition with the monthly annual savings (Rai & McAndrews 2012; Sigrin & Drury 2014). Besides, it was the only economic factor for which quantitative data on how it affects the adoption of domestic photovoltaic systems was available (Sigrin & Drury 2014) and thus it has been chosen to represent the economic criteria of consumers (see Figure 14).

In order to evaluate the payback time of domestic PV systems in Switzerland, it was necessary to know both the average cost and electricity production of this kind of systems[5] in Switzerland, and the average electricity price for households. If we begin by taking a look at the system costs, it is clear they have experience an impressive plunge in the latest years (see Figure 15).



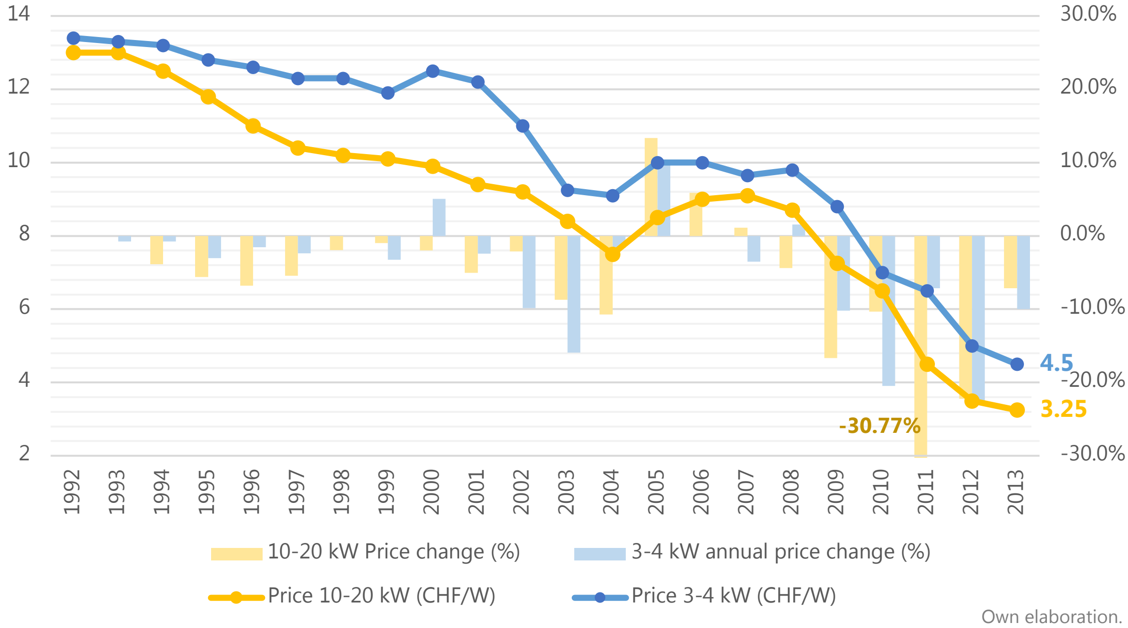
Own elaboration.

Figure 14. Economic criteria model section.

In order to simulate it, the initial cost of 4,500 CHF/kW achieved in 2013 for systems between 3 and 4 kW is used to start its progress towards lower levels. The "Learning curve" represents the annual decrease in costs of the system and what is conservatively (see Figure 15) set at 3%. To prevent an unrealistic fall of prices in the long term, based on the experience of the German market that seems to stabilize around a cost of 1,600 EUR/kW (Fraunhofer ISE 2014; BSW-Solar 2014) and the projections for the

[5] It is used the system cost that includes all necessary hardware for the installation of the photovoltaic system, as well as all the costs incurred in its installation.

US residential market (Drury et al. 2010), once the price reaches this level, it continues a slower linear decrease of 12 CHF/kW each year what would be easily noticeable in some of the scenarios (see Figure 16).

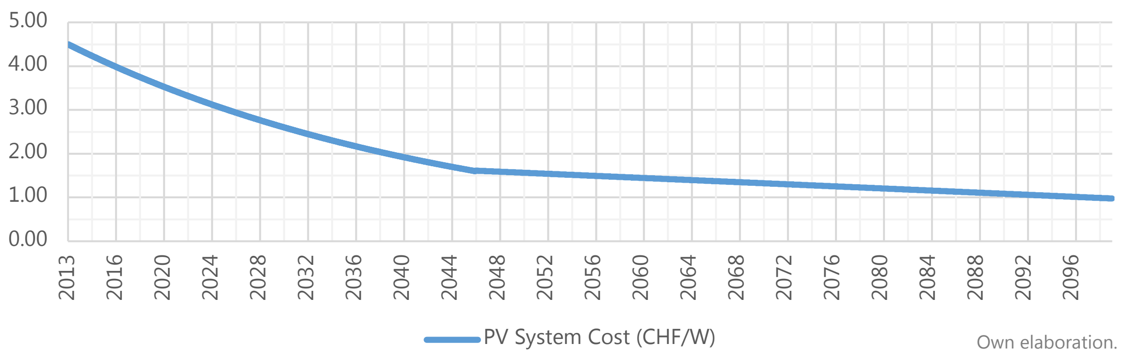


Own elaboration.

Figure 15. Evolution of photovoltaic system costs in Switzerland.

The decrease rate is heavily conservative not only taking into account the latest annual changes shown in Switzerland, but also when compared with the development of the industry elsewhere. Particularly impressive is the case of the United States where the yearly decrease was around 5% to 7% in the years 1998-2011, reaching 11% to 14% in more recent years (NREL 2012).

Coherently with the approach in the "Easiness to install" section, since we are assuming that households will have to incur in new credits to finance the investment in the solar systems, the final cost of the system is increased by the interest rate they will have to pay. Swiss adopters usually manage to enlarge its mortgages to include the investment necessary for the photovoltaic system (Husser et al. 2013) and its interest rates are commonly as low as 1% to 2.5%. According to some of the most relevant financial institutions in Switzerland, the interests are not expected to rise in the upcoming years (UBS 2015; Credit Suisse 2015) and thus a 3% is assumed.



Own elaboration.

Figure 16. PV system costs evolution estimation, in CHF/W.

Once the total costs of the system are modeled, and taking into account the specific production mentioned before, the other part necessary to establish the payback time of the technology is the average retail price of electricity. In order to avoid the complexities of relating the electricity demand and the changes in end-consumer prices, it has been simplified so as to be dependent on: the grid integration costs derived from the adoption of photovoltaic systems, the mixture of technologies producing the Swiss electricity and the consumption tax for financing the subsidies to this renewable energy, which is the second policy-related variable we introduced in the system.

Due to the highly complex behavior of electricity markets and the possibility of including it once the different models studying the energy transition in Switzerland are assembled together, the different technologies in the system are not modeled.

The "Grid integration costs" are modeled in accordance to a detailed econometric study by Ueckerdt and his team (Ueckerdt et al. 2013). Their work is based on the innovative concept of "system LCOE" that includes not only the operational costs of the technology, but also the costs produced to the whole system due to: backup costs, reduction of hours of conventional plants[6] and overproduction costs. Additionally, the reinforcement costs of the grid are also taken into account so as to achieve a cost function dependent on the share of photovoltaic energy in the mix, it is, on the penetration of the technology (see Figure 17).

Avoiding unnecessary complexities, our approach to include this important factor in the system was to linearly approximate the behavior studied by Ueckerdt and others (Ueckerdt et al. 2013). However, since the costs seem to increase substantially when 15% penetration is achieved, the estimation presents two differentiated zones that have visible repercussions in the retail electricity price and the subsequent elements of the system.

These costs are then passed to the end-consumers on top of the market price of electricity, but with the caution of only charging domestic consumers by dividing the additional costs of the system by their consumption. This is the exact same approach employed for the financing of the subsidies through the "Consumption tax" that evenly distributes the need to pay the annual budget for subsidies.

It is clearly noticeable that the decision to pass these costs to domestic consumers are not a natural result of the system, but rather of the political design of it whose implications for the whole functioning of the system are not negligible. Therefore, the simulation of different policy scenarios related with the translation of these costs into the end-consumers were built:

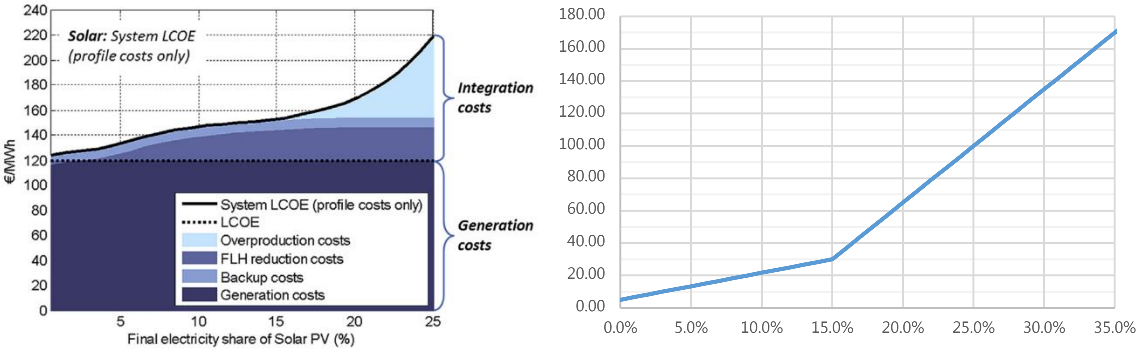
- FT – Free tax scenario: the additional cost of integration costs and subsidies are totally translated to domestic end-consumers
- LT – Limited tax scenario: the burden to end-consumers is limited

This way, the retail electricity price is increased by the grid integration costs and the subsidies to the technology in a dynamic way that is added on top of the base price of the electricity. This base price is not assumed to be constant, but to linearly increase through time. To model it, it has been required a detained study of the evolution in the latest years.

Switzerland, as many other countries, have a myriad of different consumption profiles for the different end-consumers to which different prices are charged. In our case, the most relevant profiles are those closer to the average household, namely the

[6] It is treated in detail in their work calling this factor FLH (Full-Load Hours) costs, for a more extensive explanation, please consult (Ueckerdt et al. 2013).

H4 and H5 profiles[7]. For this two profiles, the prices charged in the different cantons change quite substantially and a compromise solution had to be adopted, choosing to employ a simple average on the price among the different cantons. Given the limited information available in the OFEN reports (see Figure 1), a closer look at the prices evolution in the recent years was done by analyzing the raw data provided by ElCom (see Figure 18).



Extracted from (Ueckerdt et al. 2013). Own elaboration.

Figure 17. Grid integration costs dependence of PV electricity share of final consumption, in CHF/MWh.

It is relatively easy to extrapolate a trend of moderate increase in the average, electricity prices domestic consumers are charged in Switzerland, and it has been taken as the base price for electricity in the model, growing linearly 0.22 cents of franc per year.

Now that we have defined all the elements needed to compute the payback time of the system, we can now turn into the definition of the most influencing policy-dependent variable: the "Investment subsidy".

Given economic reasons lie at the core of the investment decisions of households (see Table 2), improving the economic performance of the photovoltaic systems has been the main goal of policy measures concerning the diffusion of this technology. The Swiss government recently decided to move into an investment subsidy policy to incentivize the adoption of PV systems, replacing the FIT scheme formerly in place (see section 2.3 or (Husser et al. 2013)). This strategy consists in reducing the total cost of the system by some percentage at the installation moment, thus reducing the payback time proportionally. Given the great impact this have in the system, and also the relevance it has concerning its impact in the retail electricity price, several policy scenarios are considered:

- Constant subsidy - a fixed 30% of the system total cost is paid by the government during all the years the policy is in place (2015-2050)
- Stepwise subsidy - the percentage of the investment covered by the government changes from 30% to just 10%

Including this investment subsidy, the payback time can be now computed by employing all the above described variables (see Equation (3)):

[7] H4 tariff is assigned to 4,500 kWh/year consumers (5 pieces apartment) and H5 is the consumption profile of a 7,500 kWh/year house (ElCom website).

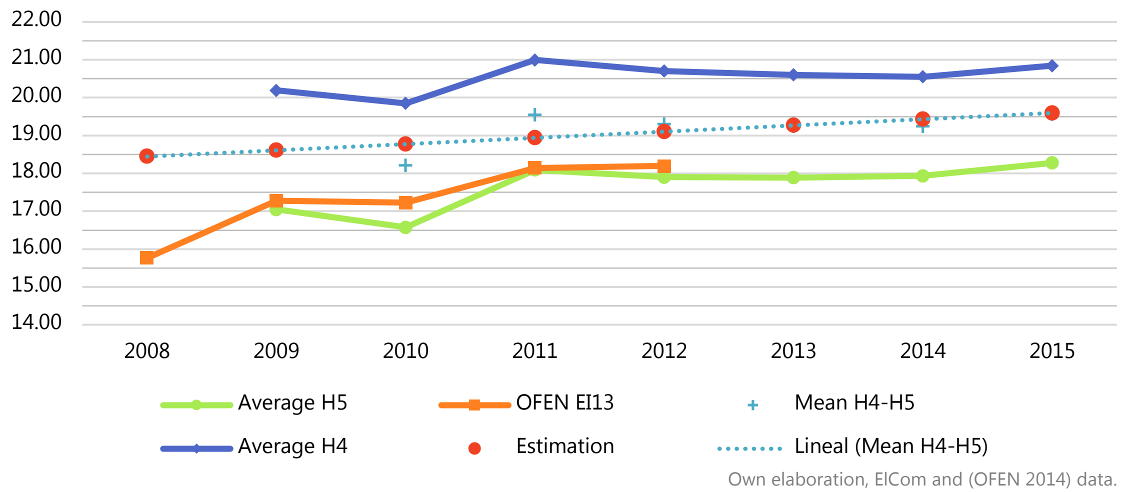


Figure 18. Retail electricity price (including VAT) recent evolution and estimation, in cents CHF/kWh.

$$\text{Payback time [years]} = \frac{\text{PV total cost [CHF/kW]} \cdot \frac{(1 - \text{Investment subsidy})}{\text{Specific annual production [kWh/(kW} \cdot \text{year)]}}}{\text{Retail electricity price [CHF/kWh]}} \quad (3)$$

This is a simplified version of the usual payback time function employed for evaluating PV systems. Most often, the total PV investment cost is divided by the annual savings in the electricity bill (which would be the annual self-consumption minus the required consumption from the grid). In our model, given the strong assumption that the PV systems installed by Swiss households are able to match their needs completely, the annual consumption is taken equal to the annual production (see Equation (4)), thus the savings results to be the price of the electricity price times the annual consumption of the household. On the other hand, the cost of the system would be described by the power installed times the cost per kW (see Equation (5)).

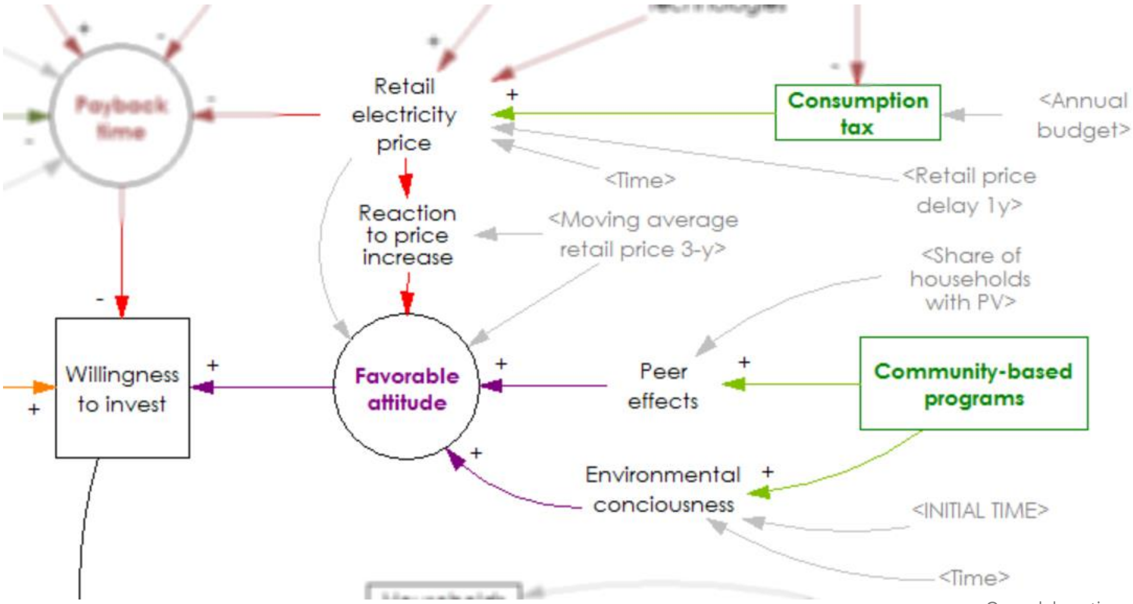
$$\text{Annual consumption [kWh/years]} = \text{PV Power [kW]} \cdot \text{Specific annual production [kWh/(kW·year)]} \quad (4)$$

$$\text{Payback time [years]} = \frac{\text{PV Power [kW]} \cdot \text{PV total cost [CHF/kW]}}{\text{Retail electricity price [CHF/kWh]} \cdot \text{Annual consumption [kWh/years]}} \quad (5)$$

Reached this point, it is straightforward to deduce Equation (3), which is used in our model with one caution: the investment subsidy is only apply when there are founds enough to do it (see below 5.2.3).

This concludes the economic subsection in the decision-making section of the model, and now the “Favorable attitude” modelling is presented, which happens to be deeply related to some aspects of the economic section.

Despite the lack of information on the subject, the combination of different sources has allowed us to establish three main drivers of a favorable attitude towards photovoltaic. Nonetheless, these three drivers are considered within the current context existing in Switzerland, this is, an environment of general support of the technology with no major concerns (i.e. the strong opposition to wind energy mainly due to its visual impact (Wüstenhagen et al. 2007)).



Own elaboration.

Figure 19. Compatibility (favorable attitude) criteria model section.

Despite the lack of research linking electricity price increases with the change in people view of the photovoltaic technology, given the relevance economic barriers bear in the decision-making of potential adopters, it has been modeled to be the most relevant factor modifying the favorable attitude of households. For doing so, an auxiliary variable has been designed “Reaction to price increase” that compares the current ”Retail electricity price” with the ”Moving average retail price 3-y”, given the assumption that customers will only be aware of price increases in their near past.

For modelling the reaction of households, a logistic curve (a.k.a. S-curve, or sigmoid curve) has been chosen, so that the reaction would be limited unless the increase is considerable. Logistic functions (see Equation (6)) are defined by three parameters: the curve maximum value (L), the point at which it reaches the sigmoid’s midpoint (x_0), and the steepness of the curve (k). For this case, we have modeled the behavior of households so that they will react most strongly when the price change is larger than 4%, both in favor (if the price drops) or against (if it raises).

$$f(x) = \frac{L}{1 + e^{-k \cdot (x - x_0)}} \tag{6}$$

Additionally, the same curve has been employed to weight the relevance into the favorable attitude of the three factors influencing it: the “Retail electricity price”, the “Peer-effects”, and the “Environmental consciousness”. It has been done so in order to reflect the logic that, despite the two latter factors relevance, if the price increases strongly, people would react with similarly strong opposition to a further diffusion of the technology. This way, when prices are more stable or grow/decrease at a moderate path, the fact that other neighbors put PV systems in their homes or that environmental awareness becomes the norm gains relevance.

The literature supporting the relevance of peer-effects in technology innovations diffusion processes, and particularly regarding the photovoltaic technology, is not extensive, and few empirical results are available (except some meritorious exemptions (Bollinger & Gillingham 2010; Müller & Rode 2013)). Therefore, a simple assumption was taken: the relevance of peer-effects would grow linearly with the "Share of households with PV" following the logic that the more households with PV, the more likely is to be exposed to social pressure for profiting of the same advantages that one's neighbors are enjoying. The effect is reinforced by the presences of "Community-based programs" that boosts the visibility of the adopters and enhances the informal transmission of experiences.

The local scale initiatives, backed by local governments (i.e. municipalities) have proved effective in expanding the adoption of photovoltaic technologies (Ornetzeder & Rohracher 2006; Brown & Hendry 2009; Seyfang & Haxeltine 2012) and the direct involvement of users in the development of the market has also been seen as useful since long (Abernathy & Utterback 1978; Ornetzeder & Rohracher 2006). Therefore, the policy-dependent variable "Community-based programs" was included in the model. Nevertheless, the complexity to model its effects at a macro-level could not be addressed properly due to lack of resources and it is left for future works. Instead, it was simplistically modeled as a stepwise effect increasing periodically by 2015 (when it enters into action), 2025 and 2035.

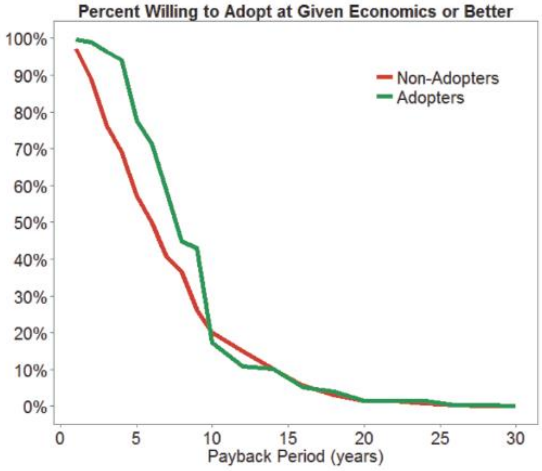
This policy also enhances the spread of "Environmental consciousness". Given that environmental reasons have been behind the adoption of PV systems in the early years of the technology, it is supposed to keep playing a significant role to legitimate the investment. Environmental awareness is modeled to grow exponentially but at a slow path, only 2% annually. This translates into a relative irrelevance in the first years of the simulation, but growing importance when 2100 is arriving. The logic behind this assumption is that growing environmental problems will boost environmental consciousness, though the gradual growth of these problems will limit the raise of those more concerned about them.

These three factors then conform the "Favorable attitude" towards the technology that, oppositely to other factors (i.e. easiness to install, payback time) is left free to go negative so as to model the potentially large opposition to the technology derived from sudden, strong price increases.

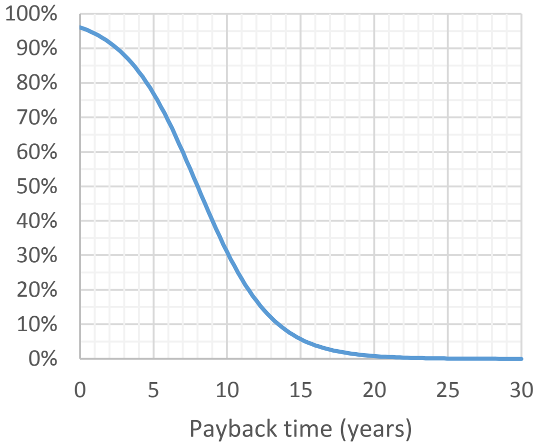
This way, all the three factors building up the "Willingness to invest" gather at this key variable of the system. Although other approaches could be explored in future works, this study has chosen to keep it relatively simple and the variable represents the share of Swiss households willing to install a photovoltaic system (without discriminating if they already have one). In other words, it is the share of households that would buy a photovoltaic system with a probability of 100%.

Due to the relevance of the economic factors in the decision making of potential adopters (see Table 2), the same strategy employed for weighting the different causes defining the favorable attitude to the technology has been put in place in here. Hence, the payback time would be weighted more when it becomes lower following the logic that if the investment makes economic sense, the rest of criteria loss some of their relevance (and also to avoid that if the subsidy becomes 1, the PV systems are fully paid by the government (!), the "Willingness to invest" could be less than 1).

The lack of data for linking the "Easiness to install" or the "Favorable attitude" to the willingness to invest in PV, a secondary reason to lower their weights in the decision-making process, has been saved by a simple approach in which their contributions are only affected by the weighting factor so that it is not possible to have a "Willingness to invest" greater than one. On the other hand, there has been found studies from the United States linking the payback time of domestic PV systems to the willingness to buy them of potential adopters (Drury et al. 2010; Sigrin & Drury 2014). The approximate shape of a logistic curve (see Figure 20) has motivated its approximation with one of them, where 8 years is the value below what the willingness becomes much higher, what mostly explains the S-shape of most scenarios.



Extracted from (Sigrin & Drury 2014).



Own elaboration.

Figure 20. Willingness to invest relation with the payback time, measured and estimated.

5.2.3. Subsidy accountancy section

The main goal this section is to control the financial resources allocated for encouraging the installations of PV systems. In doing to it automatically set the annual targets to reach the desired goals by the predefined deadline, adjusting according to it the budget assigned annually to subsidies. Additionally, it registers the subsidies delivered and stop the flow once the annual budget is reach.

So as to successfully fulfill all these aims, the system first needs to know the global target of the policy and the deadline to reach it. Both of these variables are intrinsically policy-dependent and thus are susceptible of being modified to study their effect. The deadline, for simplicity purposes and coherency with the Federal Government strategies (BFE 2012), is set to be 2050 in all scenarios (i.e. the encouraging policies are active between 2015 and 2050). Oppositely, several variations are analyzed for the definition of the global target configuring the following scenarios:

- BS - the base scenario uses a 100% global target, hence it aims at replacing all domestic consumption with photovoltaic production
- CG - the goal is kept constant at 14 GW of photovoltaic power[8]
- SG - stepwise goal in which the share of the domestic electricity demand aimed at being replaced by photovoltaic grows sequentially
- Mk - the goal is no longer fixed, but it is the system itself which regulates how much PV power it is willing to accept

The "Global target" is then compared with the "Total PV installed capacity" in order to obtain the distance still existing to reach the goal by the "Distance to global target". When the target is established as a percentage of the domestic electricity

[8] This figure comes from the among to photovoltaic capacity needed to reach the estimated 12 TWh of solar electricity by 2025, if we take around 900 kWh/kW, that the Swissolar professional association predicts as the potential capacity of PV systems in Switzerland (Swissolar 2015).

consumption, the auxiliary variables “Electricity demand” and “Specific annual production” are used.

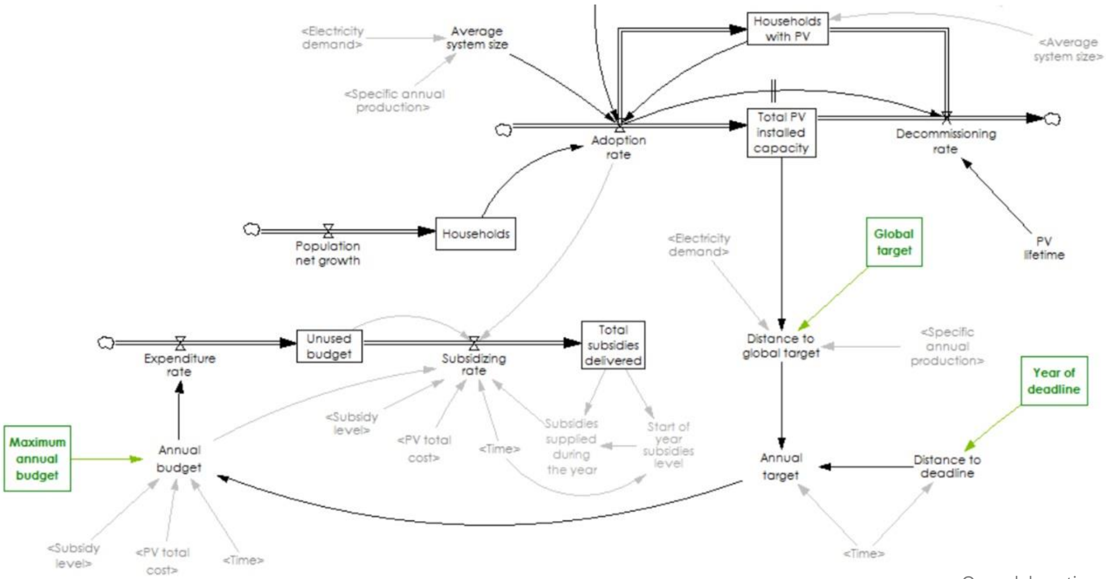
The distance to the goal, expressed in kW of PV systems needed, is then considered regarding how many years is the deadline away, and the annual target is set so that along the years remaining the same power is installed (this is, dividing the power required by the remaining number of years up to the “ Year of deadline”). We achieve then an “Annual target” thanks to the employment of an auxiliary variable “Distance to deadline” accounting the years distance to 2050.

The annual target is then the main input to compute the annual budget allocated for photovoltaic system subsidizing, with the last policy dependent variable: “Maximum annual budget”. The annual budget is equal to the cost of the annual target times the PV total cost and the subsidy level of that year (see Equation (7)), except if this amount exceeds the “Maximum annual budget” which is set constant to all simulations at CHF 250 million (Weibel 2011).

The “Annual budget” is then put to use by employing a stock variable “Unused budget” that received the annual allocation of money through the “Expenditure rate” (which equals the annual budget), and is spent according to the “Subsidizing rate”. This is the key variable of this section and it is also the inflow rate for the “Total subsidies delivered” stock variable that keeps a record of how much money has been put into subsidies.

$$\text{Annual budget [CHF]} = \text{Max}(\text{PV Total cost [CHF/kW]} \cdot \text{Annual target [kW]} \cdot \text{Subsidy level}, \text{Maximum annual budget [CHF]}) \tag{7}$$

The “Subsidizing rate” equals the cost of subsidizing all systems being installed until the amount delivered reaches the annual budget for that exercise or the available money does not reach that quantity, being equal then to the “Unused budget”. In order to carry out this task, two auxiliary variables had to be designed so as to keep a track of the money delivered every year: “Start of year subsidies level”, that reads the “Total subsidies delivered at the beginning of each year and is then used as the starting point; and the “Subsidies supplied during the year” that accounts the difference between the current “Total subsidies delivered” and the level at the start of the year. In sum, this allows us to achieve a controlled expenditure that mimics the strategies adopted by the Swiss Federal Government (Weibel 2011).

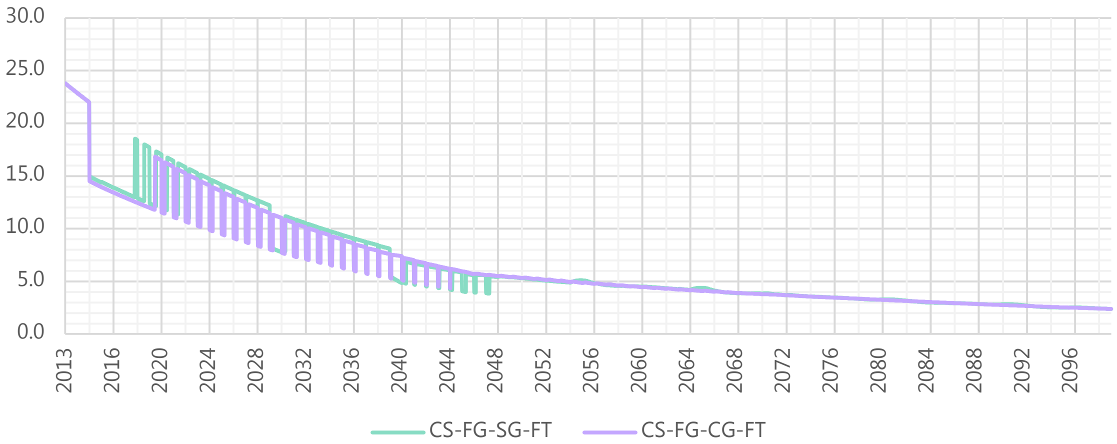


Own elaboration.

Figure 21. Subsidy accountancy model section.

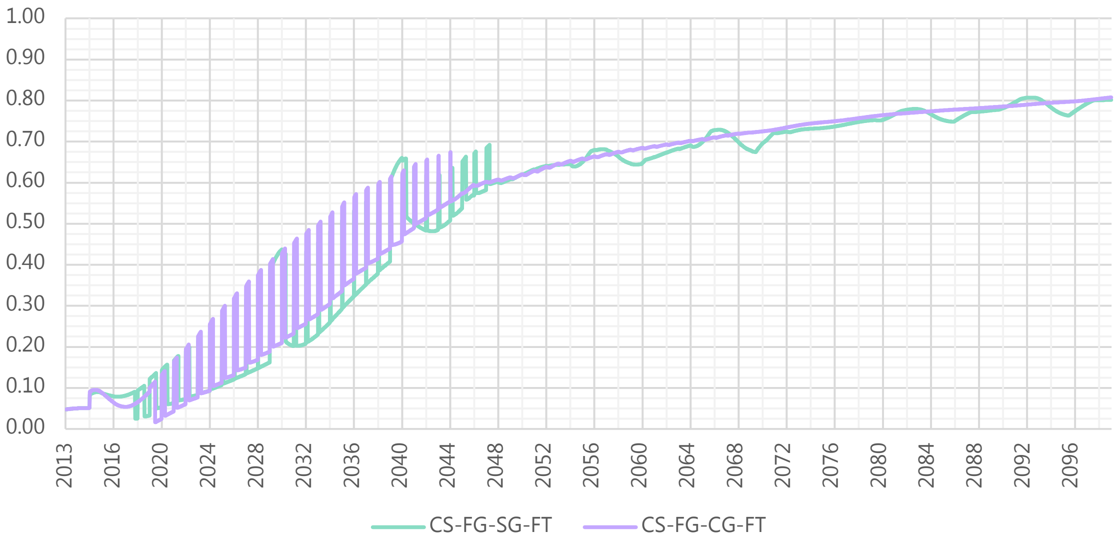
When the subsidies delivered during the year reach the maximum set for that year, the subsidizing rate falls to zero and the “Subsidy level” is then not included in the calculation of the “Payback time” (see section 5.2.2 and Equation (3)). The impact of the subsidy level in the payback time of the technology is very substantial, reaching more than 5 years in the first years of the simulations, with a similar pattern in all scenarios (only as an illustration, see Figure 22 and Figure 23).

An additional part of the system is needed for those scenarios where the cost of the subsidies are not entirely charged on the domestic consumers (LT scenarios, see section 5.2.2). In these configurations, whenever the costs derived from the integration of the technology in the grid or the financing of the annual budget exceeds, each one, the 15% of the retail electricity price. The excess is then attributed to “External financing needs” which determines the inflow rate of a stock variable measuring the total financial needs not covered by domestic consumers (see Figure 25).



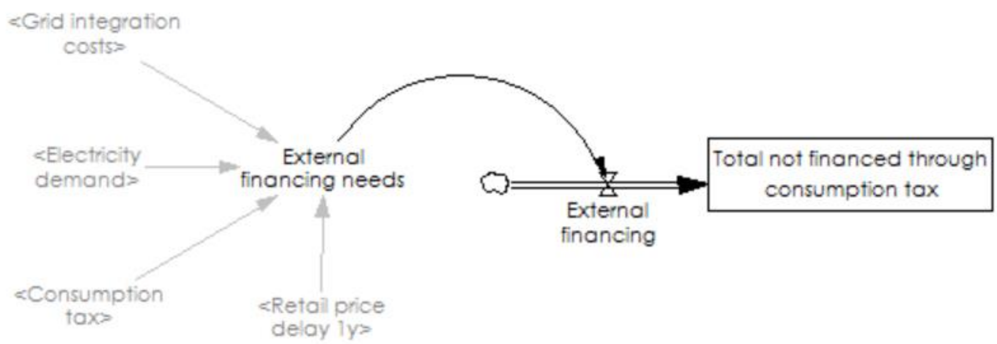
Own elaboration.

Figure 22. Illustration of the subsidies accountancy system effect on the payback time.



Own elaboration.

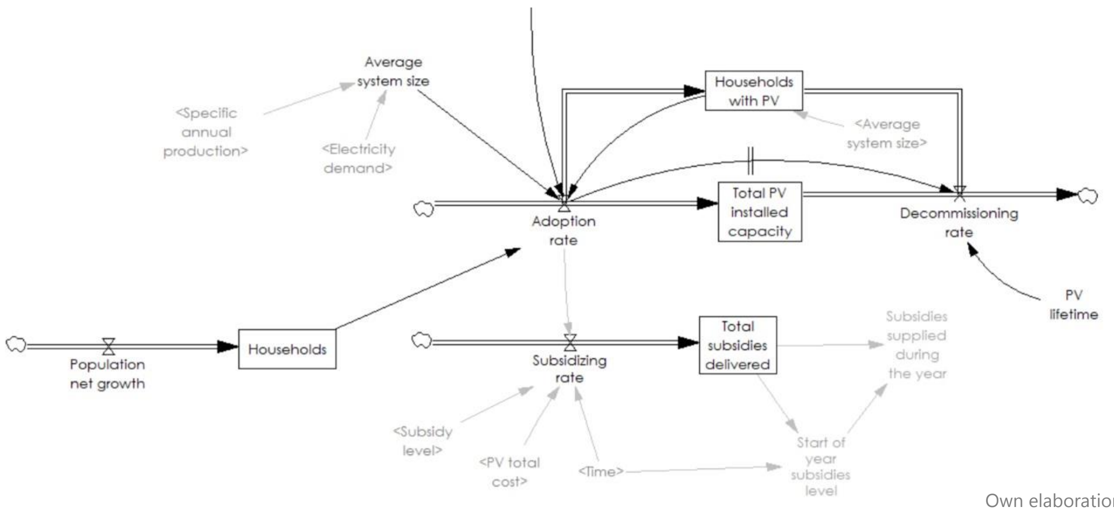
Figure 23. Illustration of the subsidies accountancy system effect on the willingness to invest.



Own elaboration.

Figure 25. External financing accounting model section.

This accountancy system is useful for the scenarios where the government defines the goals for the installation of PV systems. In the scenarios where there is any predefined goal (Mk scenarios), the installations are subsidized without any limitation in the number of them, but the increase in the price of electricity due to the integration costs and, mainly, to the financing of the subsidies delivered, regulates the system behavior. Therefore, a much smaller and simpler scheme for registering the subsidies delivered is needed (see Figure 24). Another difference derived from the new scheme is that consumers do not finance the annual budget through a consumption tax, but instead the cost of all subsidies delivered.

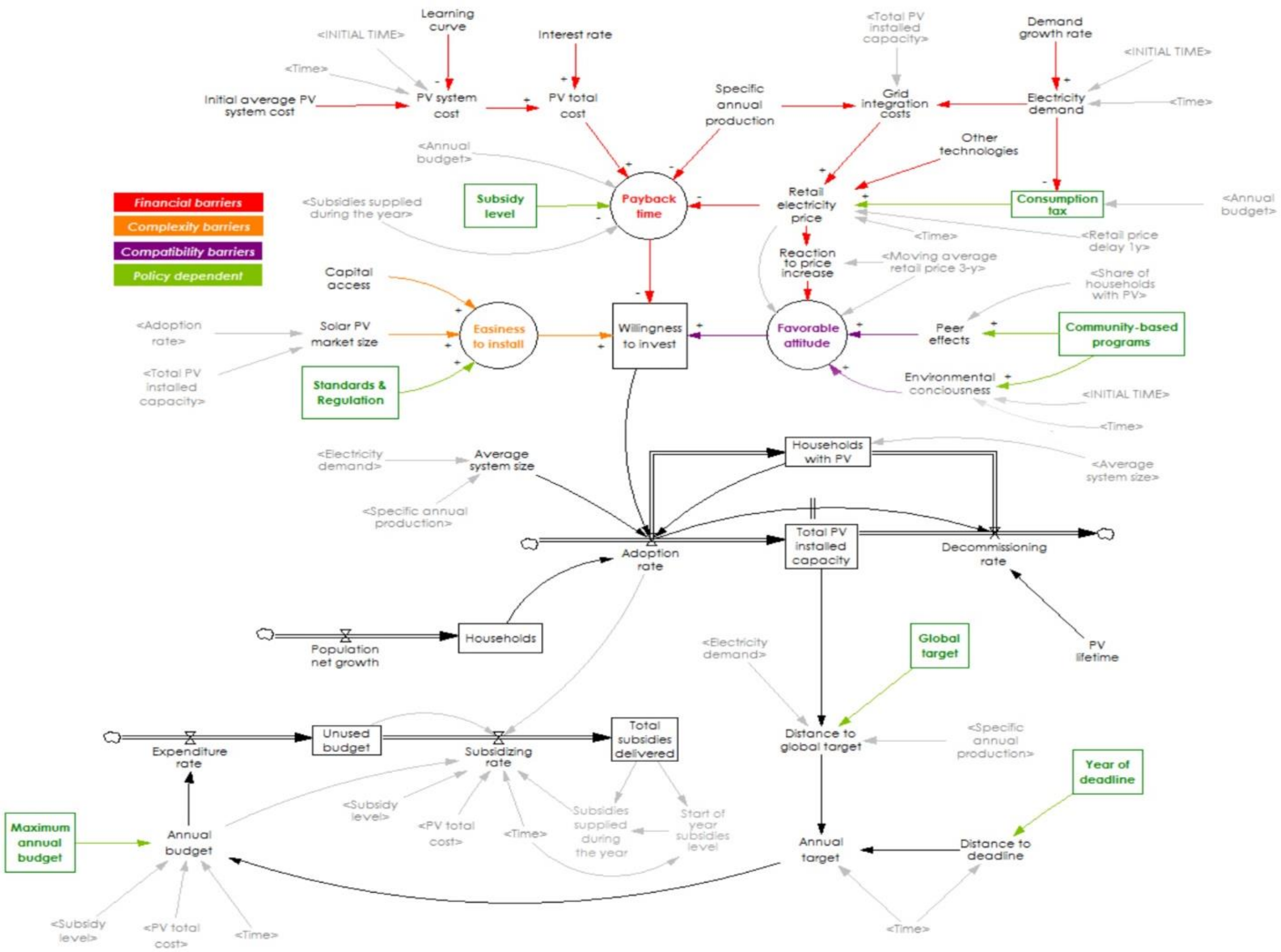


Own elaboration.

Figure 24. Subsidy accountancy model section for Mk scenarios.

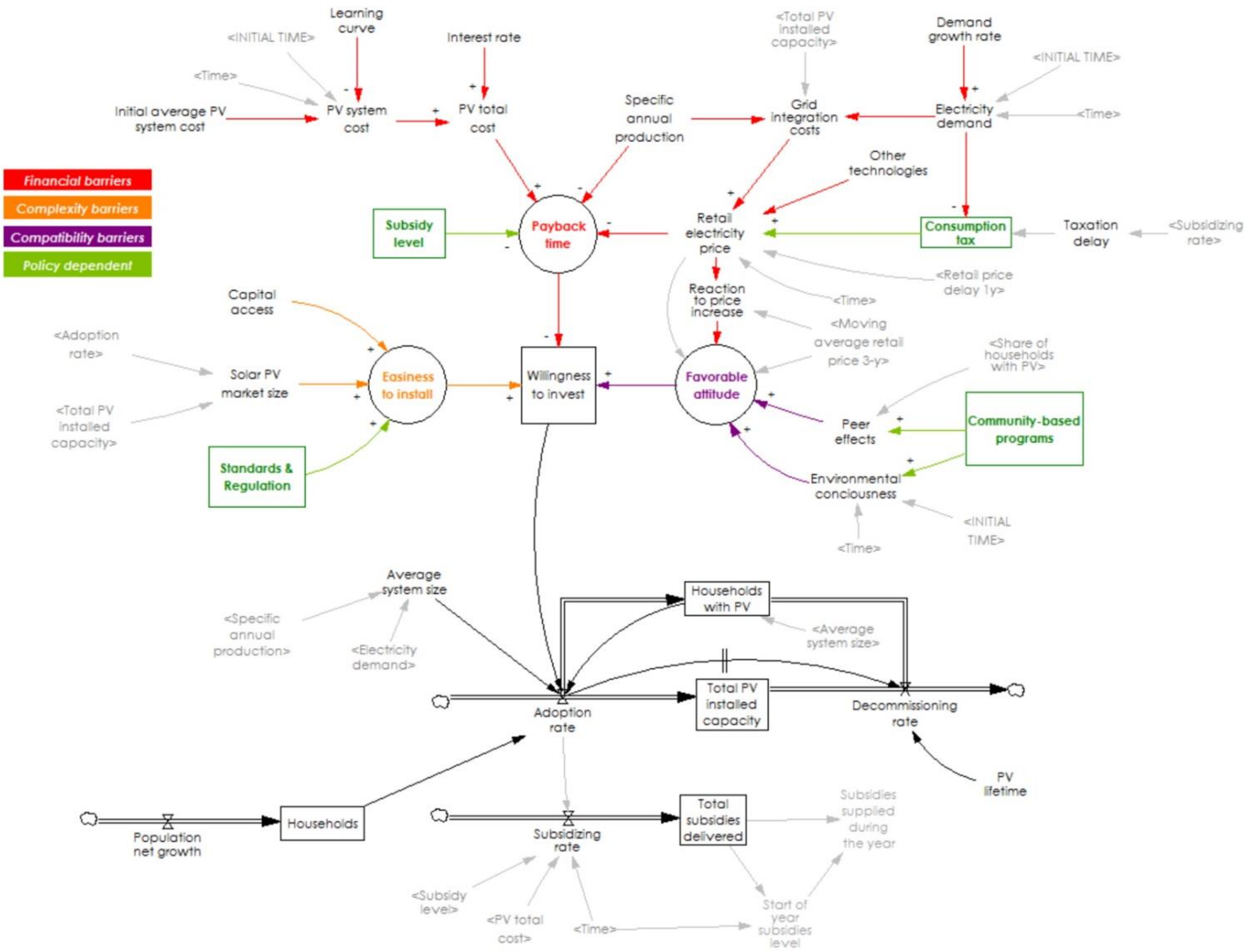
5.3.Complete model

Along the previous section, the reasoning behind the construction of our model has been detailed, as well as the assumptions taken for making it possible. Eventually, a final model was obtained with a slightly different variant for those scenarios where the government does not establish the annual goals or fixes constrains for the subsidizing scheme. Once defined the final system and the equations relating its variables, it is then used to explore the research questions and extract policy recommendations once reviewed the results under the different scenarios.



Own elaboration.

Figure 26. Complete system modelling domestic PV systems diffusion.



Own elaboration.

Figure 27. Complete system modelling domestic PV systems diffusion, for Mk scenarios.

6. Scenario definition

Under this chapter, the scenarios studied in the model are explained (beyond the introduction of them, see chapter 5), making explicit the underlying questions that motivates each variant and its relation with the general research questions of the study.

6.1. Demand and policy scenarios

For the scenario design it a trade-off between external variables (i.e. not directly influenced by the system) and policy-dependent variables had to be made. In accordance with the research questions that focus on expanding our knowledge in the possible consequences of different incentive policies for PV diffusion in Switzerland (see chapter 2), it was preferred to expand the number of policy scenarios than those of external variables.

6.1.1. Demand scenarios

Therefore, as an external variable shaping the functioning of the whole system, the "Electricity demand" was chosen. In our model, the electricity demand is taken as a completely external variable unaffected by the changes of our system, what has its limitations (see chapter 9). As explained before, several scenarios exist in the available literature for the future development of the Swiss electricity demand (see section 5.2.1), though they could be roughly classified in foreseeing a continued fast growth, a small increase with a plateau, or a moderate decrease. Simplifying the analysis, and also in the look for contrasting scenarios that could make it easier to spot divergent trends related with the demand behavior, three scenarios were defined (see Figure 11):

- FG – Fast growth, annually growing 0.6%
- C – Constant demand
- FD – Fast decline, annually shrinking by 0.3%

These three scenarios are simulated under all policy scenarios so as to identify potentially different behaviors according to a different evolution of demand.

6.1.2. Base and no policy scenarios

Two policy scenarios were designed as the starting point for later comparison with the different variations. The base scenario (BS) is inspired by the current incentivizing scheme in place in Switzerland (see section 2.3 or (Husser et al. 2013)) with the only additions of the "Standards & Regulation" and "Community-based programs". The features of the base scenario, besides those common for all scenarios (see section 5.2) are:

- Subsidy level: constant at 30%
- Global target: constant at 100% of domestic electricity consumption
- Consumption tax & GIC: completely passed through to domestic consumers (equivalent to FT)

The other basic policy scenario is the one in which no incentivizing policy is enforced called no-policy scenario (NO). Under this variant, all policy-dependent variables are set to zero and the "natural" behavior of the system is simulated under the different demand conditions.

6.1.3. Subsidy policy scenarios

Following the logic that the progressive decrease of the system costs will make it more attractive to households to install them, even with smaller government-led incentives, two alternative possibilities are explore.

- CS – Constant subsidy, fixed at 30% during all the years the policy is active
- SS – Stepwise subsidy, the "Subsidy level" is progressively diminished from 30% (2015-2025), to 20% (2025-2040) and to 10% (2040-2050)

Similar stepwise approaches has been used in other countries (i.e. the progressively lower tariffs in the German FIT scheme (Karakaya et al. 2015)), with relative success. A step forward could be relating the subsidy level or the duration of the subsidy at each level according to the performance of the scheme, though it is left for future works.

6.1.4. Goal determination policy scenarios

A clear definition of the goals to achieve is able to reduce uncertainty among the public and to better align the efforts for technology diffusion (i.e. search guidance, as a function of TIS (Hekkert & Negro 2009)). However, the limitations of the system does not allowed us to simulate the subtle effect of future expectations among households (i.e. regarding the evolution of the subsidy system). Despite this limitation, the definition of the goals heavily influence the system by constraining the subsidies that are delivered (see section 5.2.3), and, secondly, it conditions the perceived success of the policy employed (by the results obtained in terms of distance to the goals set).

Hence, different alternative approaches were studied configuring three scenarios:

- CG – Constant goal fixed at 14 GW of photovoltaic power
- SG – Stepwise goal starting at 20% (2015-2030), then 40% (2030-2040) and 60% (2040-2050) of domestic electricity consumption
- Mk – Market driven, no defined goal

The constant goal is fixed at 14 GW since it has been said to be the potential of photovoltaic systems needed to substitute 20% of electricity production by 2025 by the solar professional association Swiss-solar (Swissolar 2015). Taking the consumption in 2013 (Husser et al. 2013), reaching 20% of the total demand of electricity would only require 14 GW if the average specific production is taken as low as 850 kWh/kW. If 1000 kWh/kW is used instead, in 2013 only 11.86 GW would be required (Husser et al. 2013), and if this same value is used in 2025, then the total demand would have to increase by 18% (or 1.4% annually), much larger than the scenarios considered in the study.

Employing the demand scenarios defined previously, only the FG would reach a point where 14 GW of photovoltaic energy would substitute 20% of the demand (using a specific annual production of 1000 kWh/kW) around 2042 (see Figure 11). Therefore, it has been considered to be a suitable quantity to study the effect of a constant goal (what can also be looked at a gradually decreasing share if the demand growth, or gradually increasing if it falls). The BS scenario can be taken as the complementary vision to the CG approach since it employs a constant share of the electricity demand through time.

The stepwise goal definition follows the logic that a stepwise approach would better distribute the efforts for diffusion. After each increase of the goal, a jump in the distance to the target occurs thus heightening the annual budget dedicated to subsidies. This way, the effect of a strong increase in annual targets in the closest years to the deadline (see how they are fixed in section 5.2.3) is attenuated.

Finally, the strategy of defining a goal is abandoned and instead the own system is set free to regulate itself how much subsidies is willing to accept. The balancing loop between subsidies-willingness to invest and subsidies-retail electricity price-willingness to invest then act as the determinant for how much photovoltaic power is installed. The variations of the system needed to simulate this scenario are described elsewhere (see section 5.2.3).

The so-called market driven scenario is studied to better understand how the lack of limitations in the subsidizing scheme could influence the final outcome and also to explore to what extent it could be desirable to let the system freely operate.

6.1.5. Financing policy scenarios

The relevance of the retail electricity price evolution has been introduced at the beginning of this chapter, and thus trying to limit the impact the subsidies could have on it is an interesting policy variant to analyze. This is the motivation to present two additional policy scenarios:

- FT – Free taxation scenario, the costs of integrating the PV systems and the financial resources for the subsidizing scheme are totally passed through to domestic end-consumers
- LT – Limited taxation scenario, the burden on retail electricity price is limited to 30% (15% maximum to subsidize the GIC and another 15% maximum for financing the subsidies, totaling 30% of the electricity bill)[9]

The FT scenario, despite being unlikely to materialize, is of great help to visualize the potential effects on price of the subsidizing policies, as well as a clear indicator of the cost the policies could have on end-consumers. The more probable LT is a suggestion for limiting the burden paid by domestic end-consumer so that the influence it may have in the system is better understand. Additionally, the latter is another way to know how much would be needed to finance externally to keep the impact on consumers low. The importance of this latest factor in the policy design is considered to be substantial and it has been included in the last part of the Appendix, as an additional indicator of the system performance.

[9] The missing financial resources are accounted as external financing and assumed to come from other governmental sources.

7. Model verification and validation

In this chapter, the model defined in the previous sections is tested so as to uncover errors, remark its boundaries and highlight its limitations (Pruyt 2013). Additionally, this step is employed for contrasting the outputs of the system with the expectations of its functioning, so that a reasonable outcome is achieved and confidence in its behavior is reached.

This critical step in the definition of the model has been hurt by the time constrains of this project. An overall verification and validation of the system has been done, showing that it could be confidently used to gain insights on the research questions of this report. However, a more detailed validation remains needed to improve the model weakest section, being underlined as one key task for future works.

The following sections are divided into verification of the model and validation, in which its boundaries, its structure and behavior and its sensitivity are discussed.

7.1.Model verification

The model verification refers mainly to testing if the system works correctly checking if the equations (and units) are coherent and have been coded rightly, and if there are numerical errors due to the configuration of the simulation (Pruyt 2013).

The first part was conducted once finished the conceptualization of the system with no major issues, while the second had to be reviewed after running the base scenario simulation. It was found that the step selected for simulating (1 year) was not suitable for a correct functioning of the subsidy accountancy system (see section 5.2.3). Due to the need of accounting the subsidies delivered throughout the year each year, working with a step equal or bigger than a year prevented the system from being aware of when the limit for subsidies was reached (i.e. the annual budget). Hence, it was decided to increase the resolution of the simulation up to a step of 0.015625 (64 points a year, it is more than weekly resolution).

Once the resolution change was made, no other incident occurred and the verification of the model was completed.

7.2.Model validation

The process of model validation refers to the different tests to check the model suitability to study the research questions. Among the various processes to validate the model, questioning the adequacy of the boundaries and the structure, checking its behavior under extreme conditions, or analyzing its sensitivity to the variations in its many variables rank among the most relevant ones (Pruyt 2013).

During the conceptualization of the model, several meetings have been hold with the supervisor of this project as well as with the other students also working on the Swiss energy transition by modelling it with system dynamics. In these meetings, the definition of the system itself has been discussed with specific feedback regarding its structure and boundaries. The former has been tried to keep as simple and clean as possible, so as not to introduce unnecessary complexities to the system that may add little value. The latter, the boundaries, have been defined following a similar approach, but also with the peculiarity of coordinating with the other laboratory students for the model to be compatible with the other models analyzing complementary aspects of the Swiss energy transition (i.e. electricity imports, wind energy diffusion, natural gas power plants usage). Therefore, both the structure and the boundaries are considered to be reviewed.

7.2.1. Boundaries of the system

However, to treat them more explicitly in this report, let us consider where they lie. In the decision-making system, the most relevant boundaries of the model can be briefly be grouped in:

- **Households' expectations**: the decision-making process is modeled as occurring in the present moment, leaving out any consideration regarding the future expectations. Despite the relevance this may play in the decision-process, the strong discount rates for future revenues and the difficulty of how to model them, encouraged us not to include them in the system.
- **Households' diversity**: factors influencing the decision making (i.e. variations in the specific annual production due to the location of the households, urban or rural households, economic and educational level) that have been seen as relatively important (Balcombe et al. 2014; Sigrin & Drury 2014) were not taking into account in order not to excessively detailing the system. Nonetheless, given the drop in costs of the technology and the long-term of the simulation, it is assumed that this factors would have included little variations, keeping the conclusions unchanged.
- **Macroeconomic indicators**: several factors, mostly the electricity demand and the electricity base price, have been taken as fixed scenarios. The multiple factors involved in the determination of these variables (i.e. interest rate) made it impossible to extend the boundaries of the system. Besides, the relevance of including additional factors affecting this variable was considered very low.

The key boundaries in the installation and subsidies accountancy sections are related to the evolution of the number of Swiss households, that has been taken as an scenario based on the official reports (OFS 2010), and the possible factors influencing changes in the maximum budget allocated for subsidies or the deadline. These policy-dependent variables have not been included in the different scenarios due to the lack of data to model them, and the relative confidence in the implementation of long-term incentivizing systems similarly to neighboring countries (i.e. Germany).

7.2.2. Structure and behavior validation

Similarly to the boundaries, the structure and behavior of the system has been continuously review in periodic meetings, being the results coherent with the initial hypothesis and expectations. The S-shape shown by the system under the base and the no-policy scenarios is taken as an indicator of the overall well-functioning of the system, what is based on similar works (Yan 2009; Drury et al. 2010). The behavior of the different sections of the system has been conducted by simulating them under the base and no-policy conditions, achieving results matching the expected outcomes.

An additional behavior test for this kind of tests could be tried if historical data were available. Nevertheless, this is not the case. No historical data is available under the policy instruments displayed in the model. Switzerland has included a subsidizing scheme in the latest 6 years, based on a FIT scheme which does not exactly correlates with the system studied in this report.

Going further back in time, the available data gathers the on-grid, distributed photovoltaic power installed in Switzerland since 1992, as well as some system variables such as the system price (Husser et al. 2013). When tried to apply to our system several limitations were encountered: the drop in the system prices was faster than modeled, prices did not follow a linear path but peaked around 1995 and the decreased (see Figure 1), the reaction to price (based on a three-year-average comparison (see section 5.2.2)) suffered from strong fluctuations in the first years due to discontinuities, given the extremely high payback time in that period only the easiness to install and the favorable attitude towards the technology were acting as drivers of the willingness to invest. Precisely the latter had the most relevance, since it has been found that environmental arguments were key in the early diffusion of the technology (Balcombe et al. 2014). However, the lack of quantitative data on the environmental awareness of Swiss households obliged us to grossly assume its behavior (see section 5.2.2). Therefore, the figures for the first years did not match the behavior seen in the market due to a jump caused by the initial values of the variables.

However, the effect of these drivers (easiness to install, favorable attitude) are weakened strongly when the prices of the technology drops and the economic factors become the main driver (it is, when the prices existing since 2013 start to be present in the market). Therefore, despite the difficulties to match the historical data due to the lack of information on the compatibility and complexity drivers, their impact afterwards is small and thus the confidence in the system is not negatively affected. However, this is a clear limitation of the model that is discussed in the last chapter.

7.2.3. Sensitivity validation

Due to the lack of time, an explicit sensitivity analysis was not conducted. However, during the conceptualization of the system, in order to test the validity of the assumptions made for defining some of the sections of the model (i.e. easiness to install), the impact of the variables was tested and corrected on an iterative process.

Besides, the own definition of the weighting factors (see section 5.2.2) was done to influence the sensitivity of the system according to the hypothesis and assumptions made on it. This reflects on the relatively low influence exerted by some variables (i.e. easiness to install), which are coincident with the sections were the lack of data and literature support was more severe.

Notwithstanding it, a proper sensitivity analysis is proposed as a future work, particularly if more data can be compiled on the weaker sections of the model.

8. Discussion

Following, the results obtained for each scenario are discussed based on the two most relevant variables of the system: the total photovoltaic installed capacity and the retail electricity price. Despite having many other variables that could be meaningful for policy-makers (i.e. total subsidies delivered, unused budget, evolution of the distance to the global target), only two have been chosen to represent the functioning of the whole system.

Since the final goal is the diffusion of the technology, the total installed capacity by domestic consumers is the most relevant outcome, thus justifying its use. It could be argue that the focus should be put on the energy substituted (i.e. the electricity supplied by the photovoltaic systems), however, since a constant specific annual production of 1000 kWh/kW is taken, the total installed capacity and the total electricity produced by the PV systems are directly proportional (i.e. 1 kW produces 1 MWh each year). Therefore, in this case, the easy conversion between power and energy makes it unnecessary to convert it explicitly.

On the other hand, from a political perspective, it is key to assess the fore-seeable evolution of end-consumer prices under different scenarios. It is so due to the imperative minimization of the economic drawbacks of the adoption of PV systems for the consumers and, through them, to the whole economy. Besides, a more practical factor enters in play. Electricity end-consumers are at the same time Swiss citizens that decides with their votes the future of the political parties competing for entering the government. The political backlash that large increases in the retail electricity price could produce are paramount. Thus policy-makers would take it in serious conside-ration. Finally, the particular Swiss political system that empowers citizens through referendums that shape the federal constitution of the country, can effectively reverse the initiatives taken to enhance renewable energies diffusion if most people see them unfavorably. Therefore, large and rapid price increases are to be avoided so as not to ignite public opinion supporting the dismissal or reform of the scheme.

The results obtained when simulating the different combinations of the previous-ly described scenarios are discussed (see Appendix 0). Due to the large number of graphs and to facilitate their exploration, it has been preferred to present them in the appendices of this report, where they are classified by their features and confronted according to several criteria. It is highly recommended to have the appendices at hand when going through this discussion, although few references are made to specific graphs since the remarks made in this section could be seen in several, leaving the reader use them freely.

The results are discussed based on the two main outputs mentioned: "Total PV installed capacity" and "Retail electricity price", with a special mention to the external financing requirements in the different variants of the LT scenarios.

8.1.Total PV installed capacity

Overall, all scenarios show a transitional period during the time window in which incentivizing policies are active (2015-2050) with a more or less stable growth from 15 GW to 25 GW, in a typical S-curve behavior. Between 2015 and 2050, a rapid growth is observed in all scenarios with some differences in the speed of the adoption, the time location of it and the turbulences experienced. This time period not only hosts the active policies for encouraging adoption, but also the transition from circa 20 years payback time to 5 years, dramatically increasing the attractiveness of the technology (see Figure 22 and Figure 23).

Summarizing the results, the scenarios that show a higher power installed by 2050 are those with a more intense growth in the early years: Mk scenarios. However, in the long term the convergence of all scenarios make the differences more subtle with the SS-FG-SG-FT scenario leading the ranking (26.643 GW by 2100) and, surprisingly, the NO-FG scenario at almost the same level (26.622 GW by 2100). Not undermining the importance of it, it is to be highlighted that the installed capacity difference between the best performing and the worst, the Mk scenarios, (under FG conditions) by 2100 is only 1.044 GW (compared to 3.622 GW by 2050), with the nine best within 330 MW distance (see an illustration in Figure 28).

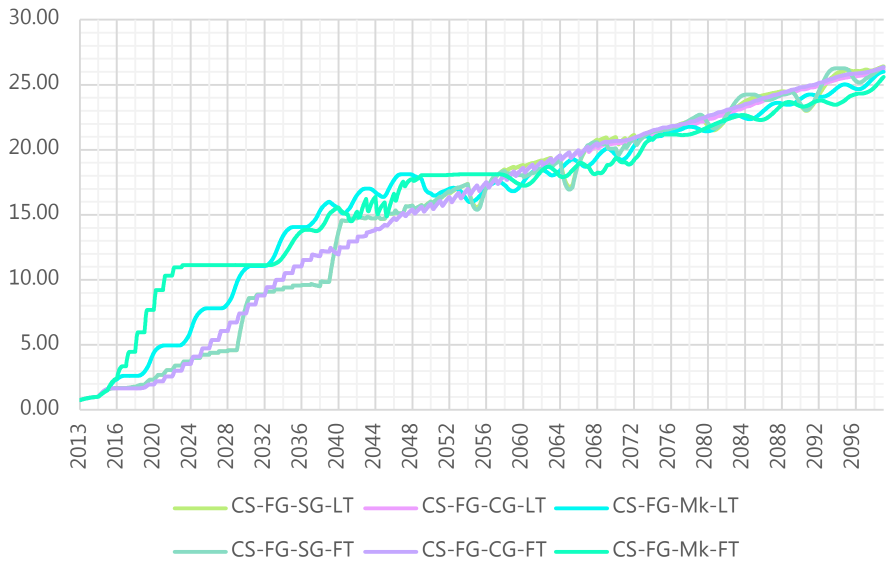


Figure 28. Constant subsidy policy, fast growth demand variants total PV installed capacity, in GW (Appendix C2).

However, the actual figures have little relevance in the analysis, being most meaningful the different trends observed. Generally speaking, a higher demand growth favors the adoption of the technology due to three key effects: (1) it increases the average size of the systems being installed[10]; (2) it reduces the additional costs added to the retail electricity price, making the attitude towards the technology more favorable, by two paths: (2.1) a lower increase per kWh since there are more consumption to distribute the burden among, and (2.2) lower integration costs because they depend on the penetration of the technologies in terms of electricity demand share covered by the PV systems[11]; (3) in BS and SG scenarios (where the target is expressed as a % of the domestic electricity demand), a larger total demand widens the distance to the target thus heightening the annual target and subsequently the annual budget destined to subsidies, further encouraging the adoption.

[10] The number of households with installed PV evolution is approximately the same under all demand growth scenarios.

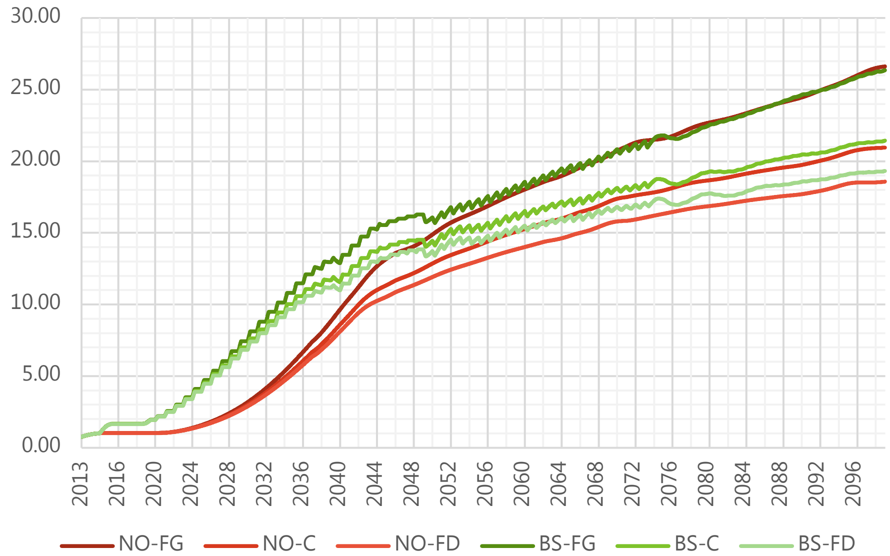
[11] This means that in order to increase the GIC the diffusion of photovoltaic technologies needs to be faster than the growth of the total demand, otherwise the grid integration costs will decrease (never realized in our scenarios). This is so because of the inclusion of balancing costs (see section 5.2.2 and (Ueckerdt et al. 2013)).

8.1.1. Base and no policy scenarios

The evolution of the BS and NO scenarios under different demand growth rates are relatively similar with the results for the BS scenario displaced upwards and to the left, what results in a higher and earlier adoption. Under the three demand scenarios, both BS scenarios and NO scenarios evolve very similarly until 2030 where there paths separate. The time gap in the adoption could be easily seen when taking a look at when BS and NO scenarios reach 5 GW installed. BS scenarios reach it around 2026 meanwhile NO scenarios do it ten years later by 2036.

The base scenario shows a smooth evolution until 2040 when the increase of grid integration costs produces a decrease in the favorable attitude towards the technology, which is easily overcome in the following years.

Although introduced before, what could be deduce from the convergent behavior of both scenario families in the long term is that the increased attractiveness of the technology once matures and cheap boosts its adoption being unnecessary incentivizing schemes. However, even though roughly the same installed capacity is reached, it would happen with a ten years delay (see Figure 29).



Own elaboration.

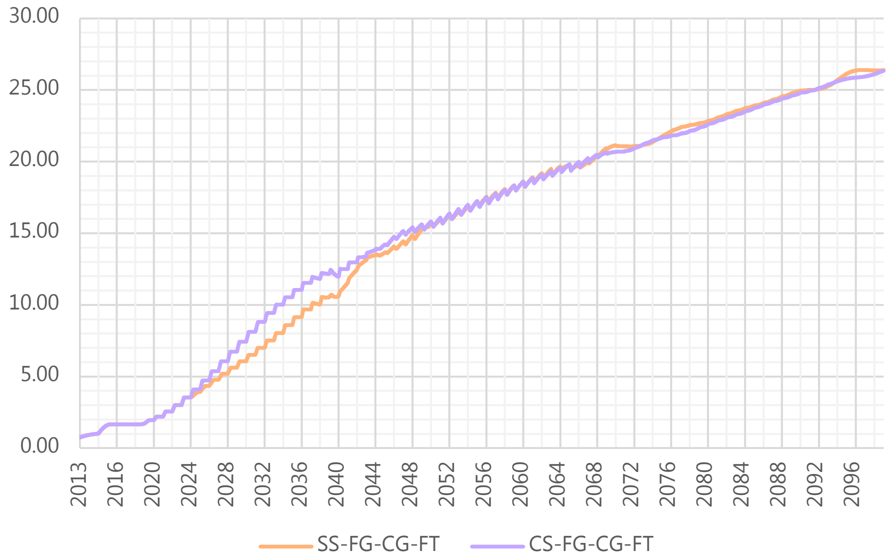
Figure 29. Base and No policy scenarios total PV installed capacity comparison, in GW (Appendix A1).

8.1.2. Subsidy policy scenarios

The different subsidy policy scenarios show distinctive behaviors according not only to its demand growth scenario, but also to the goal policy and financing policy variants, making it difficult to extract conclusions from them due to mixed effects.

The only influence of the different policies: constant and stepwise subsidy, could be noticed in all scenarios after the first change of subsidy level in SS scenarios by 2025. At that point, CS scenarios shows a slightly better performance that persists until the end of the active policies window by 2050, when both policies achieve practically the same results, evolving together until the end of the simulation (see and illustration of this in FIGURE).

From this behavior we can conclude that the subsidy policy has moderates to little effects on our system, in contrast to what was initially thought. A plausible cause for the mismatch between the results and our expectations is the limitation concerning the modeling of the expectations of households. It has been shown in other places (Karakaya et al. 2015), that the adoption rates grows when the subsidy level is about to get lower, caused by the willingness of profiting of the higher subsidy. This kind of behavior was not present in the model due to the limitations modelling the agents, in this case, the households.



Own elaboration.

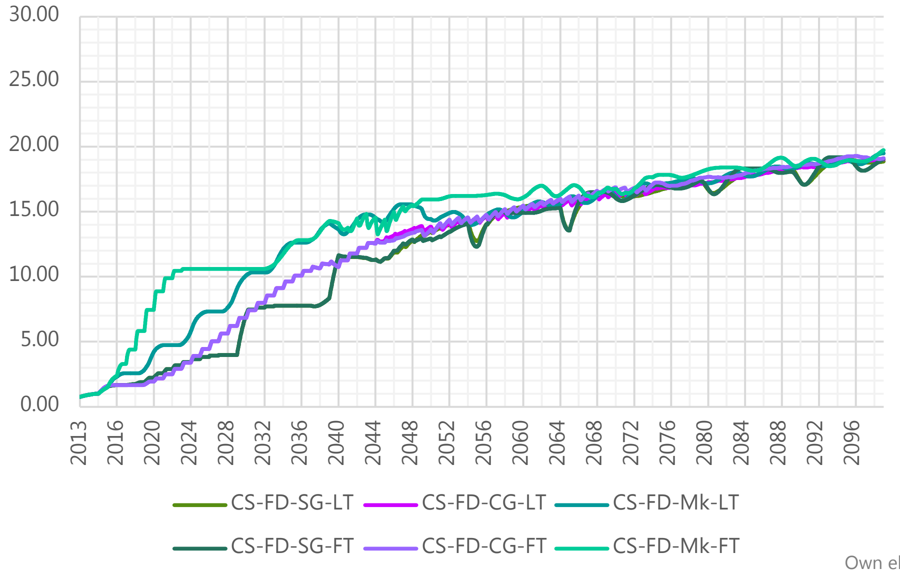
Figure 30. Stepwise and constant subsidy policies total PV installed capacity comparison under FG, CG and FT conditions, in GW (Appendix D3, adapted).

8.1.3. Goal policy scenario

In stark contrast to the subsidy policy scenarios, the goal policy scenarios clearly show distinctive scenarios where CG and SG evolve closely to each other and the Mk scenarios show a much different behavior. Nevertheless, the general comment about convergence in the long term mentioned at the beginning of this section still applies evolving closely after 2060.

Although under all demand growth conditions the scenarios are easily distinguishable, the differences increase with diminishing growth rates (see an illustration in Figure 31). It is particularly strong the divergence between the starting years of the CG and SG scenarios and the Mk ones. The latter shows an explosive start reaching the 10 GW of PV around 2020 (the FT variants) and 2030 (the LT variants), it is around 10 to 20 years earlier than CG and SG scenarios. However, the rapid growth reaches a plateau at that level that needs ten years to be overcome (in the FT variant) and then continues growing vigorously until achieving the 15 GW in the late-2040s, and from 2050 evolving similarly to CG and SG scenarios. This behavior is derived from the lack of limitation towards the subsidies delivered, being governed by the system itself through the retail electricity price changes and its impact in the favorable attitude towards the technology (see below 8.2.3). In the long term, it is interesting to see how Mk scenarios only behave slightly better under FD conditions, being net worse in more rapidly growing demand surrounding. This can be attributed

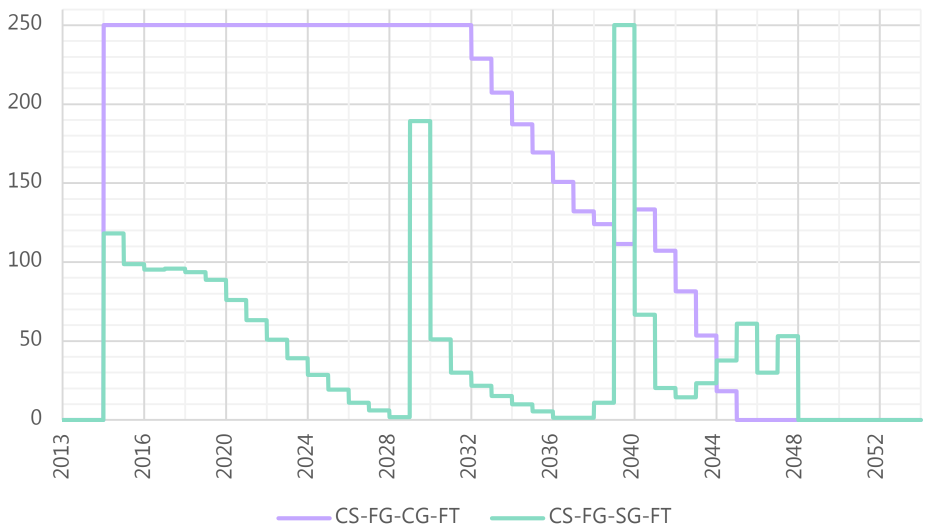
If we move to the CG and SG scenarios, again they present fairly different evolution. The constant goal (CG) scenarios show a smooth, S-type curve similar to what was seen in the base scenario, which gets closer to a linear evolution in the FG conditions. Oppositely, the stepwise goal (SG) scenarios display a progress marked by strong growth right after the goal is increased, followed by a steady state until the next rise. This behavior correlates mainly with the much larger annual budget available right after the jumps in the goal, a result of the suddenly increased distance to the global target (see Figure 32 as an example). It is then followed by a rapid increase of the additional costs in the electricity bill deteriorating the attitude towards the technology. Deterioration that could not be overcome by a small budget that only allows benefiting from reduced payback time to some few, thus lowering consistently the adoption rate and giving birth to the plateaus observed.



Own elaboration.

Figure 31. Constant subsidy, fast decline demand scenarios total PV installed capacity comparison, in GW (Appendix C2).

Notwithstanding this, the figures at the end of the active policies window are fairly similar to all scenarios, particularly to CG and SG. In terms of reaching the goal (as it is hinted in Figure 32), in the SG scenarios it is achieved or almost just before each step rise (what also explains the small budgets right before a goal rise), while the CG scenarios manage to do it also almost at the end of the active period (2050). The dynamics of smaller goals, conquered in faster, could enhance the sense of success and trigger a more favorable attitude (as well as political returns), being preferable to a constant goal that seems far away for long. However, this effects could not be modeled in the system.



Own elaboration.

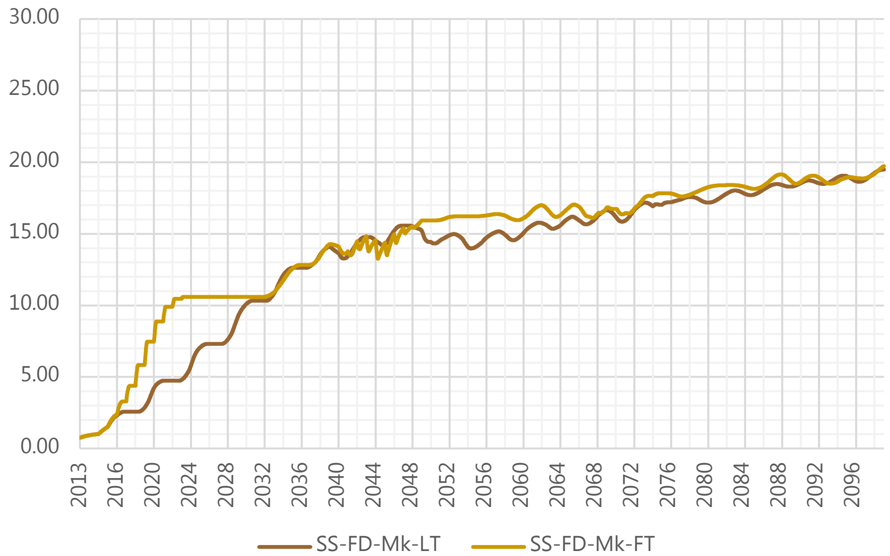
Figure 32. Illustration of the goal policy effects on the annual budget, in CHF millions.

8.1.4. Financing policy scenarios

The financing policy influences exclusively the additional burden impose to end-consumers in the retail electricity price, therefore, their effects are limited and sometimes hard to visualize.

Both FT and LT scenarios perform very similarly in all variants (CS, SS, CG, SG) except in Mk ones. In the former, the effect of limiting the additional cost paid by end-consumers only shows after 2050 and mostly by smoothening the curves, though not influencing the levels they reach (in CS, SS, CG, SG variants). One could argue that this happens due to the lower grid integration costs at lower technology penetration levels and due to the progressive adoption that goes in parallel with the rise of electricity price, making it more difficult for it to amount for more than 15% (each one) of it.

However, the FT and LT scenarios are much divergent in the Mk variants, what clearly derives from a much higher, early adoption rates that pushes high the retail electricity price (see below 8.2 and an example of it in Figure 33). The limitation in the price increase in the Mk-LT scenarios is translated into an adoption limitation given that the higher the price, the lower the payback time and the more attractive the technology. This effect is balanced by the lower negative effect on the attitude towards the technology, but it is not as powerful as the effect on the payback time.



Own elaboration.

Figure 33. Stepwise subsidy, fast decline demand, market driven scenarios total PV installed capacity comparison, in GW (Appendix D1 adapted).

The result of the limitation is that the FT scenarios the PV installed capacity grow until reaching a plateau around 10 GW. Contrastingly, in the LT scenarios, despite having similar adoption rates (i.e. curve slope), several plateaus are reached much earlier, but also much shorter. The overall outcome is that Mk-LT scenarios display a consistent growth with fluctuations almost until the end of the active policies window. When no more subsidies are in place, a decrease in the installed capacity occurs due to the decommissioning of previously adopted systems and the scarcity of households without them motivated to adopt them. Nevertheless, this drop is only temporal, evolving in the following years in the same way as the Mk-FT scenarios (performing slightly better). This could be attributed to a more favorable attitude and easier installation thanks to a larger market (in the FT scenarios it suffers from cyclical ups and downs).

8.2. Retail electricity price and external financing

During the 87 years simulated, the electricity price experiences a continued growth that, in most scenarios, at least doubles the price for end-consumers by 2013. This price increase allies with the learning curve of the technology to exceptionally decrease the payback time of the technology that ends up being around a couple years in most scenarios (see Figure 22). However, the price increases also trigger the public opposition to the technology since a higher adoption means higher integration costs and charges on consumption to finance the subsidies.

Overall, the price increases linearly from 0.2 CHF/kWh in 2015 to 0.3 CHF/kWh by 2050 in all scenarios, but the evolution for the longer term mainly depends on demand growth and the financing policy. Only the fast growth scenarios are capable of retaining the price increase at around 0.4 CHF/kWh thanks to the increase in the base among which the costs are divided. Under constant or decreasing demand, the prices grow vigorously after 2050 reaching the 0.5 CHF/kWh by 2100 if demand is constant, or up to 0.6 CHF/kWh if the demand shrinks. Unless the limited taxation policy is in place, which succeed in keeping prices around 0.4 CHF/kWh but at the cost of having to look for external financing, that could be substantial.

The price evolution is relatively smooth in all scenarios with the exception of the Mk ones (and the jumps in the SG scenarios between 2015 and 2050). The market driven scenarios show violently oscillating price behaviors, particularly intense in FT variants.

The external financing needs concentrate after 2050 once the incentivizing policies have been dismissed. This is due to the rising grid integration costs, mostly originated by the need of balancing the over- and under-production of the unpredictable solar energy (Ueckerdt et al. 2013). The requirements enlarge with more positive and higher demand growth rates, totaling around CHF 100 billion less in FD scenarios than in FG ones.

8.2.1. Base and no policy scenarios

The price evolution in the BS and NO scenarios evolves with a small spread in favor of BS scenarios (less than 0.025 CHF/kWh, due to the consumption tax financing the subsidies) until the mid-2030s when the BS scenarios start growing more rapidly than the NO scenarios. However, once the active policies are no longer in place (2050) a drop in prices occurs in BS scenarios and recover the small difference between them of around 2.5 cents, which is smaller in the constant demand scenario and almost non-existing in the fast decline scenarios.

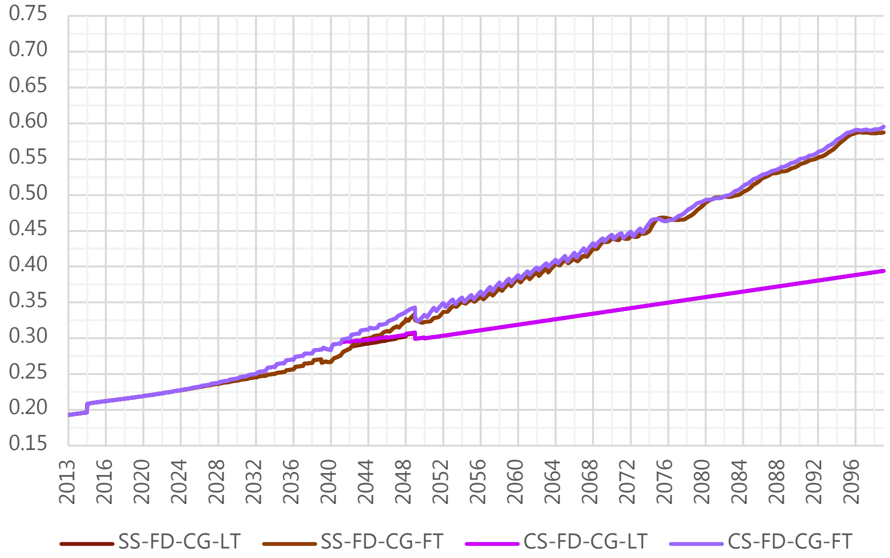
The price increase is relatively slow in both scenarios until the increase in the grid integration cost appears (approx.. 2035 in BS and 2045 in NO), with all scenarios prices ranging between 30 and 35 cents per kWh around 2050 and more divergent levels in the long term (around 60 for FG, 50 for C and 42.5 for FD).

8.2.2. Subsidy policy scenarios

In the same way to what happened with the installed capacity, the subsidy policy seems not to have a large impact in the behavior of the system, and thus it is barely noticeable the differences in the price evolution.

Taking a closer look to the system behavior, we see that the SS scenarios display a lower amount of money delivered into subsidies what determines a consistently lower consumption tax to finance the subsidizing scheme. This results in a slightly lower retail electricity price (in the range of 0.5~1.5 cents CHF per kWh) from the mid-2020s up to the end of the active policies window by 2050 (see an example of in Figure 34). From that point afterwards, the prices are the same.

The lower amount of subsidies becomes most noticeable when looking at the external financial needs (see Appendix E1), where SS scenarios display smaller needs most visible at lower demand growth rates.



Own elaboration.

Figure 34. Constant goal, fast decline demand scenarios retail electricity price comparison, in CHF/kWh (Appendix D1).

8.2.3. Goal policy scenario

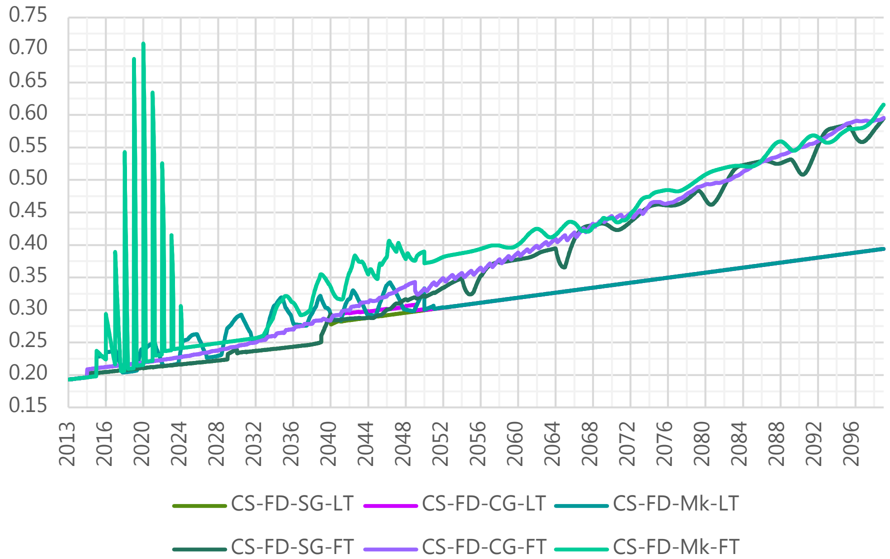
The mentioned differences between the goal policy scenarios not only persist regarding the price evolution, but become enormous, especially in the Mk scenarios.

The CG and SG scenarios translates their behaviors regarding the total capacity installed into the price evolution, with a smoother curve in the CG and a step-like form in the SG. Precisely the jumps in the price after the jump in the goals is what triggers a negative attitude towards the technology that hampers the continuation of a high adoption rate. Either way, both scenarios achieve similar prices in the mid- and long-term, with a larger spread between them right before a goal jump in the SG scenarios (up to 2.5 cents per kWh). Interestingly enough, the jumps in the adoption rate attacks back when the decommissioning of those quickly adopted systems arrive (in the FT variants), producing sequential drops (and recoveries) in the electricity price. In the LT variants, no variation is seen between the CG and SG scenarios, except for a small interval after the third jump in the SG scenarios, when CG price is higher. However, once finished the policies (beyond 2050), the LT variants of the CG and SG scenarios follow exactly the same path.

However, the fluctuations after 2050 occurred in the SG scenarios are nowhere near to those present in the Mk ones (see Figure 35). Since the system regulates itself, it tends to a highly oscillatory behavior. Households try to install as much system they can to benefit from the subsidies, but that increases equally dramatically the electricity prices (up to 0.70 CHF/kWh, or more than 350% the price at the beginning of the simulation). This rise triggers a huge opposition to the technology and thus lowering the adoption until the effect is attenuated due to the recovery of average electricity prices and the story starts again. After this period of intense oscillation, the system continuous oscillating in a more moderate way until the end of the active policies period, showing at all moment higher prices that the other scenarios.

The relative stabilization of the system after 2025 is due to the fact that all households willing to buy PV systems (in the FT variants) have installed them, being needed some time for the "Willingness to invest" to recover the levels of the years of the big oscillations to engage new households (thanks to the drop in prices of the technology, the lower price and the higher environmental awareness pushing a more favorable attitude). This period of low activity is highly detrimental for the PV market that shrinks considerably after a rapid growth, what can cause serious drawbacks if it occurred in reality.

It is most unlikely that policy-makers and regulators would look with good eyes such price oscillations, but the Mk scenarios provide us with two meaningful insights: with a 30% investment subsidy, the adoption would potentially be massive; and the blocking effect a quick rise in prices can exert on the adoption rate.



Own elaboration.

Figure 35. Constant subsidy, fast decline demand scenarios retail electricity price comparison, in CHF/kWh (Appendix C2).

Finally, in terms of external financial aid (in the LT variants of the scenarios), both CG and SG scenarios show a very similar behavior. On the other side, the Mk scenarios outstand with a consistent excess of at least CHF 50 billion, starting to request external financing since the very begin of the simulation (in contrast with the CG and SG scenarios that only needed it after 2040. This last feature confirm the inappropriateness of the Mk policy option, despite being of much help to understand the system.

8.2.4. Financing policy scenarios

The divergence between the two scenarios reveals completely when looking at the evolution of the electricity price. Although all LT scenarios display a lower retail price during the period when encouraging policies are active (2015-2050), the prices are relatively similar to the FT scenarios (except in the Mk variants). However, once the subsidizing scheme is over, the evolution in price divergence is large, particularly under FD and C demand conditions (see Figure 35). This is due to the fact that in the FD variants, the increase in the GIC occurs at the same time the costs are distributed among fewer consumption (thus widening the burden per kWh). In the constant demand conditions, the rise in prices follow both its base price linear increase (see section 5.2.2) and the grid integration costs that rises with higher integration. Interestingly enough, under fast growth conditions, the growing base of consumption among which the costs are distributed makes that both FT and LT scenarios perform similarly within a CHF 3 cents per kWh band, thus diminishing the benefits for the end-consumer of this alternative.

This latter consideration is particularly relevant when considered the needs of external financing generated in the long-term in the LT scenarios under FG conditions. The total amount needed would sum up at least CHF 400 billion by 2100, mostly needed (except in Mk variants) after 2050. Hence, if the LT strategy is considered to lower the impact of the encouraging scheme on end-consumers, it would only be truly advantageous under moderate or negative growth rates (when it can save as much as 0.1 CHF/kWh in constant demand scenarios or 0.2 CHF/kWh in fast decline scenarios).

8.3.Key findings

The summary of our key findings, under the conditions of our simulations and the conditioning of the system conceptualization are:

- Active encouraging policies can bring forward in time the adoption of photo-voltaic technologies about ten years. However, in the long-term, the drop in prices of the technology and the progressive rise in electricity prices will make the technology so attractive that its diffusion would occur naturally
- A decreasing, stepwise subsidy achieves analogous outcomes to those of a constant subsidy of 30%, requiring less financing
- An increasing, stepwise goal policy achieves equivalent outcomes to those of a constant goal, requiring less financing and succeeding in reaching its aims
- A market driven goal policy achieves an extremely fast adoption that continues with large oscillations reaching lower outcomes and requiring substantially more financing that a constant or stepwise goal approach, what translates into large price oscillations
- A limited taxation effectively limits the rise of electricity price while not affecting significantly the technology adoption. However, in the long run it would require large external financing
- The adoption of the technology is higher under faster growing electricity demand and the electricity prices keep lower due to less grid integration costs and the distribution of the burden of financing the subsidies among a larger consumption

9. Conclusions, limitations and future works

The Swiss energy transition would require a significant increase in the renewable technologies penetration. Solar photovoltaic systems, particularly when adopted by households, display a large potential for contributing to the replacement of the current nuclear power capacity and, at the same time, supplying the fastest growing electricity consumer sector. Hence, this report can substantially contribute to the discussion about how to govern the energy transition so as to favor the inclusion of PV systems in the domestic sector.

Framing our work in the TIS approach and using the system dynamic tool, we have reviewed the current projections for the most relevant components of the Swiss electricity system (regarding the diffusion of the photovoltaic technologies among households), as well as identified the most relevant factors moving private investors, households in our case, to invest in PV systems: current or future economic benefits, environmental awareness and social pressure. Additionally, it has been shown that the complexity to adopt it can harm its adoption, thus being included in the model.

Once addressed the major components of our model, it was built based on the available data and projections, or in logical assumptions whenever no sufficient data was found. Following, the different scenarios were built comparing three different demand evolutions, two policy subsidies, three different policies for goal determination and two financing policies. Besides, a base and a no-policy scenarios were simulated so as to take them as a reference.

From the simulation of the 42 scenarios, it was found that a continued rapid growth of electricity demand is most favorable for a high penetration of the technology. However, in all scenarios it displayed a characteristic S-shaped curve with a slow start that leaves place to an almost linear adoption that ends up reaching a plateau similar to all scenarios (under the same electricity demand growth rates). This behavior shows that in the long term, PV systems will be cheap enough to trigger massive adoption of the technology, being the role of the active policies to help accelerating that adoption by artificially lowering its costs. In doing so, under the simulation conditions, it is to be expected around a decade difference between putting in place encouraging policies or not, to achieve the same levels of PV installed capacity.

In terms of installed photovoltaic capacity, the most promising strategy seems to be implementing stepwise subsidies and progressive goals, without limiting the burden on end-consumers under all demand growth consumptions. Despite reaching slightly higher installed capacities under constant or decreasing electricity demands, the market driven scenarios are not consider acceptable due to the large oscillation in prices. If the impact on the end-consumer prices is to be avoided, limiting the percentage of the system costs of the technology will be needed, particularly when the penetration of the technology is larger.

This latter factor is mainly due to the balancing costs of the solar technology (Ueckerdt et al. 2013), hence, the inclusion of energy storage systems is an expansion for future works that should be included. Additionally, several limitations of the current work can be overcome in following extensions. The determination of the households willing to adopt the technology can be further refined by including an stochastic approach (Zhai & Williams 2012). A link that was included and then removed because of the lack of data needs to be studied again: the bigger the market size, the lower the system costs (Seel et al. 2013). Additionally, the influence of the adoption of PV systems, particularly now that the Swiss government is to allow self-consumption (Husser et al. 2013), could be further analyzed. And the role played by expectations (i.e. reaching the goals, knowing the subsidy level will go down at a determined date) may be added since it was found relevant in other cases (Karakaya et al. 2015). Nevertheless, maybe the most relevant future work could be translating this model into a one more general that could include different types of private investors in PV technologies (i.e. small and medium enterprises, large companies, institutional actors).

Finally, additional policy options might be included in future works such as modifying the deadline for the goals, dynamically determining the maximum annual budget and/or the subsidy level. The extension of the financing of the subsidies to all type of electricity consumers could be another alternative for limiting the impact on end-consumers, whose consequences can be studied through SD.

In the next months, this work would be assembled together with the SD models of the rest of the students under the supervision of Reinier Verhoog so as to reflect the effect of additional systems within the Swiss energy model in the energy transition of the country. In sum, what could be learned from this efforts is the value of virtual experimentation in policy-design research. The conclusions achieved need to be looked at well aware of the assumptions made and the limitations of the model. However, they are valid deductions of what the future of the energy transition could be, with deep insights to improve the governance of the process. These works significantly contribute to finding the solution of the great challenge stated at the beginning of this work: ensuring a reliable and affordable electricity supply, completing the nuclear phase-out without compromising the security of supply, and reinforcing the commitment to a sustainable future.

10. References

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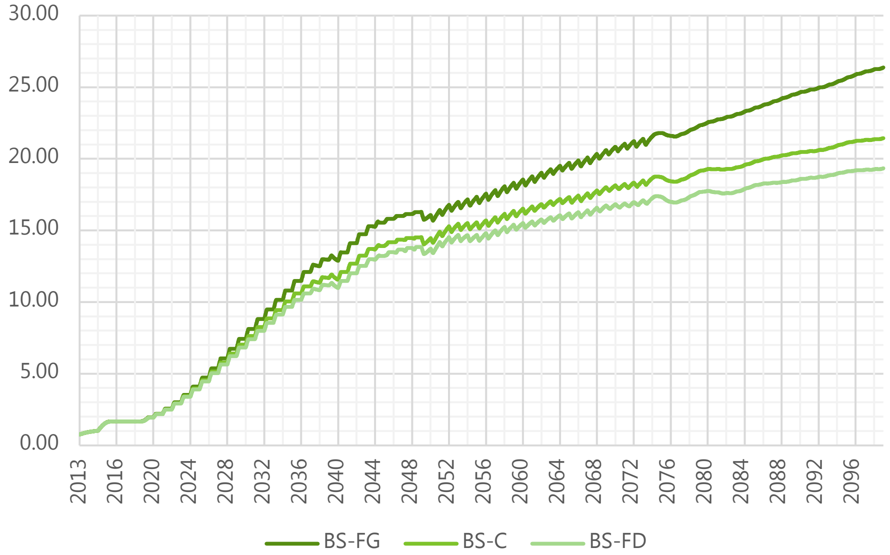
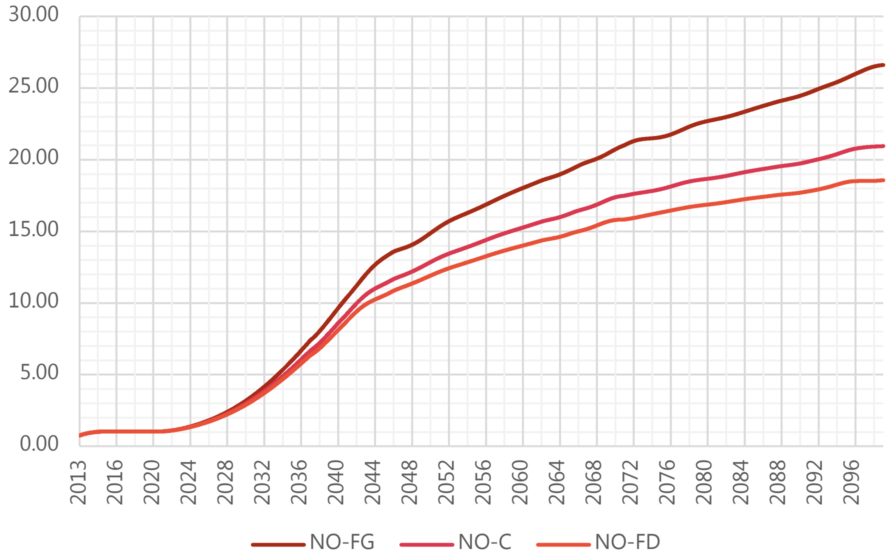
Appendices

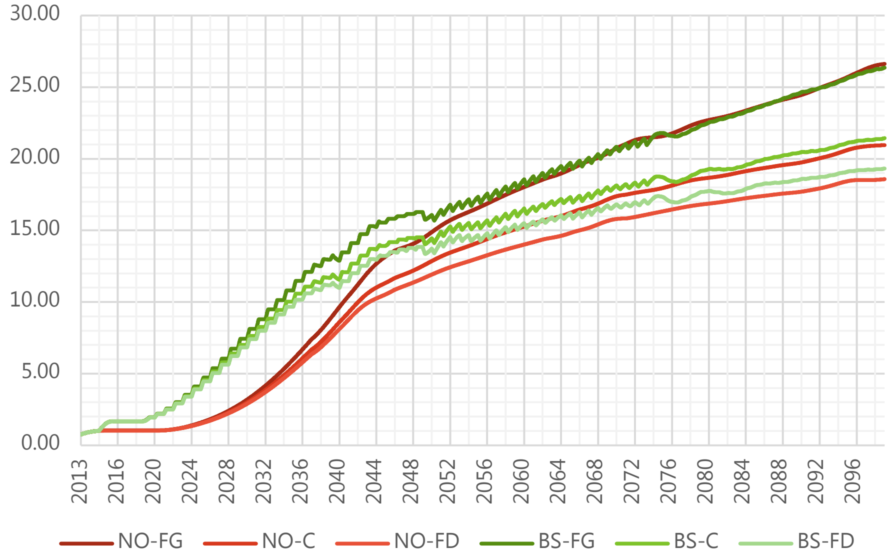
Appendix 0 – List of simulated scenarios by policy and demand

Scenario / subsidy policy scenario	Demand scenario	Goal policy scenario	Financing policy scenario	Code
BS	FG	-	-	BS-FG
BS	C	-	-	BS-C
BS	FD	-	-	BS-FD
NO	FG	-	-	NO-FG
NO	C	-	-	NO-C
NO	FD	-	-	NO-FD
SS	FG	SG	LT	SS-FG-SG-LT
SS	FG	SG	FT	SS-FG-SG-FT
SS	FG	CG	LT	SS-FG-CG-LT
SS	FG	CG	FT	SS-FG-CG-FT
SS	FG	Mk	LT	SS-FG-Mk-LT
SS	FG	Mk	FT	SS-FG-Mk-FT
SS	C	SG	LT	SS-C-SG-LT
SS	C	SG	FT	SS-C-SG-FT
SS	C	CG	LT	SS-C-CG-LT
SS	C	CG	FT	SS-C-CG-FT
SS	C	Mk	LT	SS-C-Mk-LT
SS	C	Mk	FT	SS-C-Mk-FT
SS	FD	SG	LT	SS-FD-SG-LT
SS	FD	SG	FT	SS-FD-SG-FT
SS	FD	CG	LT	SS-FD-CG-LT
SS	FD	CG	FT	SS-FD-CG-FT
SS	FD	Mk	LT	SS-FD-Mk-LT
SS	FD	Mk	FT	SS-FD-Mk-FT
CS	FG	SG	LT	CS-FG-SG-LT
CS	FG	SG	FT	CS-FG-SG-FT
CS	FG	CG	LT	CS-FG-CG-LT
CS	FG	CG	FT	CS-FG-CG-FT
CS	FG	Mk	LT	CS-FG-Mk-LT
CS	FG	Mk	FT	CS-FG-Mk-FT
CS	C	SG	LT	CS-C-SG-LT
CS	C	SG	FT	CS-C-SG-FT
CS	C	CG	LT	CS-C-CG-LT
CS	C	CG	FT	CS-C-CG-FT
CS	C	Mk	LT	CS-C-Mk-LT
CS	C	Mk	FT	CS-C-Mk-FT
CS	FD	SG	LT	CS-FD-SG-LT
CS	FD	SG	FT	CS-FD-SG-FT
CS	FD	CG	LT	CS-FD-CG-LT
CS	FD	CG	FT	CS-FD-CG-FT
CS	FD	Mk	LT	CS-FD-Mk-LT
CS	FD	Mk	FT	CS-FD-Mk-FT

Appendix A1 – Base scenario and no policy scenario by demand growth



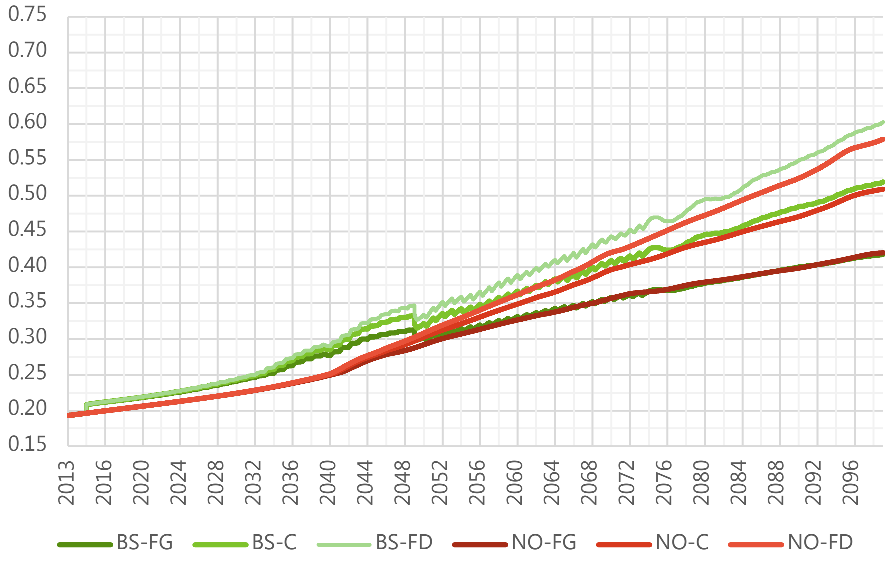




Nomenclature:
BS – Base scenario
NO – No policy

Electricity demand scenario:
FG – Fast growth
C – Constant
FD – Fast decline

All figures show the total domestic, photovoltaic installed capacity expressed in GW.

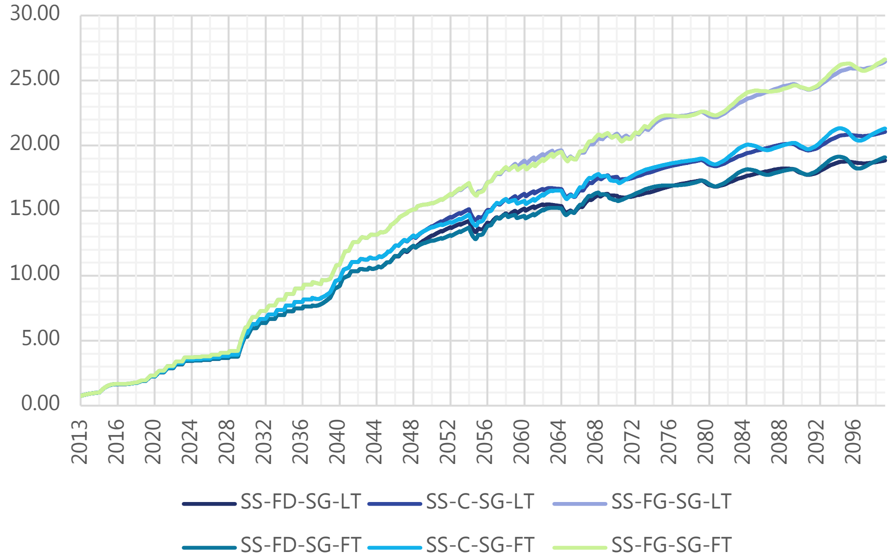


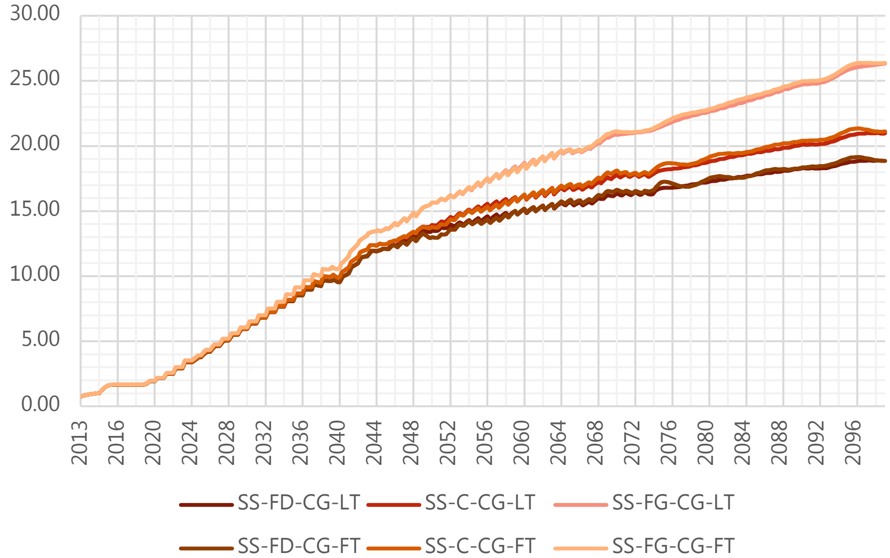
Nomenclature:
BS - Base scenario
NO - No policy

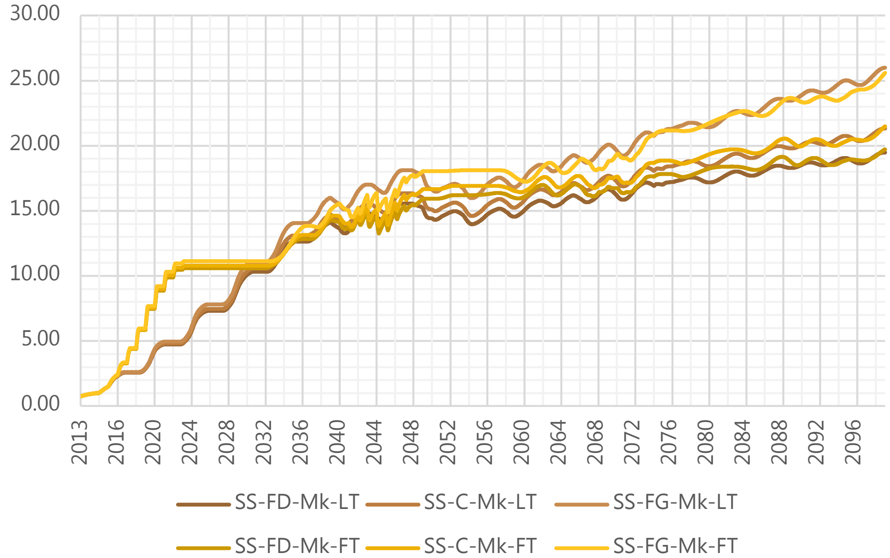
Electricity demand scenario:
FG – Fast growth
C – Constant
FD – Fast decline

This figure shows the average retail electricity price expressed in CHF/kWh.

Appendix B1 – Stepwise subsidy scenario by target and financing policy







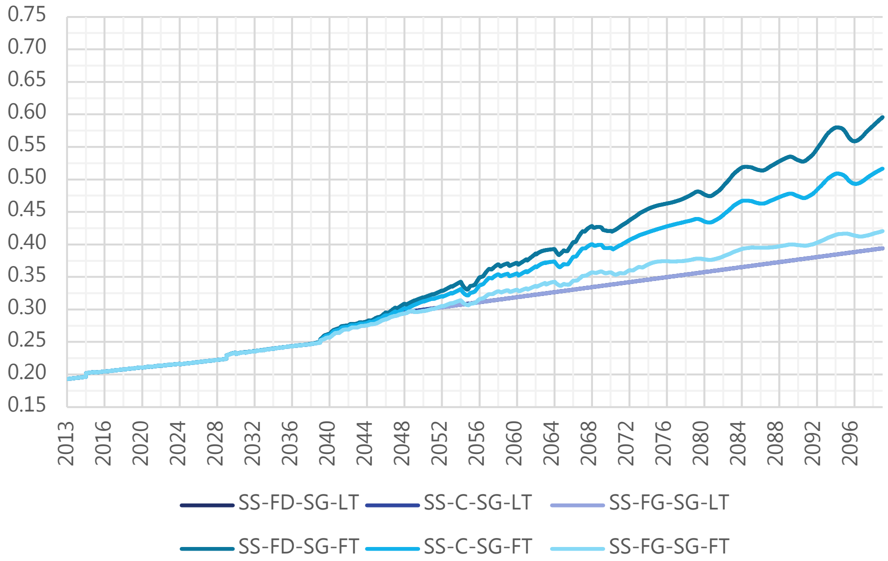
Nomenclature:

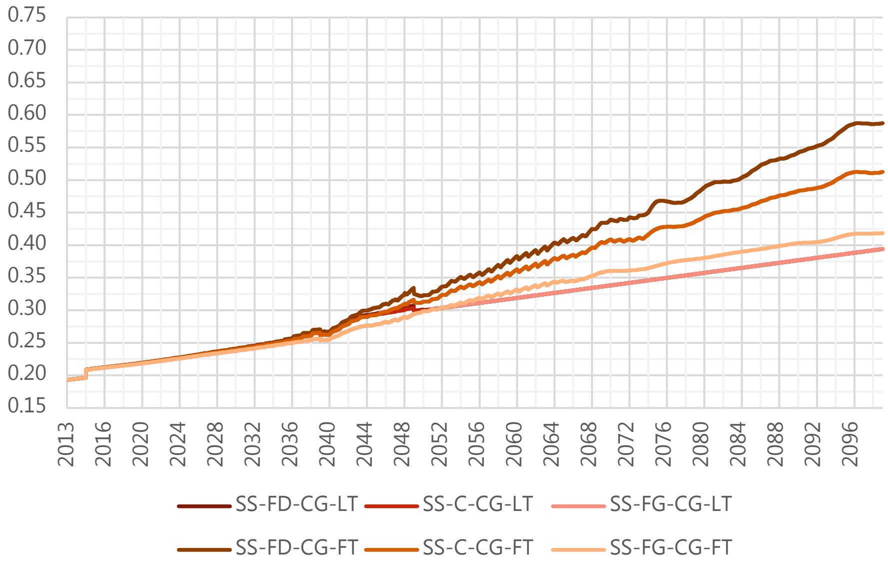
LT	- Limited tax	SG	- Stepwise goal
FT	- Free tax	CG	- Constant goal
		Mk	- Market driven

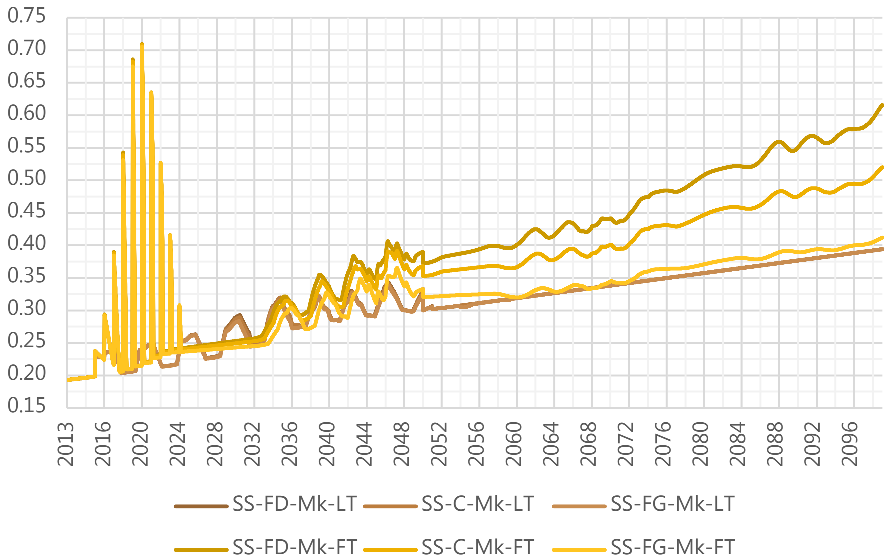
Electricity demand scenario:

FG	– Fast growth
C	– Constant
FD	– Fast decline

All figures show the total domestic, photovoltaic installed capacity expressed in GW.







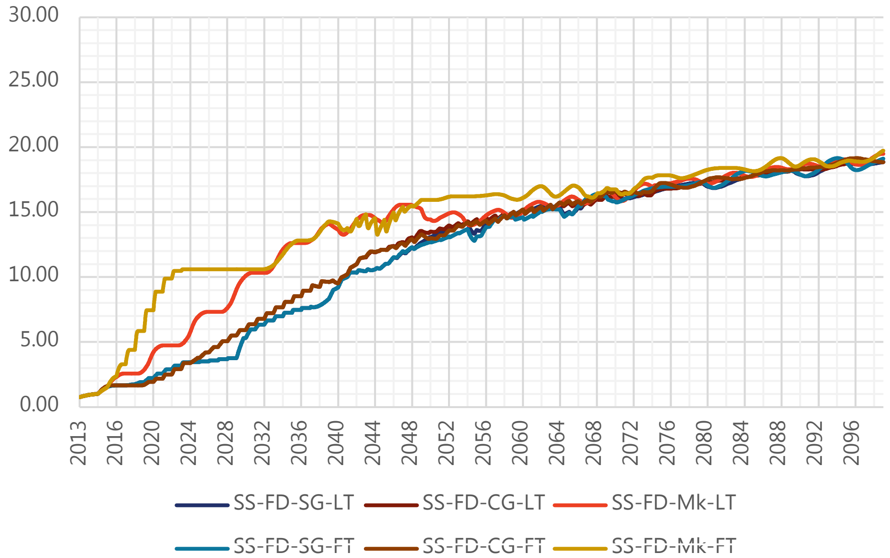
Nomenclature:

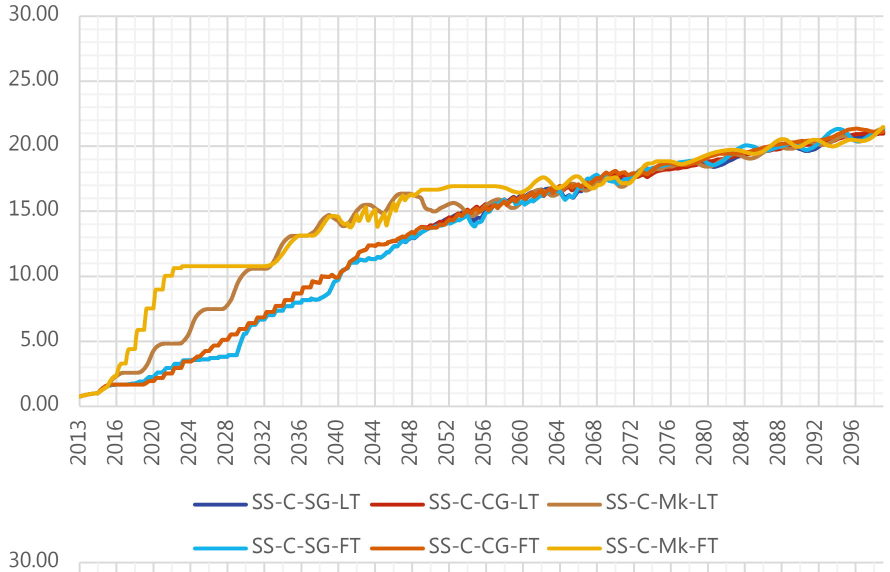
LT	- Limited tax	SG	- Stepwise goal	FG	– Fast growth	
FT	- Free tax	CG	- Constant goal	C	– Constant	
		Mk	- Market driven	FD	– Fast decline	

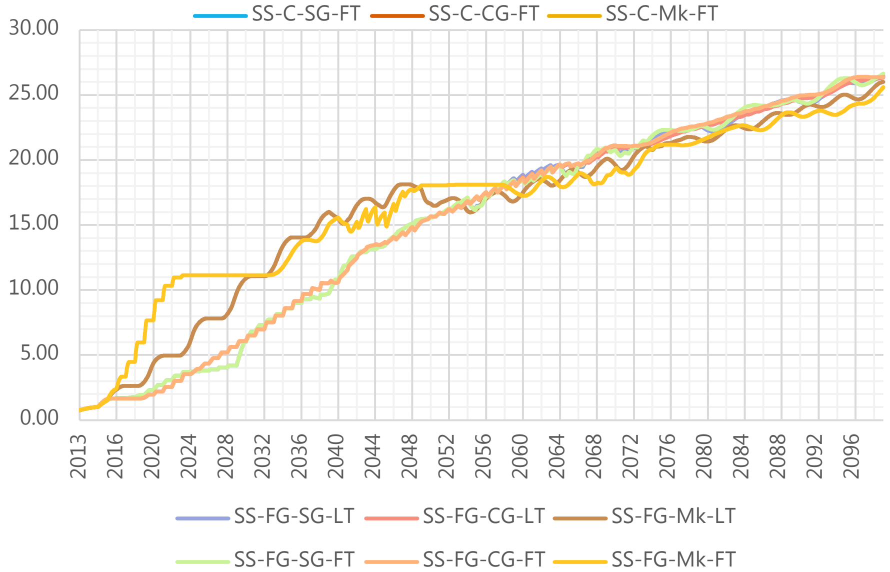
Electricity demand scenario:

All figures show the average retail electricity price expressed in CHF/kWh.

Appendix B2 – Stepwise subsidy scenario by electricity demand scenario





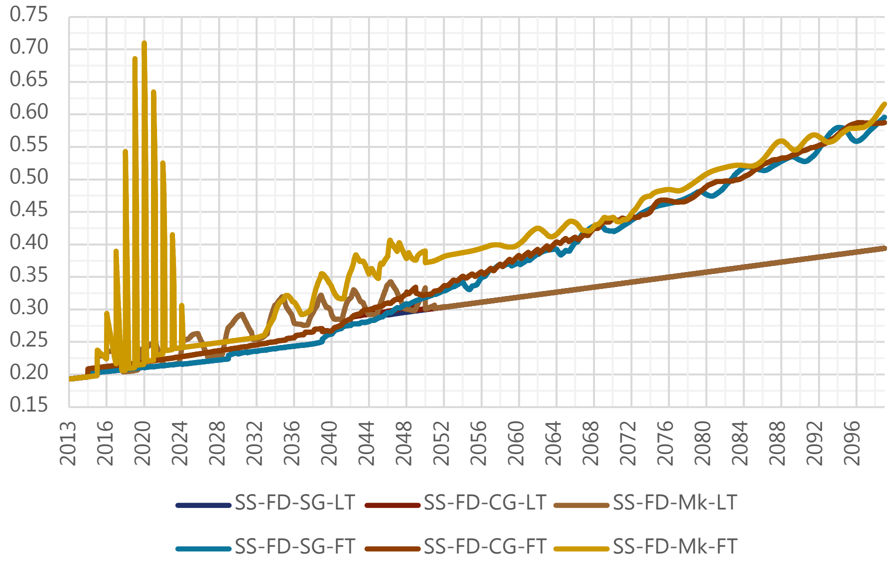


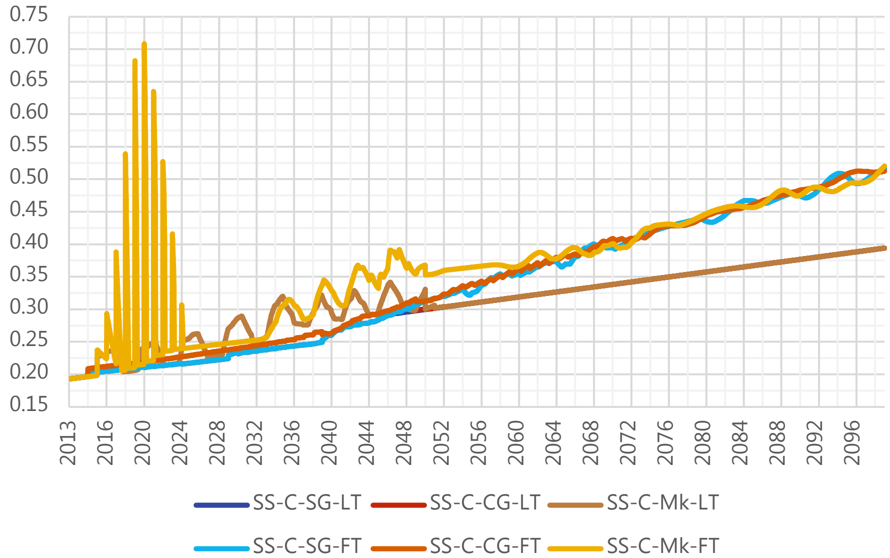
Nomenclature:
LT - Limited tax
FT - Free tax

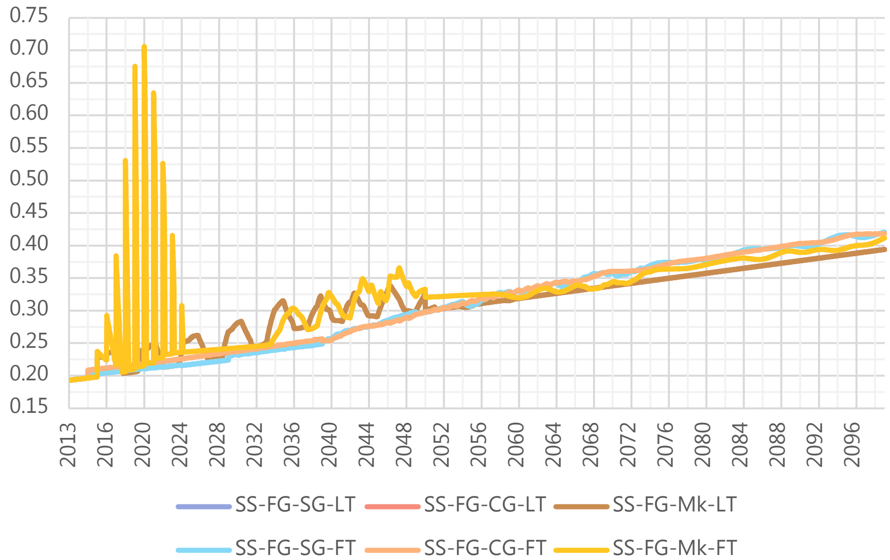
SG - Stepwise goal
CG - Constant goal
Mk - Market driven

Electricity demand scenario:
FG – Fast growth
C – Constant
FD – Fast decline

All figures show the total domestic, photovoltaic installed capacity expressed in GW.

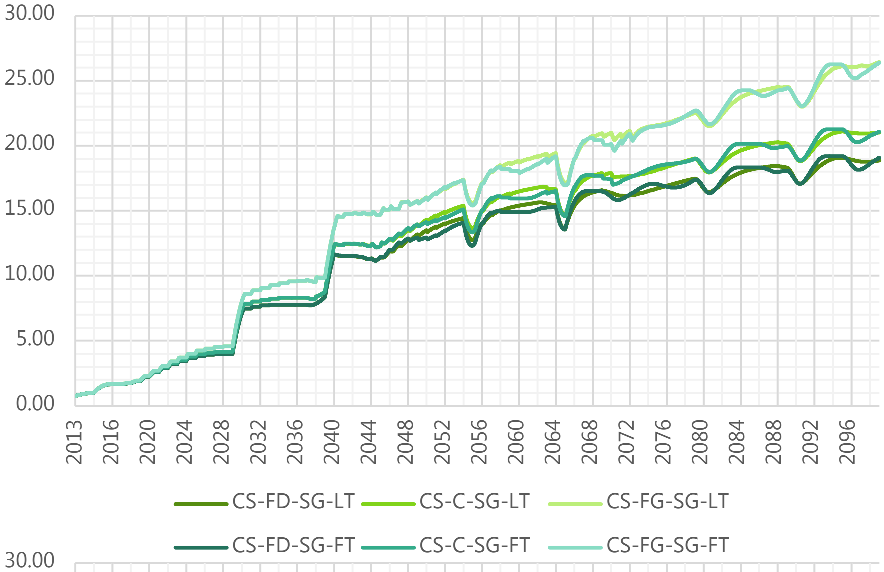


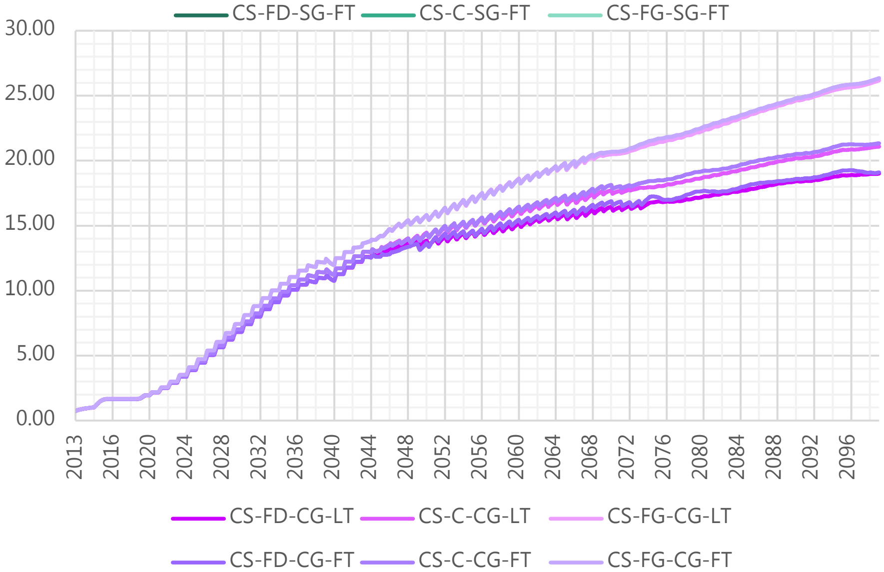


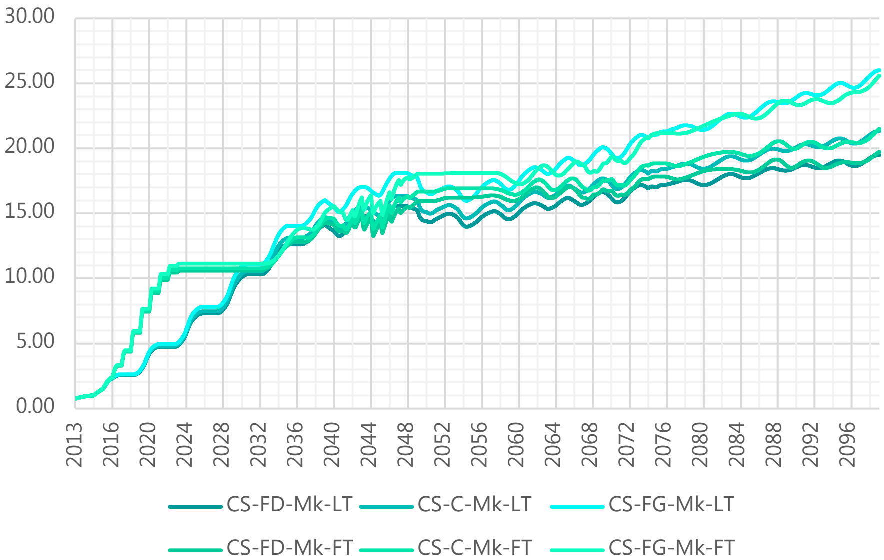


Nomenclature:				Electricity demand scenario:		All figures show the average retail electricity price expressed in CHF/kWh.
LT	- Limited tax	SG	- Stepwise goal	FG	– Fast growth	
FT	- Free tax	CG	- Constant goal	C	– Constant	
		Mk	- Market driven	FD	– Fast decline	

Appendix C1 – Constant subsidy scenario by target and financing policy





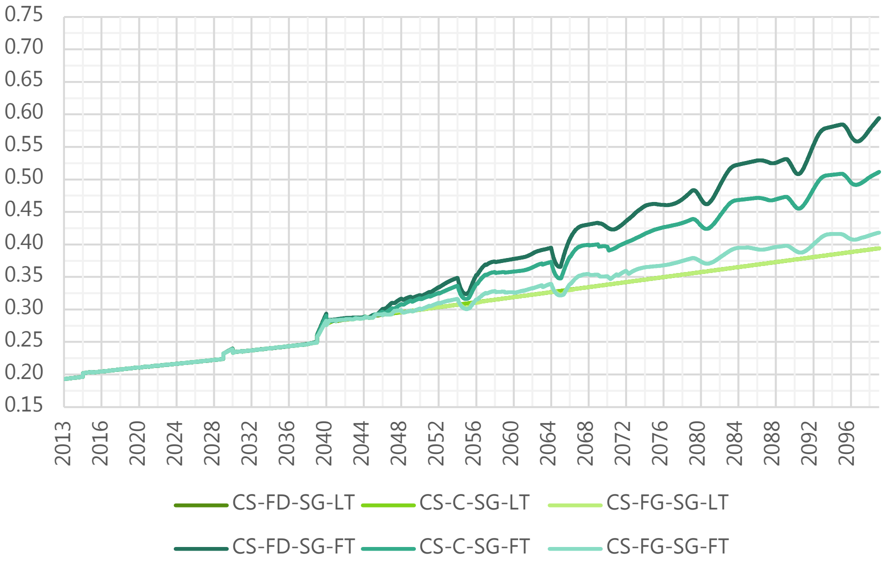


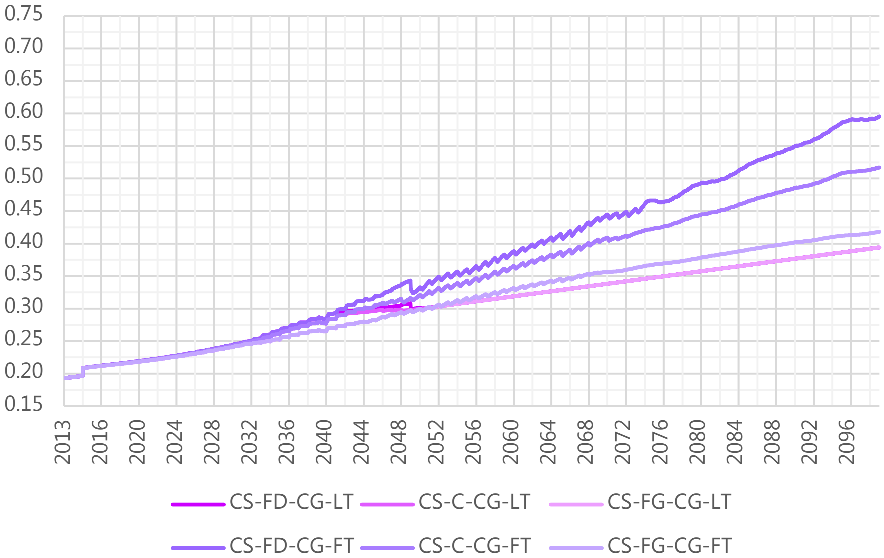
Nomenclature:
LT - Limited tax
FT - Free tax

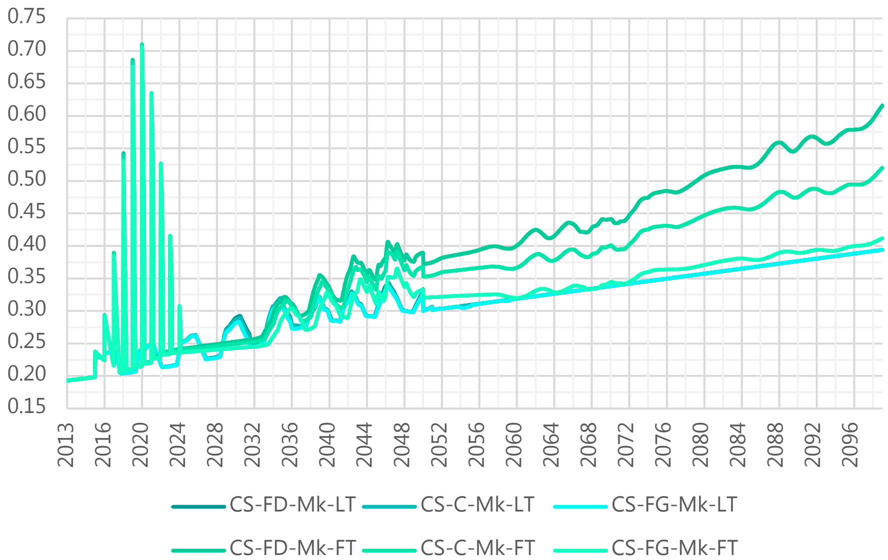
SG - Stepwise goal
CG - Constant goal
Mk - Market driven

Electricity demand scenario:
FG – Fast growth
C – Constant
FD – Fast decline

All figures show the total domestic, photovoltaic installed capacity expressed in GW.







Nomenclature:

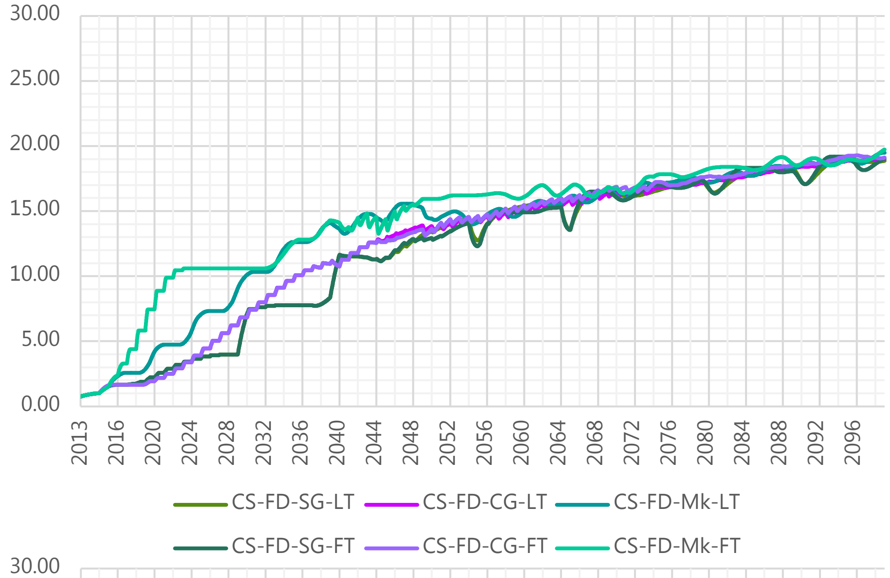
LT	- Limited tax	SG	- Stepwise goal		
FT	- Free tax	CG	- Constant goal		
		Mk	- Market driven		

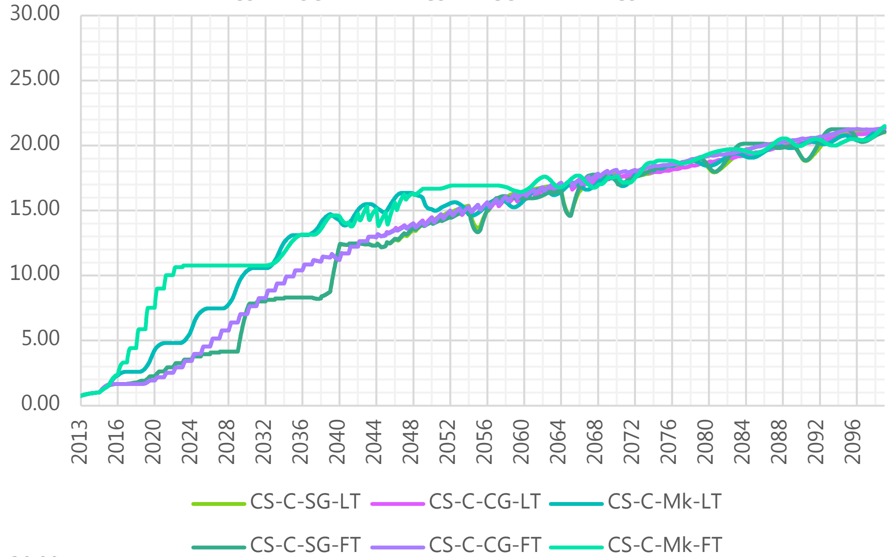
Electricity demand scenario:

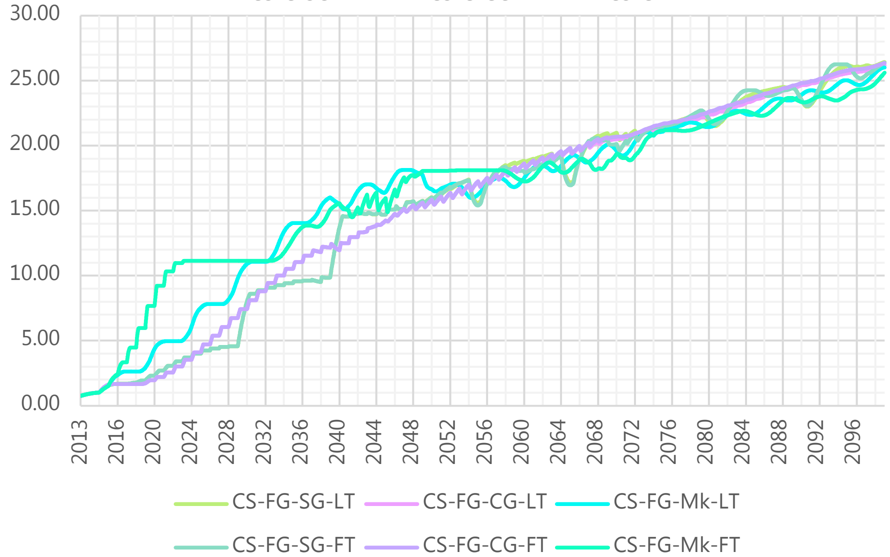
FG	– Fast growth
C	– Constant
FD	– Fast decline

All figures show the average retail electricity price expressed in CHF/kWh.

Appendix C2 – Constant subsidy scenario by electricity demand scenario





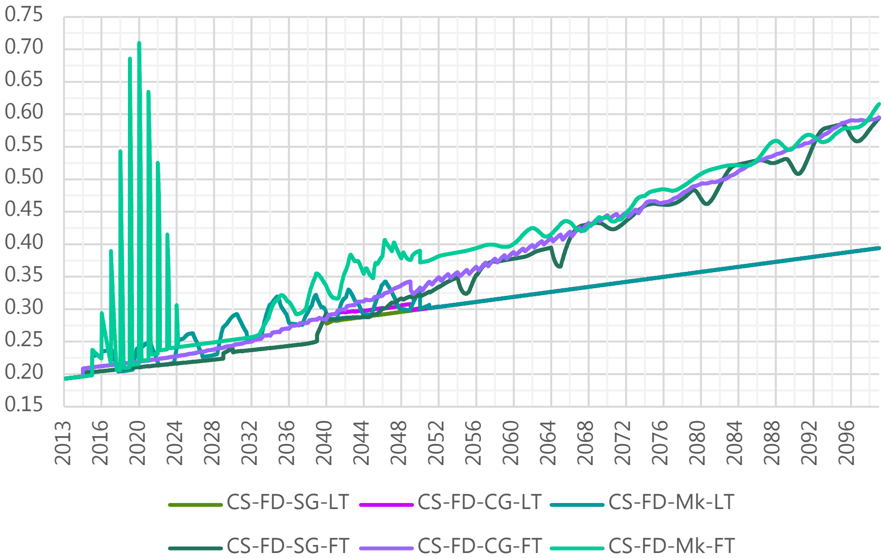


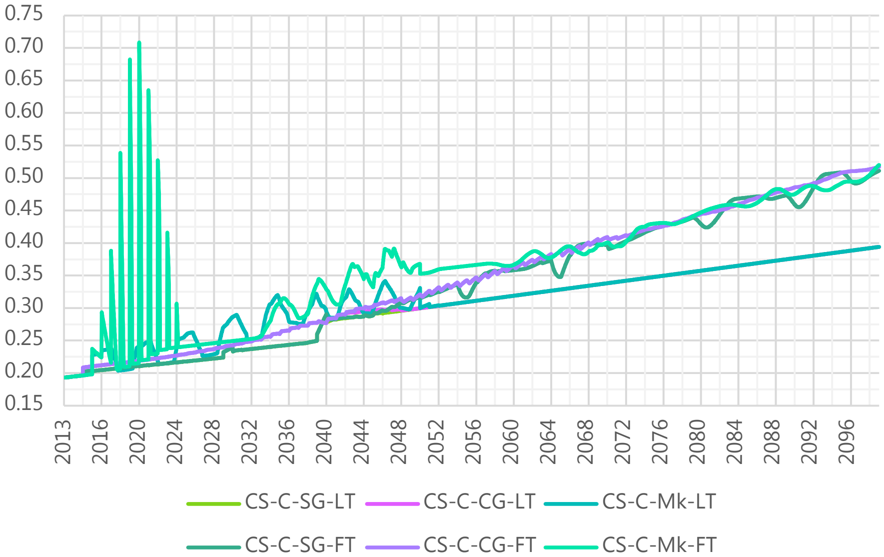
Nomenclature:

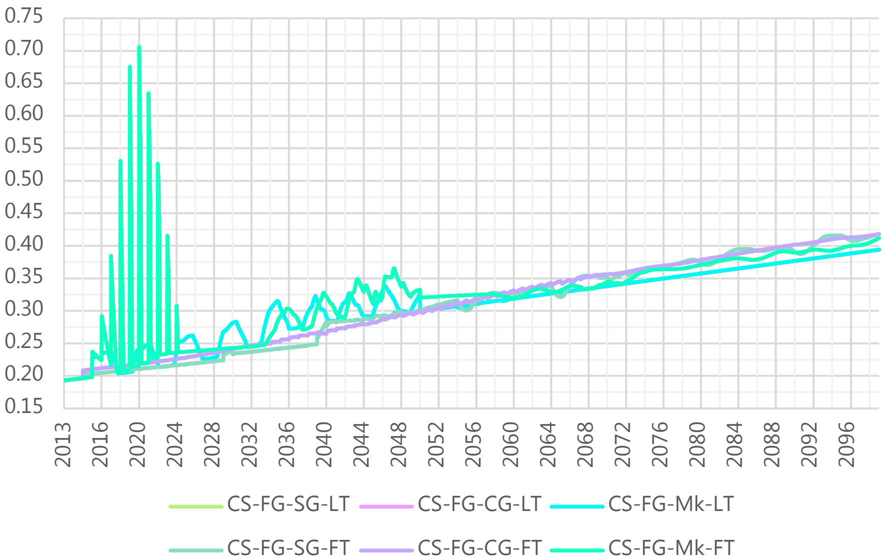
LT	- Limited tax	SG	- Stepwise goal	FG	– Fast growth	
FT	- Free tax	CG	- Constant goal	C	– Constant	
		Mk	- Market driven	FD	– Fast decline	

Electricity demand scenario:

All figures show the total domestic, photovoltaic installed capacity expressed in GW.







Nomenclature:

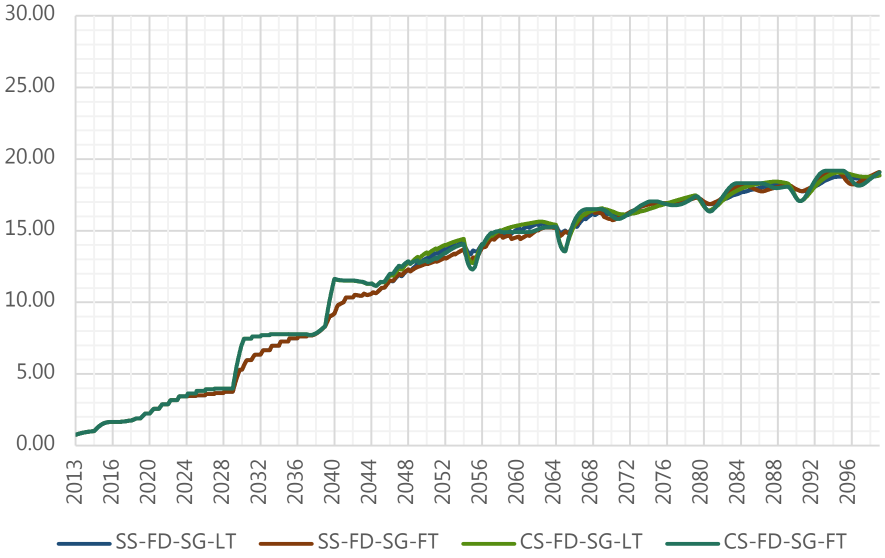
LT	- Limited tax	SG	- Stepwise goal
FT	- Free tax	CG	- Constant goal
		Mk	- Market driven

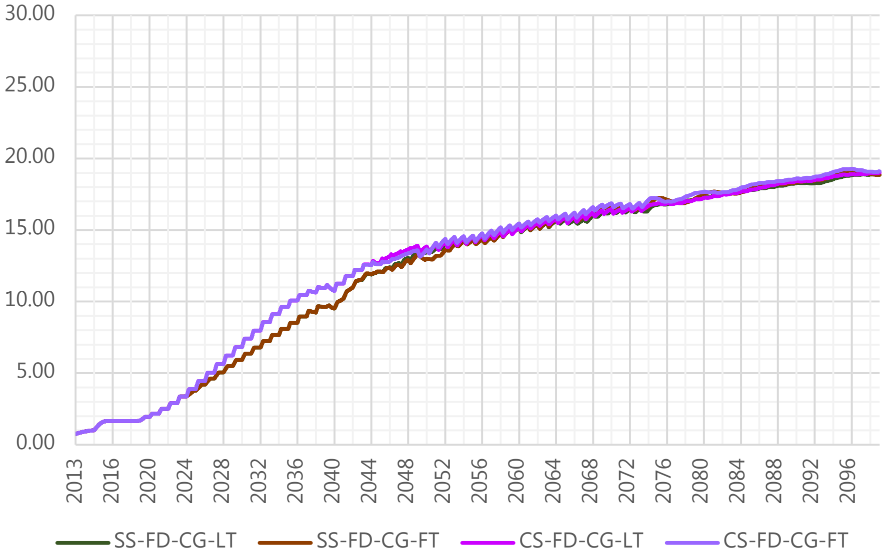
Electricity demand scenario:

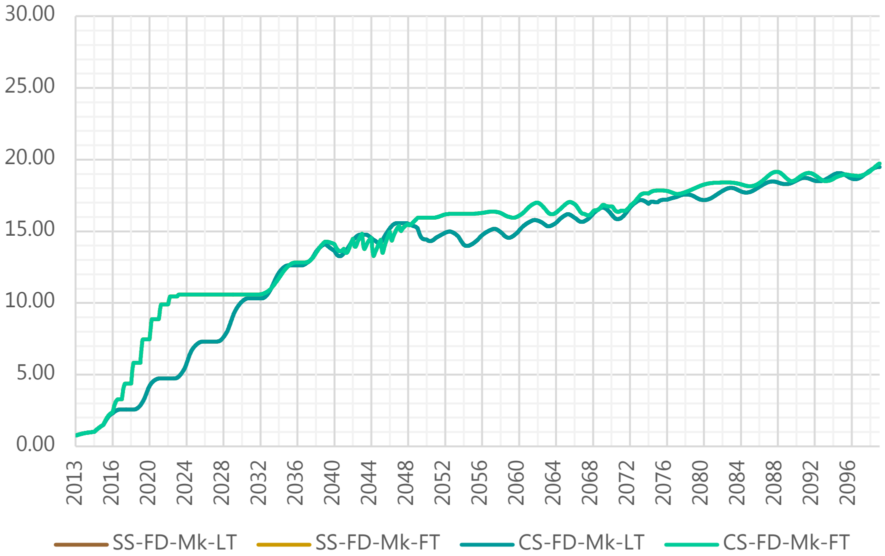
FG	– Fast growth
C	– Constant
FD	– Fast decline

All figures show the average retail electricity price expressed in CHF/kWh.

Appendix D1 – Fast decline electricity demand scenario by target policy



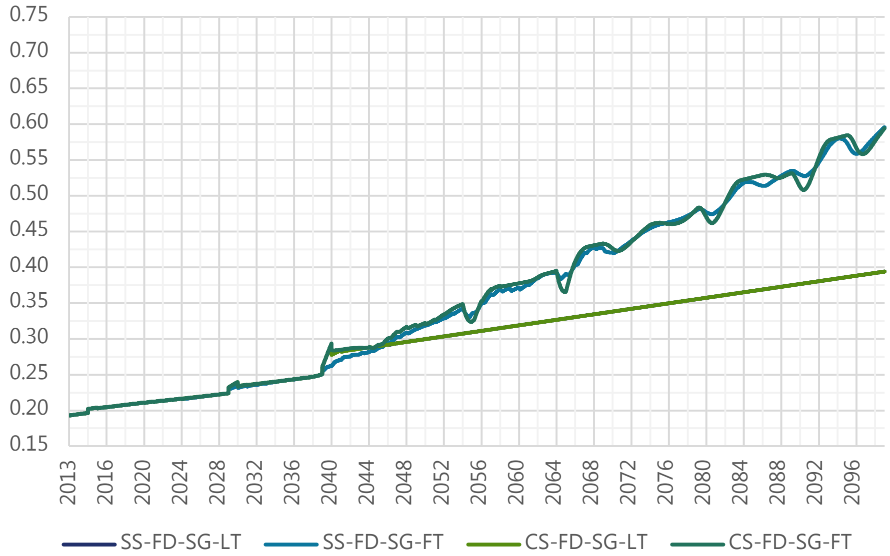


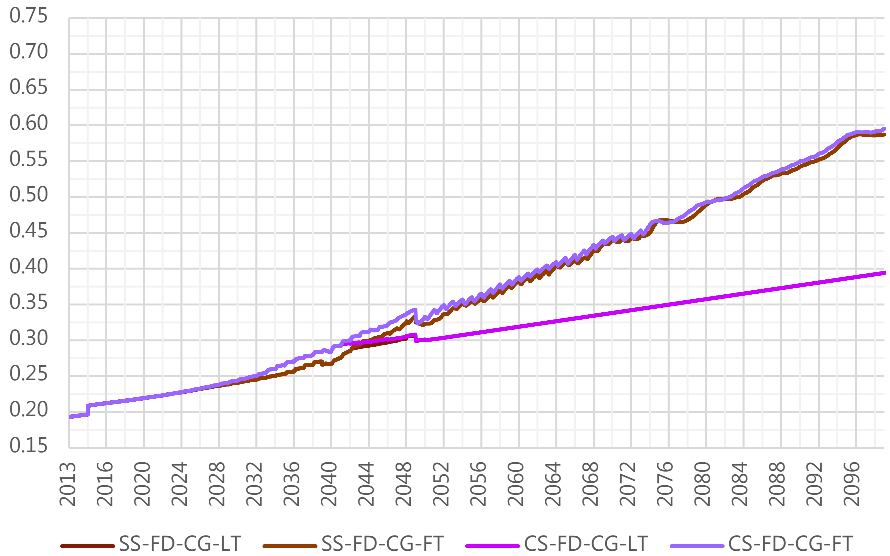


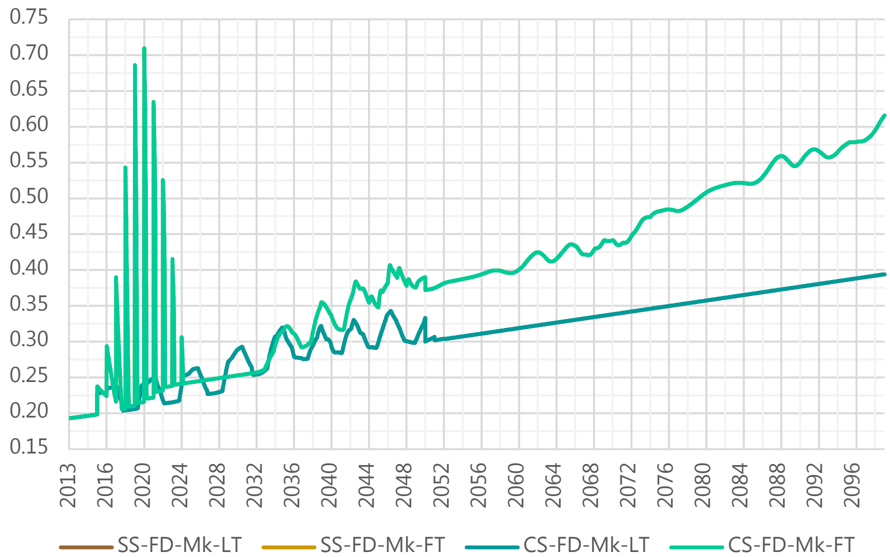
Nomenclature:

LT	- Limited tax	SG	- Stepwise goal	SS	- Stepwise subsidy
FT	- Free tax	CG	- Constant goal	CS	- Constant subsidy
		Mk	- Market driven		

All figures show the total domestic, photovoltaic installed capacity expressed in GW.





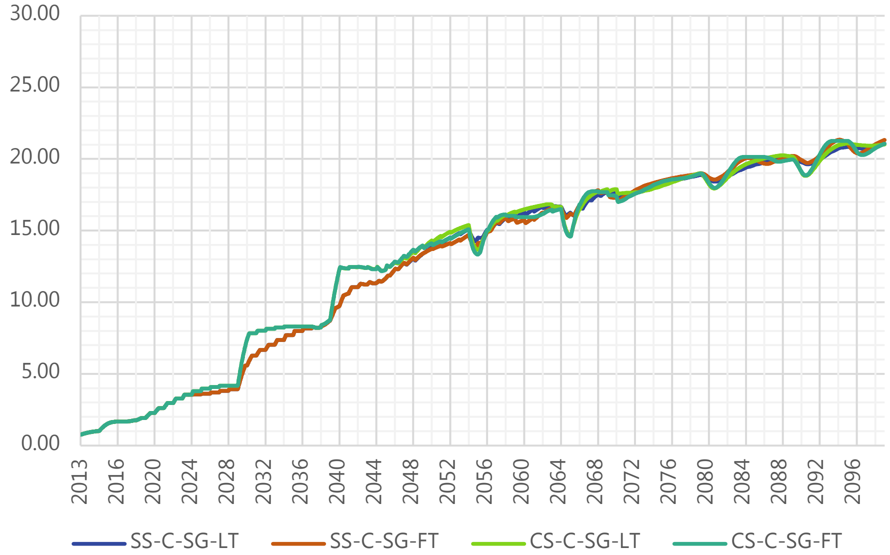


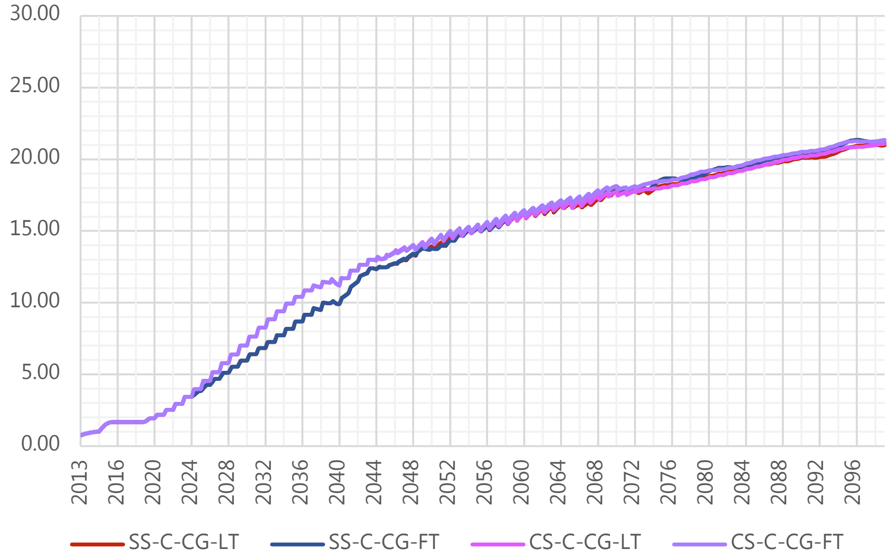
Nomenclature:

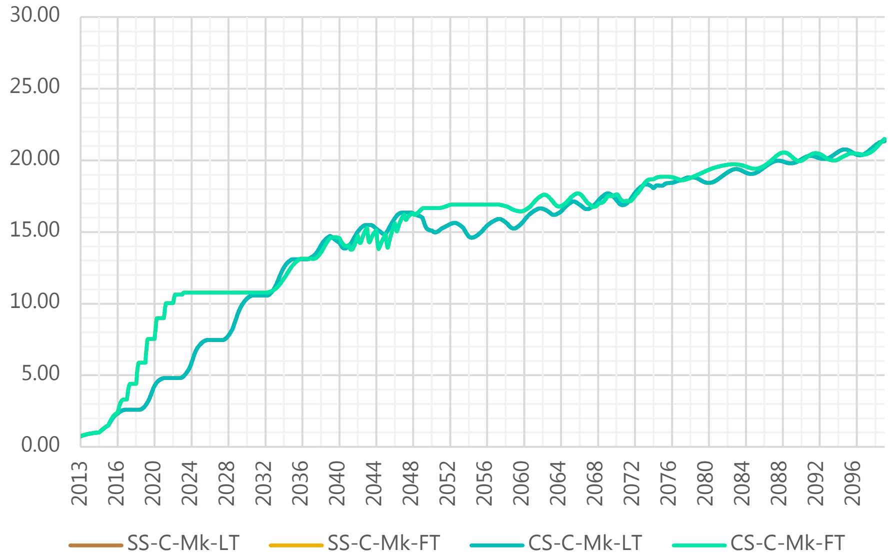
LT	- Limited tax	SG	- Stepwise goal	SS	- Stepwise subsidy	
FT	- Free tax	CG	- Constant goal	CS	- Constant subsidy	
		Mk	- Market driven			

All figures show the average retail electricity price expressed in CHF/kWh.

Appendix D2 – Constant electricity demand scenario by target policy



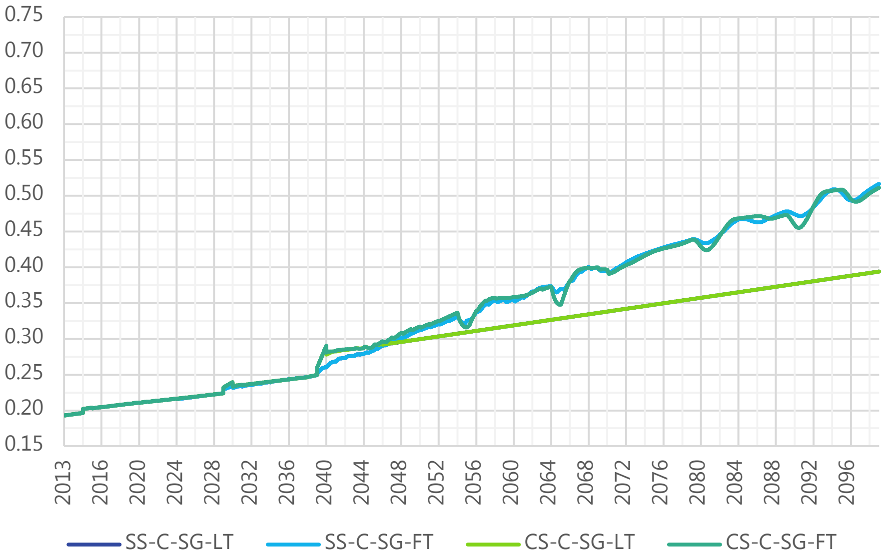


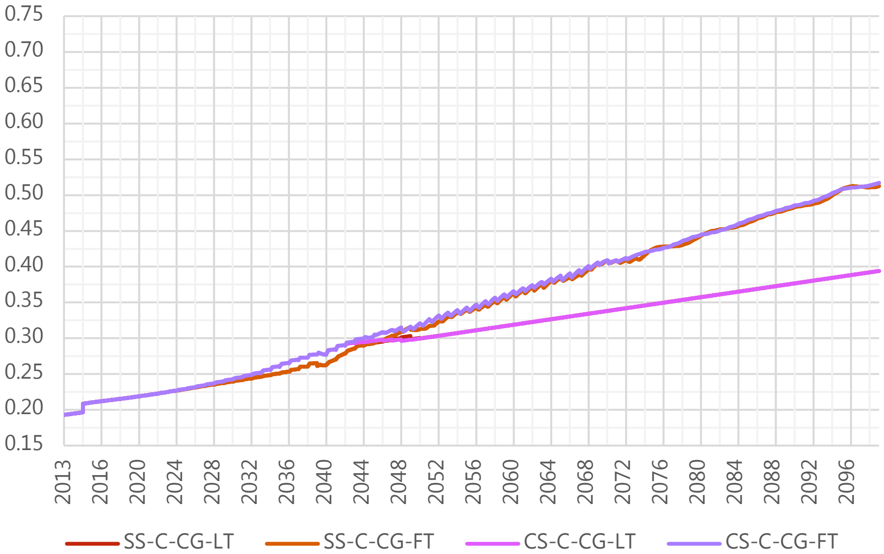


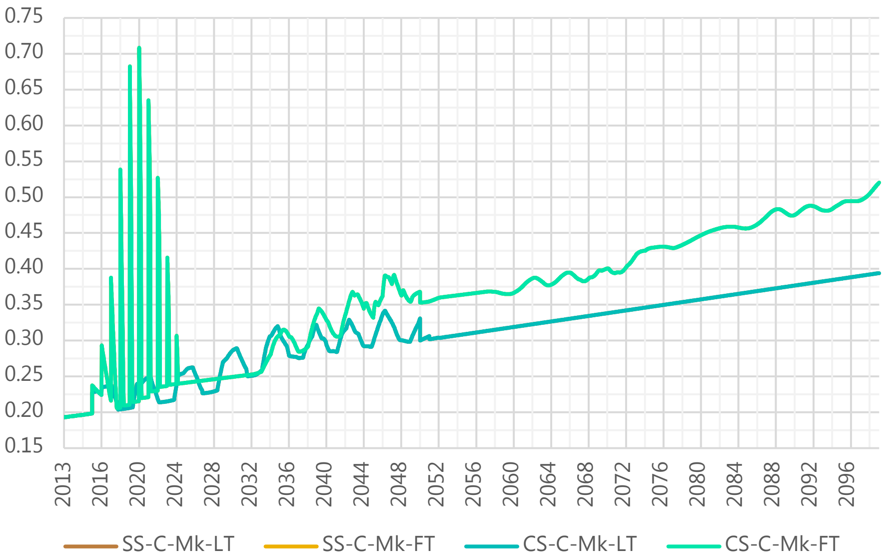
Nomenclature:

LT	- Limited tax	SG	- Stepwise goal	SS	- Stepwise subsidy
FT	- Free tax	CG	- Constant goal	CS	- Constant subsidy
		Mk	- Market driven		

All figures show the total domestic, photovoltaic installed capacity expressed in GW.





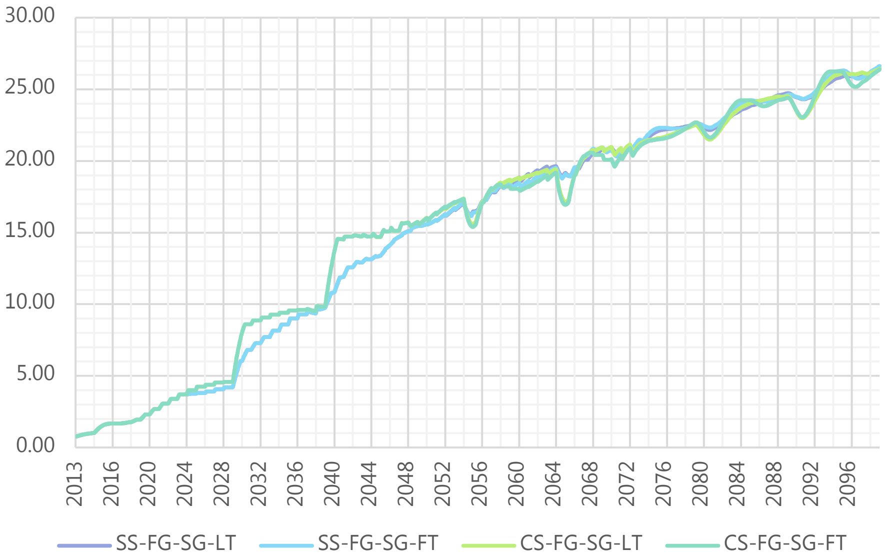


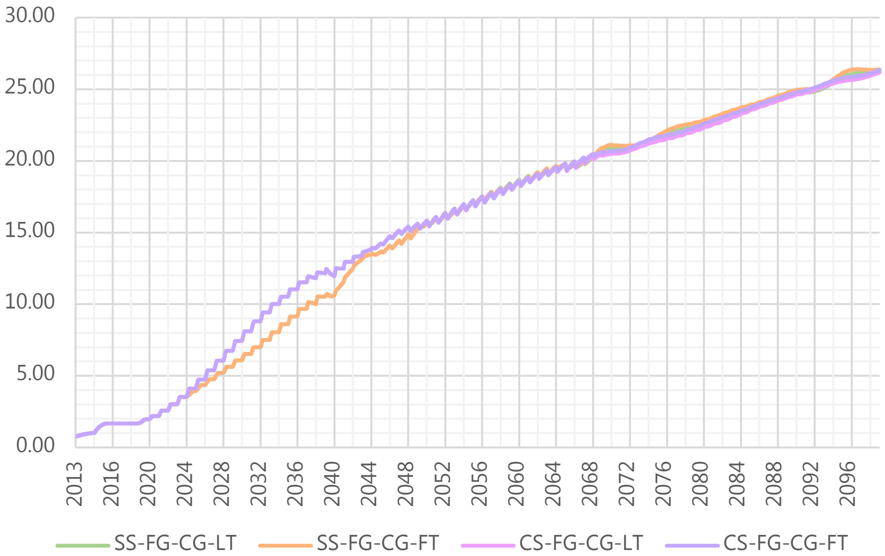
Nomenclature:

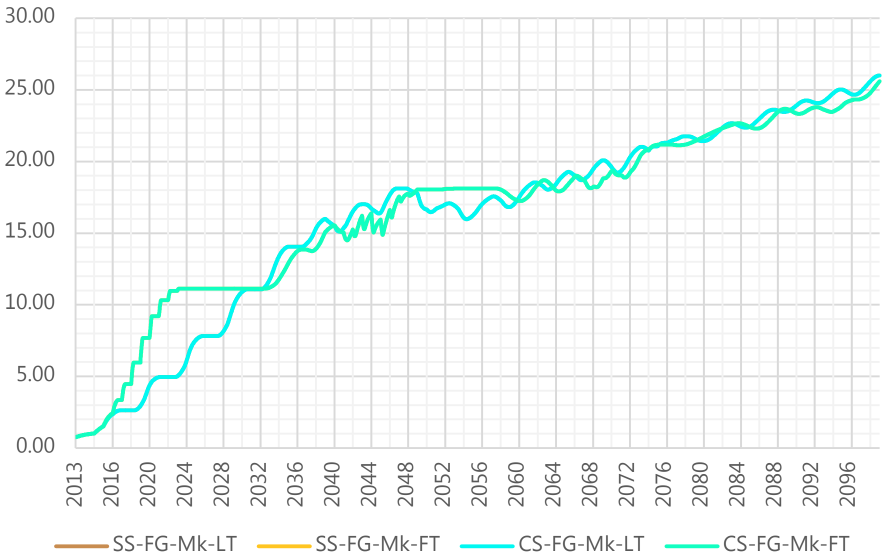
LT	- Limited tax	SG	- Stepwise goal	SS	- Stepwise subsidy
FT	- Free tax	CG	- Constant goal	CS	- Constant subsidy
		Mk	- Market driven		

All figures show the average retail electricity price expressed in CHF/kWh.

Appendix D3 – Fast growth electricity demand scenario by target policy



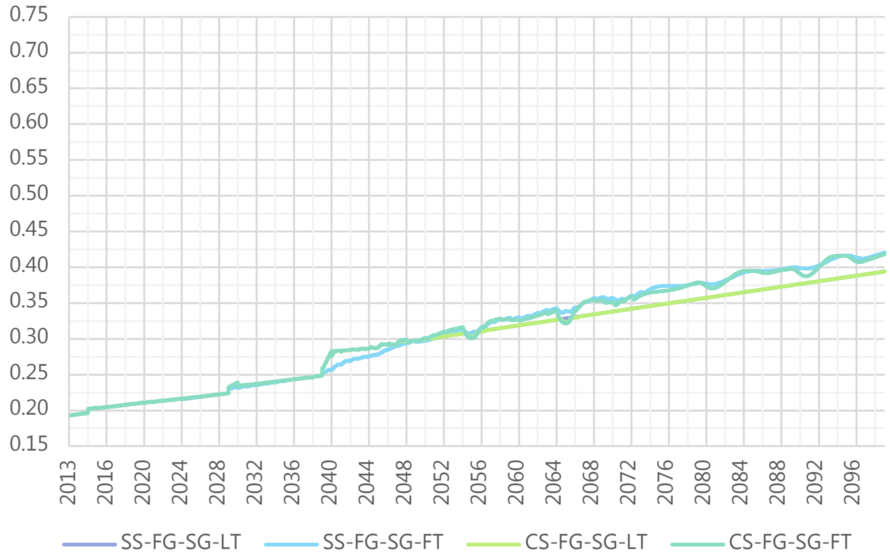


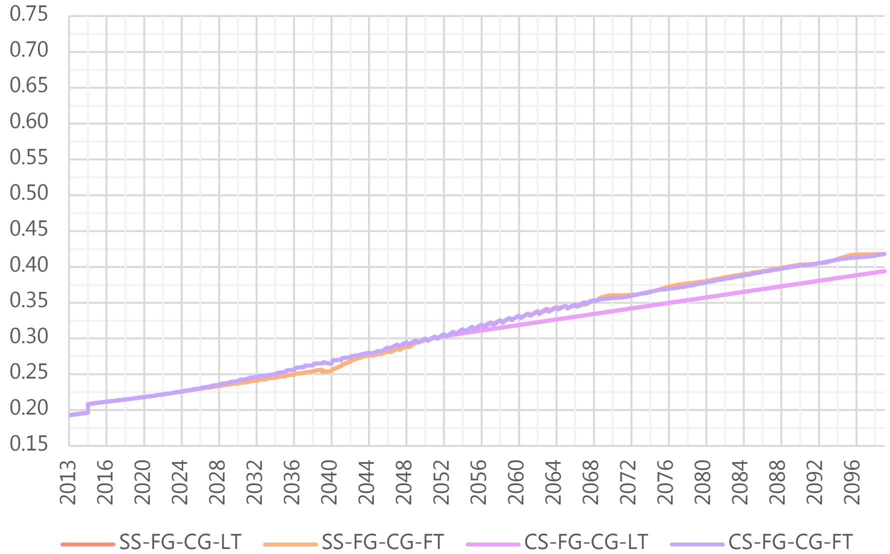


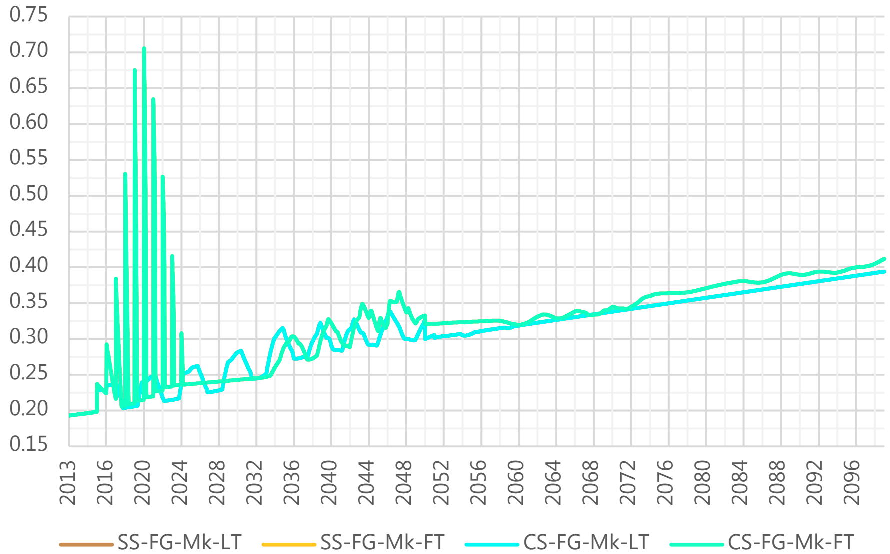
Nomenclature:

LT	- Limited tax	SG	- Stepwise goal	SS	- Stepwise subsidy	
FT	- Free tax	CG	- Constant goal	CS	- Constant subsidy	
		Mk	- Market driven			

All figures show the total domestic, photovoltaic installed capacity expressed in GW.





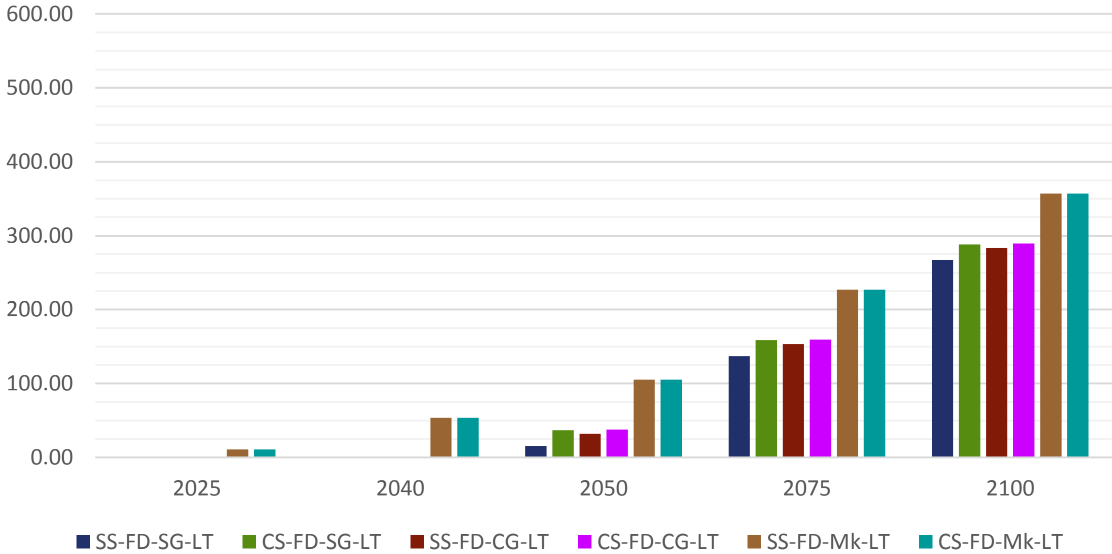


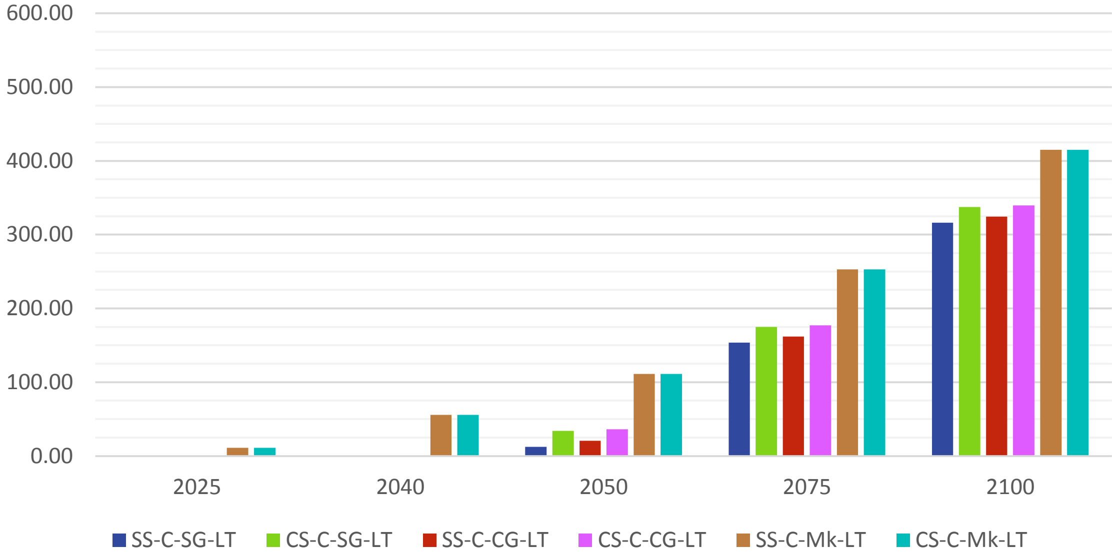
Nomenclature:

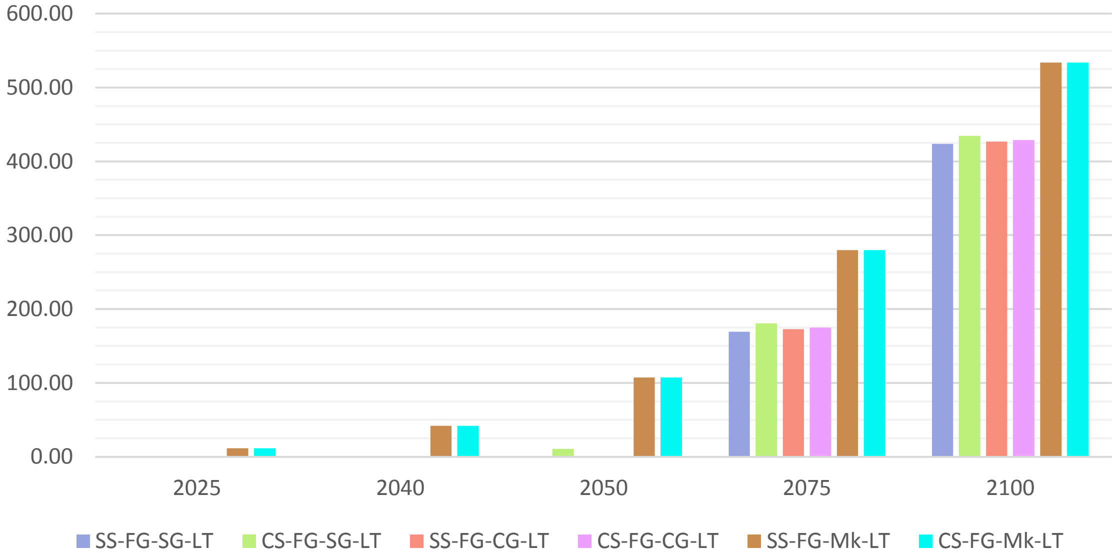
LT	- Limited tax	SG	- Stepwise goal	SS	- Stepwise subsidy
FT	- Free tax	CG	- Constant goal	CS	- Constant subsidy
		Mk	- Market driven		

All figures show the average retail electricity price expressed in CHF/kWh.

Appendix E1 – Cumulated external financing in limited taxation scenarios by electricity demand growth scenario







Nomenclature:

LT	- Limited tax	SG	- Stepwise goal	SS	- Stepwise subsidy
FT	- Free tax	CG	- Constant goal	CS	- Constant subsidy
		Mk	- Market driven		

All figures show the cumulated external financial requirements in billion CHF.