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The economic and CO_2 mitigation potential of the innovation of the power network. A multi-dimensional analysis of Super-Grids and Smart-Grids.

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"The Stone Age did not end for lack of stone"
(Sheikh Zaki Yamani, former Saudi Arabian oil minister)

"Because 99 is not 100, and that single one will make the difference"
(Valter, catador of Jardim Gramacho)

Contents

Chapter 1

Introduction

1.1 Scenario description

Nowadays, general consensus on the impacts of human activities on global climate change has been reached and the interest related to climate issues is growing also among the general public. The debate now focuses on the actions that need to be undertaken to avoid damages that are unacceptable from an economic, social, ethical or environmental point of view and on the policies that can lead to the achievement of such objectives (Nordhaus 1993; Stern 2006; IPCC 2007).

Around the world, initiatives aimed at reducing anthropogenic greenhouse gas (GHG) emissions are beginning to spread, though an operative and effective international agreement is far from being reached. The 16th United Nations Framework Convention on Climate Change (UNFCCC) Conference of the Parties (COP 16) in Cancun has moved the situation a step forward by confirming, and slightly extending, the results of the Copenhagen Accord in an official, though non-binding, UNFCCC agreement (the Cancun Agreement). Discussions in Durban (COP 17) have led to a formal agreement to work for a legally binding global treaty in the coming years. Policies aimed at drastically reducing GHG emissions - like for example the discussion about 50% global emission reduction by 2050 emerged at the 2009 L'Aquila G8 meeting - might entail large economic costs; however inaction may lead to even higher costs in the future (Stern 2006; Weitzman 2009).

It is therefore, very important to analyse what the true costs and impacts of the proposed climate policies may be. Extensive work in this field has already been carried out (WGIII of IPCC 2007; Clarke et al. 2009; Edenhofer et al. 2009); more specifically, this work aims at evaluating the changes in the policy costs and in the power system when the option of the innovation of the power network (Super-Grids and Smart-Grids) is added to the portfolio of available technological options.

The focus is on the electric sector, as a wide range of model simulations consistently find that in stringent mitigation scenarios it is optimal to electrify the energy supply (Richels et al. 2007; Bosetti et al. 2009). In addition, due to its peculiar characteristics and to the fact that the non-electric energy sector is still far from finding viable solutions to drastically reduce its carbon emissions, the electric power sector will have to reach high levels of decarbonization already from the first half of the century. For instance, stabilization scenarios at 550ppm CO_2-eq that emerge from long term models require almost carbon-free electricity generation (Bosetti et al. 2007b; Gurney et al. 2009; ECF 2010).

The electric power sector is, indeed, one of the most relevant sources of carbon emissions and at the same time electricity is becoming more and more important for the contemporary society, with its demand growing at a high rate, especially in developing countries. Emissions from the power sector[1] in Europe and worldwide exceed 39% (1.6 $MtCO_2e$) and 45% (12.8 $MtCO_2e$) of their global emissions, respectively (WRI 2010), and electricity demand is expected to increase 76% by 2030 worldwide according to the IEA (2009) and 87% by 2035 according to the EIA (2010). These projections (IEA 2009) assume that more than one billion of people will still lack access to electricity in 2030 compared with the current 1.5 billion people.

Moreover, the power sector is characterised by long term investments that necessarily shape future emission scenarios and it is particularly relevant also because low carbon technologies - that can help target the problem of reducing GHG emissions - already exist or are in an advanced phase of development (nuclear power, carbon capture and storage for hydrocarbon sources, renewable technologies).

The pull for reducing the electric power sector's GHG emissions is coming not only from the policies, but also form the demand side. Evidence that supports the existence of a willingness to pay - of a certain fraction of consumers - for "greener energy" is, in fact, increasing (Bird et al. 2006; Wiser 2007; Carlsson et al. 2010).

Reaching stringent emission targets with present technologies may be technically feasible, but serious political and social issues arise especially in scenarios with a high penetration of nuclear power and production based on coal with carbon capture and storage. More specifically, nuclear power generation through fission is technologically mature and would be technically able to expand and decarbonize electricity generation. However, there are still large unsolved issues regarding: (i) the safe treatment and disposal of radioactive waste and (ii) proliferation of nuclear technology, knowledge and reprocessable waste, with its geopolitical implications. This, together with the operational risks made apparent by past and recent incidents, induces scepticism towards a nuclear expansion in a significant part of the general

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[1] Data is taken from CAIT 2010 and refers to emissions from electricity and heat plants in 2006 for EU-27 and Worldwide.

public and in the political arena[2]. The technology needed for carbon capture and storage (CCS) operations is already commercially available, but used separately for different production processes. Consequently, there is no need for technological breakthroughs, but for large-scale demonstration plants, to be used as learning opportunities to solve some of the concerns regarding CCS. The major problematic issues about this technology are related to: (i) the very high costs of capture operations compared to the price attached to carbon emissions; (ii) the uncertainties regarding storage operations, related mainly to storage capacity and leakage; (iii) the uncertain legal and regulatory framework for storage and long-term liability; (iv) public acceptance of storage[3].

Given the issues related to the expansion of nuclear power and CCS, strong decarbonization targets will necessarily require the introduction of new technologies and/or a greater reliance on renewables. Especially for these, it will be important to focus on the opportunities induced by structural transformations of the distribution system and its management, i.e., the innovation of the power network.

The current discussion about new technological options that may be added to the optimal mitigation portfolio, indeed, includes important innovations in the distribution system and focuses on Super-Grids and Smart-Grids that may increase the exploitation of renewable sources (WBGU 2003; Trieb 2006; Battaglini et al. 2008; ECF 2010; IEA 2010c; Jacobson and Delucchi 2010). These innovations entail a re-engineering of the power systems towards a more evolved structure that will require a more complex management capable of dealing with new and distributed production sources and even possible changes in consumer involvement.

1.2 Main objectives and structure of the thesis

Current power systems have remained qualitatively similar to how the were in the last century, especially with respect to the interaction with the end-users. Though present global challenges are putting pressure and questioning their architecture. The increasing demand for electricity - that has become an essential commodity, fundamental for all activities of today's lifestyle - coupled with the concerns about climate change and the need to improve the quality and reliability of the provision urge a modernization of the network. A modernization that needs: to be low carbon, to be reliability and security improving, and to develop new models of customer relationship.

Indeed, the thesis deals with important issues that are today in the

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[2] For a deeper discussion on the topic see Deutch et al. (2003) and Jacobson and Delucchi (2010).

[3] For a more detailed discussion on the topic see IPCC (2005) and Herzog (2010).

limelight, such as: i) the importance of the electricity sector in the implementation of climate change mitigation strategies, ii) the innovation of the electricity network as a strategy for reducing emissions, iii) the design of new policies of management of renewable energies and of the new services available, iv) the need to actively involve the users of the network into new styles of consumption / production of energy. All of this is evaluated in a context of evolving energy policies, where the relative long-term importance of the different power generating technologies is changing, especially after the recent events in Japan.

The thesis aims at demonstrating the need to promote a qualitative transformation in the system architecture of the "grid" to make it suitable for managing the complexity of the economic scenarios and advanced services that characterize the emerging "knowledge society", in compliance with the objectives of environmental sustainability and in response to concerns about global climate change. In fact, because of these concerns and of social and political acceptability issues of nuclear power, as we know it today, the energy scenarios for the next few decades see the emergence of an increasingly important role for renewable energy sources.

The general assumption of the thesis is that such a change in the sources of production is likely to cause a major qualitative leap in the power grid. This transformation may induce the evolution of the electricity grid from a classical architecture, top-down and hierarchical, to a more innovative architecture, that will configure the grid (more and more) as a "social ecosystem", able to include the empowerment of all its stakeholders and to enhance, in particular, the more active role of all users of the new network services.

To demonstrate and operationalize the complex nature of this change and the emerging trends, the thesis is organized into three integrated papers that develop and disentangle the system effects of the two technologies that today seem to be at the basis of the possible evolution: Super-Grids and Smart-Grids. The analysis will be conducted using a qualitative-quantitative methodological approach through simulations for both technologies and their integration.

The first paper - **New electricity generation networks and climate change: the economic potential of national and trans-national super-grids powered by Concentrated Solar Power** - develops the analysis of Super-Grids. More in detail, it analyses the system effects and the *technological* and *economic* opportunities of transmitting large amounts of electricity over long distances, for the *stabilization* of anthropogenic emissions of greenhouse gases, with particular attention to the resulting *geopolitical* dynamics.

The analysis is conducted using the simulation platform WITCH, an Integrated Assessment Model (IAM), able to compare this option with other mitigation opportunities, in a framework of intertemporal optimization of resources. In particular, the focus is on the production of electricity from concentrated solar power (CSP) in areas of high solar intensity in places located far from demand centers and, until now, not economically advantageous.

> The quantitative analysis focuses on the electricity supply made available by the Super-Grid - both domestically and for export/import - evaluating their economic, technological and CO_2 mitigation potentials.We have analyzed, in particular, the EU-MENA trade case, though, the results can be expanded qualitatively to consider also the North-South European energy axis, extending the analysis of the geopolitical implications.

The second paper - **Smart-Grids and Climate Change. Consumer adoption of smart energy behaviour: a system dynamics approach to evaluate the mitigation potential** - develops the analysis of Smart-Grids. More in detail, it analyses the system effects of engaging with consumers. More specifically, it looks at the impacts of allowing consumers to: (*i*) manage more actively and consciously their consumption patterns; (*ii*) participate to innovative contracting; (*iii*) generate electricity for own consumption and /or to inject into the grid. Particular interest is directed to the increase in variety of user behaviour (*shift, demand response, home automation, generation*), caused by the implementation of Smart-Grids, which allows: (*i*) to form new relationships among actors of the network, (*ii*) to trigger new processes of “micro production” for energy self-sufficiency to be integrated into the network; and to (*iii*) improve the management and optimization of the power network. In short, to transform the network into a “sensitive network” capable of opening new organizational spaces/times of action.
The analysis is conducted by means of simulations of the adoption dynamics of “smart energy behaviours” by citizens, using the methodology of System Dynamics (J. Forrester) to address the complexity of the dynamics involved.

> The quantitative analysis focuses on the power supply made available by the change in consumption patterns and by domestic generation, in a “energy self-sufficiency” perspective and on the impacts in terms of demand, system costs and opportunities for mitigation. The qualitative analysis studies the organizational transformations, and the social and cultural evolutions induced by the new interactivity with the end-user.The concept of Smart Grid connects the power system to the emerging qualitative transformations and scenarios of the “Knowledge Society” and its newly empowered “Smart Prosumer”.

In the third paper - **Super & Smart Grid integrated investment scenarios: Green Sustainable Energy Management Strategies &**

Scenarios - the complex effects of Super and Smart Grid are analysed together. The paper is divided in two parts: the first one where Super and Smart Grids are integrated in one simulation environment to conduct an in-depth economic analysis, and the second part where they are jointly evaluated and compared considering the effects of the innovation of the electricity grid on the different levels: environmental, technological, economic, organizational, social and geopolitical, by means of the GEMS (Green Energy Management Strategies foe sustainable scenarios) multi-level evaluation function: GEMS = (Env, Tech, Ec, Org, Soc, GeoP).
The proposal is to identify an approach for the analysis and management of the various strategies of green energy generation, that is able to grasp the complexities and interactions of the multiple effects induced by the different options.

> The quantitative analysis focuses on the integration of the power supply made available jointly by Super and Smart Grids. The qualitative analysis has investigated the new dynamics of empowerment among all the stakeholders involved and the possible impacts on various levels. The synergies of system integration, related to the potential mix of Super and Smart Grids, to manage the evolution of green electricity are also analysed.

Concluding, the thesis started with a substantial economic and computational approach, and then was expanded to take into account qualitative aspects that govern the dynamics of the complex "social ecosystem" in play. In synthesis, we analyze the quali-quantitative system effects induced by the impact of the innovation processes in the power network, in an energy market that is not able, alone and in a classical economic perspective, to jointly optimize aspects concerning the environment, technology, organizational structures, economics, society and geopolitics, that are put into play by the introduction of these technological options. These tools are also needed to manage the inevitable conflicts of interest that will arise with the change. We propose an approach "beyond grid parity", in the sense that we aim at analyzing a broader concept of "costs", to: (*i*) identify the paths of evolution of the electrical system in the scenarios of the knowledge society, (*ii*) the nature and extent of the processes involved, and (*iii*) to assess the feasibility of accepting the challenge of a low-carbon economy based on renewable energy.

Chapter 2

New electricity generation networks and climate change: the economic potential of national and trans-national Super-Grids powered by Concentrated Solar Power

Abstract

We extend the WITCH model to consider the possibility to produce and trade electricity generated by large scale concentrated solar power plants in highly productive areas that are connected to the demand centres through High Voltage Direct Current (HVDC) cables. We find that it becomes optimal to produce with this source only from 2040 and trade from 2050. In the second half of the century, CSP electricity shares become very significant especially when penetration limits are imposed on nuclear power and on carbon capture and storage operations (CCS). Climate policy costs can be reduced by large percentages, up to 66% with respect to corresponding scenarios without the CSP-powered Super-Grid option and with limits on nuclear power and CCS. We also show that MENA countries have the incentive to form a cartel to sell electricity to Europe at a price higher than the marginal cost. Therefore we advocate the institution of an international agency with the role of regulating a hypothetical Mediterranean electricity market.

Keywords: Climate Policy, Integrated Assessment, Renewable Energy, Concentrated Solar Power, Super-Grids, Electricity Trade.

2.1 Introduction

This study assesses the role of concentrated solar power (CSP) transmitted through Super-Grids (SG) as a technology option in long-term scenarios of climate change mitigation policies. The paper examines the economic attractiveness of CSP powered Super-Grids (CSP-SG), the optimal timing and size of investments, the implications for the optimal mix of power sector technologies, and it carefully discusses the timing, size and institutional requirements of an electricity trade across the Mediterranean.

Super-Grids are high capacity wide area transmission networks intended to transmit power over long distances. Although they allow the connection of all kinds of power generation plants, their link with renewable energy is particularly interesting because it allows to take advantage of sources distantly located from consumption areas. The development of high-voltage direct current (HVDC) cables, indeed, allows the exploitation of sources that where previously non-economically viable due to transmission losses. In addition, such cables allow the integration of inter-regional electric power systems, facilitating trade and helping to smooth the variations in supply and demand (Wolff 2008) taking advantage of meteorological or time differences.

The investments needed for projects that aim at connecting different regions or very distant national areas are high, and in order to attract investors and be profitable such infrastructure needs to be used consistently, and therefore to be subject to long-term agreements. Especially for the implementation of international Super-Grids, issues of security exist and need to be carefully considered, as these lines have the potential to cover large percentages of the regional power loads.

All water, wind and solar related technologies are likely to play an important role in decarbonising electricity production (ECF 2010; Jacobson and Delucchi 2010). In particular, this paper focuses on concentrated solar power, and more specifically on parabolic troughs.
In CSP plants direct solar radiation heats a liquid, solid or gas, that is then used to generate electricity as in any other thermoelectric power plant. CSP is an attractive option in climate change mitigation scenarios because it has no direct emissions of CO_2 nor of other pollutants and it relies on a virtually infinite energy source. CSP has a great advantage also over photovoltaic and wind power because heat can be stored (up to fifteen hours) in order to generate a constant flow of electricity. However, CSP needs direct solar beams (direct normal irradiance, DNI) while photovoltaic also relies on horizontal irradiation. The best sites for CSP are therefore dry regions near the equator - e.g. the Sahara Desert - which are typically areas with a low opportunity cost for land and located far away from where electricity is consumed, therefore the need for the deployment of high-efficiency and

high-capacity transmission cables that can cover long distances with minimal losses. The future of CSP and the development of future power grids is therefore strictly intertwined.

The possibility to use CSP to generate electricity with no CO_2 emissions and very low intermittency is clearly very attractive and explains the growing interest that surrounds this technology option. Researchers, government agencies and environmental activists are supporting very ambitious deployment plans for CSP on both the sides of the Atlantic. For example, the Desertec project foresees a large number of CSP plants in Northern Africa connected to European power grids by means of SG that stretch across the Mediterranean and supply up to 15% of the electricity consumed in Europe (Trieb and Mller-Steinhagen, 2007). The Mediterranean Solar Plan, sponsored by the Union for the Mediterranean, has the objective to set up a trade between the European Union (EU) and developing countries belonging to the newly established international organization by 2020 with electricity generated from 10-12 GW of installed capacity. The U.S. Department of Energy (DOE) has ambitious plans for solar energy and CSP in particular. The objective is to make CSP competitive in the intermediate power market by 2015. By developing advanced technologies that will reduce systems and storage costs the goal is to make CSP competitive in the base-load power market by 2020 (US DOE, 2008). Also the International Energy Agency (IEA) sees a bright future for CSP. In the CSP Technology Roadmap (IEA, 2010b) the IEA illustrates a scenario that foresees 148 GW of capacity installed globally by 2020 to supply electricity for intermediate and peak loads. This requires a 200-fold expansion of the global installed capacity, equal to 0.7 GW at beginning of 2009.

Some economic studies that investigate the feasibility of this option have already been carried out. The tools that have been applied, though, are mainly policy analysis and scenario analysis (Trieb 2006; Patt et al. 2008; Ummel and Wheeler 2008; IEA 2010b, Jacobson and Delucchi 2010). These methods identify potential risks, implementation barriers, required subsidies and policies or choose and describe feasible future situations to evaluate their effects and pathways towards them. To our knowledge, the only attempt to introduce a Super-Grid in a more sophisticated economic model is that of Bauer et al. (2009), that aims at finding the political barriers to the electricity trade between Europe and MENA, analysing the effects on macroeconomic activity, sectoral outputs and trade relations.

The present work aims at evaluating the impacts and the incentives to invest in a Super-Grid capable of delivering long distance electricity generated with concentrated solar power plants. The optimal timing and quantity of investments are determined as the outcome of a long-term optimization process in which economic resources are allocated efficiently across sectors and time. To do so, we build on a pre-existing model - the WITCH (World

Induced Technical Change Hybrid) Model - where investment decisions for all regions in which the world countries are grouped in the model, are the outcome of a strategic interaction modelled as an open loop Nash game (Bosetti et al., 2006, 2007a, 2007b 2009;).

More precisely, we extend the model so that it is able to consider concentrated solar power production and its transmission over long distances within or between regions. In particular, we model the possibility for Western and Eastern Europe to import electricity generated in highly productive areas of the Middle-East and North Africa, allowing the latter to use this electricity also for domestic consumption, without the need of a SG. We also simulate the possibility for the USA and China to invest in a domestic CSP powered SG connecting highly insolated areas with distant highly energy demanding areas of the same region. This may enable an increased diversification of electricity sources and also an increased usage of low carbon technologies, reducing the electric power sector CO_2 footprint.
Future work will try to account for the main socio-economic effects of the increased availability of (carbon-free) electricity in the MENA region, starting from the possibility of producing relatively cheap and low-carbon fresh water, in line with some exploratory work that has appeared in the literature (Trieb and Mller-Steinhagen 2007; Trieb 2009).

We examine and disentangle the driving forces that create the incentive to invest in CSP and in SG with a regional detail. In particular, we evaluate how the incentive to invest in CSP changes when we limit the expansion of nuclear power and of Integrated Gasification Combined Cycle (IGCC) coal with carbon capture and storage (CCS). However, we do not limit our analysis to technological aspects. We examine also economic and geo-political issues.
On the technological side we are interested in examining (i) the optimal timing and size of CSP power generation, (ii) the Europe-MENA trade of CSP electricity, (iii) the impact of CSP on the energy mix. On the economic and geo-political side we examine (iv) investments and cost dynamics, (v) the option value of CSP, (vi) the feasibility of the foreseen expansion of CSP, (vii) the economic and energy-system implications of forcing earlier investments in CSP and (viii) the plausibility, implications and the regulatory requirements of a non-competitive Europe-MENA electricity market.

Compared to previous policy scenarios analysis (Trieb 2006; Patt et al. 2008; Ummel and Wheeler 2008; Jacobson and Delucchi 2010), we use a solid energy-economy modelling framework, while with respect to Bauer et al. (2009) we make further considerations on the nature of the electricity trade between the Euro-MENA; we also introduce CSP powered SG also in the USA and in China.

The next sections will describe the WITCH model (Section 2.2) and the insertion of the Super-Grid option (Section 2.3), discuss the calibration procedure (Section 2.4) and then (Sections 2.5, 2.6, and 2.7) evaluate the costs, benefits and potential effects of the Super-Grid option, to understand if the necessary technological upgrades are economically justifiable. Section 2.8 evaluates the costs and benefits of an anticipated common deployment of CSP while Section 2.9 analyses the Euro-MENA trade situation in the presence of market power. Section 2.10 illustrates the sensitivity analysis and conclusions follow.

2.2 A Brief Introduction to the WITCH Model

WITCH - World Induced Technical Change Hybrid - is a regional integrated assessment model structured to provide normative information on the optimal responses of world economies to climate policies (Bosetti et al. 2006, 2007a).

It is a hybrid model because it combines features of both top down and bottom up modelling: the top-down component consists of an inter-temporal optimal growth model in which the energy input of the aggregate production function has been integrated into a bottom-up like description of the energy sector. WITCH's top down framework guarantees a coherent, fully intertemporal allocation of investments, including those in the energy sector.

World countries are aggregated in twelve regions on the basis of geographic, economic and technological vicinity. The regions interact strategically on global externalities: GHGs, technological spillovers, a common pool of exhaustible natural resources[1].

WITCH contains a representation of the energy sector, which allows the model to produce a reasonable characterization of future energy and technological scenarios and an assessment of their compatibility with the goal of stabilizing greenhouse gases concentrations. In addition, by endogenously modelling fuel prices (oil, coal, natural gas, uranium), as well as the cost of storing the CO_2 captured, the model can be used to evaluate the implication of mitigation policies on the energy system in all its components.

In WITCH emissions arise from fossil fuels used in the energy sector and from land use changes that release carbon sequestered in biomasses and soils. Emissions of CH4, N2O, SLF (short-lived fluorinated gases), LLF (long-lived fluorinated) and SO2 aerosols, which have a cooling effect on temperature, are also identified. Since most of these gases arise from agricultural practices,

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[1] The regions are USA, WEURO (Western Europe), EEURO (Eastern Europe), KOSAU (South Korea, South Africa and Australia), CAJANZ (Canada, Japan and New Zealand), TE (Transition Economies), MENA (Middle East and South Africa), SSA (Sub-Saharan Africa), SASIA (South Asia), SEASIA (South-East Asia), CHINA, LACA (Latin America and the Caribbean).

the modelling relies on estimates for reference emissions, and a top-down approach for mitigation supply curves[2].

A climate module governs the accumulation of emissions in the atmosphere and the temperature response to growing GHGs concentrations. WITCH is also equipped with a damage function that provides the feedback on the economy of global warming. However, in this study we exclude the damage function and we take the so-called "cost-minimization" approach: given a target in terms of GHGs concentrations in the atmosphere, we produce scenarios that minimize the cost of achieving this target.

Endogenous technological dynamics are a key feature of WITCH. Dedicated R&D investments increase the knowledge stock that governs energy efficiency. Learning-by-doing curves are used to model cost dynamics for wind and solar power capital costs. Both energy-efficiency R&D and learning exhibit international spillovers. Two backstop technologies - one in the electricity sector and the other in the non-electricity sector - necessitate dedicated innovation investments to become competitive. In line with the most recent literature, the costs of these backstop technologies are modelled through a so-called two-factor learning curve, in which their price declines both with investments in dedicated R&D and with technology diffusion.

The base year for calibration is 2005; all monetary values are in constant 2005 USD. The WITCH model uses market exchange rates for international income comparisons.

2.3 Super-Grids: Major Characteristics and Modelling Assumptions

This paper considers the production of solar thermal power focusing on parabolic trough power plants. Such power plants are characterised by arrays of parabolic reflectors that concentrate incident solar radiation on to an absorber, positioned in the focal line of the concentrator, converting it into thermal energy which is then used to generate superheated steam for the turbine (Richter et al. 2009). More specifically, we consider collectors that are able to track the sun diurnal course by means of a single-axis system and to store the equivalent of seven hours of production at the nominal plant capacity.

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[2] Reducing emissions from deforestation and degradation (REDD) is estimated to offer sizeable low-cost abatement potential. WITCH includes a baseline projection of land use CO_2 emissions, as well as estimates of the global potential and costs for reducing emissions from deforestation, assuming that all tropical forest nations can join an emission trading system and have the capacity to implement REDD programs. However, avoided deforestation is not a source of emissions reductions in the version of the model that we used for this study

The choice to, firstly, focus on concentrating solar power (CSP) is driven by a number of reasons: (*i*) it can be integrated with storage or in hybrid operation with fossil fuels; (*ii*) it is suitable for peak-loads and base-loads if thermal energy storage systems are installed; (*iii*) it has a short pay back period of the energy used for construction; (*iv*) according to the literature, costs are rapidly decreasing (Richter et al. 2009). In particular, parabolic trough power plants are: (*i*) already commercially available (*ii*) with a commercially proven efficiency of 14%; (*iii*) and commercially proven investment and operating costs; (*iv*) they are also modular; (*v*) and have a good land-use factor with respect to other CSP technologies (*vi*) and the lowest demand for materials (Richter et al. 2009).

Drawbacks of CSP technology are instead related to the land requirements and water usage for cooling and cleaning operations. More in detail, (*i*) although land requirements for CSP plants are higher than those for photovoltaic (PV) solar generation (Jacobson and Delucchi 2010) the areas that are ideal for large CSP plants are usually desert areas characterised by a low opportunity cost for land; (*ii*) wet-cooling operations - that use water - can be substituted with dry-cooling - that uses air to cool the solar panels -, though the latter reduces plant efficiency and is more costly, up to 5-10% (Richter et al. 2009); (*iii*) new techniques of automated cleaning or electrostatic-based self-cleaning[3] should drastically reduce the demand for water of cleaning operations (Williams 2010). In addition, operating temperatures are quite low - around 400C - implying a moderate conversion efficiency; central receiver CSP plants have instead good prospects for reaching higher temperatures, though this technology has not yet been commercially proven (Richter et al. 2009).

The choice of the production locations - characterised by high and stable levels of irradiance - and the inclusion of power plants equipped with integrated thermal storage allows us to target, at least partly, the problem of intermittency of solar power.

In this version of the model, the geographic location of the power plants can not be endogenously chosen. Production is modelled as if positioned in one unique point characterized by the average regional conditions.

The infrastructure that enables the trade of solar electricity from MENA to Europe or to transfer the CSP electricity within China or the USA - that is High Voltage Direct Current (HVDC) cables and conversion stations - is costly and it is not adjustable in size, therefore in order for a SG to be implemented there is the need for a significant and stable demand of such product. As results will show, this is not a major modelling problem.

Even if they require the construction of converter stations that are costly and

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[3] This technique is based on sensors that measure the dust on the surface of the panels: when the latter reaches a certain level, the panel surface is energised so that a dust-repelling wave lifts the dust and it transports it to the edge of the screen.

have a high footprint[4] in terms of land-requirements, HVDC cables are more suitable than high-voltage alternating current (HVAC) cables for large-scale and long distance transmission, because of: (*i*) lower transmission losses over long distances; (*ii*) the possibility of submarine cables over long distances and of (*iii*) underground cables over long distances and with high power; (*iv*) a lower number of lines is needed to transmit the same power; (*v*) smaller footprint, in terms of occupied land, of the over-head lines; (*vi*) smaller magnetic fields from the lines; (*vii*) greater control over power transfers, that is important for electricity trade (Heyman et al. 2010).

The main problematic issue is related to the high investment costs, thus we need to evaluate the economic convenience to invest in this technology that will ultimately determine its success. To do so, different scenarios with and without this option will be analysed and compared to assess the economic and environmental potential effects of this option.

In addition, for the MENA-Europe case where trade is allowed, strong security of supply and geopolitical issues arise, especially as this market involves two regions at different levels of development and therefore more complex considerations, above the economic ones, are involved.

2.3.1 Modelling Assumptions: Supply

The SG is considered as an add-on to the existing regional power system networks that enables their connection. The costs related to modifications to the previous infrastructure that may need to be implemented in order to manage and distribute such electricity at the low voltage level are not considered.

National power grids are dynamic structures that have a “history”, tied with economic, technological and social preferences, that strongly determines their evolution. Although it is difficult to account for such issues, the WITCH model considers that these systems are not able to take on any “shape” in little time, but need time in order to evolve, as investments in power generation or transmission are long-lived. In this direction, the use of a constant-elasticity function (CES) makes moving away from an established and differentiated energy mix costly. The model starting values for each region are calibrated to replicate the real situation in 2005 (Bosetti et al. 2007a).

Electricity generated with CSP can be consumed domestically or it can be exported. Regions in which solar irradiance is low and the opportunity cost of land is relatively high, can choose to import electricity from abroad by exploiting the new technological options that allow transmission over long

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[4] Footprint here refers to the area around the converter station or the power line on which no buildings or high trees are allowed.

distances with low losses. We apply the restriction that regions that decide to import electricity cannot generate it domestically.

The amount of CSP electricity ($EL_{CSP,prod}$) supplied to the grid of each region n is determined combining in fixed proportions: (*i*) the generation capacity accumulated in each region ($K_{CSP,n}$), measured in power units, corrected through an efficiency coefficient (plant utilization rate) $\mu_{CSP,n}$, that indicates the number of yearly full load hours that a concentrating solar power plant in the specific region may provide; (*ii*) CSP plants operation and maintenance ($O\&M_{CSP,n}$), measured in USD, converted into energy units by θ_{CSP}; (*iii*) the capacity of the SG ($K_{grid,n}$) to transmit electricity from remote areas to the local grid, measured in power units, with its efficiency coefficient $\mu_{grid,n}$; and (*iv*) operation and maintenance for the SG ($O\&M_{grid,n}$), measured in USD, converted into energy units by θ_{grid}. The production function of CSP electricity is of the Leontief type:

$$\begin{aligned} EL_{CSP,prod}(n,t) \quad = \quad & min\left\{\mu_{CSP,n} \cdot K_{CSP}(n,t); \theta_{CSP} \cdot O\&M_{CSP}(n,t);\right. \\ & \left.\mu_{grid,n} \cdot K_{grid}(n,t); \theta_{grid} \cdot O\&M_{grid}(n,t)\right\} \ . \end{aligned}$$

Power generation capacity in CSP accumulates as follows:

$$K_{CSP}(n,t+1) = K_{CSP}(n,t)(1-\delta_{CSP}) + \frac{I_{CSP}(n,t)}{SC_{CSP}(n,t)} \ ,$$

where $I_{CSP}(n,t)$ represents the investments in concentrated solar power plants made by region n at time t, δ_{CSP} the CSP capital depreciation rate, and SC_{CSP} the unit investment cost of installing CSP generation capacity.

Investment costs follow a one-factor learning curve depending on cumulative[5] world capacity in CSP power plants (TK) and decrease as experience/technology diffusion increases. To take into account the limited expansion possibilities at each time step - due to supply restrictions on intermediate goods - unit costs also increase with investments in the same period and region:

$$SC_{CSP}(n,t{+}1) = SC_{CSP}(n,t_0) {\frac{TK_{CSP}(t)}{TK_{CSP}(t_0)}}^{-\alpha} \left(1 + \left(\frac{\left(\frac{I_{CSP}(n,t+1)}{SC_{CSP}(n,t+1)}\right)}{\beta}\right)^{\gamma}\right) \ .$$

The investment costs in the SG infrastructure have not been simply modelled as higher investment costs for the production of the solar thermal electricity for export, as they are not perfectly proportional to the amount of electricity exported but are instead directly related to the SG maximum capacity. Moreover, a separate formulation would enable to analyze the SG as an

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[5] The cumulative capacity is calculated aggregating - at each time step - installed capacity of all regions, gross of depletion.

electricity vector and therefore to test the effects of exporting electricity generated from different energy sources.

Theoretically, SG investments should not be modelled as a continuous function with respect to quantity. There is, indeed, a minimum amount of investments necessary to allow for the transmission between the two regions or two distant areas of the same region. Though, our simulations show that a continuous modelling of SG investments is not affected by this constraint as solar power demand is large enough to imply sufficient grid investments from the very beginning of its production. Therefore, we model investments ($I_{grid,n}$) and capital in the SG infrastructure similarly to those for other technologies:

$$K_{grid}(n,t+1) = K_{grid}(n,t)(1-\delta_{grid}) + \frac{I_{grid}(n,t)}{SC_{grid}(n,t)} \ ,$$

If investments in transmission infrastructure - i.e. the SG - are sufficient to cover the distance between the networks of two regions, the electricity from CSP power plants can also be exported. The production function for exported CSP electricity differs from the production function of CSP electricity consumed domestically only for different grid requirements:

$$\begin{aligned} EL_{CSP,X}(n,t) &= min\,\{\mu_{CSP,n} \cdot K_{CSP}(n,t); \theta_{CSP} \cdot O\&M_{CSP}(n,t); \\ &\qquad \mu_{grid,n} \cdot K_{grid,X}(n,t); \theta_{grid} \cdot O\&M_{grid,X}(n,t)\} \ . \end{aligned}$$

where the index X stands for exports. Therefore, electricity from CSP produced in region n at time t must be equal to domestic production plus exports:

$$EL_{CSP,prod}(n,t) = EL_{CSP}(n,t) + EL_{CSP,X}(n,t) \ ,$$

with $EL_{CSP,X}(n,t) < 0$ in importing regions and $EL_{CSP,X}(n,t) = 0$ in regions that are not connected to an international electricity grid.

Investments in CSP generation and in the SG infrastructure together with the $O\&M$ costs enter the budget constraint:

$$\begin{aligned} C(n,t) &= Y(n,t) - I_c(n,t) - \sum_w p_w Z_w(n,t) - I_{CSP}(n,t) - I_{grid} + \\ &\quad -O\&M_{CSP}(n,t) - O\&M_{grid}(n,t) \ , \qquad (2.1) \end{aligned}$$

where Y is net output of the economy, I_c is the investment in the final good sector, $\sum_w p_w Z_w(n,t)$ is the expenditure for investments in the energy sector, in R&D and other expenses that are detailed in .

2.3.2 Modelling Assumptions: Demand

In the model, electric power use (EL) is an aggregate of electricity generated by the various sources, combined using a CES function:

$$EL(n,t) = \left(EL_2(n,t) + \alpha_{HYDRO}EL_{HYDRO}(n,t)\right); \tag{2.2}$$

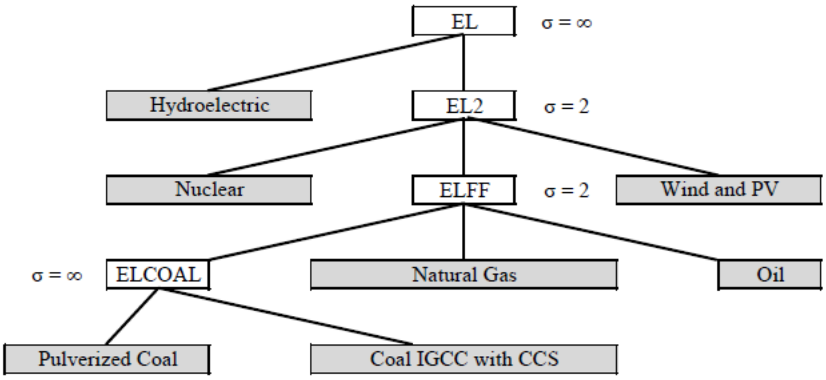
$$\begin{aligned} EL_2(n,t) = {} & (\alpha_{FF}FF(n,t)^{\rho_{EL2}} + \alpha_{NUKE}EL_{NUKE}(n,t)^{\rho_{EL2}} + \\ & +\alpha_{W\&S}EL_{W\&S}(n,t)^{\rho_{EL2}})^{\frac{1}{\rho_{EL2}}}; \end{aligned} \tag{2.3}$$

$$EL_{NUKE}(n,t) = \left(EL_{NUKE}(n,t) + EL_{BACKSTOP}(n,t)\right); \tag{2.4}$$

$$\begin{aligned} FF(n,t) = {} & (\alpha_{COAL}EL_{COAL}(n,t)^{\rho_{FF}} + \alpha_{OIL}EL_{OIL}(n,t)^{\rho_{FF}} + \\ & +\alpha_{GAS}EL_{GAS}(n,t)^{\rho_{FF}})^{\frac{1}{\rho_{FF}}}; \end{aligned} \tag{2.5}$$

$$EL_{COAL}(n,t) = \left(EL_{PC}(n,t) + EL_{IGCC}(n,t)\right); \tag{2.6}$$

All of the above quantities are endogenously determined in the optimization process except for hydroelectric power that is exogenous.



Notes: Elasticities of substitution σ are detailed at each nest. Electricity is measured in energy units. Electricity generation follows a Leontief specification.

Figure 2.1: The constant elasticity of substitution nested structure of electricity supply.

Figure 2.1 describes the energy nest graphically. In our simulations, electricity from CSP power will enter various nodes depending on the region. Section 2.4 will give a more detailed description of the various assumptions. For further details on the general structure of the model see Bosetti et al. (2007a).

2.3.3 Electricity Trade

The equilibrium of the international market of CSP electricity requires that demand and supply are equal for each time period:

$$\sum_n EL_{CSP,X}(n,t) = 0 \quad \forall t.$$

The market clearing price (P_{CSP}) is the price that will determine the trade flows. The revenue (expenditure) for CSP electricity is added (subtracted) from the regional output (Y):

$$Y(n,t) = \frac{GY(n,t)}{\Omega(n,t)} - \sum_q p_q V_q(n,t) + EL_{CSP}(n,t)P_{CSP}(t)$$

where GY is gross output, Ω the damage function[6] and $\sum_q p_q V_q(n,t)$ the sum of expenditures, as better detailed in Bosetti et al. (2006).

2.4 Calibration

Economic data on solar thermal power plants are taken from Kaltschmitt et al. (2007). More precisely, we consider parabolic trough power plants, with nominal capacity of 50MW each, 100% solar share and equipped with integrated thermal storage units for 7 hours. The latter characteristic helps to deal with the intermittency issues of solar power.

Parabolic trough power plants are one of the solar thermal technologies for which more is known about the real market costs as some installations have already been built. Existing plants include the SEGS plants in California, Nevada One in Nevada and the Andasol Plants in Spain. Installed capacity in 2009 was 500 MW, while under-construction or proposed capacity currently exceeds ten thousand MW (Richter et al. 2009).

We set investment cost at 6,500 USD per kW, assuming integrated thermal storage units for seven hours; operation and maintenance costs are equal to 127.5 USD per kW (Kaltschmitt et al., 2007). The data refer to state-of-the-art technology and to installations in a geographic area with a high share of direct radiation (Kaltschmitt et al. 2007). These investment costs are also in line with those expected from the latest Californian development project: the Blythe Solar Power Project (Streater 2010). Moreover, The SRREN finds capital costs in the range of 6,000 to 7,300 USD/kW and operation and maintenance costs in the range of 60 to 82 USD/kW (Bruckner et al., 2011).

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[6] Note that, as discussed in Section 2.2, in this work we do not include the damage function as we take a cost-minimization approach.

We have modelled a learning by doing effect with a progress ratio of 90% as suggested in Neij (2008), IEA (2010c), Arvizu et al. (2011). This means that investments costs are reduced by 10% at every doubling of the installed capacity. Learning rates estimates in the literature vary from 8% to 15% (Arvizu et al., 2011; Enermodal Engineering Limited, 1999; IEA, 2003, 2010c; Kearney, 2003; Neij, 2008; Ummel and Wheeler, 2008; Williges et al., 2010). A wider range of learning ratios is tested in the sensitivity analysis.

The learning process occurs as an externality, both domestic and internationally. Countries benefit from the positive technological externality but do not govern it. However, WITCH is a perfectly forward looking model and countries exactly forecast technology options and costs that they will face in the future.

Data on Direct Normal Irradiation (DNI) are taken from the U.S. National Renewable Energy Laboratory (NREL) estimates available from the NASA Atmospheric Science Data Center. This dataset uses NREL's Climatological Solar Radiation (CSR) Model which accounts for cloud cover, atmospheric water vapor, trace gases, and aerosol in calculating the insolation with measurements checked against ground stations where available.

In this study we restrict the possibility to invest in CSP to MENA, the USA and China. These regions have sites with high DNI and represent a large share of global energy consumption and global emissions (approximately 60% of global primary energy supply and of fossil fuels emissions from 2005 to 2050 in our BaU scenario). Future work will include Australia, Brasil and Indonesia as these are the other world regions with the most potential for CSP production (Trieb 2009b).

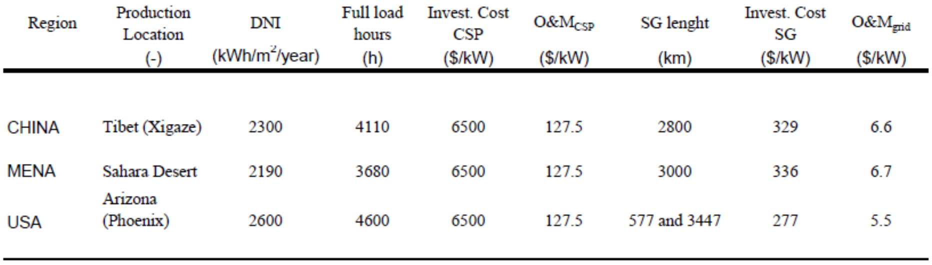
More specifically, for MENA, we consider delocalised production in different sites in the Sahara Desert region as currently discussed (Trieb 2006; Trieb and Mller-Steinhagen 2007); for China we have chosen the Tibet area around the city of Xigaze, as one of the options described in Chien (2009), and for the USA we consider production in Arizona, around Phoenix, as it would be the most productive part of the country.
The number of full load hours of operation per year of the reference plant in the various regions, given their levels of solar irradiation (DNI), is taken from Trieb (2009b). Such value for MENA is also available in Kaltschmitt et al. (2007). Moreover, we use an annual depreciation rate of 10%, which corresponds to a power plant lifetime of 20 years.

For what concerns the Super-Grid infrastructure that should transmit the CSP power, connections lines in the order of thousands of km have been assumed. We consider High Voltage Direct Current (HVDC) cables that connect two AC-DC converter stations. Transmission power losses are in the range of 3% for 1000 Km, while HVDC terminal losses are 0.6% per inlet or outlet station (May 2005). Power transmission over distances of 3000

Km entail transmission losses around 10%, while high voltage alternating current (HVAC) cables would cause power losses of around 20% and higher investment costs (Breyer and Knies 2009).

Estimates of investment costs for such infrastructure vary in the literature and depending on the characteristics of the cables: voltage, power capacity and overhead/submarine. We consider cables with 5GW of power capacity and ± 800 kV voltage, and costs have been extrapolated from May (2005) and Trieb (2006). The adaptation of the values presented in the latter papers to our conditions has led us to use the estimates presented in Table 2.1.

For the Europe-MENA interconnection we assume a connecting power line of 3000 Km as in Czisch (2004), Trieb (2006), and Bauer et al. (2009). More specifically, we consider connection lines of overhead and submarine cables in the ratio of $\frac{3}{4}$ and $\frac{1}{4}$ respectively. Such lines would allow the connection of the most northern parts of the Sahara with Scandinavia or more inland areas with the centre of Europe, considered to be Strasbourg. For China we consider overhead transmission lines in the order of 2800 Km, calculated as the average between the distances of Xigaze from three of the major industrial centres: Beijing, Shanghai and Guangzhou. For the USA, we assume the transmission of the electricity generated to be split in half between the West Coast and the East Coast. Considering Phoenix, Los Angeles and New York as reference points this entails overhead transmission lines of 577 and 3447 km respectively.



Region	Production Location (-)	DNI (kWh/m^2/year)	Full load hours (h)	Invest. Cost CSP ($/kW)	O&M$_{CSP}$ ($/kW)	SG lenght (km)	Invest. Cost SG ($/kW)	O&M$_{grid}$ ($/kW)
CHINA	Tibet (Xigaze)	2300	4110	6500	127.5	2800	329	6.6
MENA	Sahara Desert	2190	3680	6500	127.5	3000	336	6.7
USA	Arizona (Phoenix)	2600	4600	6500	127.5	577 and 3447	277	5.5

Table 2.1: Parameter assumptions overview

In our simulations, CSP electricity directly substitutes electricity from Oil and Gas in MENA, as these are its major power generation sources ($ELCSP, oil$ and $ELCSP, gas$ are added to equation 2.5).

$$FF(n,t) = (\alpha_{COAL} EL_{COAL}(n,t)^{\rho_{FF}} + \alpha_{OIL}\,(EL_{OIL}(n,t)$$
$$+ EL_{CSP,oil}(n,t))^{\rho_{FF}} + \alpha_{GAS}\,(EL_{GAS}(n,t) + EL_{CSP,gas}(n,t))^{\rho_{FF}})^{1/\rho_{FF}}\,;$$

For all other regions, CSP electricity enters in direct competition with nuclear power (EL_{CSP} is added to the right-hand side of equation 2.4) and

IGCC power with CCS (EL_{CSP} is added to the right-hand side of equation 2.6) as these, together with renewable sources, are the most promising options to target Climate Change. It is interesting to study these two technologies also because their expansion may be limited by issues of public acceptability and CSP could provide a valuable alternative.

$$\begin{aligned} EL_{NUKE}(n,t) &= (EL_{NUKE}(n,t) + EL_{BACKSTOP}(n,t) + EL_{CSP,nuke}(n,t))\,; \\ EL_{COAL}(n,t) &= (EL_{PC}(n,t) + EL_{IGCC}(n,t) + EL_{CSP,ccs}(n,t))\,; \end{aligned}$$

All regions without the CSP option still have a generic electric backstop technology that enters as a substitute to nuclear power.

A sensitivity analysis of the key parameters is reported in Section 2.10.

2.5 Scenario design

To analyze the potential economic and environmental effects that the introduction of a CSP powered Super-Grid - among the options to reduce the electricity sector's carbon footprint - may have, we have modelled and analyzed different potential climate change stabilization policies and/or technological evolution scenarios. More precisely, we analyze a "business as usual" scenario where no climate policy is in place and therefore there is no market value attached to CO_2 emissions and four different stabilization scenarios where instead a global climate policy is enacted, imposing a limit on greenhouse gas emissions. Under the chosen climate change policy, which GHG concentration needs to be stabilized at 535 ppme in 2100. This requires that global emissions are about 30% lower than the 2005 level in 2050. The stabilization scenarios share different assumptions on the availability of nuclear power and IGCC coal power with CCS.

The policy tool considered is a world carbon market in which carbon allowances can be traded among regions without limits. The allocation of carbon permits follows a "Contraction and Convergence" rule[7], which assigns global emissions targets to each region, initially in proportion to current emissions and then, progressively, in proportion to each region's population, with the aim of reaching similar per-capita emissions by the end of the century (Meyer, 2000). We set a ceiling to GHG emissions consistent with the concentration target in 2100. To be able to achieve such emission targets, the twelve regions of the model have the possibility of undertaking the following actions: (*i*) reduce consumption of energy; (*ii*) change energy

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[7] The distribution of permits affects only the distribution of stabilization costs and alternative allocation rules would therefore leave unchanged investment decisions in CSP as well as in other technologies (Coase, 1960). Minor changes would appear in case of strong revenue effects.

mix; (*iii*) trade emission permits; (*iv*) reduce emissions from LULUCF and emissions of non-CO_2 gasses.

More in detail, the scenarios analysed are:

- **Business as usual:** i.e. no climate policy and therefore no restriction on GHG emissions (indicated as "Bau"), however energy efficiency and other technological options can be implemented for domestic concerns;
- **Unconstrained Stabilization.** GHG atmospheric concentration needs to be stabilized at 535 ppm CO_2 equivalent by 2100 (indicated as "U-Stab");
- **Constrained Stabilization with limit on Nuclear Power.** U-Stab + constraint on the expansion of Nuclear Power that cannot exceed 2005 levels (indicated as "NC-Stab");
- **Constrained Stabilization with limit on CCS.** U-Stab + no possibility of executing Carbon Capture and Storage (CCS) operations (indicated as "CC-Stab");
- **Constrained Stabilization with penetration limits on Nuclear power and CCS.** U-Stab + NC-Stab + CC-Stab (indicated as "NCC-Stab").

All of the above scenarios include the possibility for the USA, China and MENA to produce and domestically consume CSP electricity and for Western and Eastern Europe to import from MENA. Moreover, all scenarios include a constraint on domestic renewable sources: regional Wind and Solar electricity generation cannot exceed 25% of the total regional generation. This is due to the incapability of current power systems to manage large percentages of intermittent electricity sources[8].

In addition to these different climate policy scenarios, we also simulate all the corresponding cases without the possibility to produce or trade CSP power to use as counter-factuals and evaluate the effects of the introduction of the CSP powered Super-Grid (the latter are indicated as "policy_name-without CSP" in the graphs).

2.6 Results

This sections explores simulations results and focuses on (*i*) the optimal timing and size of CSP power generation and long distance transmission, (*ii*) investments and cost dynamics, (*iii*) the Europe-MENA trade of electricity from CSP, (*iv*) the impact of CSP on the energy mix, (*v*) the option value of CSP (*vi*) it assesses the feasibility of the foreseen expansion of CSP.

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[8] Note that this 25% limit does not apply to the CSP electricity.

2.6.1 The optimal timing and size of investments in CSP

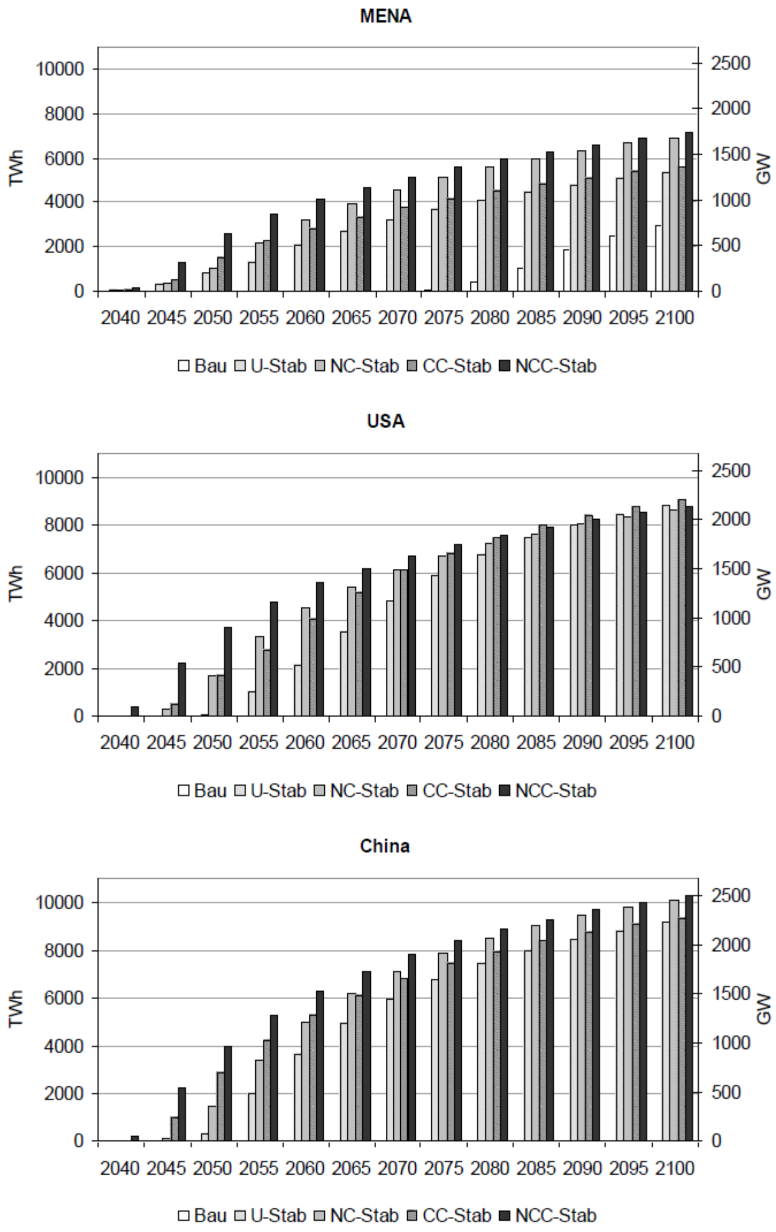
One of the main interests of this work is to evaluate the economic convenience of the Super-Grid with CSP-power option. Indeed, we have allowed three regions to produce CSP power and transmit it over long distances. Our results show that it is optimal to invest in such technology under various scenarios. In particular, we find that for MENA CSP is not only a valid mitigation strategy, but it is also an economically viable generation technology even in the absence of climate policies. For the USA and China this is true only if we insert penetration limits to other zero-carbon technologies such as nuclear.

Figure 2.2 reports the optimal timing, quantity produced and installed capacity of CSP electricity generation for MENA, USA and China. In the BaU scenario MENA is the only country for which it is optimal to produce and consume CSP power; this means that CSP in MENA becomes competitive with other generation sources even in the absence of concerns about CO_2 emissions. Under the stabilization scenarios, for MENA, it is optimal to invest in CSP from 2075 even without the climate policy. Investments start in 2035 under all stabilization policy scenarios and are higher in the scenarios with constraints to nuclear (power) and IGCC coal with CCS. In the USA and China it is instead not optimal to invest in long distance CSP without the climate policy starting from 2075. In the climate policy scenarios with technological constraints, generation starts from 2040-2045, when the global price of carbon is equal to 175-200 US\$/tCO_2-eq while, in the unconstrained scenario, in 2050 it becomes competitive with nuclear and IGCC coal with CCS (price of carbon equal to 492 US\$/tCO_2-eq).

Overall, we see that it becomes optimal to produce CSP electricity starting from 2035-2040, but this source becomes important only in the second half of the century. The quantity produced increases over time and tends to be larger with stronger technological penetration limits.

In absolute terms, China is the region with the largest production of CSP electricity, followed closely by the USA. This is explained by the size of the Chinese economy, which reaches the USA at the end of the century in our BaU scenario. Recall that the total quantity produced by MENA shown in Figure 2.2 includes both domestic consumption and export to Europe.

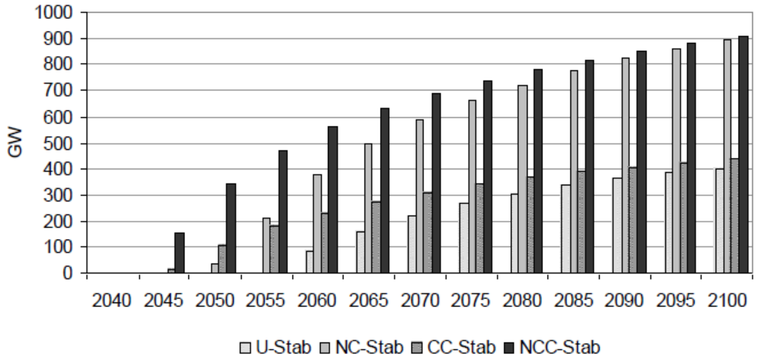
Moreover, simulations show that the unconstrained stabilization converges to the stabilization with no IGCC power with CCS and that the stabilization with limited nuclear power production tends to the stabilization with both penetration limits; this is due to the fact that the importance of CCS in the electricity mix decreases towards the end of the century. This technological option is not completely carbon-free (the capture rate is assumed to be 90% in line with current technological predictions), and towards the end of the century the residual 10% of GHG emissions becomes significant. Notice



Notes: Bau = Business as usual; U-Stab = unconstrained stabilization; NC-Stab = constrained stabilization with cap on nuclear; CC-Stab = constrained stabilization with no CCS; NCC-Stab = constrained stabilization with cap on nuclear and no CCS.

Figure 2.2: CSP Installed Capacity and Electricity Generation

though, that, domestic consumption of CSP for MENA is not very sensitive to the different policy scenarios (Figure 2.2); the differences that can be seen in Figure 2.2 mostly depend on the import demand from Europe.



Notes: Bau = Business as usual; U-Stab = unconstrained stabilization; NC-Stab = constrained stabilization with cap on nuclear; CC-Stab = constrained stabilization with no CCS; NCC-Stab = constrained stabilization with cap on nuclear and no CCS.

Figure 2.3: Super-Grid Installed Capacity Europe-MENA

Figure 2.3 shows the installed capacity of Super-Grid infrastructure for MENA that allows the export of CSP electricity to Europe. The sensitivity of import demand with respect to the different policy scenarios is evident. For the USA and China the installed capacity of Super-Grid is equal to the CSP capacity shown in Figure 2.2.

2.6.2 Investments and cost dynamics

Figure 2.4 reports the paths of investments, in billions of US$, that are necessary for building the CSP and SG capacities depicted in the previous Figures. Similar trends of convergence between scenarios can be identified. Notice also that while capacity presents a clear increasing trend until the end of the century, investments remain rather stable from 2060 onwards. This happens because investment costs decline as the global cumulative installed capacity increases, for the Learning by Doing effect of technology diffusion.

In all cases, the investments needed for the construction of the Super-Grid infrastructure are significantly lower than those for the generation power plants and range between 1-9% of the total investment costs for MENA, 5-15% for the USA[9]. Their share increases over time as we have assumed non decreasing investment costs for the Super-Grid infrastructure.

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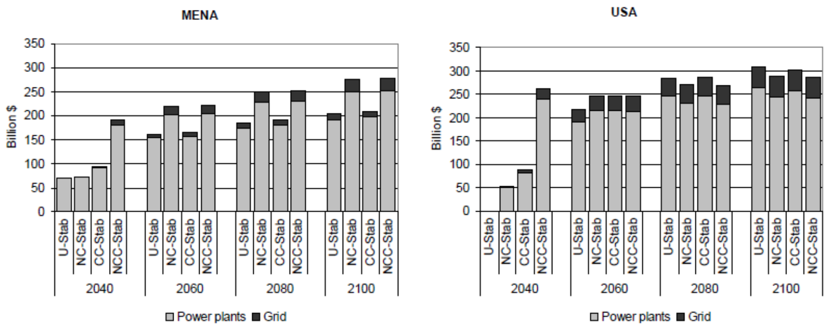
[9] Investments needed to build CSP capacity and the super-grid in China are similar to those needed in the USA.



Notes: Bau = Business as usual; U-Stab = unconstrained stabilization; NC-Stab = constrained stabilization with cap on nuclear; CC-Stab = constrained stabilization with no CCS; NCC-Stab = constrained stabilization with cap on nuclear and no CCS.

Figure 2.4: Investments for CSP-Plants and the Super-Grid Infrastructure in MENA and the USA

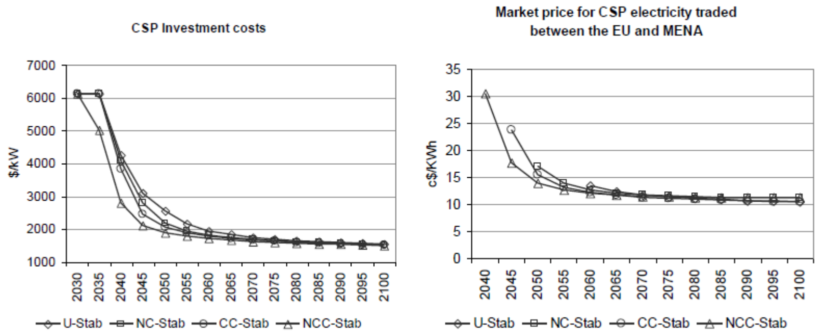


Figure 2.5: CSP Investment Cost and Market Price for CSP Electricity Trade Between the EU and MENA

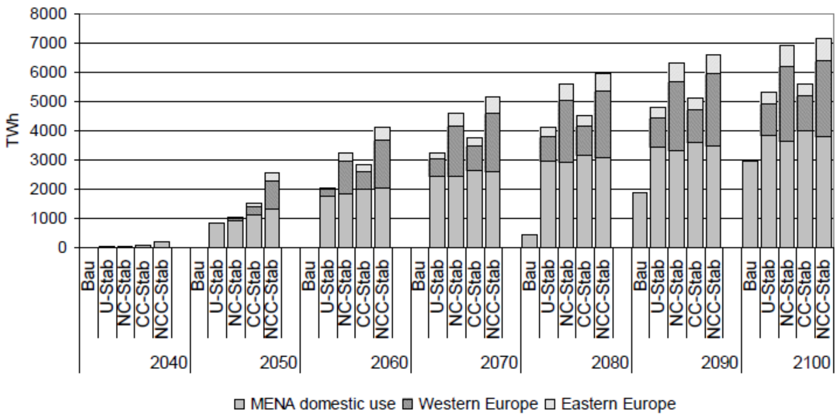


Figure 2.6: Distribution of CSP Power Produced by MENA.

The cost paths depicted in the left panel of Figure 2.5 represent the weighted average of the costs across regions that we obtain for the four policy scenarios. The main decreasing trend is induced by world cumulative capacity that is quite sensitive to the policy scenario. There are some differences in the regional investment costs due to the component of the investment cost that mimics short term frictions (see Equation 2.3).
In the first ten year during which investments in CSP occur the cost drops by at least 50%. Eventually the cost reaches a floor of about 1,500 US$/kW. Therefore, in our model, the major reason for postponing the investment in CSP is the presence of cheaper abatement possibilities. Appendix A reports the costs of all electricity generation technologies, divided into capital, fuel and CO_2 emissions components, that emerge from our simulations as a useful reference.

2.6.3 The Euro-MENA trade of CSP electricity

Our results also show that a SG that connects the power networks of MENA and Europe becomes remunerative in the CC-Stab and the NCC-Stab scenarios from 2045. Without constraints to nuclear and/or IGCC coal with CCS the Mediterranean SG becomes an attractive option from 2060 onwards. Figure 2.6 shows how the total CSP electricity generated by MENA is divided between domestic consumption and exports to E-EU and W-EU. We find that: (*i*) most of the electricity produced is for domestic consumption; (*ii*) that a market for this electricity and its transmission over long distances does arise, even if only in the presence of a stabilization policy and mainly in the second half of the century; (*iii*) electricity directed to W-EU is higher than towards E-EU, but imports represent a greater share of E-EU electricity consumption (see Figure 2.6) and in value, a relative greater portion of E-EU gross domestic product (GDP) (Table 2.2), (*iv*) both domestic consumption and exports increase over time, but exports are more sensitive to the technology scenarios. This is mainly due to the fact that MENA has low levels of generation with both nuclear and IGCC with CCS power plants[10].

The later and lower consumption of CSP electricity by the European regions, compared to the other regions is related to the lower solar intensity considered for MENA and to the fact that for Western and Eastern Europe the import of CSP electricity constitutes a net loss and not an expenditure that induces positive effects on other sectors of the domestic economy.

The fact that the largest part of the CSP production by MENA is for domestic consumption is an important result from a policy point of view.

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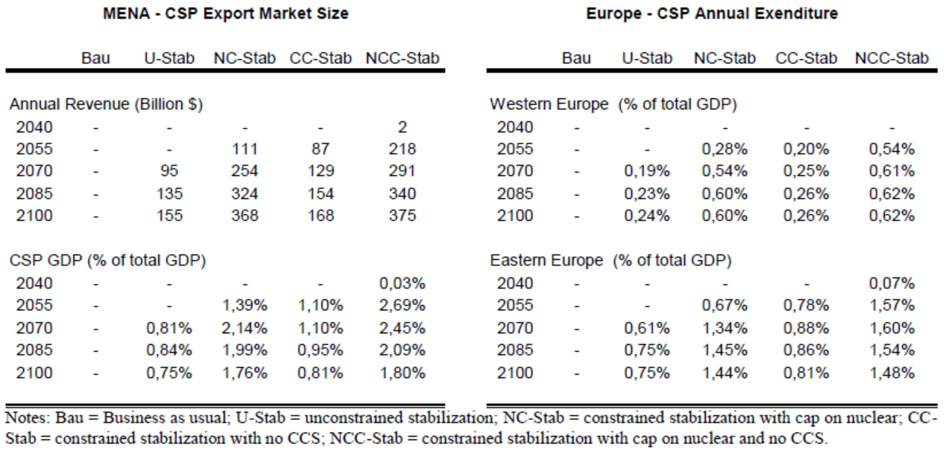
[10] Differences in production for domestic consumption by MENA depend on the varying investment costs associated with installed capacity at the world level.

Indeed, it is optimal to build CSP plants first for domestic reasons and then as an export opportunity. Therefore, the discussion around deployment projects needs to be concerned not only with export demand, but also domestic demand, that is likely to increase even further as opportunities for carbon-free and relatively cheap desalinization are included in the modelling framework.

The right panel of Figure 2.5 shows the market clearing price for the Euro-MENA CSP electricity trade under the different scenarios. The price has a decreasing trend that is related to investment costs. It starts - in the most extreme case - from just over 30 c$/kWh and decreases to 10-11 c$/kWh at the end of the century. The large price differences at the beginning of the trade are due to the different costs of production that arise for the different scenarios. As discussed in Section 2.3.1, investment costs for MENA strongly depend on world cumulative capacity, that is very sensitive to policy and technological penetration limits.



MENA - CSP Export Market Size

	Bau	U-Stab	NC-Stab	CC-Stab	NCC-Stab
Annual Revenue (Billion $)					
2040	-	-	-	-	2
2055	-	-	111	87	218
2070	-	95	254	129	291
2085	-	135	324	154	340
2100	-	155	368	168	375
CSP GDP (% of total GDP)					
2040	-	-	-	-	0,03%
2055	-	-	1,39%	1,10%	2,69%
2070	-	0,81%	2,14%	1,10%	2,45%
2085	-	0,84%	1,99%	0,95%	2,09%
2100	-	0,75%	1,76%	0,81%	1,80%

Europe - CSP Annual Exenditure

	Bau	U-Stab	NC-Stab	CC-Stab	NCC-Stab
Western Europe (% of total GDP)					
2040	-	-	-	-	-
2055	-	-	0,28%	0,20%	0,54%
2070	-	0,19%	0,54%	0,25%	0,61%
2085	-	0,23%	0,60%	0,26%	0,62%
2100	-	0,24%	0,60%	0,26%	0,62%
Eastern Europe (% of total GDP)					
2040	-	-	-	-	0,07%
2055	-	-	0,67%	0,78%	1,57%
2070	-	0,61%	1,34%	0,88%	1,60%
2085	-	0,75%	1,45%	0,86%	1,54%
2100	-	0,75%	1,44%	0,81%	1,48%

Notes: Bau = Business as usual; U-Stab = unconstrained stabilization; NC-Stab = constrained stabilization with cap on nuclear; CC-Stab = constrained stabilization with no CCS; NCC-Stab = constrained stabilization with cap on nuclear and no CCS.

Table 2.2: MENA CSP Export Market Size and European expenditure relative to regional GDP.

Table 2.2 indicates the money flows induced by the trade and their relevance with respect to regional gross domestic product (GDP). From 2055 onwards the market grows to the size of several hundreds of billions of US$. Imports in W-EU never exceed in value the 0.6% of GDP; in E-EU they do not exceed 1.6% of GDP. This is a market of remarkable size. As a comparison, total fuels imports of the EU-27 were equal to 192 US$ billions in 2009, or 1.3% of GDP. Total fuels exports of the Middle-East (not including Northern African countries) was equal to 437 billions in 2009, 68% of merchandise exports[11].

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[11] Data from table II.2 and II.5 and the trade profiles of the International trade statistics 2010 publication by the WTO. Economic data in 2005 US$. For an analysis of the

The investments for the construction of the SG infrastructure range between 1-26 billion US$ per year in absolute terms and, in relative terms, between 0.02-0.27% of the GDP of MENA. The annual investment effort needed for the deployment of the CSP capacity and the SG infrastructure is not far from the aggregated budgeted government expenditure on infrastructure of various MENA countries in the next decades. Therefore, MENA would be able to have an active role in such development projects, and funds need not to be necessarily European.

2.6.4 The impact of CSP on the electricity mix

In these simulations, domestic consumption of CSP by MENA enters in direct competition with electricity generated with oil and gas.

Figure 2.7 displays the optimal switching strategy. CSP power substitutes both oil and gas generation in all stabilization policy scenarios; in the first half of the century and in the business as usual scenario, instead, only the more expensive oil fuelled power generation is substituted by CSP. Similar graphs are also plotted for the competition between CSP and nuclear and IGCC with CCS power for Western Europe, Eastern Europe, the USA and China. The graphs relative to Western and Eastern Europe and China, clearly show that CSP substitutes nuclear power only if limits on penetration are imposed. This reveals a high option value for nuclear power in those regions. . IGCC power with CCS is not completely carbon free and therefore it is more easily substituted. In the USA the higher full load hours make generation costs for CSP power lower than in other regions, up to the level that makes CSP competitive with nuclear power; therefore in the USA, after 2070, CSP substitutes both IGCC with CCS and Nuclear power even without limits on the latter.

Although CSP is in direct competition only with two specific generation alternatives for each region, it can ultimately substitute all generation sources by changing the optimal technology mix.

Figure 2.8 shows the electricity mix of the five regions that we are studying together with the global electricity mix. We present the different policy scenarios at three time steps: 2030, 2050 and 2100.

In the business as usual scenario the main sources of electricity for Western Europe are fossil fuels (in particular coal and gas), nuclear power, and renewable sources. Over time there is a contraction in the electricity share of gas, oil and coal and an increase in the share of wind and solar power. Nuclear power remains fairly stable. The introduction of a climate change stabilization policy (without technological penetration limits) induces a contraction

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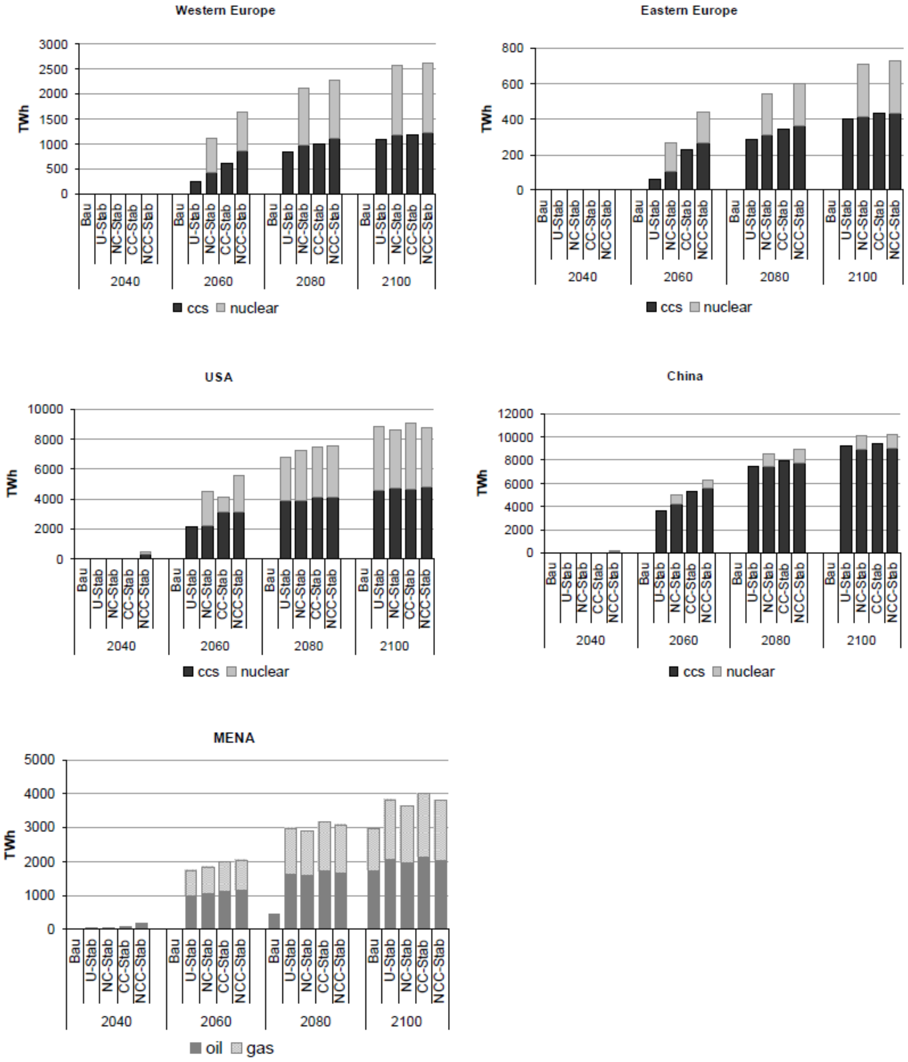
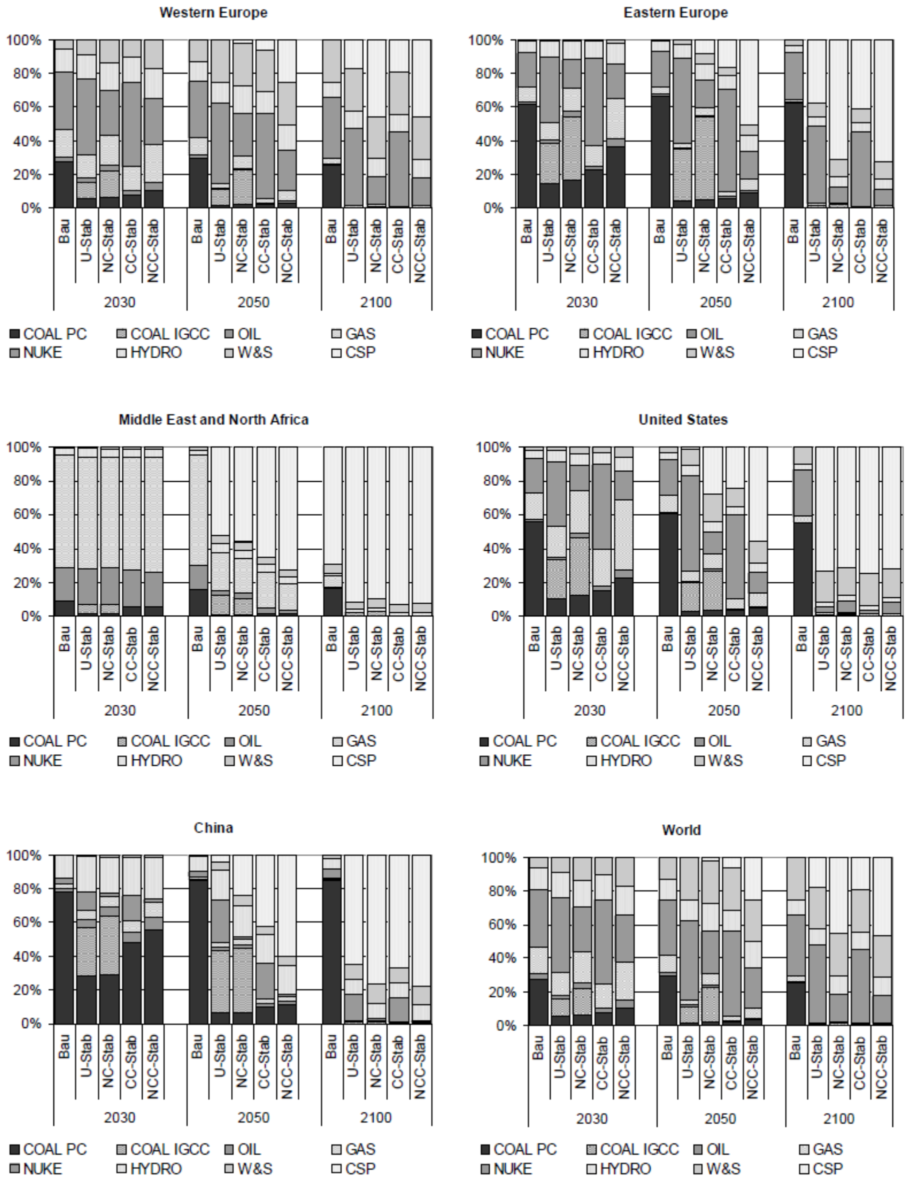
contraction of revenues from oil trade in a stabilization scenario see Massetti and Sferra (2010).



Notes: Bau = Business as usual; U-Stab = unconstrained stabilization; NC-Stab = constrained stabilization with cap on nuclear; CC-Stab = constrained stabilization with no CCS; NCC-Stab = constrained stabilization with cap on nuclear and no CCS.

Figure 2.7: Regional Concentrated Solar Power use



Notes: Bau = Business as usual; U-Stab = unconstrained stabilization; NC-Stab = constrained stabilization with cap on nuclear; CC-Stab = constrained stabilization with no CCS; NCC-Stab = constrained stabilization with cap on nuclear and no CCS.

Figure 2.8: Regional and World Electricity Mix

of all fossil fuel sources - especially coal - and the appearance of IGCC with CCS and an expansion of nuclear power and renewable resources, though the latter are limited by the constraint on domestic wind and solar power. When generation constraints on nuclear power are introduced, the latter contracts and the share of hydrocarbon sources (especially IGCC with CCS where it is allowed) increases until CSP starts to have a relevant share in the mix. When IGCC production with CCS is not allowed the nuclear share expands significantly.

By the end of the century, the Western European electricity mix is dominated by three main sources: nuclear, domestic renewable power including hydroelectric power, and imported CSP power; generation with fossil fuels becomes irrelevant. In particular, in the scenarios where limits on nuclear power expansion are imposed, CSP imports become the single most important electricity source.

In the scenarios without the CSP import option, the Western European electricity mix is still dominated by nuclear and domestic renewable resources, though a relevant percent is still generated by fossil fuels: mostly IGCC with CCS and gas, i.e. the less carbon intensive fossil fuel sources. In addition, the global amount of electricity consumed is much lower; some of this reduction is due to an increase in energy efficiency, but the other implies a loss in economic activities.

The electricity mix of E-EU is dominated by coal power. IGCC coal power plants have a much greater role than in W-EU. Nuclear is the dominant abatement technology at the end of the century when carbon leakages from CCS are heavily penalized. For this reason imported CSP has a great role to play after 2050 in those scenarios where nuclear power is limited. By the end of the century, in the presence of a climate policy, electricity production is based on nuclear power and domestic and imported renewable sources.

The corresponding scenarios without the option of importing CSP from MENA are dominated by nuclear power with a strong share of IGCC with CCS where these technologies are not limited. In the presence of a limit on the expansion of nuclear power, and even more so with the additional limit on IGCC with CCS, the amount of electricity consumed is strongly decreased.

The electricity mix of MENA is dominated by gas generation until 2050. After 2050 high gas prices and cost reductions in CSP plants make it optimal to use solar power plants even in the BaU. With the climate policy in place, this trend is reinforced and the CSP share of total electricity generation reaches 90%. An increase in the share of IGCC with CCS - where available - and traditional renewable sources is also visible.

There might be technical limits to very high penetration shares of CSP, but the possibility to store heat for many hours and/or to use hybrid CSP-natural gas power plants supports our findings (IEA, 2010b; Trieb, 2009a;

Trieb and Mller-Steinhagen, 2007). Similar penetration shares seem to be not easily sustainable, but are coherent with the fact that, in the current version of the model, CSP costs do not increase as the generation share increases. When high levels of penetration are reached, costs for CSP generation should be increased due to the difficulties in managing such large shares of solar energy, and consequent need for extra storage or back-up capacity. We have not included this in the model because in the literature CSP with thermal storage is considered as a good candidate for base-load power generation (Trieb and Mller-Steinhagen 2007,Trieb 2009; IEA 2010b). Though, extreme shares like the resulting ones may introduce the need to extend the thermal storage capacity (leaving a 100% solar share) or the consideration of differently-fuelled back-up capacity.
In the absence of the CSP option and in the presence of a climate policy, the amount of electricity consumed is strongly reduced.

Notice also that the differences between the unconstrained stabilization and the stabilization with limit on nuclear power, and also those between the CCS constrained scenario with the one with both penetration limits, are due mainly to the differences in investments costs of CSP related to world installed capacity, as the limit on nuclear power should be un-influential in the domestic electricity mix of MENA.

Under a Business as Usual scenario, the main generation sources in the United States are coal, nuclear and gas. With the introduction of a climate policy the share of pulverised coal generation is drastically reduced substituted mainly by IGCC with CCS and Nuclear power - where available - or gas. Towards the mid part of the century renewable sources drastically increase their share of electricity generation, especially CSP. By the end of the century- in the stabilization scenarios - CSP generation reaches 70%. The other generation sources are traditional wind and solar and, in small part, nuclear power.

The Chinese electricity mix is instead dominated by coal and hydro-electric power. With a stabilization policy, pulverised coal is substituted by IGCC with CCS and nuclear power, where these technologies are available. Starting form the mid part of the century it becomes optimal to generate electricity with CSP and this technology increasingly gains importance, reaching very large shares by the end of the century, especially when nuclear power is limited. Fossil fuel generation, that is the largest source of electricity in the Business as Usual case, almost disappears in the stabilization scenarios. Interestingly, nuclear is a “bridge” technology in our U-Stab scenario and decreases in share after 2050.

Also for both the USA and China, in the absence of CSP, nuclear power is the main source of electricity together with IGCC with CCS. In the presence of a limit on the expansion of nuclear power, and even more with the additional limit on IGCC with CCS, the amount of electricity consumed is strongly decreased.

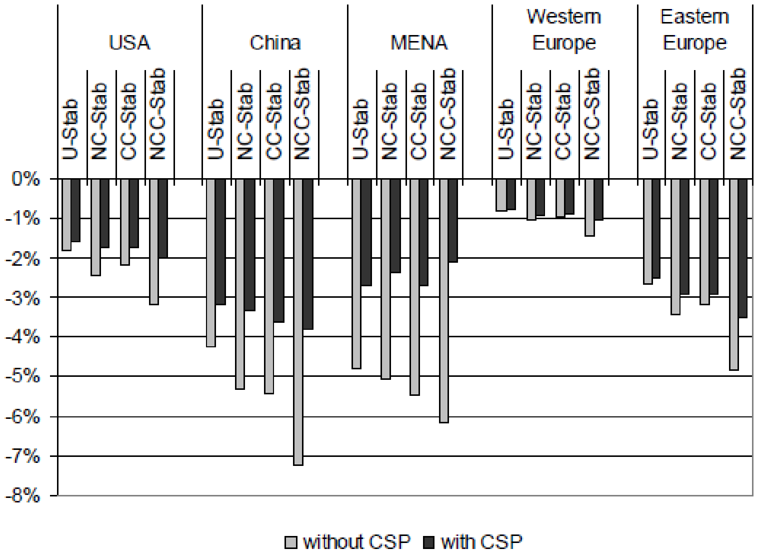
The changes in the single regions also indirectly affect the decisions of the regions that do not have the possibility to generate or consume CSP and have an aggregated effect on the world electricity mix, via prices in fuels and emission permits (Figure 2.8). In a Business as Usual scenario electricity is generated using mainly pulverised coal, nuclear, gas and renewable sources, such as traditional wind and solar and hydro-electric power. As for the regional cases analysed before, the introduction of a GHG emission target reduces the share of pulverised coal in favour of nuclear power and IGCC power with CCS and renewable sources. When an expansion of the former technologies is not available, generation with gas becomes more relevant. Starting from 2045-2050, in the presence of a stabilization policy, CSP generation starts to have an increasingly important role reaching almost 50% of the generation share when nuclear power is limited for social and political reasons. In the Business as usual scenario world electricity mix, it is still optimal to produce electricity with CSP, though only at the end of the century and with its share reaching only 4% of the total.

More in detail, Figure 2.8 highlights how - especially for the cases of Western and Eastern Europe and at the world level - potential limits to nuclear power and/or CCS operations can change the relative importance in the electricity mix of CSP generation and long-distance transmission through a Super-Grid. This is a relevant message in a post-Fukushima world.

2.6.5 The option value of CSP

In this section we assess the value of the CSP powered SG (CSP-SG) as an alternative power technology option. We define the increase in mitigation costs that occurs when a technology is not available relative to the scenario with the technology as the stabilization cost option value (see also Luderer et al., 2011). The metric used is the percentage of discounted GDP interest rate 5% (Figure 2.9). Moreover, we define the increase in the global carbon price when a technology is not available relative to the scenario with the technology as the carbon price option value. The metric used is US$ per tonne of CO_2-eq.

Table 2.6.5 displays estimates of the option value of nuclear and IGCC with CCS when the CSP-SG is either available or not, and the option value of the CSP-SG when nuclear and IGCC coal with CCS are either available or not. When the CSP-SG is available the stabilization cost option value of nuclear and IGGC coal with CCS, separately or jointly, is reduced greatly, especially in China and in the USA. The stabilization cost option value of MENA is negative because the region gains from exports of CSP to Europe.

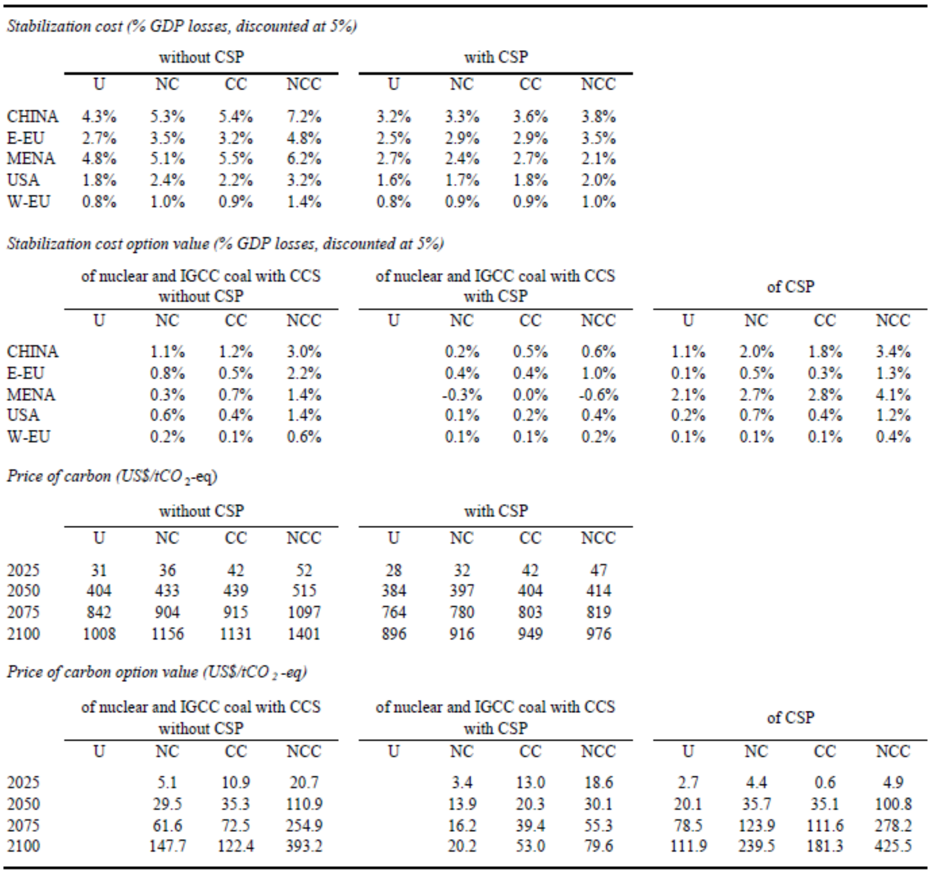


Notes: The values are aggregated over 2005-2100 and the discount rate used is a declining 3% rate. Bau = Business as usual; U-Stab = unconstrained stabilization; NC-Stab = constrained stabilization with cap on nuclear; CC-Stab = constrained stabilization with no CCS; NCC-Stab = constrained stabilization with cap on nuclear and no CCS.

Figure 2.9: Aggregated Discounted (5%) Policy Costs with respect to Bau

CSP reduces the option value of nuclear more than coal. The carbon price option value provides a synthetic assessment of the value of the CSP-SG option at global level. Without the CSP-SG the marginal cost of abatement increases by 30 US$ per tonne of CO_2-eq in 2050 if there are limits to nuclear power, by 35 US$ if there is not IGCC coal with CCS and by 111 US$ if both CCS and nuclear are limited. With the CSP-SG the increment of the marginal abatement cost is 30 US$ at worst in 2050. With a global carbon market this advantage spreads to all regions.

The stabilization cost option value of the CSP-SG in all regions excluding MENA ranges between 0.1% and 1.1% in the U-Stab scenario, from 0.1% to 2.0% in the NC-Stab scenario, from 0.1% to 1.8% in the CC-Stab scenario and from 0.4% to 3.4% in the NCC-Stab Scenario. CSP is a relatively less attractive option in W-EU because the share of coal power is relatively low and the share of nuclear is relatively high (recall that the NC-Stab scenario is not a phase-out scenario: it constraints nuclear capacity to present levels). The carbon price option value of the CSP-SG is relatively small in 2025. This indicates that long distance CSP is not a key technology until 2050 in our scenarios. After 2050, the CSP-SG proves to be extremely valuable and reduces marginal abatement costs by up to 425 US$ in 2100, when nuclear and IGCC coal with CCS are limited.



Stabilization cost (% GDP losses, discounted at 5%)

	without CSP				with CSP			
	U	NC	CC	NCC	U	NC	CC	NCC
CHINA	4.3%	5.3%	5.4%	7.2%	3.2%	3.3%	3.6%	3.8%
E-EU	2.7%	3.5%	3.2%	4.8%	2.5%	2.9%	2.9%	3.5%
MENA	4.8%	5.1%	5.5%	6.2%	2.7%	2.4%	2.7%	2.1%
USA	1.8%	2.4%	2.2%	3.2%	1.6%	1.7%	1.8%	2.0%
W-EU	0.8%	1.0%	0.9%	1.4%	0.8%	0.9%	0.9%	1.0%

Stabilization cost option value (% GDP losses, discounted at 5%)

	of nuclear and IGCC coal with CCS without CSP				of nuclear and IGCC coal with CCS with CSP				of CSP			
	U	NC	CC	NCC	U	NC	CC	NCC	U	NC	CC	NCC
CHINA		1.1%	1.2%	3.0%		0.2%	0.5%	0.6%	1.1%	2.0%	1.8%	3.4%
E-EU		0.8%	0.5%	2.2%		0.4%	0.4%	1.0%	0.1%	0.5%	0.3%	1.3%
MENA		0.3%	0.7%	1.4%		-0.3%	0.0%	-0.6%	2.1%	2.7%	2.8%	4.1%
USA		0.6%	0.4%	1.4%		0.1%	0.2%	0.4%	0.2%	0.7%	0.4%	1.2%
W-EU		0.2%	0.1%	0.6%		0.1%	0.1%	0.2%	0.1%	0.1%	0.1%	0.4%

Price of carbon (US$/tCO$_2$-eq)

	without CSP				with CSP			
	U	NC	CC	NCC	U	NC	CC	NCC
2025	31	36	42	52	28	32	42	47
2050	404	433	439	515	384	397	404	414
2075	842	904	915	1097	764	780	803	819
2100	1008	1156	1131	1401	896	916	949	976

Price of carbon option value (US$/tCO$_2$-eq)

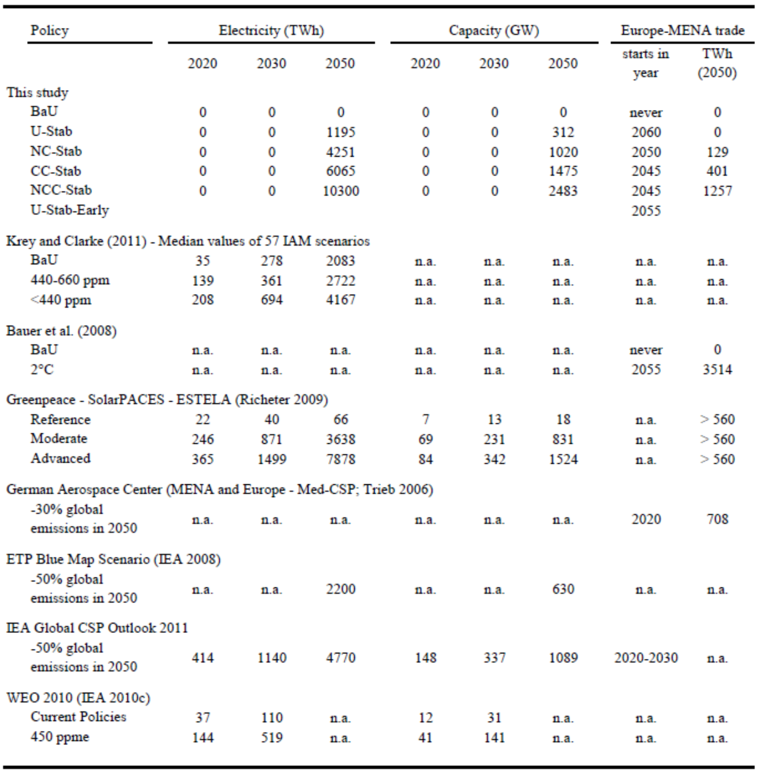
	of nuclear and IGCC coal with CCS without CSP				of nuclear and IGCC coal with CCS with CSP				of CSP			
	U	NC	CC	NCC	U	NC	CC	NCC	U	NC	CC	NCC
2025		5.1	10.9	20.7		3.4	13.0	18.6	2.7	4.4	0.6	4.9
2050		29.5	35.3	110.9		13.9	20.3	30.1	20.1	35.7	35.1	100.8
2075		61.6	72.5	254.9		16.2	39.4	55.3	78.5	123.9	111.6	278.2
2100		147.7	122.4	393.2		20.2	53.0	79.6	111.9	239.5	181.3	425.5

Table 2.3: The option value of CSP

In absolute terms, having the possibility to import electricity from CSP power plants in Northern Africa decreases the stabilization policy costs by between 5 and 27% for Western Europe and between 6 and 27% for Eastern Europe, compared to the corresponding policy cases without the CSP option (see Table). For the USA and China these policy costs are reduced by 12-37% and 25-47%, respectively. MENA reduces its losses by between 44 and 66%.

2.7 Comparison with the literature and discussion

The scenarios discussed in Section 2.6 indicate that it is not optimal to invest in CSP generation before 2035 for all three producing regions. Significant investments should occur only from 2050 onwards. Other studies though, suggest that investments should start earlier, around 2020-2030, as reported in Table 2.7 (IEA, 2008, 2010a, 2010c, 2011; Richter, 2009; Trieb, 2006, 2009a; Trieb and Mller-Steinhagen, 2007; Ummel and Wheeler, 2008). Some studies see a potential for CSP trade also in a world without climate policies (Richter et al., 2009).



Policy	Electricity (TWh)			Capacity (GW)			Europe-MENA trade	
	2020	2030	2050	2020	2030	2050	starts in year	TWh (2050)
This study								
BaU	0	0	0	0	0	0	never	0
U-Stab	0	0	1195	0	0	312	2060	0
NC-Stab	0	0	4251	0	0	1020	2050	129
CC-Stab	0	0	6065	0	0	1475	2045	401
NCC-Stab	0	0	10300	0	0	2483	2045	1257
U-Stab-Early							2055	
Krey and Clarke (2011) - Median values of 57 IAM scenarios								
BaU	35	278	2083	n.a.	n.a.	n.a.	n.a.	n.a.
440-660 ppm	139	361	2722	n.a.	n.a.	n.a.	n.a.	n.a.
<440 ppm	208	694	4167	n.a.	n.a.	n.a.	n.a.	n.a.
Bauer et al. (2008)								
BaU	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	never	0
2°C	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	2055	3514
Greenpeace - SolarPACES - ESTELA (Richeter 2009)								
Reference	22	40	66	7	13	18	n.a.	> 560
Moderate	246	871	3638	69	231	831	n.a.	> 560
Advanced	365	1499	7878	84	342	1524	n.a.	> 560
German Aerospace Center (MENA and Europe - Med-CSP; Trieb 2006)								
-30% global emissions in 2050	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	2020	708
ETP Blue Map Scenario (IEA 2008)								
-50% global emissions in 2050	n.a.	n.a.	2200	n.a.	n.a.	630	n.a.	n.a.
IEA Global CSP Outlook 2011								
-50% global emissions in 2050	414	1140	4770	148	337	1089	2020-2030	n.a.
WEO 2010 (IEA 2010c)								
Current Policies	37	110	n.a.	12	31	n.a.	n.a.	n.a.
450 ppme	144	519	n.a.	41	141	n.a.	n.a.	n.a.

Table 2.4: Comparison with the literature

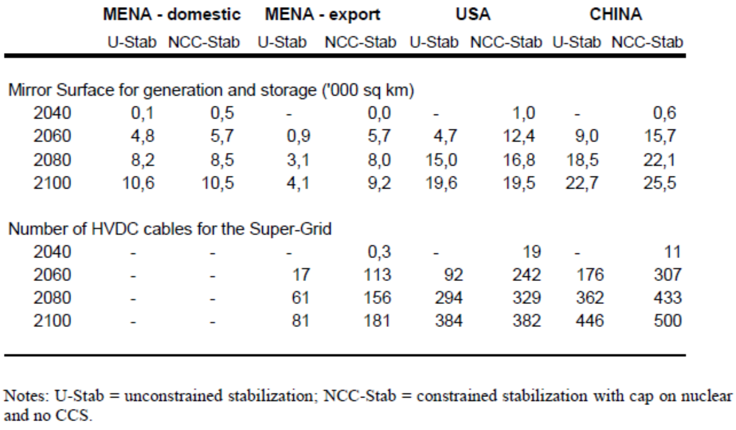
Bauer et al. (2008) have similar results for what concerns the start of the Europe-MENA trade: in the BaU scenario it is never optimal to trade, in the 2°C target it is optimal to trade from 2055. Krey and Clarke (2011) do not show data on trade. They examine 57 scenarios from the recent IAM literature, divided in a BaU scenario, a moderate climate policy scenario (440-660 ppm) and a stringent climate policy scenario (¡440 ppm). Table displays the median values of electricity generation with CSP for each scenario class. Our study (535ppme, -30% of global emissions in 2050 wrt 2005) falls in the moderate climate policy category. With respect to the literature we are rather pessimistic on the possibility that CSP electricity has a viable future without climate policy. We achieve a level of electricity generation similar to the literature when we consider constrained policy scenarios. Part of the studies surveyed by Krey and Clarke (2011) also include technological and/or political constraints. Therefore the comparison is not straightforward.

Our CC-Stab and NCC-Stab scenarios foresee the highest expansion of CSP that we find in the literature. The model has therefore enough flexibility to allow a large use of long distance CSP. There are however not sufficiently strong price signals to make it convenient to invest in CSP. The key message is that long distance CSP enters into competition with technologies that can generate base-load electricity at much lower costs. Without accounting for external costs other than CO_2 costs and/or for technological uncertainties associated with nuclear and IGCC coal with CCS, our results indicate that CSP is a niche technology, for areas in which the DNI is high, when the price of fossil fuels increases considerably. The large subsidies that are driving CSP capacity expansion corroborate our hypothesis (Feed in tariffs are: France 30 €cents/kWh, Spain 27 €cents/kWh, Italy 22-28 €cents/kWh, India 19 US$ cents/kWh, Turkey 24-20 €cents/kWh. Source: Richter et al., 2009). Indeed, there may be many reasons for which governments want to support the expansion of CSP. In Section 2.8 we show that a moderate level of subsidies can be motivated by learning externalities. However, part of the non-peer reviewed literature seem to be overly optimistic on the short-term weight that CSP should have in a balanced mitigation portfolio.

In the long-term instead, especially with constraints on nuclear or on IGCC coal with CCS, the price signals alone are sufficiently strong to expand enormously the capacity of CSP. It is important to assess if these production levels can be implemented in practice.

Such a large deployment of CSP electricity generation and its transmission over long distances to reach highly populated and electricity-demanding areas necessarily implies a large footprint in terms of land and infrastructure. Indeed, Table 2.5 reports the mirror surface needed for such production levels. Notice that 5/8 of the surface is for direct electricity generation, while 3/8 is used for heat-storage operations for overnight or overcast electricity generation.

To help the visualization of the amount of land needed for production, note that the mirror surface needed by MENA - in the most extreme case where penetration limits are imposed on both nuclear power and IGCC power with CCS - for export generation is similar to the surface of Cyprus, while for total production (domestic consumption plus export) is similar to the area of Slovenia. If we compare the total surface of the Sahara desert to the portions needed for the CSP mirrors for domestic consumption and export to Western and Eastern Europe, we find that the latter, although very large, correspond to about 3/1000 and 1/1000 of the available surface, respectively. In the USA instead, the surface for the largest expansion of mirrors would require 0.26% of total land in the contiguous 48 States, but about 6% of land in Arizona; in China, 2% of Tibet should be used to host CSP power



	MENA - domestic		MENA - export		USA		CHINA	
	U-Stab	NCC-Stab	U-Stab	NCC-Stab	U-Stab	NCC-Stab	U-Stab	NCC-Stab
Mirror Surface for generation and storage ('000 sq km)								
2040	0,1	0,5	-	0,0	-	1,0	-	0,6
2060	4,8	5,7	0,9	5,7	4,7	12,4	9,0	15,7
2080	8,2	8,5	3,1	8,0	15,0	16,8	18,5	22,1
2100	10,6	10,5	4,1	9,2	19,6	19,5	22,7	25,5
Number of HVDC cables for the Super-Grid								
2040	-	-	-	0,3	-	19	-	11
2060	-	-	17	113	92	242	176	307
2080	-	-	61	156	294	329	362	433
2100	-	-	81	181	384	382	446	500

Notes: U-Stab = unconstrained stabilization; NCC-Stab = constrained stabilization with cap on nuclear and no CCS.

Table 2.5: CSP mirror surface and HVDC cables

plants. It is not clear if this large expansion is feasible or not.

Table 2.5 also reports the number of 5GW HVDC cables that would need to be installed for the transmission of CSP electricity within the USA, China and between MENA and Western and Eastern Europe. Notice that the number of cables needed is very high, especially if compared to the existing or planned interconnections. Therefore, scenarios of this kind pose very strong engineering and administrative challenges for the authorization and implementation of such infrastructure.

Such large shares of CSP electricity consumption and trade pose not only large engineering and administrative challenges but also political ones. The next Section analyses the effects of coordination between producing regions, here we want to very briefly discuss the energy security implications. Indeed, scenarios of penetration shares of imported electricity - for Western and Eastern Europe - like the kind that have emerged in our analysis are difficult to sustain politically as they go in the direction of increasing energy dependence from foreign sources. More precisely, if the CSP trade option is available, both Western and Eastern Europe increase their import dependency - in the second half of the century - under all stabilization scenarios. Indeed, import dependency for Western and Eastern Europe, analysed together, starts at 52%, close to current levels of import dependency of EU-27, and grows up to 66% in 2100. Scenarios without the CSP option have much lower levels of import dependency but also lower levels of energy consumption and GDP. For the business as usual scenario import dependency is not influenced by CSP electricity as import is not optimal.

Though, it needs to be noticed that the market structure - that is similar to a dual monopoly - and the high level of investments needed to build the connecting infrastructure, that is difficultly re-convertible, make the switching costs of stopping to import or export very high, once the infrastructure is built. Therefore, stability in demand or supply is - at least theoretically - more likely than in other markets where the traded goods can be easily sold to different demanding countries. On the other hand though, the direct connection of the Europe-MENA Super-Grid to the European power network makes the latter vulnerable, more than for imports of primary energy sources, due to the absence of time-lags between import and use of the imported electricity. Even if the benefits for MENA countries are large - indeed CSP plants enable electrification, diversification of energy supply that may increase the hydrocarbon sources available for export, zero-carbon desalination of water, job creation and a valuable stream of revenue from exports - the present political conditions do not guarantee a stable supply. Before any trade can take place there is the need to build a strong and solid cooperation between countries, able to generate reciprocal trust. Future analysis will be at a greater geographical detail and will be able to analyse this issue more profoundly.

2.8 Anticipating investments in CSP

In the sensitivity analysis (Annex A) we examine how the optimal timing of investment changes with alternative assumptions on CSP capital cost. We find that when the cost of CSP drops by thirty percent, investments occur earlier than in the central case, but always later than in other studies. Therefore the slower expansion of CSP that we find with respect to the literature is explained by: (1) much lower capital costs of CSP and SG (also thanks to subsidies), (2) much higher costs or limits to the penetration of other carbon free electricity generation technologies, (3) less opportunities for energy efficiency improvements, (4) other non-tangible benefits or positive spillovers.

In this Section we focus on the latter explanation and we examine the role of learning externalities. It must be recalled that the standard solution of WITCH is the outcome of a non-cooperative game. Since the cost of CSP is governed by a one-factor learning curve, regional social planners do not internalize the knowledge spillovers and invest less - and later - than what it would be socially optimal (See Equation 2.3)[12].

We assume that MENA, China and the USA introduce a coordinated policy that forces the investments in CSP to be above a minimal threshold from 2010 until 2030. This threshold is different for all regions and varies over time in order to replicate the investment pattern in CSP found in the "New Policies Scenario" of the World Energy Outlook 2010 (IEA, 2010c). According to this scenario China and the Middle East deploy 17 GW of CSP in

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[12] Externalities within each region are instead fully internalized.

2035 and the USA 12 GW. The target is to stabilize GHG concentrations at 535 ppme by 2100, with no limits to the penetration of nuclear or IGCC with CCS power ("Anticipated-U-Stab").

The new scenario shows that a more rapid expansion of CSP determines a faster contraction of investment costs, due to learning by doing (Figure 2.10). However, after 2050 the learning effect vanishes and costs converge in the two scenarios. After 2030 the USA and China stop investing, while MENA keeps adding CSP capacity. When the USA and China resume investments in 2045, they add much more capacity than in the U-Stab scenario because the cost of CSP is lower. However, they rapidly converge to the investment pattern of the U-Stab scenario. CSP electricity trade with Europe starts five years earlier, in 2055.

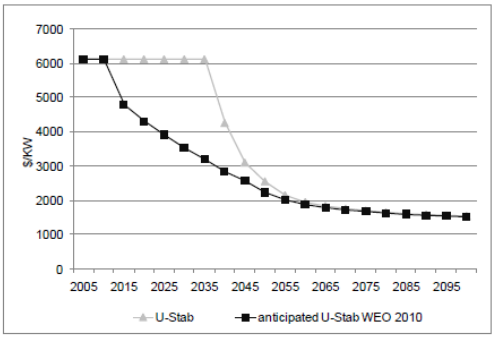

Figure 2.10: CSP Investments costs for in the unconstrained scenario and in the anticipated investments scenario.

The forced anticipation of investments has positive welfare effects. MENA, CHINA, the USA and Europe have higher discounted welfare than in the U-Stab scenario. The policy acts as a coordination mechanism and internalizes the learning externalities. However, the discounted consumption gains are very small: +0.16% (5% interest rate) or +0.24% (3% interest rate) in MENA; much lower in all other regions.

Therefore, learning externalities might motivate the introduction of moderate subsidies to invest in CSP all in countries with high production potential. However, they do not suggest that it would be optimal for Europe to import CSP electricity before the second half of the century.

2.9 Building a Mediterranean Power Market: Energy Security and Regulation Issues

The literature and the debate over the possibility to develop an international Super-Grid across the Mediterranean to exploit the solar potential of Northern Africa have examined two very relevant issues only marginally.

The most overlooked issue regards the security of the future European power market if a large fraction of electricity will be imported from MENA countries. In our scenarios, CSP electricity covers from 18% to 46% of total electricity consumption in Europe. The Desertec concept foresees 17% of electricity consumption to be provided by the MENA region in 2050. In Bauer et al. (2008) electricity from the MENA region covers about one-third of electricity consumption in Europe. These large shares of imported electricity pose a technical and political challenge for the European power market, which is now practically self-sufficient. Particular attention must be paid to avoid negative repercussions from disruptions in the power supply from MENA countries. A sudden collapse of supply, either intentional or un-intentional, would put the whole European network under stress. A large share of imported CSP therefore requires investments in back-up capacity, which reduce the convenience to displace electricity generation in Northern Africa[13].

Second, the creation of a large trans-Mediterranean market for electricity requires the establishment of an international regulatory agency to oversee the functioning of the grid and to ensure the highest possible level of market competition. We believe that the discussion of the institutional aspects of a large Mediterranean grid should be moved on top of the agenda, before any large investment project starts. It is not unrealistic that a future Europe-MENA trade could become a bilateral monopoly, with both monopoly and monopsony features. Therefore, market price and output will likely be determined as the outcome of an international bargaining process. A badly regulated market can cause serious international frictions and might eventually jeopardize the establishment of the market itself.

In particular, countries part of the MENA aggregate might have the incentive to form a cartel to sell electricity at prices higher than the marginal cost. This hypothesis is not unrealistic and is supported by the historic ties that many MENA countries have in the Organization of Petroleum Exporting Countries (OPEC). This Section tests this hypothesis. In the standard

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[13] The Desertec concept is very optimistic on the development pattern of Northern Africa and assumes that the South Mediterranean region will have roughly the same economic power of Europe in 2050 (http://www.desertec.org/en/concept/questions-answers/#c809). In Trieb (2006), it is instead recognized that trade of electricity across the Mediterranean scenario will not become reality automatically. A developmental path “enlarging the gap” is not an exotic fiction, according to Trieb (2006).

solution of WITCH all regions are “price takers”, i.e. they are not able to excerpt any market power. This implies that in all the scenarios examined in the previous sections, MENA exports electricity at a price equal to its marginal cost. Those scenarios constitute the best possible market structure for Europe. In order to test if MENA countries have the incentive to build a cartel we prepared an additional set of scenarios. Instead of letting supply and demand forces determine the market price, in these new scenarios we fix the price of CSP electricity and we let demand adjust to it. It is important to note that the returns to scale to the CSP industry are linear, with space not being a limiting factor. Therefore supply can support any level of demand if the price is above the marginal cost. If the price is below the marginal cost supply goes to zero and no market arises. If the price of electricity is too high, demand drops to zero because alternative carbon-free power generation options in Europe become more affordable. The left panel of Figure 2.11 displays the minimum and the maximum price vectors for which a Mediterranean market for CSP exists. Since we do not pose any constraint to the deployment of nuclear and CCS, the p-min price is equal to the price in the U-Stab scenario.

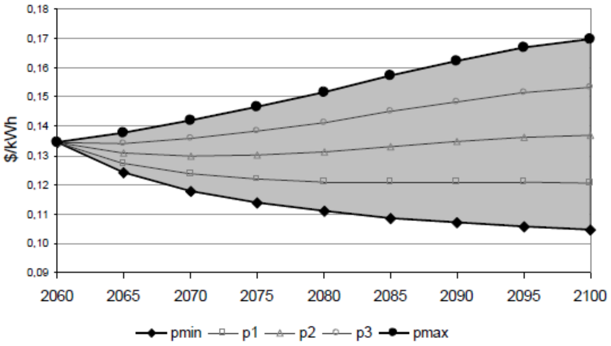

Figure 2.11: Price for traded CSP Electricity

All combinations of prices and the corresponding quantities traded, included in the grey area, are Pareto improving compared to the corresponding simulations where CSP trade is not allowed. We tested three intermediate combinations of prices.

We find that as price increases the quantity traded decreases and therefore both revenues and costs decrease (see the right panel of Figure 2.12). Profits, defined as the difference between revenues from CSP sales and costs to generate and transmit electricity, follow an inverted-U relationship with prices of electricity because demand in Europe - in particular in Western Europe - is elastic and domestic carbon-free options are available.

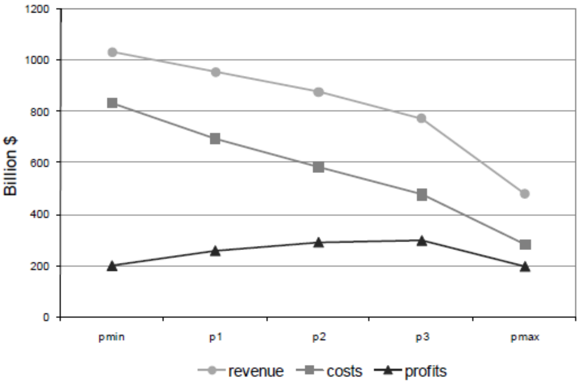

Figure 2.12: MENA Aggregated costs, Revenue and Profits from CSP Electricity trade

On welfare grounds, MENA's consumption and welfare levels also follow an inverted-U relationship with prices of electricity and reach their maximum in correspondence to the price in the vicinity of the price vector "p3". Therefore, compared to the competitive equilibrium case, MENA is better off with prices around those tested with vector "p3". Western and Eastern Europe instead are better off in correspondence with the minimum price vector where they are able to import a larger amount of zero-carbon electricity at lower prices. What the exchange price will be will depend on the relative strengths of the regions in the bargaining process of the long-term international agreements that necessarily need to take place for the implementation of the Super-Grid infrastructure to be possible.

The proponents of the Desertec concept do not believe that MENA countries might form a cartel because Europe has the potential to generate CSP domestically and would discourage any monopoly[14]. We show here that there are instead incentives for MENA countries to behave as a block and to supply electricity at a price above the marginal cost. However, prices cannot increase too much because Europe can expand the domestic supply of electric power from nuclear, coal with CCS and renewables. Of course, the bargaining position of Europe gets weaker if the deployment of nuclear and CCS is limited.

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[14] http://www.desertec.org/en/concept/questions-answers/#c809, accessed on June 8, 2011.

2.10 Sensitivity Analysis

In this Section we test the robustness of our results by varying the values of the key input parameters. We focus on the assumptions for CSP electricity generation, long-distance transmission through a Super-Grid and its trade. We test the alternative assumptions using as a reference case the unconstrained stabilization scenario. More in detail, we test variations ceteris paribus of ±5%, ±10%, ±20% and ±30% of the reference value of: (*i*) initial CSP investments costs (SC_{CSP}); (*ii*) SG infrastructure investments costs (SC_{grid}); and ($iii - v$) the parameters of the cost function, related to the learning by doing effect (α) and to the cost increase due to limited supply of intermediate goods (β, γ).

The graphs reported in Appendix A depict the changes of: (*i*) future investment costs, (*ii*) trade of CSP Electricity between MENA and Europe, and (*iii*) world CSP installed capacity, for the alternative assumptions on the above parameters. For simplicity, in the graphs we report the values of the variables for variations of 0%, ±5%, ±30%. We find that all three output variables are more sensitive to the initial value of the CSP investment cost and to the progress ratio used in the learning by doing term of the cost function, compared to the other three. For small input parameters variations (5-10%), output results are stable; for larger variations results differ sensibly, though in all cases the differences are mainly quantitative and not qualitative.

The timing of CSP deployment for MENA is influenced by variations only in CSP investment costs, while for the USA and China also by the progress ratio. The optimal timing for the Europe-MENA trade is mainly sensitive to the previous two parameters; Super-Grid investment costs are also influential but to a smaller extent.

To conclude, the sensitivity analysis shows that the crucial parameters for this analysis are the initial investment costs for the CSP power plants and the rate at which these will decrease as cumulative installed capacity grows, therefore particular care should be devoted to their estimation.

2.11 Conclusions

This paper examines the effects of introducing Concentrated Solar Power (CSP) transmitted by means of Super-Grids (SG) in five regions of the world: China, Eastern Europe (E-EU), Western Europe (W-EU), the Middle East and North Africa (MENA) and the United States of America. The analysis evaluates the technological, economic and CO_2 mitigation potentials of this low-carbon option for electricity generation - using the Integrated Assessment Model WITCH -, under a Business as Usual scenario and under a 535ppm-CO_2eq policy target in the presence of a global carbon market. Results are tested under different assumptions regarding the expansion of nuclear power and coal power with carbon capture and storage (CCS), that, together with renewable power, are considered the most promising technologies to tackle the electricity sector's greenhouse gas (GHG) emissions, though might be subject to opposition by the general public, high costs, technological and geo-political challenges.

The analysis of the simulation scenarios shows that (*i*) an extensive use of CSP will become optimal only in the second part of the century, both for domestic consumption (in MENA, USA, China) or for export (in the case of the Europe-MENA Super-Grid). Constraints on the use of nuclear and/or of IGCC coal with CCS have an impact on the size of investments in 2050, but a smaller effect on later years, when the cost of CSP declines sharply. CSP generation by MENA is optimal from 2040 onwards and large, under all climate policy scenarios. In the second part of the century it becomes optimal even in the Business as Usual scenario. For what concerns MENA, domestic demand is high, therefore, (*ii*) development projects regarding a Europe-MENA CSP-SG need to take into account a large domestic use of CSP by MENA, that is most likely to increase further if demand for low-carbon desalination is included in the model.

After investments start around 2040, (*iii*) the cost of CSP drops quickly as global installed capacity increases. In the first ten year during which investments in CSP occur the cost drops by at least 50%. Eventually the cost reaches a floor of about 1,500 US$/kW.

We also find that (*iv*) in the first part of the century, it is convenient for Europe to import electricity from the MENA region only when there are constraints to the expansion of nuclear and/or the use of IGCC coal with CCS. Trade starts around 2040, at about 30c$/KWh, in the most extreme case. The price of CSP decreases over time to 10-11 c$/KWh.

In this paper, we do not simulate the domestic balancing opportunities for Europe; though, our results suggest that an intra-regional super grid-network within Europe, able to connect and integrate different domestic renewable source potentials (for example, North-South), is likely to be optimal, possibly before the import of CSP electricity from MENA.

In the second part of the century (*v*) the electricity mix of the USA, China, MENA, W-EU and E-EU will strongly be modified by the additional CSP option that will reach very large shares of electricity generation.

The CSP powered SG (CSP-SG) is an important technology option that (*vi*) has a high stabilization cost option value, especially in coal-intensive countries: 1.1%-3.4% of discounted GDP in China, 0.1%-1.3% in E-EU and 0.2%-1.2% in the USA. CSP has the highest stabilization cost option value in MENA from 2.1% to 4.1% of GDP. The option value measured using the price of carbon traded internationally (the global marginal abatement cost) ranges from 2.7 US$ per tonne of CO_2-eq in 2025 to 112 US$ in 2100 without technological limits. If there are limits to nuclear and IGCC coal with CCS the option value of CPS ranges between 36 and 101 US$ per tonne of CO_2-eq in 2050 and between 240 and 425 US$ per tonne of CO_2-eq in 2100. Most importantly, CSP reduces greatly the option value of nuclear and IGCC coal with CCS. If we compare our results with the literature (*vii*) we find it optimal to invest later than most studies do. We also find that it is optimal to invest less in CSP if we do not constrain nuclear and/or IGCC coal with CCS. The constrained scenarios increase the expansion of CSP and anticipate it.

Once it starts to become optimal to invest in long distance CSP, penetration shares reach very high levels. Though, our scenarios might be overly optimistic in the long run because they do not take into account the difficulties that can arise from a large surface area occupied by CSP plants and by a large number of grid connections, especially across the Mediterranean.
Earlier investments in CSP could be motivated by some external benefits beyond the reduction of CO_2 emissions. This study examines if learning externalities motivate subsidies and government support to CSP-SG projects already in the next decade. Results reveal that a moderate subsidy or a command-and-control policy (beyond the pricing of the environmental externality), might indeed increase welfare.

Finally, the literature on CSP and the political debate have largely neglected the complexities of building the institutions capable of managing a large Mediterranean market for electricity. Without a sound institutional framework tensions among the two regions might emerge and jeopardize the overall deployment of CSP power. In particular, high attention should be devoted to the mechanisms and rules that will determine the price of electricity. This study shows that there are incentives that may lead MENA countries to form a cartel. The emergence of market power can be troublesome for Europe. Equally problematic, in the case of a large deployment of CSP-SG, might be the large exposure of the European power network to foreign shocks. Instead of increasing energy security, a massive use of imported CSP might increase energy dependency.
Therefore our scenarios may be overly optimistic, with respect to the penetration shares of this technology. Realistically, imported CSP will be able to contribute only up to some extent (set politically) to the European power mix and domestic carbon-free power sources need to be developed and enhanced. Very large is instead the potential of CSP in China, the USA, and in MENA countries, where the only constraints are technological.

2.12 Future developments

Future developments of this work will expand the number of regions that can invest profitably in CSP, such as Australia, Brasil and Indonesia as these are the other world regions with the most potential for CSP production. In particular, we aim at developing the option of building Super-Grids within Europe, that offer the opportunity to integrate different and distant domestic renewable power sources helping to smooth variations in supply and demand taking advantage of meteorological or time differences.
Moreover, we will explore more stringent stabilization targets and investigate with greater precision the optimal geographical location of CSP plants and Super-Grids, to be able to improve the comparison between domestic generation opportunities with import from abroad.
Furthermore, we will try to account for the main socio-economic effects of the increased availability of (carbon-free) electricity in the MENA region, starting from the possibility of producing relatively cheap and low-carbon fresh water.

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2.14 Appendix A

Additional Results

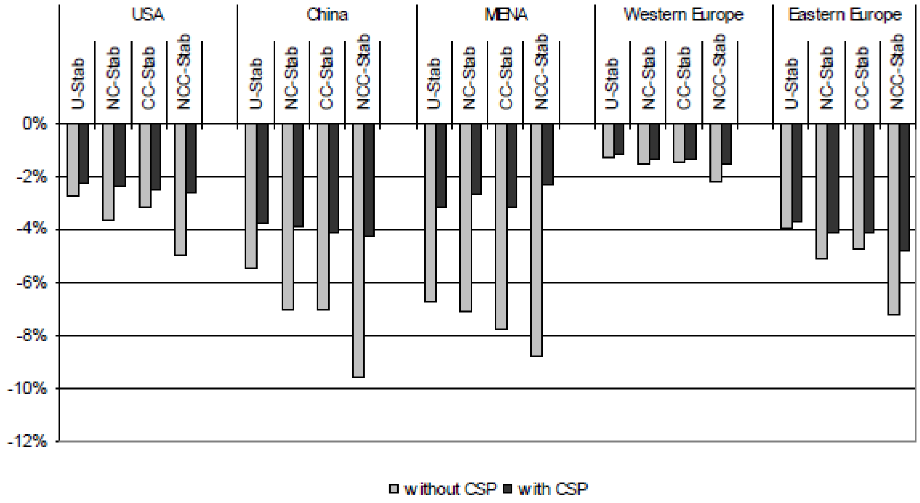


Table 2.6: Aggregated Discounted (3%) Policy Costs with respect to Bau

USA	COAL PC			COAL IGCC				OIL			GAS			NUKE		HYDRO	W&S	CSP
	Capital	Fuel	CO_2	Capital	CCS	Fuel	CO_2	Capital	Fuel	CO_2	Capital	Fuel	CO_2	Capital	Fuel	Capital	Capital	Capital
2005	2,79	1,62	-	5,37	0,49	1,35	-	2,06	7,67	-	1,62	5,13	-	6,05	0,14	5,53	10,13	0,00
2010	2,65	1,60	-	5,07	0,49	1,38	-	1,97	8,00	-	1,56	4,79	-	5,84	0,16	5,24	9,30	0,00
2015	2,57	1,58	0,67	4,87	0,49	1,42	0,06	1,92	8,62	0,46	1,52	4,86	0,27	5,74	0,19	5,05	8,42	0,00
2020	2,51	1,57	1,18	4,75	0,49	1,44	0,11	1,89	9,40	0,85	1,49	5,04	0,47	5,70	0,23	4,94	7,52	0,00
2025	2,46	1,55	2,57	4,63	0,49	1,47	0,24	1,85	10,35	1,96	1,47	5,29	1,04	5,67	0,30	4,82	6,65	0,00
2030	2,43	1,53	5,00	4,58	0,49	1,50	0,49	1,84	11,29	4,02	1,45	5,57	2,06	5,70	0,38	4,77	5,94	0,00
2035	2,40	1,51	7,58	4,52	0,51	1,53	0,77	1,82	12,07	6,40	1,44	5,84	3,15	5,72	0,49	4,71	5,32	0,00
2040	2,37	1,50	13,52	4,43	0,53	1,56	1,40	1,80	12,66	11,94	1,42	6,11	5,68	5,76	0,62	4,63	4,74	0,00
2045	2,33	1,50	20,31	4,36	0,58	1,60	2,17	1,78	12,90	18,71	1,41	6,33	8,63	5,82	0,78	4,56	4,24	0,00
2050	2,30	1,49	30,03	4,28	0,64	1,64	3,29	1,76	12,89	28,75	1,39	6,50	12,87	5,93	0,97	4,49	3,80	11,79
2055	2,30	1,49	37,51	4,28	0,70	1,67	4,22	1,76	12,64	37,22	1,39	6,62	16,23	5,98	1,21	4,49	3,51	10,36
2060	2,29	1,51	44,90	4,27	0,75	1,70	5,05	1,75	12,27	44,90	1,39	6,84	19,43	5,99	1,44	4,47	3,35	9,47
2065	2,28	1,54	50,71	4,24	0,80	1,73	5,70	1,75	11,87	51,07	1,38	7,05	21,94	5,94	1,64	4,45	3,20	8,89
2070	2,27	1,56	54,64	4,22	0,84	1,75	6,15	1,74	11,45	56,39	1,38	7,28	23,65	5,92	1,78	4,43	3,08	8,52
2075	2,25	1,58	58,25	4,19	0,87	1,78	6,55	1,73	11,06	59,41	1,37	7,51	25,21	5,91	1,86	4,40	2,97	8,25
2080	2,24	1,60	61,82	4,15	0,90	1,80	6,96	1,72	10,68	63,42	1,36	7,76	26,75	5,92	1,88	4,36	2,87	8,03
2085	2,22	1,62	65,04	4,11	0,92	1,82	7,32	1,71	10,31	67,09	1,36	8,02	28,15	5,95	1,86	4,33	2,77	7,85
2090	2,20	1,64	67,80	4,07	0,93	1,84	7,63	1,70	9,96	70,29	1,35	8,30	29,34	5,99	1,81	4,29	2,69	7,69
2095	2,19	1,65	69,49	4,04	0,94	1,86	7,82	1,69	9,63	72,39	1,34	8,59	30,07	6,04	1,72	4,26	2,62	7,56
2100	2,18	1,67	68,34	4,01	0,95	1,88	7,69	1,69	9,32	71,52	1,34	8,89	29,58	6,10	1,61	4,24	2,56	7,46

CINA	COAL PC			COAL IGCC				OIL			GAS			NUKE		HYDRO	W&S	CSP
	Capital	Fuel	CO_2	Capital	CCS	Fuel	CO_2	Capital	Fuel	CO_2	Capital	Fuel	CO_2	Capital	Fuel	Capital	Capital	Capital
2005	2,62	1,60	-	6,04	0,49	1,22	-	2,63	10,31	-	2,14	5,70	-	6,57	0,14	6,26	11,59	0,00
2010	3,14	1,57	-	7,41	0,49	1,26	-	3,07	10,68	-	2,50	5,26	-	7,70	0,16	7,57	13,48	0,00
2015	3,18	1,54	0,71	7,52	0,49	1,29	0,06	3,11	11,40	0,53	2,53	5,27	0,29	7,85	0,19	7,67	12,77	0,00
2020	3,06	1,51	1,25	7,20	0,49	1,32	0,11	3,00	12,30	0,99	2,44	5,40	0,51	7,64	0,23	7,37	11,00	0,00
2025	2,89	1,48	2,69	6,76	0,49	1,35	0,24	2,86	13,39	2,26	2,33	5,61	1,11	7,36	0,30	6,95	9,27	0,00
2030	2,76	1,45	5,19	6,43	0,49	1,37	0,49	2,76	14,48	4,63	2,24	5,84	2,15	7,16	0,38	6,63	8,02	0,00
2035	2,66	1,43	7,80	6,16	0,50	1,40	0,77	2,67	15,38	7,37	2,18	6,06	3,27	7,02	0,49	6,38	7,00	0,00
2040	2,54	1,41	13,80	5,84	0,54	1,44	1,40	2,57	16,05	13,76	2,09	6,28	5,84	6,88	0,62	6,08	6,06	0,00
2045	2,43	1,40	20,59	5,55	0,66	1,47	2,17	2,48	16,34	21,57	2,02	6,44	8,78	6,76	0,78	5,79	5,25	0,00
2050	2,30	1,39	30,22	5,20	0,96	1,51	3,29	2,37	16,32	33,15	1,93	6,55	12,98	6,66	0,97	5,47	4,49	15,54
2055	2,27	1,37	37,51	5,11	1,43	1,55	4,22	2,34	16,03	42,90	1,90	6,62	16,23	6,63	1,21	5,38	4,12	13,63
2060	2,22	1,40	44,90	4,98	2,03	1,58	5,05	2,29	15,61	51,77	1,87	6,84	19,43	6,55	1,44	5,26	3,86	12,36
2065	2,16	1,43	50,71	4,84	2,74	1,60	5,70	2,25	15,14	58,88	1,83	7,05	21,94	6,40	1,64	5,12	3,63	11,48
2070	2,11	1,45	54,64	4,70	3,50	1,63	6,15	2,20	14,67	63,86	1,80	7,28	23,65	6,29	1,78	4,99	3,43	10,84
2075	2,06	1,47	58,25	4,57	4,26	1,65	6,55	2,16	14,21	68,48	1,76	7,51	25,21	6,20	1,86	4,86	3,25	10,34
2080	2,01	1,49	61,82	4,44	4,96	1,67	6,96	2,12	13,77	73,11	1,73	7,76	26,75	6,14	1,88	4,74	3,09	9,94
2085	1,97	1,51	65,04	4,33	5,58	1,70	7,32	2,09	13,35	77,34	1,70	8,02	28,15	6,12	1,86	4,64	2,96	9,63
2090	1,93	1,53	67,80	4,23	6,11	1,72	7,63	2,05	12,95	81,03	1,67	8,30	29,34	6,11	1,81	4,54	2,84	9,37
2095	1,90	1,54	69,49	4,14	6,55	1,74	7,82	2,02	12,57	83,46	1,65	8,59	30,07	6,11	1,72	4,45	2,74	9,15
2100	1,87	1,56	68,34	4,07	6,90	1,76	7,69	2,00	12,21	82,45	1,63	8,89	29,58	6,12	1,61	4,39	2,65	8,97

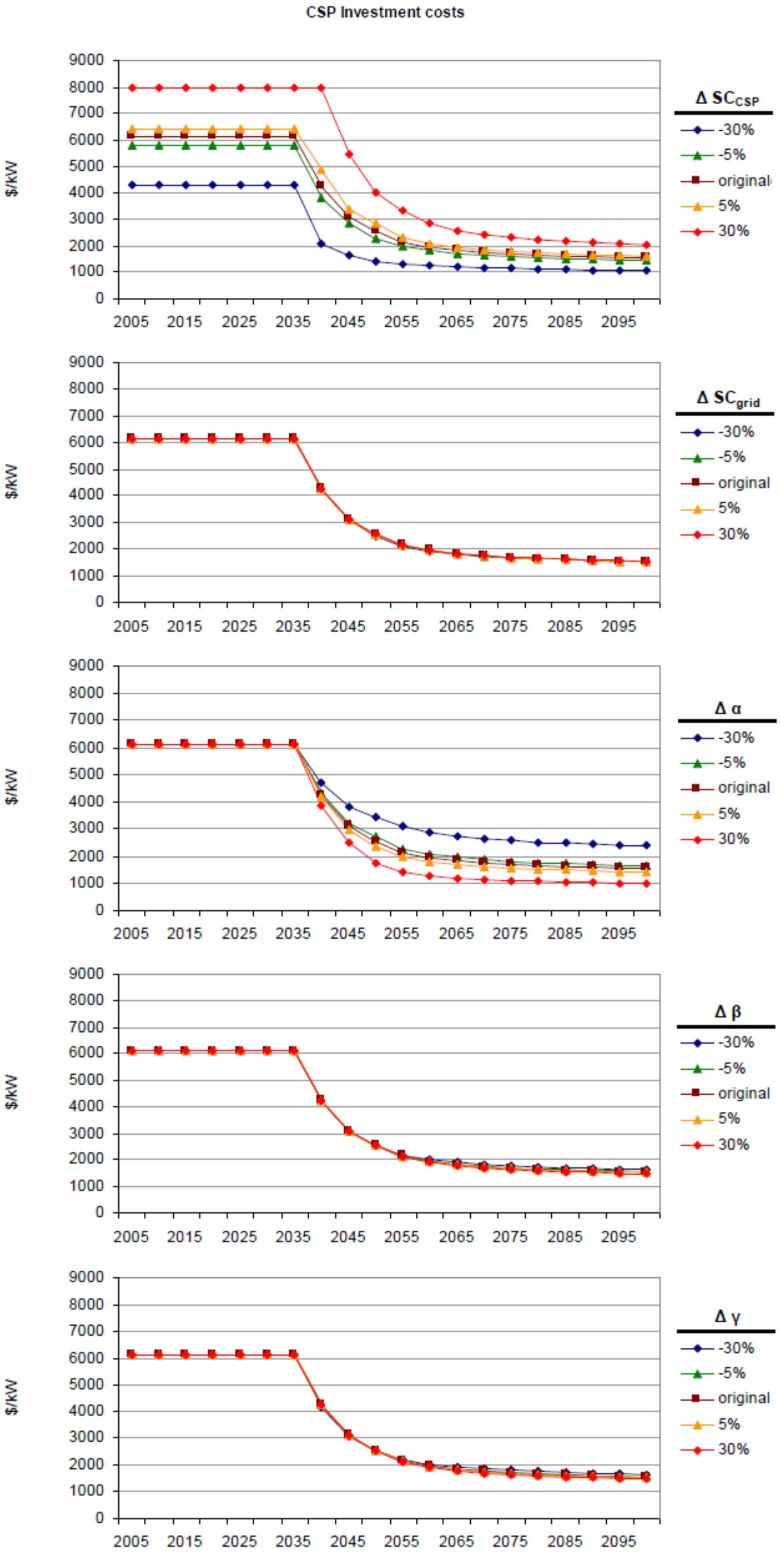
MENA	COAL PC			COAL IGCC				OIL			GAS			NUKE		HYDRO	W&S	CSP
	Capital	Fuel	CO_2	Capital	CCS	Fuel	CO_2	Capital	Fuel	CO_2	Capital	Fuel	CO_2	Capital	Fuel	Capital	Capital	Capital
2005	3,62	2,31	-	6,07	0,98	2,22	-	2,60	3,83	-	2,13	2,67	-	6,91	0,14	6,51	11,05	0,00
2010	3,53	2,31	-	5,91	0,98	2,26	-	2,55	4,15	-	2,09	2,25	-	6,81	0,16	6,35	10,43	0,00
2015	3,42	2,30	0,60	5,71	0,98	2,29	0,06	2,48	4,77	0,46	2,03	2,34	0,31	6,71	0,19	6,16	9,44	0,00
2020	3,35	2,29	1,08	5,59	0,98	2,32	0,11	2,44	5,54	0,85	2,00	2,55	0,55	6,67	0,23	6,05	8,39	0,00
2025	3,27	2,28	2,38	5,44	0,98	2,35	0,24	2,40	6,48	1,94	1,96	2,83	1,17	6,62	0,30	5,91	7,34	0,00
2030	3,18	2,27	4,69	5,27	0,98	2,37	0,49	2,34	7,42	3,98	1,92	3,13	2,26	6,55	0,38	5,74	6,38	0,00
2035	3,15	2,27	7,22	5,22	0,98	2,40	0,77	2,33	8,19	6,34	1,91	3,41	3,40	6,58	0,49	5,70	5,70	0,00
2040	3,09	2,26	13,04	5,09	0,98	2,44	1,40	2,29	8,77	11,83	1,87	3,68	6,00	6,59	0,62	5,58	5,02	26,49
2045	3,10	2,26	19,84	5,12	0,98	2,47	2,17	2,29	9,01	18,54	1,88	3,87	8,93	6,73	0,78	5,60	4,65	19,97
2050	3,10	2,27	29,68	5,12	0,98	2,51	3,29	2,29	9,00	28,49	1,88	4,02	13,10	6,90	0,97	5,60	4,36	16,20
2055	3,08	2,26	37,51	5,09	0,98	2,55	4,22	2,28	8,75	36,88	1,87	4,12	16,23	6,93	1,21	5,57	4,02	14,13
2060	3,08	2,29	44,90	5,09	0,98	2,58	5,05	2,28	8,39	44,50	1,87	4,34	19,43	6,95	1,44	5,57	3,85	12,36
2065	3,07	2,31	50,71	5,06	0,98	2,60	5,70	2,27	7,99	50,61	1,86	4,55	21,94	6,90	1,64	5,54	3,66	11,30
2070	3,05	2,34	54,64	5,02	0,98	2,63	6,15	2,26	7,58	54,89	1,85	4,78	23,65	6,86	1,78	5,50	3,48	10,58
2075	3,02	2,36	58,25	4,97	0,98	2,65	6,55	2,25	7,18	58,87	1,84	5,01	25,21	6,84	1,86	5,46	3,32	10,05
2080	2,99	2,38	61,82	4,91	0,98	2,67	6,96	2,23	6,81	62,85	1,83	5,26	26,75	6,83	1,88	5,40	3,18	9,65
2085	2,96	2,40	65,04	4,86	0,98	2,70	7,32	2,21	6,44	66,48	1,81	5,52	28,15	6,85	1,86	5,35	3,06	9,33
2090	2,93	2,41	67,80	4,81	0,98	2,72	7,63	2,19	6,10	69,66	1,80	5,80	29,34	6,88	1,81	5,30	2,96	9,07
2095	2,91	2,43	69,49	4,77	0,98	2,74	7,82	2,18	5,77	71,74	1,79	6,09	30,07	6,93	1,72	5,26	2,87	8,86
2100	2,89	2,45	68,34	4,73	0,98	2,76	7,69	2,17	5,46	70,88	1,78	6,39	29,58	6,97	1,61	5,23	2,80	8,70

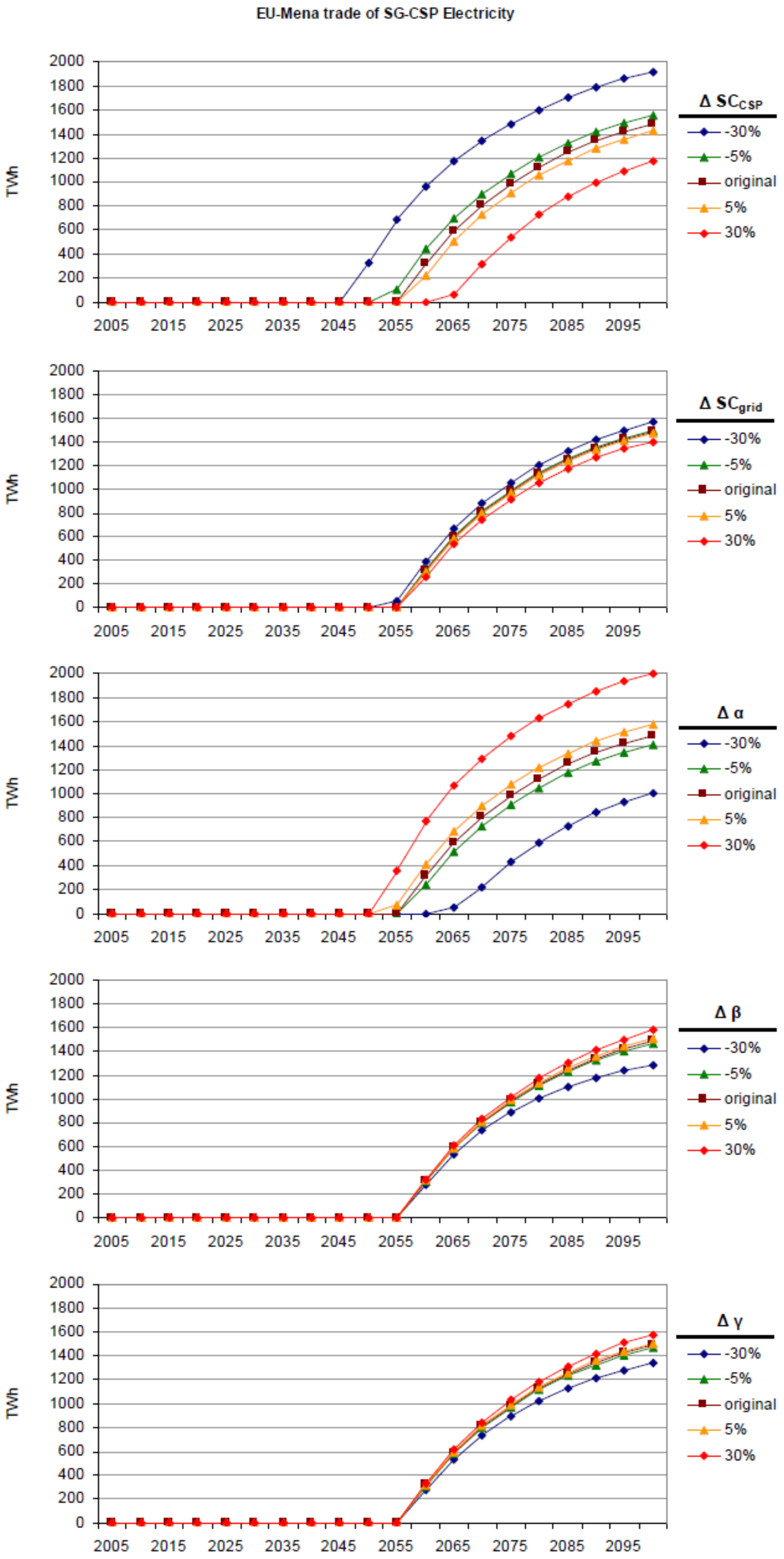
Western Europe	COAL PC			COAL IGCC				OIL			GAS			NUKE		HYDRO	W&S	CSP
	Capital	Fuel	CO_2	Capital	CCS	Fuel	CO_2	Capital	Fuel	CO_2	Capital	Fuel	CO_2	Capital	Fuel	Capital	Capital	Import
2005	2,98	2,98	-	5,54	0,49	2,77	-	2,35	10,54	-	1,85	4,13	-	6,18	0,14	5,71	10,14	-
2010	2,85	2,96	-	5,25	0,49	2,81	-	2,26	10,86	-	1,78	3,81	-	5,98	0,16	5,43	9,34	-
2015	2,76	2,93	0,62	5,06	0,49	2,84	0,06	2,21	11,49	0,46	1,74	3,90	0,27	5,89	0,19	5,26	8,50	-
2020	2,71	2,90	1,10	4,94	0,49	2,87	0,11	2,17	12,28	0,86	1,71	4,10	0,47	5,85	0,23	5,14	7,60	-
2025	2,66	2,87	2,42	4,84	0,49	2,90	0,24	2,14	13,23	1,97	1,68	4,37	1,04	5,83	0,30	5,04	6,75	-
2030	2,63	2,85	4,77	4,78	0,49	2,92	0,49	2,12	14,18	4,05	1,67	4,66	2,06	5,85	0,38	4,99	6,03	-
2035	2,61	2,82	7,31	4,73	0,49	2,95	0,77	2,10	14,97	6,44	1,66	4,95	3,15	5,88	0,49	4,94	5,41	-
2040	2,57	2,80	13,16	4,66	0,49	2,99	1,40	2,08	15,55	12,02	1,64	5,24	5,68	5,93	0,62	4,87	4,84	-
2045	2,55	2,79	19,96	4,60	0,50	3,02	2,17	2,07	15,80	18,84	1,63	5,47	8,63	6,01	0,78	4,82	4,36	-
2050	2,52	2,77	29,77	4,54	0,50	3,06	3,29	2,05	15,79	28,95	1,62	5,65	12,87	6,13	0,97	4,76	3,95	-
2055	2,50	2,75	37,51	4,50	0,51	3,10	4,22	2,03	15,53	37,47	1,61	5,79	16,23	6,15	1,21	4,73	3,66	-
2060	2,49	2,78	44,90	4,47	0,51	3,13	5,05	2,02	15,17	45,21	1,60	6,01	19,43	6,14	1,44	4,69	3,47	13,45
2065	2,47	2,80	50,71	4,44	0,51	3,15	5,70	2,01	14,76	51,42	1,59	6,22	21,94	6,09	1,64	4,66	3,31	12,41
2070	2,46	2,82	54,64	4,41	0,51	3,18	6,15	2,00	14,34	55,77	1,58	6,44	23,65	6,06	1,78	4,63	3,17	11,79
2075	2,44	2,85	58,25	4,37	0,52	3,20	6,55	1,99	13,94	59,82	1,58	6,68	25,21	6,05	1,86	4,60	3,04	11,38
2080	2,42	2,87	61,82	4,33	0,52	3,22	6,96	1,98	13,56	63,86	1,57	6,93	26,75	6,07	1,88	4,56	2,93	11,08
2085	2,41	2,88	65,04	4,30	0,52	3,25	7,32	1,97	13,19	67,55	1,56	7,19	28,15	6,10	1,86	4,53	2,83	10,87
2090	2,39	2,90	67,80	4,26	0,52	3,27	7,63	1,96	12,84	70,78	1,55	7,46	29,34	6,14	1,81	4,49	2,74	10,70
2095	2,37	2,92	69,49	4,22	0,52	3,29	7,82	1,95	12,51	72,89	1,54	7,75	30,07	6,18	1,72	4,46	2,66	10,57
2100	2,36	2,94	68,34	4,19	0,52	3,31	7,69	1,94	12,19	72,02	1,53	8,06	29,58	6,23	1,61	4,43	2,59	10,44

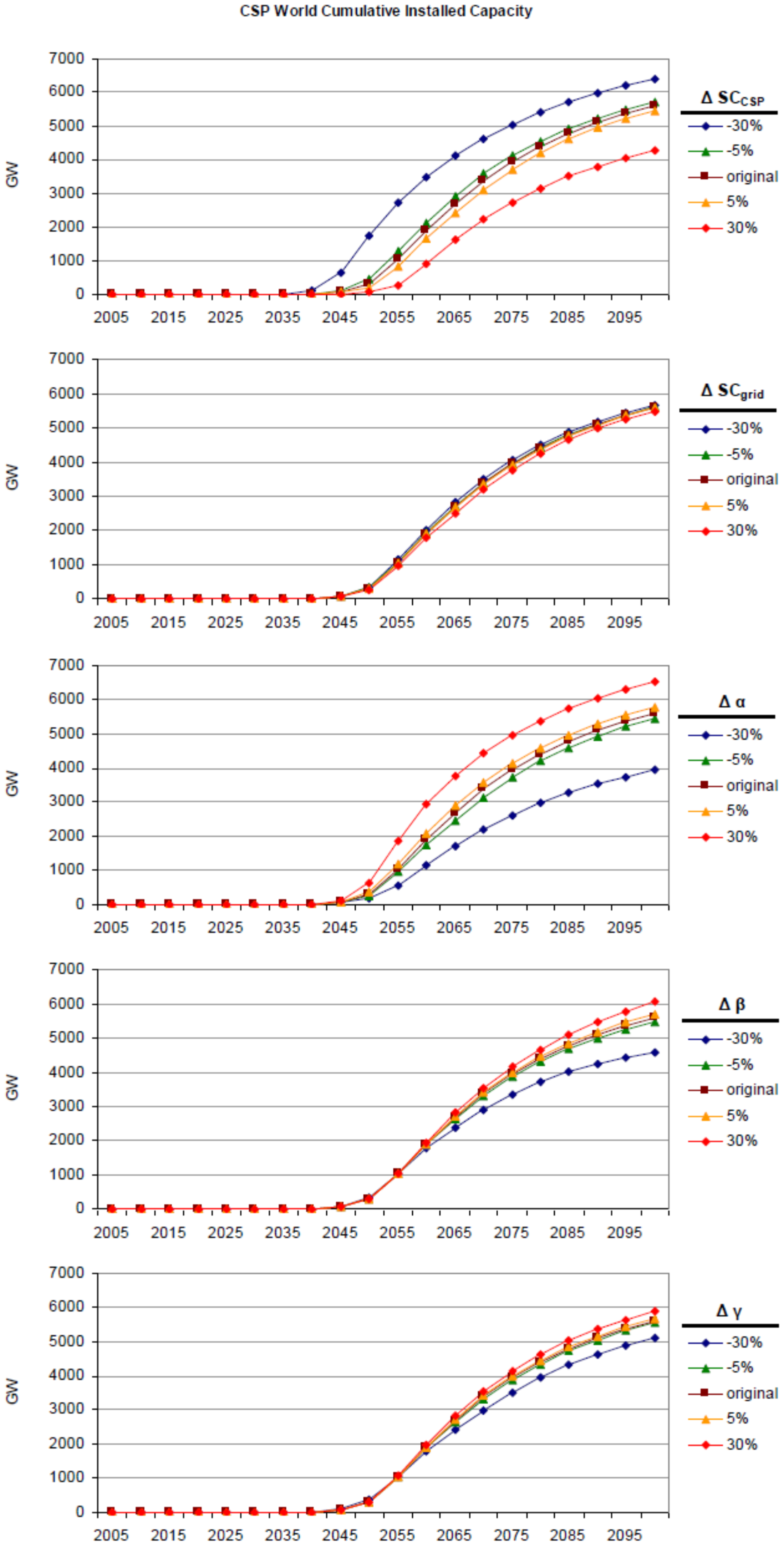
Eastern Europe	COAL PC			COAL IGCC				OIL			GAS			NUKE		HYDRO	W&S	CSP
	Capital	Fuel	CO_2	Capital	CCS	Fuel	CO_2	Capital	Fuel	CO_2	Capital	Fuel	CO_2	Capital	Fuel	Capital	Capital	Import
2005	2,54	2,18	-	5,20	0,29	1,72	-	2,36	10,74	-	2,03	4,13	-	6,24	0,14	5,24	10,13	-
2010	2,82	2,13	-	5,85	0,29	1,76	-	2,56	11,13	-	2,20	3,81	-	6,80	0,16	5,86	10,88	-
2015	2,85	2,09	0,70	5,93	0,29	1,79	0,06	2,58	11,87	0,55	2,22	3,90	0,27	6,92	0,19	5,94	10,31	-
2020	2,81	2,04	1,22	5,83	0,29	1,82	0,11	2,55	12,81	1,03	2,20	4,10	0,47	6,89	0,23	5,84	9,22	-
2025	2,74	2,00	2,64	5,67	0,29	1,85	0,24	2,50	13,94	2,35	2,15	4,37	1,04	6,83	0,30	5,69	8,15	-
2030	2,65	1,95	5,11	5,46	0,29	1,87	0,49	2,44	15,08	4,82	2,10	4,66	2,06	6,73	0,38	5,49	7,10	-
2035	2,55	1,92	7,71	5,24	0,30	1,90	0,77	2,37	16,02	7,68	2,04	4,95	3,15	6,63	0,49	5,28	6,20	-
2040	2,47	1,89	13,69	5,04	0,30	1,94	1,40	2,31	16,72	14,33	1,99	5,24	5,68	6,57	0,62	5,09	5,43	-
2045	2,40	1,87	20,48	4,88	0,31	1,97	2,17	2,26	17,01	22,46	1,94	5,47	8,63	6,56	0,78	4,93	4,80	-
2050	2,32	1,84	30,15	4,71	0,33	2,01	3,29	2,20	17,00	34,52	1,90	5,65	12,87	6,60	0,97	4,77	4,25	-
2055	2,29	1,82	37,51	4,63	0,36	2,05	4,22	2,18	16,70	44,68	1,88	5,79	16,23	6,59	1,21	4,70	3,81	-
2060	2,26	1,85	44,90	4,56	0,39	2,08	5,05	2,16	16,26	53,91	1,86	6,01	19,43	6,55	1,44	4,63	3,69	13,45
2065	2,23	1,87	50,71	4,49	0,42	2,10	5,70	2,14	15,77	61,32	1,84	6,22	21,94	6,47	1,64	4,56	3,42	12,41
2070	2,20	1,89	54,64	4,42	0,45	2,13	6,15	2,11	15,27	66,50	1,82	6,44	23,65	6,40	1,78	4,50	3,27	11,79
2075	2,16	1,91	58,25	4,34	0,47	2,15	6,55	2,09	14,80	71,32	1,80	6,68	25,21	6,36	1,86	4,42	3,13	11,38
2080	2,13	1,93	61,82	4,26	0,50	2,17	6,96	2,06	14,34	76,14	1,78	6,93	26,75	6,34	1,88	4,34	3,00	11,08
2085	2,10	1,95	65,04	4,18	0,51	2,20	7,32	2,04	13,90	80,55	1,76	7,19	28,15	6,34	1,86	4,27	2,89	10,87
2090	2,07	1,97	67,80	4,11	0,53	2,22	7,63	2,02	13,49	84,40	1,74	7,46	29,34	6,35	1,81	4,20	2,78	10,70
2095	2,04	1,99	69,49	4,04	0,54	2,24	7,82	2,00	13,09	86,92	1,72	7,75	30,07	6,37	1,72	4,14	2,69	10,57
2100	2,01	2,00	68,34	3,98	0,55	2,26	7,69	1,98	12,71	85,87	1,70	8,06	29,58	6,40	1,61	4,08	2,61	10,44

Notes: Capital costs also include costs for operation and maintenance.

Table 2.7: Electricity cost. The above tables refer to the unconstrained stabilization scenario (U-Stab). Similar tables for all other scenarios are available upon requests.


CSP Investment costs
$/kW
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
2005
2015
2025
2035
2045
2055
2065
2075
2085
2095
Δ SC$_{CSP}$
Δ SC$_{grid}$
Δ α
Δ β
Δ γ
-30%
-5%
original
5%
30%


EU-Mena trade of SG-CSP Electricity
TWh
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2005
2015
2025
2035
2045
2055
2065
2075
2085
2095
Δ SC_{CSP}
Δ SC_{grid}
Δ α
Δ β
Δ γ
-30%
-5%
original
5%
30%


CSP World Cumulative Installed Capacity
GW
7000
6000
5000
4000
3000
2000
1000
0
2005
2015
2025
2035
2045
2055
2065
2075
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Δ SC$_{CSP}$
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Chapter 3

Smart-Grids and climate change. Consumer adoption of smart energy behaviour: a system dynamics approach to evaluate the mitigation potential

Abstract

We build a system dynamics model to evaluate the potential dynamics of consumer adoption of "Smart Energy Behaviour". Within this term we include different levels of: i) shift in electricity consumption towards less costly-less polluting and congestioning hours; ii) the reduction of mainly wasteful electricity consumption, that maintains similar levels of comfort; iii) the enrolment in demand response programs; iv) electricity generation via residential micro-photovoltaic (PV) systems. These behavioural changes are triggered by the installation of advanced metering systems and a tariff policy that prices electricity according to time-of-use. The context analysed is that of Italy, where the largest diffusion of smart meters has taken place. We perform a set of 2500 simulations of our model with stochastic parameters to take into account the uncertainty in their estimation, to find that on average consumer involvement may induce on aggregate a shift in residential electricity consumption of 13.0% by 2020 and of 29.6% by 2030; and reduction in residential electricity consumption (just by reducing wasteful consumption) of 2.5% by 2020 and 9.2% by 2030. These consumption changes may have strong impacts on the system operating costs (in the order of 380 M€/y by 2020, 1203 M€/y by 2030), on the CO_2 emissions (in the order of 1.56 MtonCO_2/y by

2020, 5.01 MtonCO_2/y by 2030), confirming the value of consumer participation.

Keywords: Smart-Grids, Demand Response, Demand Management, System Dynamics, Consumer Choices, Climate Policy.

3.1 Introduction

Nowadays, national power networks are faced with various challenges: i) increasing demand and reliance on electricity implies the necessity to improve their efficiency, security and quality of service; ii) climate change issues bring about the need to manage an increased amount of renewable energy sources; iii) current trends in society suggest to aim at a greater interactivity with consumers, that are becoming used to be more active.

Though, even with these new pressures arising, current electric power systems have remained qualitatively very similar to how they where in the last century; although capacity and efficiency have been increased, the qualitative architecture of the network has not changed significantly, especially from the consumer side.

Recently, there is a lot of interest regarding Smart-Grids, i.e., the idea of introducing I&CT features into the power network, so that it will be able to transmit and manage not only electricity but also information. Indeed, in the US, 4.5 billion$ of the economic stimulus package of the Obama administration were allocated to smart grid related projects (O'Grady, 2009). In the EU, smart grids have been part of the strategic research agenda since, at least, 2007 (SmartGrids, 2007) and "The Commission has acknowledged that, by enabling substantial gains in energy efficiency, ICT-based innovations may provide one of the potentially most cost-eff ective means to help Member States achieve the 2020 targets" (European Commission, 2009).

The analysis of the mitigation potentials of smart-grids is quite complex because it includes various technologies and possibilities under one term and also because its effects will depend on the level of consumer participation. This, in fact, is not a mitigation option that cannot only be centrally planned and implemented, but in order to unravel its whole potential it needs to be combined with end-user engagement.

For these reasons it is important to take into consideration not only costs and technical aspects, but also consumer behavior/responses, in line with the new *Knowledge-Society* trends that are emerging in various disciplines. Smart-grids - differently from Super-grids or other more traditional technologies - open towards a *Knowledge Economy* context where the enhancement of consumer empowerment and knowledge is particularly taken into account.

The broad aim of this work is to highlight and evaluate the potential that a qualitative transformation of the power grid may have. More specifically, in this paper, we analyse how a greater and active involvement of the end-users may contribute to the reduction of the electric sector carbon footprint. The interest in this topic is confirmed by the EU Commission that welcomes a paradigm shift in the structure of the electric distribution grid so that it will become: "user and customer centric, service oriented and [...] able to support the migration towards a low-carbon economy and society" (European Commission, 2009).

Indeed, in order to take advantage of the full potential of the electric grid modernization it is necessary to aim at a qualitative evolution of the network able to grasp and deal with the social and cultural trends that are emerging in current society. An example of these trends is that of Smart-Cities, that is a new emerging concept of cities where new models of active involvement of citizens are being experimented within the integrated management of many sectors (such as mobility, electricity generation, logistics, security, etc.)

Modern technology developments allow a greater interaction with clients and current global environmental problems need the active participation of citizens in order to be tackled effectively (Chakravarty et al., 2009). These circumstances, together with current trends in other sectors that aim at empowering citizens, are the main motivational drivers of our analysis. Smart-Grids, in particular, and the innovation of the power network could represent the opportunity for the power system to align itself with the new services of the new knowledge-based society.

We are therefore interested in analysing the potentials embedded in consumer engagement in the context of the power system. This includes end-user production, but also demand management, i.e. the effects, for example, of information diffusion and of the management of differentiated pricing policies. The idea is to outline an analysis that includes the different technological options and possible consumer behavior/responses enabled by the implementation of smart-grid technologies and services.

This paper aims at identifying possible consumer adoption dynamics of smart-grid enabled behavior and to evaluate the resulting impacts in terms of demand reduction, system cost reduction, opportunities for mitigation. To do so, we (*i*) identify the most important phenomena and motivations that influence the uptake of the actions enabled by smart grid technologies; (*ii*) highlight the complex feedback relations among them; (*iii*) build a system dynamics model to simulate these interactions and identify possible consumer adoption dynamics; (*iv*) analyze the temporal evolution of the stock of consumers that exploits the smart grid opportunities; and (*v*) translate these behaviours in impacts.

In this paper, the phenomena are analysed both qualitatively and quantitatively with the aim of, eventually, producing results that can be used

to include smart grids within the technological mitigation options of the WITCH model or other integrated assessment models (IAMs). These models have up to now excluded Smart-Grids because the calibration for this technology is not straightforward as there are many aspects to take into account, some of which are at a scale that is not representable in such models. Though, we consider important to include, even if in an approximated manner, this option into the IAM framework, as these models are often used to inform and influence policy decisions. In this direction, our aim is to develop consumer adoption dynamics that can allow to consider, even if in an approximated way and with a certain degree of uncertainty, this important option in economic-climate models. This is a first prototype and its relevance is mainly methodological. It builds on the currently available data, that are scarce as implementations of consumer empowerment are at their primitive stages. Nevertheless, the model is a flexible platform that can be easily modified and calibrated once more specific data becomes available. Note that this data should be of quite easy access for policy makers.
The paper looks at a part of the literature that is quite scarce; i.e., the economic evaluation of consumer engagement potentials for mitigation objectives and the economic evaluation of the new emerging role of the consumer/“prosumer” as an active agent within the power system. Instead, most of the literature on Smart-Grids takes more of a technological and engineering perspective.

The rest of the chapter is structured as follows, Section 3.2 briefly discusses the new options introduced by Smart-Grids; Section 3.3 describes the methodology adopted; Section 3.4 reports the model specifications for the application to the case of Italy. Sections 3.5 and 3.6 discus and summarize the results.

3.2 Smart-Grids and consumers

’Smart-Grid’ is an umbrella term that includes many different technological options that enable the transformation of the power grid into a sensitive network.
In particular, for our analysis, we are interested in studying the effects of the introduction of smart metering systems. The technological options enabled by smart meters, at the household level, are:

- the bi-directional flow of electricity;
- the two-way flow of real-time information.

These technological features allow:

- end-points to introduce electricity into the system;
- utilities to gain more information on real-time loads and load patterns;
- consumers to have access to better information on their consumption;
- to implement time-related tariffs.

The latter four consequences of smart meter implementation, generate the following economic implications, respectively:

- the empowerment of the consumer, that can become a prosumer;
- an increased control on the power system, which in turn has societal benefits, such as a more efficient management, a decrease in the number of power outages and the reduction of extra capacity needed to sustain the system;
- avoid some of the informational problems at the base of the “energy paradox”;
- the establishment of the correct price signals that allow product differentiation of electricity consumption, that is non-homogeneous over time and season, in terms of production costs and impacts.

Indeed, up to now the consumer has always had a passive role in the system with very little choice. Because the demand for electricity, and energy in general, is not a demand *per se*, but a demand for the services that electricity can provide (lighting, refrigeration, food preparation, washing, entertainment, heating, cooling, etc.), end users had - or still have - no access to data concerning the costs of the energy services used. In addition, payment is often distant from consumption and aggregated, making it even more difficult for the consumer to associate a price to the service. A good description of the consumer’s electricity-consumption decisional-environment is given by Kempton and Montgomery, 1982 and Kempton and Layne, 1994:

> consider groceries in a hypothetical store totally without price markings, billed via a monthly statement... How could grocery shoppers economise under such a billing regime? (Kempton and Layne, 1994).
>
> In such a store, the shopper would have to estimate item price by weight or packaging, by experimenting with different purchasing patterns or by using consumer bulletins based on average purchases (Kempton and Montgomery, 1982).

Indeed, Darby, 2006 shows the importance of feedback in making energy use more visible and quantifiable and, consequently, for triggering energy-use behavioural changes. Feedback is a 'self-teaching tool' and it also improves the effectiveness of other information or advise on energy-use (Darby, 2006).

The invisibility of energy resources makes consumers blind not only to their level of consumption, but also to the level of consumption of others and the "appropriate" consumption level, that may serve as reference (Ehrhardt-Martinez, Donnelly and Laitner, 2010). Thus, it also hinders the effect that social norms may have on consumption patterns (Ehrhardt-Martinez, Donnelly and Laitner, 2010).

Therefore, this new amount and timing of information could have significant effects; even in the worst case scenario - with no behavioural changes that favour the environment or society - smart metering will at least make the consumer (potentially) more conscious of its choices.

The increased monitoring potentials of Smart-Grids both at the system and consumer level will enable to identify and remove 'previously hidden sources of waste' (Ehrhardt-Martinez, Donnelly and Laitner, 2010). Indeed, flat tariffs and low information on the impacts of power consumption make consumers use energy 'at random' (Block, Neumann and Weinhardt, 2008). Therefore, the conveying of price signals and ethical awareness will also enable to reach consumption patterns that are closer to those optimal for society.

3.3 Methodology

3.3.1 Modelling approach

The complexity of the decisional processes related to the end-user when deciding his energy management strategies, now enriched with new additional options, poses some methodological issues in the selection of the modelling platform to use for the analysis. For Super-Grids it was appropriate to set up an optimization model based on the assumption of perfect rationality of the agents, as the investments in Super-Grids will involve policy-makers and industries, that can be approximated as rational agents. The decisional process of citizens, with regards to daily consumption decisions, is a complex process, as human rationality is different from that of profit-maximising agents, and it is characterised by utility functions that include many more dimensions over and above economic gains (e.g., ethical principals, social acceptability, imitation, information retrival costs and effort, etc.). Moreover, the concept of perfect information is far away from reality due to information availability, time-constraints and cognitive limitations (Simon, 1955). Indeed, nonlinear models of social system behaviour are arising in the literature (Vogstad, 2004; Sterman, 2000).

We have decided to study the dynamics of consumer adoption of 'smart energy behaviour'[1] building a model based on System Dynamics as we believe this is an appropriate method to analyse from a systemic point of view the behaviour of complex systems. System Dynamics is a modelling framework first introduced by Jay Forrester in the mid-fifties and published with the book 'Industrial Dynamics' (Forrester, 1961) that is now applied to various scientific domains (Forrester, 1991).

These kinds of models are developed to study systems characterized by interdependences, mutual interactions, informational feedbacks, and circular causality, mainly for the purpose of policy analysis and design (System Dynamics Society). The concept at the core of this approach is that of feedbacks[2] - mainly informational -, loops and endogenous change to study how the system structure and its rules determine its behaviour. Indeed, exogenous disturbances are the triggers of system behaviour, but the main causes are contained within the structure of the system itself (System Dynamics Society).

The first step is that of building a conceptual model based on causal-loop diagrams, that is very close to the Systems Thinking discipline, that builds qualitative models in which the relation and the complex interconnections between the parts of the system are made explicit (Meadows, 2008).

The second step is to build a simulation model translating mathematically these relations; this is usually done by means of coupled non-linear first-order differential (or difference) equations.
Given the large number of variables involved and the complexity of their interdependencies, there is the need of a further step, that is the building a computer-based numerical platform to evaluate quantitatively and graphically the resulting dynamics (System Dynamics Society, Mella 2007).
The main aim is that of having a simulation tool able to test different policies and evaluate how things change over time[3] and how to influence the dynamic paths.
In this work, we have also added a Section in which the stability of the equilibrium of the system is studied theoretically/analytically. Moreover, because the phenomena under evaluation are at their primitive stages and because of the consequent absence of good data, we have built a model with stochastic parameters.

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[1] The concept of 'smart energy behaviour' in the specific context of our modelling framework will be defined more specifically in Section 3.3.2

[2] <<A feedback structure is a setting where existing conditions lead to decisions that cause changes in the surrounding conditions that influence later decisions. That is the setting in which all our actions take place>> (Forrester, 1991).

[3] Please note that time by itself is not seen as a cause (System Dynamics Society); although the behaviour of the system changes over time it is not modelled as a function of time itself, but it is dependent on conditions within the system that change over time.

The basic structure of our model builds on Bass, 1969 and on the models used in epidemiology. We take inspiration from the Susceptible-Infectious (SI) Models used in epidemiology to describe the evolution of epidemics (Murray, 2002). In these models, the population is divided into two classes: those "susceptible" to the disease and those that are "infectious". The interactions between these types of individuals determine the spread of the infectious disease and the pattern of its diffusion. In our model, the "disease" is what we have called 'smart energy behaviour'.
The Bass diffusion model, developed by Frank Bass in the late 1960s (Bass, 1969), is a system dynamics model that studies the diffusion of products focusing on the interactions between individuals divided into two categories: "users" and "potential users". In addition to the logistic innovation diffusion model, Bass takes into account also external information sources - such as advertising - that are able to generate "early adopters" (Sterman, 2000).

Except for the case of home electricity generation, the adoption of smart energy behaviour differs from the classical innovation diffusion process by three main characteristics:

1. the cost for the adoption is not monetary, but in personal effort terms;
2. the adopted behaviour does not make life easier, but if anything, more difficult;
3. the gain is not an increase in comfort, but is an economic or social reward.

Differently from biological epidemics, in the case of smart energy behavior:

- the "infection/contagion" is voluntary both for the infected and for the infectant;
- the diffusion pattern is not strictly related to territorial closeness, as communication can travel long distances; although, social mechanisms still maintain a linkage with territorial distribution, think for example at the imitation effect that seeing solar panels installed on neighboring houses may have on households.

In the specific context of Smart-Grids and consumers, we are aware of two agent based simulation models of technology adoption by Hamilton, Nuttall and Roques, 2009 and Zhang and Nuttall, 2007. In the first paper, the authors build a spatial model to analyse the diffusion of the switch from grid supply to autonomous production of electricity through solar power or micro combined heat and power within a virtual city. The main driving force for change is the perceived relative attractiveness between old and new technologies (Hamilton, Nuttall and Roques, 2009), but there is also a “fashion” effect. In the second paper, the authors apply another spacial agent-based model to study the interactions between residential customers and electricity suppliers when the former decide whether to acquire a smart meter or not and from which supplier. The authors model two interaction effects: price information - from the suppliers - and word of mouth - among the residential customers. Although both of these papers are of high interest and well developed , our aim is to try to focus more deeply on the motivations underlying the change and to analyse a greater variety of consumer behaviour enabled by the implementation of Smart-Grids, with the similar aim (Nuttall et al., 2009) to study the dynamics of the system before it reaches the equilibrium and to highlight to policy-makers the importance of the modeling choices when dealing with the evaluation of complex systems.

3.3.2 Model Description

Our model has been designed specifically to study the behaviour of small end-users of the electric power sector, that in our opinion is under-studied in the economic literature, but corresponds to the novelty of the effects induced by the introduction of smart-grids in the electricity system. Indeed, we focus on the residential sector and the unit of our analysis is the household at the level at which contracts are decided, bills are paid and electric meters are installed.

Having considered households as the main unit of our analysis, we have grounded the model of the variety of consumer behaviour on six (basic) options that can emerge once smart meters and tariff policies are in place. Indeed, our model comprises:

- shift of consumption to less expensive (less polluting - congesting) hours,
- reduction of consumption while maintaining similar comfort levels,
- behaviour and home automation,
- enrolment in demand response programs,
- energy efficiency improvements,
- electricity autonomous generation;

more in general, we will refer to these activities as ’smart energy behaviours’. The main characteristics of these actions in terms of benefits, costs and effort are described in Table 3.1.

	Upfront Costs	Economic Savings	Eco-friendly 'label'	Effort
Shift	no	immediate	yes, private	yes
Reduction	no	immediate	yes, private	yes
Automation	small to large	yes	yes, private	no
Energy Efficiency	medium Δ costs	yes	yes	no
Demand Response	no	yes	yes, private	initial[4]
Production	large	in the future	private+public	initial

Table 3.1: Costs and benefits of consumer behavioural options

This table is an example of the multi-level facets of the possible actions analysed in this paper. Indeed, each consumer may be drawn by some of them and not by others, depending on its preferences.

More specifically, the variety of consumer behaviour has been modelled through ten different 'styles of behaviour' that each consumer may adopt. These are depicted in the squared boxes of Figure 3.1 and are characterized by different levels of the five previously described activities. The styles/boxes are organized under three general categories/branches of the model.

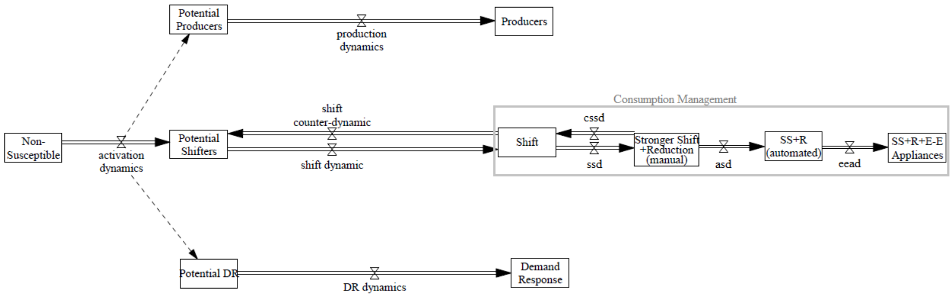

Figure 3.1: Stock and Flow diagram

Indeed, in our model the empowerment of the end users and the increased variety of possible behaviours has been analysed with the function:

Smart Behaviour = (Production, Consumption Management, Contract Management).

Production. The introduction of two-way smart meters, enables the end-user to become not only a sink node but also a source node in the grid. This will stimulate a change towards a new power grid architecture that moves away from the previous paradigm of centralised large-scale generation. The feature of production is certainly a very important novelty in the behaviour of the consumer, not available in the old architecture of the power grid. This means that every household that has capital and "space" availability - here intended as a rooftop or some land that can be equipped with solar panels - may become a producer of electricity. Policies to incentive end-user grid-injection are already in place in various countries.

Consumption Management. The introduction and diffusion of smart-meters and the related price policies allows an empowered consumption management by the end-users. The consumer is now able to better associate a price to the energy services that he consumes, and is therefore able to better optimise his consumption patterns. In addition, electric power system operators are able to give more accurate price signals that induce a finer electricity-good differentiation. Indeed, electricity consumption in different hours or different days of the year is associated with different production costs and environmental and societal impacts. In this model, we test the simplest price policy: that is the application of a differentiated tariff to the consumer, but other more complex and advanced options are available. The consumer response to these new information and tariffs is varied. The first easier option is to shift some of its consumption, and secondly to reduce its consumption, most likely, maintaining the comfort level by means of various options discussed in Section 3.2 and 3.3.3.

Contract Management. The implementation of advanced metering systems allows new and more advanced user-provider relationships. With the liberalization of the electricity market, the consumer is able to select its electricity provider and choose among different consumption plans. The increased information and price signals on the costs associated to the energy services used, strengthen consumer capability of optimizing consumption patterns. The additional technological opportunities introduced by smart meters allow the proposal/enrolment in innovative schemes, such as, for example, rewarded curtailment contacts (Demand Response), real-time pricing or other tariff structures.

All these three new lines of action increase the variety of services that can be provided by electricity-providers and open to the possibility of new players/businesses entering the market. Indeed, the evolution of the power grid towards a 'smart network' might induce a greater level of competition on the electricity market, that has proved in recent years - at least in Europe - difficult to flourish (European Commission, 2011a). Indeed, Hartway, Price and Woo, 1999 considers these options related to smart-metering and time-differentiated tariffs to be:

> value-added products [for utilities] to profitably retain and attract load [in a deregulated market].

The aim of this work is to study the dynamics of consumer adoption of these ten different stylized behaviours to be able to grasp the effects of the more general smart-energy-behaviour dynamics induced by smart-grids. The evolution of consumer behaviour is influenced by several motivations and context variables. Figure 3.2 shows which variables are included in our model and how they are interconnected. A more in detail explanation of the single variables will be included in the next Section (Section 3.3.3).

Different structures of the model could be possible; after several trials we have chosen this one as we consider these ten styles to well represent the situation, keeping in mind the parsimony principle in building a model and the need to capture into the model the complexity of the phenomena.

3.3.3 Model Specification

The ten behavioural styles (or “boxes”) represent the stock variables of the model and the double arrows represent the flowsof households that move from one style to another.

As it is possible to see in Figure 1, the model starts with the ’Non-susceptible’ box, that contains, at a certain time *t*, all the households that, at time *t*, are not able to adopt ’smart energy behaviours’ - as defined in our framework - because they do not have an activated smart meter or they are not aware of the changes occurred to their electricity meter and billing system that enable them to consider a change of habits. This corresponds to the stadium zero of the model, similar to the situation where the power grid is not “smart”.

The installation and activation of a smart metering system together with the introduction of ’smart energy behaviour’ incentive-policies and the knowledge of this, triggers the availability of a variety of options for the end-user. This is due to: *i*) the increased awareness of own consumption and related costs; *ii*) the saving opportunities; *iii*) the new selling option. Together with these two triggering effects, we assume the existence of information campaigns and Demand-Side-Management (DSM) policies aimed at increasing consumer awareness of the economic opportunities and of the environmental protection possibilities, as well as at triggering a willingness to be “greener”. As specified in the previous Section (Section 3.3.2), we have chosen to model these “styles” on three different and interconnected levels - production, consumption management and contract - that are represented in three different branches of Figure 3.1.

More in detail, the central branch is a sequence of activities:

- Shift;
- Stronger Shift + Reduction, done manually;
- Stronger Shift + Reduction, automatized;
- automatized Stronger Shift + Reduction + Energy Efficient Appliances;

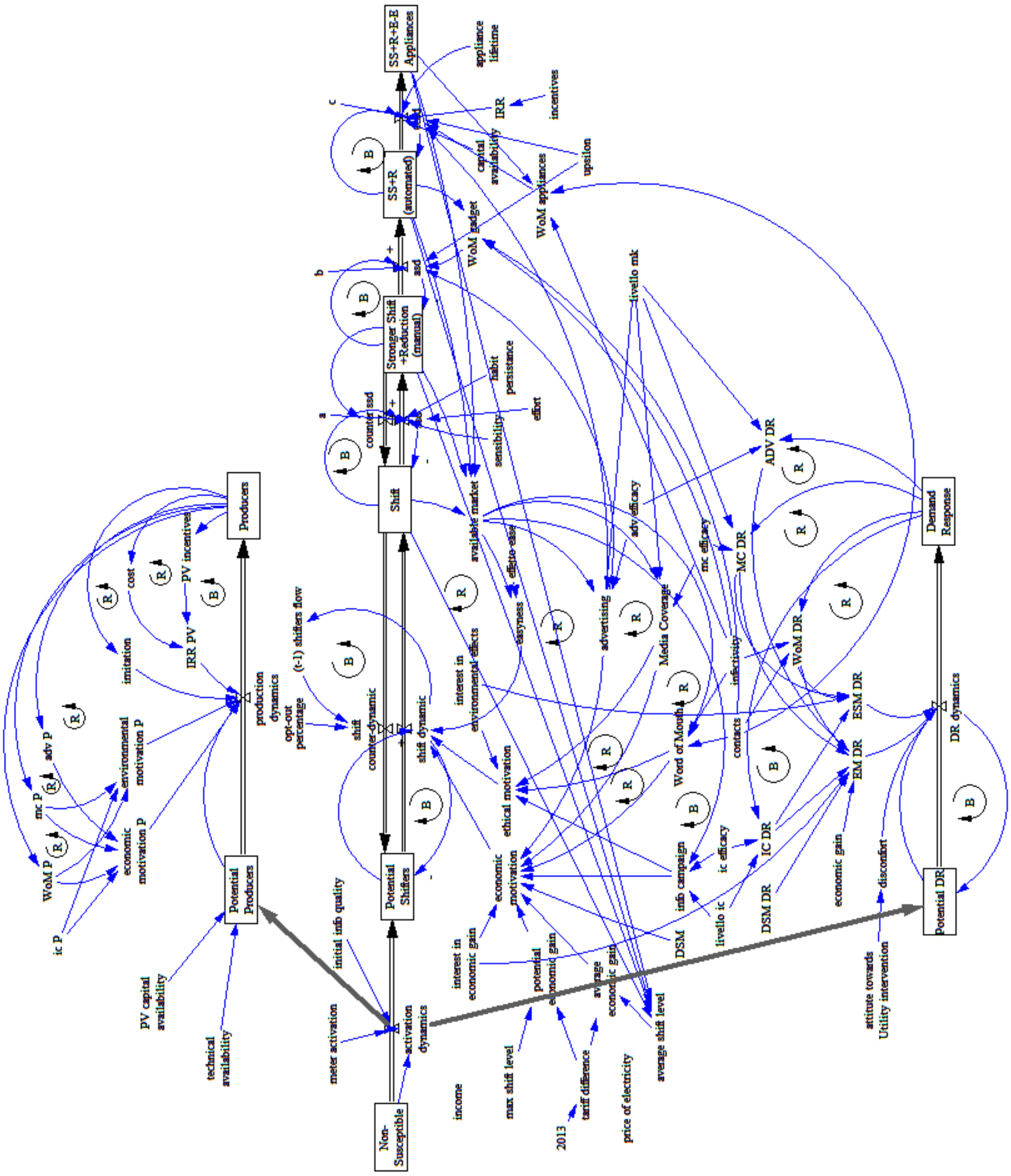

Figure 3.2: Stock and Flow diagram

that involve the management of household consumption and that we have assumed can be ordered.

As depicted in Figure 3.1, the households belonging to the 'Non-susceptible' box can change box and become susceptible of a behavioural change once their electric meter is smart and activated, and they become aware of the change. The latter two activities determine the 'activation dynamic' flow, depicted in Figure 3.1 between box 'Non Susceptible' and box 'Potential Shifters'.
Once certain households become susceptible to the “smart energy behaviour epidemic”, they move into the 'Potential Shifters' box. Here are all the households that would be able to undertake a behavioural change but do not do so. Over time and under specific “influences” considered in the model (See Figure 3.2), some households decide to change their behaviour and they may adopt a first easy type of action, that is the shift of some electricity consumption from more expensive (polluting and congesting) hours to some cheaper (less polluting and congesting) hours. Doing so, they move from the 'Potential Shifters' box to the 'Shift' box. We have also modelled the possibility for households to change their mind once they have tried the “new” behaviour if they perceive that the effort is not worth the benefit, see the left-pointing double arrow that exits the 'Shift' box entering the 'Potential Shifters' box[5].
The people in this box are assumed to undertake only a minor level of shifting; once they get more accustomed to it and/or they gain a stronger motivation for doing so, they may move to the 'manual Stronger Shift+Reduction' box, that collects households that undertake a stronger level of shift in energy consumption and they also reduce some of their electricity usage, mainly wasteful, maintaining their comfort level essentially unchanged. We have also model the counter-flux for households that decide to return to a lower effort condition. The consumption shift and reduction actions - of the latter box - are assumed to be done manually; some households may also decide to buy (or might be given) some device and/or service that may help the acquisition of price/cost information or automatize some shifting/electricity saving activities improving the shifting/saving efficacy of the household. Doing so, they move from the 'manual Stronger Shift+ Reduction' box to the 'automated Stronger Shift + Reduction' box.
Finally, the household may decide to purchase energy-efficient appliances reducing even the non directly controllable part of their power load.

Households that are susceptible to smart energy behaviour, i.e. those that exit the 'Non-susceptible' box can also decide whether to enrol in demand

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[5] We have assumed that the people that return to the previous box are able to move back into the more proactive box in the future. This is a simplifying assumption, that captures the fact that a change in outside conditions may induce households that opted-out in the past to restart the “smart” behaviour

response programs and - for those that have capital and “space” availability - to start producing electricity themselves. These actions are not mutually exclusive, but instead, in our model each household has to decide “its position” with respect to the three different types of actions.

Figure 3.2 depicts the motivations that - in our model - may induce households to move between the ten styles. In particular, starting from the central branch, we have assumed that the main motivations that may induce the choice to start to actively manage the household consumption patterns are two: the possibility of encountering an economic saving on the electricity bill (namely “economic motivation”) and of protecting the environment (“ethic motivation”); we have included the social motivation for the de-congestion of the power grid in the environmental-social motivation. Imitation for reasons not related to economic savings or environmental and social issues - like fad and fashion - has not been included for this set of actions, as they are “invisible” to people outside of the household, but it could be included if empirical data were to to show its relevance. Indeed, certain DSM policies could trigger a competition among households on who is “greener”, if they allow environmental friendly behaviour to be visible and quantified (Nye and Burgess, 2009; Allcott, 2011).

The strength of the economic motivation depends essentially on: (*i*) the level of interest in an economic saving, that is in turn related to income, (*ii*) the level of potential and average saving induced by the pricing policy and the price of electricity, and (*iii*) the effectiveness of different channels of information in delivering motivation for a behavioural change. The latter, together with the level of interest in environmental issues, determines the strength of the ethical motivation.

The information channels that we have included in our study are:

- *Information Campaigns.* We include here all public awareness campaigns on electricity consumption and their effects on the electricity system costs and/or environmental impacts. The messages conveyed (together or individually) are that it is possible to save money,the environment and induce societal benefits.

- *Demand Side Management.* We include here all the options that the utility has to inform the customer on its consumption patterns and the available options to change them in order to incur an economic saving and/or a positive effect on the environment and society.

- *Media Coverage.* We assume that once the behavioural changes start to spread (available/market size), the Media is going to report and comment on this phenomenon, allowing for a greater number of people to become aware of the options and consider the possibility to change, likewise, their consumption behaviour.

- *Advertising.* We have assumed that once the market size - of people that are interested in changing their consumption patterns - becomes interesting, more companies/businesses will enter the market offering products and services that can increase the saving potentials, and that these will start to advertise their products/services allowing a greater number of people to become aware of the saving possibilities that a change in consumption is able to induce.
- *Word of Mouth.* We have also included the "word of mouth" channel that is a very powerful persuasion mechanism. The idea is that the households that have tried the new type of behaviour and are satisfied with it, will spread the word about the benefits of this change. The people that are in contact with the latter households receive this additional and personal information that may "infect" them, generating a positive feedback.

All of the above effects are made more effective/enhanced as the the easiness to undertake the various actions increases. This easiness is in turn affected by the availability of additional products and services that arise once the market size of potential customers gets large enough.
In our setting, the first two[6] information channels are modelled as exogenous as they depend on policy decisions, the last three channels instead arise within the model. These feedback loops are singled out from Figure 3.2 in the graphs reported in Appendix A.

Once the household has decided to undertake, at least, the first behavioural change, it can decide to do even more. On average, as habit persistence decreases and sensibility increases more people will move to the more effort involving boxes. Moreover, the purchase or free receival of gadgets - that can help *i*) the visualization of consumption patterns and costs, *ii*) improve the (remote) controllability of appliances, or *iii*) allow the use of services that provide tailored information and recommendation - can improve the effectiveness of the household decision to shift and reduce electricity consumption. As these nodes get more relevant, they are also more able to attract new households due to a reinforcing loop.

For what concerns the demand response branch, we here consider the enrolment in contracts whereby the utility is allowed to intervene on the household consumption, with no or little notice, for a certain number of critical times during the year. The service curtailments and the availability provided are rewarded in monetary terms. We have assumed that the motivations of taking part to these programs are similar to those for deciding to shift

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[6] Although the Information Campaigns start as exogenous stimuli, they stop once a certain level of "infected" population is reached.

and reduce consumption, though an increased discomfort may arise in correspondence of the curtailment; this, in addition to the fact that certain households would not approve of the utility directly being able to control their meter, has led us to model this flow at a lower level than the previously described ones. There again, some household may instead prefer to be curtailed for a few hours a year and gain the same amount of money with no effort at all.

Potentially, consumers should be divided into classes that try to model the differences in consumer sensitivity to different stimuli. These classes could be based on ideological categories (related, for example, to the weight given to environmental or social issues when taking consumption decisions), interest in technology, age and propensity to change, income, education, or other variables that emerge from the literature; and should be characterised by different reaction function calibration. Though, due to the lack of data, in the first example application of the model described in Section 3.3.4, we only account for welfare differences, so as to not include additional assumptions that would be difficult to estimate and justify.

3.3.4 Model equations

The previous Section (Section 3.3.3) has described qualitatively the stocks, the flows, the "motivational" variables and all the interconnections of our model (Figure 3.2). In order to be able to build a simulation tool we have translated there relations into equations.

The main structure of the model is a system of ten non-linear first-order differential equations with stochastic parameters, that depict the integrated evolution of the different "styles" of consumer behaviour. These are:

$$
\begin{cases}
\dfrac{d(NS_t)}{dt} = -\,ad(NS_t,t) & (3.1)\\
\dfrac{d(PS_t)}{dt} = ad(NS_t,t) - sd(PS_t,S_t,SSRm_t,SSRa_t,EA_t,t)+ & (3.2)\\
\qquad + csd(PS_t,S_t,SSRm_t,SSRa_t,EA_t,t) & \\
\dfrac{d(S_t)}{dt} = sd(PS_t,S_t,SSRm_t,SSRa_t,EA_t,t) + cssd(S_t,t)+ & (3.3)\\
\qquad - csd(PS_t,S_t,SSRm_t,SSRa_t,EA_t,t) - ssd(S_t,t) & \\
\dfrac{d(SRRm_t)}{dt} = ssd(S_t,t) - cssd(S_t,t) - asd(SSRm_t,t) & (3.4)\\
\dfrac{d(SRRa_t)}{dt} = asd(SSRm_t,t) - eead(SSRa_t,t) & (3.5)\\
\dfrac{d(EA_t)}{dt} = eead(SSRa_t,t) & (3.6)\\
\dfrac{d(PP_t)}{dt} = ad(NS_t) - pd(NS_t,PP_t,t) & (3.7)\\
\dfrac{d(P_t)}{dt} = pd(NS_t,PP_t,t) & (3.8)\\
\dfrac{d(PDR_t)}{dt} = ad(NS_t) - drd(PDR_t,DR_t) & (3.9)\\
\dfrac{d(DR_t)}{dt} = drd(PDR_t,DR_t) & (3.10)
\end{cases}
$$

In the previous system of equations, the state variables are indicated as:

- NS_t is the number of households that, at time t, are non able to adopt a 'smart energy behaviour';
- PS_t is the number of households that, at time t, are potentially able to adopt the shift consumption behaviour;
- S_t is the number of households that, at time t, actually adopt the shift consumption behaviour;
- $SSRm_t$ is the number of households that, at time t, actually adopt the manual stronger shift and reduction of consumption behaviour;
- $SSRa_t$ is the number of households that, at time t, actually adopt the automated stronger shift and reduction of consumption behaviour;
- $SSRa_t$ is the number of households that, at time t, actually adopt the energy efficient appliances and automated stronger shift and reduction of consumption behaviour;

- PP_t is the number of households that, at time t, are potentially able to adopt the electricity production behaviour;
- P_t is the number of households that, at time t, actually adopt the electricity production behaviour;
- PDR_t is the number of households that, at time t, are potentially able to adopt the demand responce behaviour;
- DR_t is the number of households that, at time t, actually adopt the demand responce behaviour.

We refer to the total population as $TP_t = TP_o$ that is constant.
The flows between stocks are indicated as:

- *ad* - activation dynamics - Flow of new people that have the possibility to change their behaviour (knowledge+technology);
- *sd* - shift dynamics - Flow of new people that decide to change their behaviour by shifting part of their electricity consumption to the lower rate/lower impact segment;
- *csd* - counter shift dynamics - Flow of new people that decide to stop shifting;
- *ssd* - (manual) stronger shift dynamics - Flow of new people that decide to increase their behaviour by manually shifting a larger part of their electricity consumption and reducing wasteful consumption;
- *cssd* - counter (manual) stronger shift dynamics - Flow of new people that decide to stop the manual stronger shift and consumption reduction behaviour;
- *asd* - automated stronger shift dynamics - Flow of new people that decide to increase the effectiveness of their consumption shift/reduction behaviour by using some products or services to automate some actions;
- *eead* - energy efficient appliances dynamics - Flow of new people that decide to buy energy efficient appliances in addition to the previous actions.
- *pd* - production dynamics - Flow of new people that decide to change their behaviour by starting to produce electricity;
- *drd* - demand response dynamics - Flow of new people that decide to change their behaviour by enrolling in demand response programs.

A detailed description of a particular implementation of this model, in the case of Italy, is reported in Section 3.4.1.

3.4 Case Study

We here apply the general model described in the previous Sections to the particular case of Italy. Italy is an interesting laboratory because there has been the largest deployment of smart-meters that covers the entire population. Although the electric network has not completely been innovated to become a smart-grid, the deployment of smart-meters is the most relevant step in the empowerment of the end-user.

3.4.1 Model explicitation

For this particular implementation, the fluxes have been detailed with the following auxiliary variables, due to some specific context-dependent driving forces and due to the available data in the literature and in national databases. This particular implementation is meant to be just a first attempt to study the evolution of a very interesting and important phenomenon. We do not claim this model to be exhaustive nor conclusive, but rather a compromise between the interest in a quantitative analysis and the data availability at this very primitive stage.

In order to account for the differences that economic welfare may have on certain parameters, we have stratified the population according to their level of satisfaction of the economic condition of the household. This stratification will be mostly useful when estimating the parameters related to the interest in environmental problems and in the economic saving potentials of behavioural changes. Values have been elaborated from the micro-data of ISTAT, 2011.

The *ad* flux of Equations (3.1) and (3.2) has been detailed as follows:

$$\begin{aligned} ad(NS_t, t) &= ma(t) \cdot NS_t \cdot qi \ , \\ ma(t) &= \min(0.33 \cdot t, 1) \ , \end{aligned}$$

with ma - meter activation - being the percentage of smart meters that are activated by time t, and qi - initial-information quality - being the percentage of people that take notice of the information provided, i.e., that know they have new options, equal to 0.78. These parameters have been estimated from the activation rate of 2010 (AEEG, 2011b) and on the basis of the percentage of consumers that state to be satisfied of the comprehensibility of the display on the smart meter, taken as a lower bound for the households aware of the change and able to access the additional information (ISTAT, 2011).

The numeric value of the *sd* flow represents the number of households that move to the 'shift' stock in an infinitesimal unit of time. The households that change box/behaviour are those that are sensitive to at least one of the motivational drivers (economic and/or ethic). This is, formally, the union of the households that are sensitive to economic and/or environmental and social issues. To calculate this quantity it would be necessary to know the joint-distribution of these two motivational drivers among the households. Unfortunately, this value is not available in the literature. Values for the single effects are instead available, but for these to be of use - and avoid double-counting - it is necessary to also know the size of the intersection, i.e., the number of households that are sensitive to both stimuli. The size of the intersection can be calculated from the single values only if one of the following three assumptions holds:

- *disjunction* (i.e., households are sensitive to one or the other stimulus, but never to both). In this case, the measure of the union is the sum of the two individual values;
- *inclusion* (i.e., being sensitive to one stimulus (the smallest) implies being sensitive also to the other). In this case, the the measure of the union is the maximum between the two single values;
- *independence* (i.e., the proportion of households that are sensitive to the economic motivation is identical among the households that are interested or not interested in the environmental motivation, and viceversa). In this case, the measure of the union is the sum of the two values minus their product).

The first two assumptions are quite extreme and certainly not realistic, the third is an intermediate case and therefore might be closer to the real situation. For this reason, we introduce in our model the third assumption, and in order partially overcome this approximation, we have: (i) stratified the population for economic welfare and assumed independence just within the stratum, and (ii) performed a multivariate sensitivity analysis of these (and other) values.

The *sd* flux depends on all the active consumption management stocks, therefore, to simplify notation we indicate as CM_t the set of the variables S_t, $SSRm_t$, $SSRa_t$, and EA_t. Indeed, the *sd* flux of Equations (3.2) and (3.3) has been detailed as follows:

$$\begin{aligned} sd(PS_t, CM_t, t) = & [em(CM_t, t) + esm(CM_t, t) - em(CM_t, t) \cdot esm(CM_t, t)] \\ & \cdot (1 + ea(CM_t)) \cdot PS_t \ , \end{aligned}$$

where *em* - economic motivation - is the percentage flow of people that decide to shift because of economic reasons (without the effect of ease) and *esm* - environmental social motivation - is the percentage flow of people that decide to shift because of environmental/social reasons (without the effect of ease).

The auxiliary variable ea - ease - represents a reinforcing effect that “ease in shifting” has on the decision to shift and is defined as:

$$ea(CM_t) \quad = \tfrac{1}{3} \cdot mk(CM_t) \ ,$$

where mk - available market - represents the percentage of people that have already changed behaviour by starting to actively manage their electricity consumption ($(S_t{+}SSRm_t{+}SSRa_t{+}EA_t)/TP_o$) and that therefore constitute potential customers for firms interested in producing related goods and services.

The economic and ethical (environmental/social) motivation percentage flows are constituted by the percentage of households, that in the unit of time, change their behaviour due to some information, channeled through one of informational vectors of model. Again, to avoid double counting households that are sensitive to more than one informational channel, we have assumed the - less extreme - hypothesis of independence. The percentage flows em and esm are, consequently, defined as:

$$em(CM_t, t) = 1 - (1 - ic_e)(1 - dsm_e)(1 - mc_e)(1 - adv_e)(1 - wom_e) \ ,$$
$$esm(CM_t, t) = 1 - (1 - ic_{es})(1 - mc_{es})(1 - wom_{es}) \ ,$$

where ic_e (information campaigns effect), dsm_e (demand side management effect), mc_e (media coverage effect), adv_e (advertising effect), and wom_e (word of mouth effect), are the percentage of people that change behaviour (shift) because of info-campaigns / demand-side-management / media-coverage / adversing / word-of-mouth on the economic benefits of the new behavioural options induced by smart-metering. Similarly, ic_{es}, mc_{es}, and wom_{es} are defined for the environmental and social benefits. More specifically, they are defined as:

$$
\begin{aligned}
ic_e(CM_t,t) &= \begin{cases} \eta_{ic} \cdot ies \cdot \sqrt{\frac{pg(t)}{pg_o}} & \text{for } mk_t(CM_t) < 0.5 \\ 0 & \text{for } mk_t(CM_t) \geq 0.5 \end{cases} , \\
ic_{es}(CM_t) &= \begin{cases} \eta_{ic} \cdot iee & \text{for } mk_t(CM_t) < 0.5 \\ 0 & \text{for } mk_t(CM_t) \geq 0.5 \end{cases} , \\
dsm_e(t) &= \eta_{dsm} \cdot ies \cdot \sqrt{\frac{pg(t)}{pg_o}} , \\
mc_e(CM_t,t) &= \eta_{mc}(CM_t) \cdot ies \cdot \sqrt{\frac{pg(t)}{pg_o}} , \\
mc_{es}(CM_t,t) &= \eta_{mc}(CM_t) \cdot iee , \\
adv_e(CM_t,t) &= \eta_{adv}(CM_t) \cdot ies \cdot \sqrt{\frac{pg(t)}{pg_o}} , \\
wom_e(CM_t,t) &= \eta_{wom}(CM_t) \cdot ies \cdot \sqrt{\frac{ag(CM_t,t)}{ag_o}} , \\
wom_{es}(CM_t) &= \eta_{wom}(CM_t) \cdot iee .
\end{aligned}
$$

The quantities η_j - effectiveness of the jth information channel - represent the effectiveness of the informational channels on households that are interested in their content. Instead, the variables ies - interest in economic savings - and iee - interest in the environmental effects - represent the percentage of households (for each segment of the population) that are interested in economic savings and the percentage of households that are interested in the environmental effects of their actions (and act consequently), respectively. We have estimated these values analysing the micro data of ISTAT, 2011, calculating the joint distribution of these interests and the welfare condition. More specifically, as a proxy for the share of households interested in the environment we have calculated the distribution of people that declare that environmental problems are among the three worst problems of the country. As a proxy for the share of households interested in economic savings, we have considered the percentage of consumers that have changed their electricity provider or decided not to change for lack of information on the savings or for lack of actual savings, conditioned to knowing of the possibility to do so. For more information on the values used, please refer to the Appendix. For the economic motivation, we have also added a reinforcing/reducing effect related to the potential economic gain - pg - (or average economic gain - ag - in the case of personal communication) associated with the behavioural change, that is related to the price difference in the tariff for the various time segments (td - tariff difference). The values of $pg_\circ$ and $ag_\circ$ are those of the reference situation. More specifically, these quantities are defined as:

$$pg(t) = msl \cdot td(t) \ ,$$
$$ag(CM_t, t) = asl(CM_t) \cdot td(t) \ ,$$

with

$$td(t) = \begin{cases} 0.1 & \text{for } t < 2013 \\ 0.3 & \text{for } t \geq 2013 \end{cases} \ ,$$
$$msl = 0.5 \ ,$$
$$asl(CM_t) = \frac{(\theta_S \cdot S_t + \theta_{SSRm} \cdot SSRm_t + \theta_{SSRa} \cdot SSRa_t + \theta_{EA} \cdot EA_t)}{S_t + SSRm_t + SSRa_t + EA_t} \ .$$

We define the msl - maximum shift level - as the maximum percentage of electricity consumption that can be managed by the residential consumer from Molderink et al., 2009 and Block, Neumann and Weinhardt, 2008. The quantity asl - average shift level - is, instead, the average of the percentage savings that are incurred (and reported) by the households that are actively managing their electricity consumption, where θ_k is the percentage saving for the kth behavioural style.

As described in Section 3.3.3, the information-campaign effect and the demand-side-management effect are exogenous stimuli that trigger the first-adopters; the central values of the relative parameters η_{ic} and η_{dsm}, used in our simulations, are: 0.05 and 0.074. These values are taken from Snyder and Hamilton, 2002, Haug, 2004, Snyder, 2007 and adapted from eMeter, 2010. Note that we estimate these parameters from the literature by assuming that the percentages referring to people can be transferable to the household unit/level.

Moreover, we assume that while demand side management policies can continuously be improved, information campaigns cease once a certain level of population has adopted the targeted behaviour. The central value of this level is assumed to be 50%. The efficiency parameters of the remaining three effects, that are endogenous in the model and arise only once (and proportionally) there are already some adopters of the behaviour, are modelled as follows:

$$\begin{aligned} \eta_{mc}(CM_t) &= \begin{cases} \frac{0.05}{0.3} \cdot mk(MC_t) & \text{for } mk(CM_t) < 0.3 \\ 0.05 & \text{for } mk(CM_t) \geq 0.3 \end{cases} \ , \\ \eta_{adv}(CM_t) &= \begin{cases} \frac{0.016}{0.3} \cdot mk(MC_t) & \text{for } mk(CM_t) < 0.3 \\ 0.016 & \text{for } mk(CM_t) \geq 0.3 \end{cases} \ , \\ \eta_{wom}(CM_t) &= c \cdot i \cdot mk(MC_t) \ , \end{aligned}$$

where c is number of contacts that a household has in the unit of time - i.e., number of households to which a “smart-energy behaving household” talks about its benefits - and i is their relative infectivity, i.e., the percentage of people that are affected by the contact and decide to act consequently. The values for these two parameters ($c = 19$ and $i = 0.02$) and the numerical values in the above equations for η_{mc} and η_{adv} are adapted from the literature (Sultan, Farley and Lehmann, 1990; Yoo et al., 2010; Haug, 2004). In particular, for the media-coverage case the values are taken from the literature on a wide interest topic like health. Assuming that health is of interest to the whole population, we use this literature value as a proxy for the effectiveness of media coverage on interested population. Recall that the percentages of households interested in economic savings and/or in the environmental effects - namely, *iee* and *ies*, are calculated from ISTAT, 2011.

The counter-flow *csd* is defined as the number of people that decide to stop shifting after having tried this behaviour for one year, more specifically:

$$csd_t(CM_{t-1}, t-1) = op \cdot sd_{t-1}(CM_{t-1}, t-1) \ ,$$

with *op* being the opt-out percentage, equal to 0.005 (REF).

Once the household has entered the active consumption management macro-box, by starting with the soft shifting behaviour, it can increase its effort and effectiveness in achieving economic savings and benefits for the environment and society by moving along the other sub-boxes. The fluxes are defined as follows:

$$\begin{aligned}
&ssd_t(S_t, SSRm_t) = \gamma_{ssd} \cdot S_t \ , \\
&cssd_t(S_{t-1}, SSRm_{t-1}) = op \cdot ssd_{t-1}(S_{t-1}, SSRm_{t-1}) \ , \\
&asd_t(SSRm_t, SSRa_t) = \left(\gamma_{asd} + c \cdot i \cdot \frac{SSRa_t}{TP_o}\right) \cdot (1 + \upsilon \cdot \eta_{adv}(CM_t)) \cdot SSRm_t \ , \\
&eead_t(SSRa_t, EA_t) = \left(\gamma_{eead} + c \cdot i \cdot \frac{EA_t}{TP_o}\right) \cdot (1 + \upsilon \cdot \eta_{adv}(CM_t)) \cdot SSRa_t \ .
\end{aligned}$$

We are not able, at present, to estimate the γs from the literature as the phenomenon is at its primitive stages, therefore we choose the following central values 0.2, 0.1 and 0.05, but we choose a probability distribution with a high variance. Note also that here we model advertising as having a strengthening effect on adoption as found in Haug, 2004. Indeed, we multiply η_{adv} by a term υ ($\upsilon = \frac{0.09}{0.016}$) so that this product's saturation level is 0.09.

As described in Section 3.3.3, the demand response dynamic - *drd* - is modelled as having similar motivational channels as the active consumption management case, though the reduced comfort in the curtaillement periods has lead us to reduce its diffusion speed, compared to that of the soft shifting behaviour. Indeed,

$$\begin{aligned}
drd(PDR_t, DR_t) = &[em_{dr}(DR_t) + esm_{dr}(DR_t) - em_{dr}(DR_t) \cdot esm_{dr}(DR_t)] \\
&\cdot dsc \cdot PDR_t \ ,
\end{aligned}$$

$em_{dr}(DR_t) = 1 - (1 - ic_{e,dr})(1 - dsm_{e,dr})(1 - mc_{e,dr})(1 - adv_{e,dr})(1 - wom_{e,dr})$,
$esm_{dr}(DR_t) = 1 - (1 - ic_{es,dr})(1 - mc_{es,dr})(1 - wom_{es,dr})$,

$$\begin{aligned}
ic_{e,dr}(DR_t) &= \begin{cases} \eta_{ic} \cdot ies \cdot \sqrt{\frac{eg(t)}{eg_o}} & \text{for } DR_t < 0.5 \\ 0 & \text{for } DR_t \geq 0.5 \end{cases} , \\
ic_{es,dr} &= \begin{cases} \eta_{ic} \cdot iee & \text{for } DR_t < 0.5 \\ 0 & \text{for } DR_t \geq 0.5 \end{cases} , \\
dsm_{e,dr}(t) &= \eta_{dsm} \cdot ies \cdot \sqrt{\frac{eg(t)}{eg_o}} , \\
mc_{e,dr}(DR_t) &= \eta_{mc,dr}(DR_t) \cdot ies \cdot \sqrt{\frac{eg(t)}{eg_o}} , \\
mc_{es,dr}(DR_t)) &= \eta_{mc,dr}(DR_t) \cdot iee , \\
adv_{e,dr}(DR_t) &= \eta_{adv,dr}(DR_t) \cdot ies \cdot \sqrt{\frac{eg(t)}{eg_o}} , \\
wom_{e,dr}(DR_t) &= \eta_{wom,dr}(DR_t) \cdot ies \cdot \sqrt{\frac{eg(t)}{eg_o}} , \\
wom_{es,dr}(DR_t) &= \eta_{wom,dr}(DR_t) \cdot iee ,
\end{aligned}$$

$$\begin{aligned}
\eta_{mc,dr}(DR_t) &= \begin{cases} \frac{0.05}{0.3} \cdot \frac{DR_t}{TP_o} & \text{for } DR_t < 0.3 \\ 0.05 & \text{for } DR_t \geq 0.3 \end{cases} , \\
\eta_{adv,dr}(DR_t) &= \begin{cases} \frac{0.016}{0.3} \cdot \frac{DR_t}{TP_o} & \text{for } DR_t < 0.3 \\ 0.016 & \text{for } DR_t \geq 0.3 \end{cases} , \\
\eta_{wom,dr}(DR_t) &= c \cdot i \cdot \frac{DR_t}{TP_o} ,
\end{aligned}$$

where dsc - discomfort - is the parameter that reduces the diffusion rate. No literature quantitative has been found on this topic, therefore we have chosen a hypothetical conservative central value of 1/3 and included such parameter in the stochastic analysis.

For the production dynamic branch we have decided to change approach (at least in this first modelling attempt) and model it so that it replicates estimates of distributed generation diffusion from the literature, due to the fact that some specific data and estimates are available.

Model improvements and refinements would be certainly possible but at the moment there are two main obstacles, namely the very early primary stages of the process and the commercial interest in the data necessary that has made it not possible for us to retrieve some important data for the model calibration. This will be possible once initial data will be gathered and made available.

For what concerns the electricity production branch of the model, although the problem can be theoretically approached in a similar way than for the other branches, in this case, the phenomenon is not at such early stages and, therefore, it is possible to extrapolate some trends from the data. We choose to do so as, currently, data on the time dynamics is more available in the literature compared to data for estimating the parameters that define the different cognitive decisions of the consumers when considering if and when to become prosumers. For the other two branches of the model we have considered the modelling approach more appropriate as the data to extrapolate the time dynamics of adoption have not yet been collected or disclosed. The only results available are those of pilot studies that we use for estimating the impacts of consumer adoption, but that in most case concern samples of people that voluntarily decide to take part to the experiment.

3.4.2 Theoretical study of the equilibrium

Our system of equations is too complex to be able to solve it to find an analytical solution. Nevertheless, it is possible to prove theoretically the existence, and uniqueness, of the equilibrium and to study its stability.
This is useful to prove the coherence between the numerical simulations that will be described in the following Section (Section 3.4.3) and the theoretical properties of the system.
To find the equilibrium and to study its stability characteristics, we have had to simplify the model slightly, by:

- removing the time dependency of the variables - in order to have an autonomous system of equations, even if our model has proved to be at least asymptotically autonomous, as time-varying parameters converge to constants.
- simplifying the step functions, in order for the values to be differentiable;

For this kind of analysis, we have collapsed all the variables into time-varying, time-invariant, and stock-variable dependent terms. We have solved the system so that the above derivatives are contemporaneously set to zero and found the following equilibrium solutions:

$$\begin{cases} NS_t = 0 \\ PS_t = 0 \\ S_t = 0 \\ SSRm_t = 0 \\ SSRa_t = 0 \\ EA_t = \overline{EA_t} \\ PDR_t = 0 \\ DR_t = \overline{DR_t} \\ PP_t = 0 \\ P_t = \overline{P_t} \end{cases} \tag{3.11}$$

Moreover, it can be proved that the following conservation laws hold:

$$\begin{aligned} &\frac{dNS_t}{dt} + \frac{dPS_t}{dt} + \frac{dS_t}{dt} + \frac{dSSRm_t}{dt} + \frac{dSSRa_t}{dt} + \frac{dEA_t}{dt} = 0 && \forall t \\ &\Rightarrow \frac{d(NS_t + PS_t + S_t + SSRm_t + SSRa_t + EA_t)}{dt} = 0 && \forall t \\ &\Rightarrow NS_t + PS_t + S_t + SSRm_t + SSRa_t + EA_t = cost && \forall t \end{aligned}$$

$$\begin{aligned} &\frac{dNS_t}{dt} + \frac{dPDR_t}{dt} + \frac{dDR_t}{dt} = 0 && \forall t \\ &\Rightarrow \frac{d(NS_t + PDR_t + DR_t)}{dt} = 0 && \forall t \\ &\Rightarrow NS_t + PDR_t + DR_t = cost && \forall t \end{aligned}$$

$$\begin{aligned} &\frac{dNS_t}{dt} + \frac{dPP_t}{dt} + \frac{dP_t}{dt} = 0 && \forall t \\ &\Rightarrow \frac{d(NS_t + PP_t + S_t + P_t)}{dt} = 0 && \forall t \\ &\Rightarrow NS_t + PP_t + P_t = cost && \forall t \end{aligned}$$

Given the above conservation laws and the initial conditions (below), it straighforward to identify the equilibrium points:

$$\begin{cases} NS(0) = 13.4 * 10^6 & \\ PS(0) = 6.7 * 10^6 & \\ S(0) = 0 & \\ SSRm(0) = 0 & \\ SSRa(0) = 0 & \Rightarrow \overline{EA} = NS(0) + PS(0) = 20.1 * 10^6 \\ EA(0) = 0 & \Rightarrow \overline{DR} = NS(0) + PDR(0) = 20.1 * 10^6 \\ PDR(0) = 6.7 * 10^6 & \Rightarrow \overline{P} = NS(0) + PP(0) = 20.1 * 10^6 \\ DR(0) = 0 & \\ PP(0) = 6.7 * 10^6 & \\ P(0) = 0 & \end{cases}$$

The system admits ∞^3 equilibrium points that are univocally determined by the initial conditions.
To investigate the stability of the equilibrium points, we have linearised the system and computed the eigenvalues of the Jacobian Matrix; these turn out to be all negative except for three that are equal to zero, confirming the stability of all equilibrium solutions.

In the current version of the model all classes, except for the last ones, are expected to get empty as t increases. If future empirical evidence will contradict this asymptotic behaviour, frictions could be added to the model, i.e., replacing, where appropriate, $Stock_i(t)$ with $Stock_i(t) - \phi_i$ in the right-hand-side terms of the differential equations of system **??**. Though, these would only mean that a certain amount of the stock of households would remain in the various boxes, generating an equilibrium of the type:

$$\begin{cases}\overline{NS} = \phi_{NS} \\ \overline{PS} = \phi_{PS} \\ \overline{S} = \phi_{S} \\ \overline{SSRm} = \phi_{SSRm} \\ \overline{SSRa} = \phi_{SSRa} \\ \overline{EA} = NS(0) + PS(0) - \sum_i \phi_i \\ \overline{PDR} = \phi_{PDR} \\ \overline{DR} = NS(0) + PDR(0) - \sum_i \phi_i \\ \overline{PP} = \phi_{PP} \\ \overline{P} = NS(0) + PP(0) - \sum_i \phi_i \ . \end{cases}$$

Note that some of the above ϕ_i could be zero.

3.4.3 Simulation results

To perform the calculations for identifying the adoption dynamics we have implemented the theoretical model in the Vensim PLE Plus computer-based platform. This software applies the Runge-Kutta method, of order four and with time step 2^{-7} years, for solving numerically the system of differential equations.

Due to the uncertainty embedded in most of the parameters included in the model, we adopt a Monte-Carlo (MC) approach and configure the system of equations with stochastic parameters. We perform 2500 simulations, for each of which the values of the parameters are obtained by joint independent random sampling from the following reference probability distribution. More specifically, we have used beta-distributions between [0;1] for the following parameters:

- *qi* - initial-information quality;
- *ies* - interest in economic gain;
- *iee* - interest in environmental effects;
- tariff-difference in 2013;
- available market threshold value;

- available market threshold value for information campaigns;
- η_{dsm} - Demand-Side-Management efficacy;
- η_{ic} - information-campaigns efficacy;
- η_{mc} - media-coverage efficacy;
- η_{adv} - advertisement efficacy;
- ea - ease parameter;
- i - infectivity;
- op - opt-out percentage;
- γ_{ssd} - SSRm flow parameter;
- γ_{asd} - SSRa flow parameter;
- γ_{eead} - EEA flow parameter;
- dsc - discomfort parameter;
- $\eta_{dsm,dr}$ - Demand-Side-Management efficacy for Demand Response;

adopting as the mean value the one found in the literature, described in Section 3.4.1, and 0.01 as the standard deviation. A graph depicting the sample densities is reported in the Appendix.
We have also made the c - number of contacts - parameter stochastic, though we used a Poisson probability distribution with mean and variance equal to 19.
We obtain 2500 solutions associated with 2500 possible realizations of the vector of the parameter values. These results have been analysed using the statistical environment R (R Development Core Team, 2010).
Figure 3.3 shows the trajectories of each of 2500 simulations, highlighting the dynamics of the stocks along time from year 2010 to 2100. The color is used to distinguish among different dynamics and is the same across all Figures. The 2500 MC replications are ordered and colored according to the value of aggregated shift at year 2030.

Figure 3.4 instead shows the pairwise quantile distribution (0.05, 0.10, 0.25, 0.50, 0.75, 0.90, 0.95), according to a gray scale.

These Figures show the growth and the decline of the different stocks of the Consumption Management branch of the model. At first site, at least two major features are evident: i) an increasing effect of the uncertainty of the parameters moving from stock 1 to stock 6; ii) an increasing delay of the

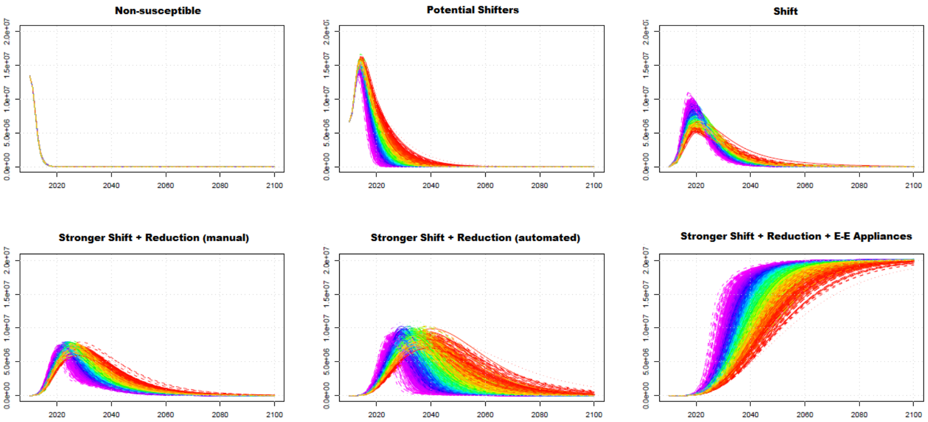

Figure 3.3: Consumption Management stock dynamics with MC repetitions colored by Shift value at t=20

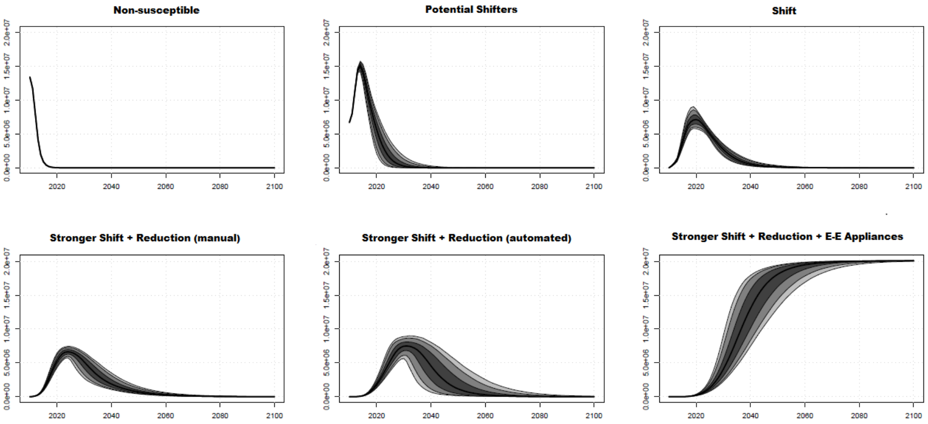

Figure 3.4: Consumption Management stock quintile dynamics

peaking period, moving from plot 2 to plot 4.
Indeed, the dynamic of the first stock, corresponding to the 'Non-susceptible' population, is almost unaffected by uncertainty; indeed the related flow is mainly affected by the speed of the activation of the smart-meters by the utility, which is known. In all simulations, this stock results almost completely empty by 2023.
The second stock - that of the Potential Shifters - always presents a peak around 2014 of about 15 million households, with quite a low variability. Looking at the different MC replications, a higher peak seems to generally mean a slower decline dynamic.
This high-peak slow-decline pattern is associated with a delayed and lower peak of the Shift stock (plot 3, Figure 3.3). In this stock, early peaks can reach values up to ten million people, while delayed peaks can go down to five million households. Notice also that all MC replications tend to peak around 2020.
The early/late dynamic of the different MC replications - identified by the colour of the curves - is preserved (and probably imputable to the hight of the peak reached in plot 2) along all the successive stocks. Despite this, differently from plot 2 and 3, the height of the peaks observed in plot 4 and 5 seems to be independent of the delay of the trajectories. The peak reaches a value between 6-8 million households around 2022-2030 in plot 4, and between 7-12 million around 2030-2040 in plot 5. In the latter box there is a very high level of uncertainty concerning the emptying time, that ranges from 2040 to more than 2100, causing for example, that in 2040 the stock ranges between zero and one million households, making prediction very hard. A similar level of uncertainty is transmitted and amplified in the last box.
Figures 3.5 and 3.6 show these dynamics for the first 15 years when predictions are more credible both because of the effect of the parameter uncertainty and because closer to the situation for which parameters where estimated.

From these graphs we can notice some short-term internal dynamics within the Consumption Management super-box, i.e., that the 'automated Stronger Shift+ Reduction' and 'automatized Stronger Shift + Reduction + Energy Efficient Appliances' stocks do not fill significantly before 2015 and 2020, respectively.
Recall from Section 3.4.1 that the flows between the last four boxes - included in the Consumption Management super-box - have been modelled in a very simplistic way for lack of specific literature. Therefore, due to this lack of literature, the most sound results are those depicted in Figure 3.7 and 3.8, where the last four classes are aggregated.

These Figures confirm that the uncertainty of the parameters largely affects the dynamics of the last three stocks, while their aggregation is less affected.

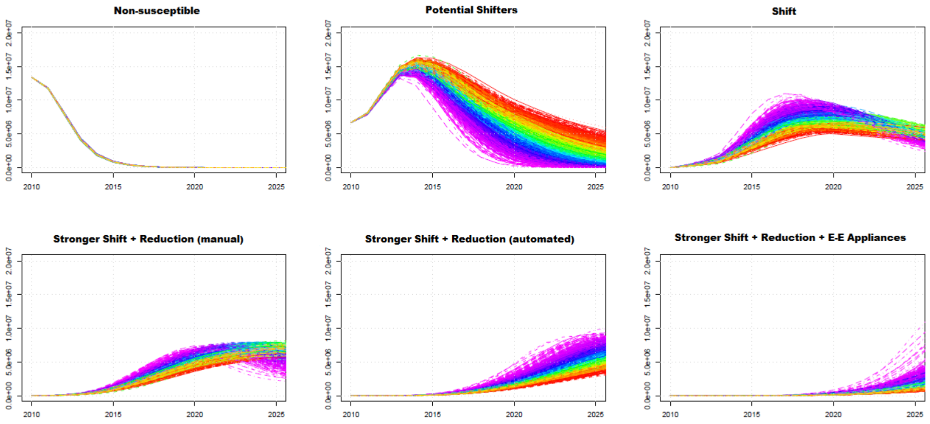

Figure 3.5: Consumption Management stock dynamics up to 2025

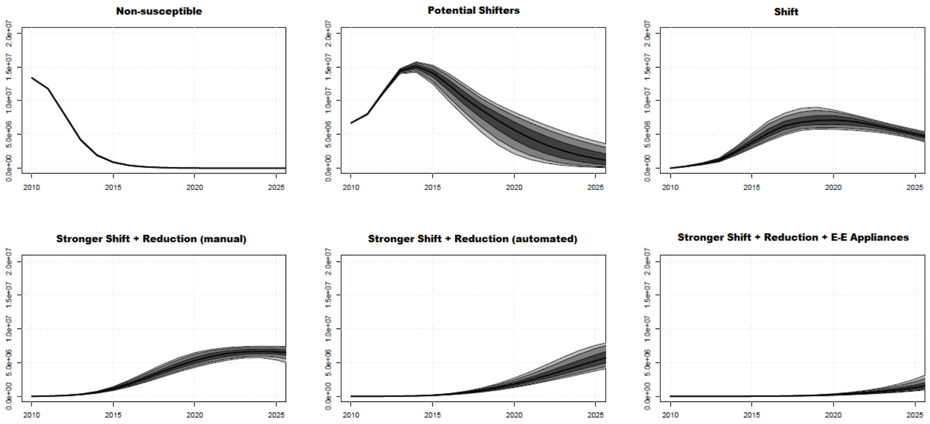

Figure 3.6: Consumption Management stock quintile dynamics up to 2025

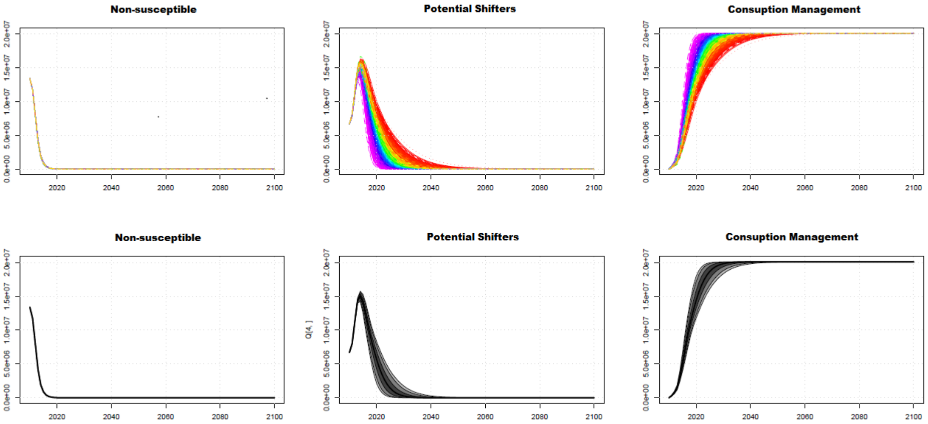

Figure 3.7: Aggregate Consumption Management stock and quintile dynamics

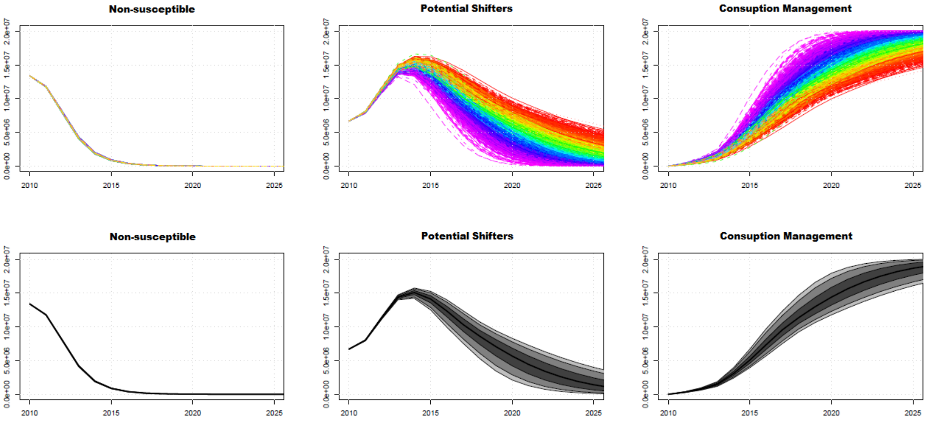

Figure 3.8: Aggregate Consumption Management stock and quintile dynamics up to 2025

Figure 3.9 depicts the stock dynamics and the relative pairwise quantiles for the enrolment in demand response programs.

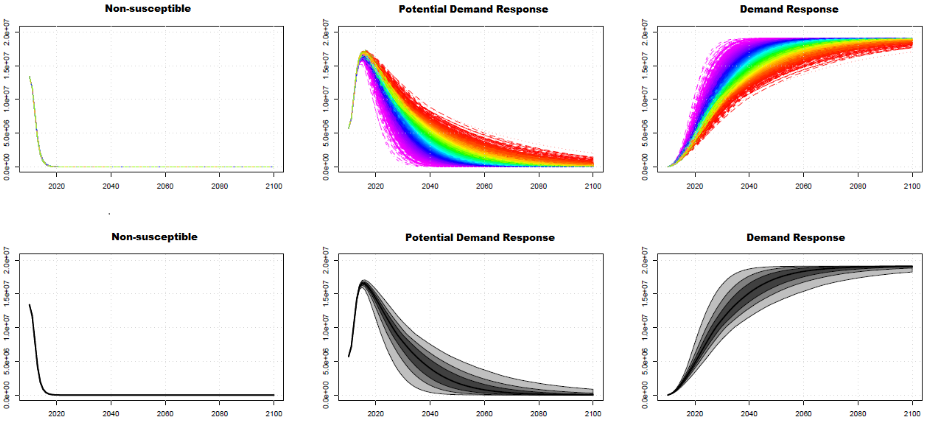

Figure 3.9: Demand Response stock and quintile dynamics - colored by DR value at t=20

Compared to the dynamics of consumption management (3.7), the dynamic of adoption is slower, as expected due to the discomfort parameter. Moreover, the resulting dynamics are also characterised by more uncertainty.

3.4.4 Adoption impact assessment

After having solved the system of equations and identified the adoption dynamics, we are interest in evaluating the impacts of such adoption patterns on the power system. To do so, we need to attach a specific effect on electricity consumption for each of the ten behavioral stages analysed.
In recent years, various pilot studies have been performed, to estimate the effects of behavioural changes that follow the installation of smart meters and/or the application of differentiated tariffs (Ehrhardt-Martinez, Donnelly and Laitner, 2010; Olmos, Ruester and Jen Liong, 2010). Moreover, the literature on informational feedbacks is quite large even if results are not always consistent (Darby, 2006; Neenan and Robinson, 2009). The values that we use in this assessment are taken from the PowerCents DC pilot experiment (eMeter, 2010) and adapted from (European Commission, 2011b); indeed, we use as reference the following values:

- Shift box: 9% consumption shift and 0% consumption reduction;
- manual Stronger Shift+ Reduction box: 23% consumption shift and 5% consumption reduction;

- automated Stronger Shift+ Reduction box: 36.8% consumption shift and 10% consumption reduction;
- automatized Stronger Shift + Reduction + Energy Efficient Appliances: 40% consumption shift and 20% consumption reduction;

Figure 3.10 depicts the overall shift in energy consumption, i.e, the percentage of total residential electricity consumption that is shifted, due to the evolution of the stocks described in the previous Section. On the left panel the 2500 trajectories are reported, while on the right-hand-side panel the pairwise quantiles are outlined. Notice how consumption shifting starts from 2010 and its level grows fast, at nearly one percentage point per year between 2015 and 2030. Compared to the evolution of the stocks, that was characterised by a significant uncertainty, the variability of the dynamic of the aggregate shifting effect is strongly reduced, due to some kind of balancing effect among the last four stocks. This is good news since these are the values that will be used for the impact assessment of smart grids.

Electricity consumption reduction (Figure 3.11) presents similar trends, but starts later and reaches lower values with a lower slope. This is due to the increased effort and/or comfort loss entailed in consumption reduction with respect to consumption shift.

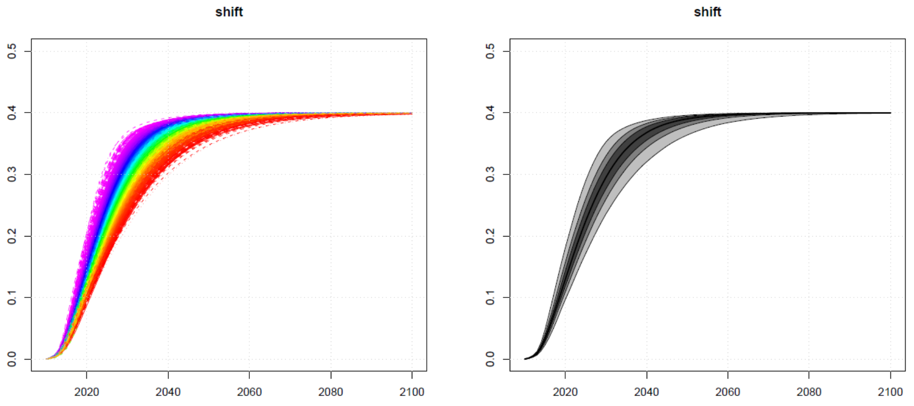

Figure 3.10: Total percentage shift

The value of shifting consumption is related to the patterns of electricity demand, which are not constant during the day or the year, but are instead characterised by peaks. Electricity generation and transmission systems are sized according to the maximum peak load (plus a margin to account for forecasting errors or emergencies), as demand needs to be satisfied at all times. This means that part of the capacity installed is used only for a very

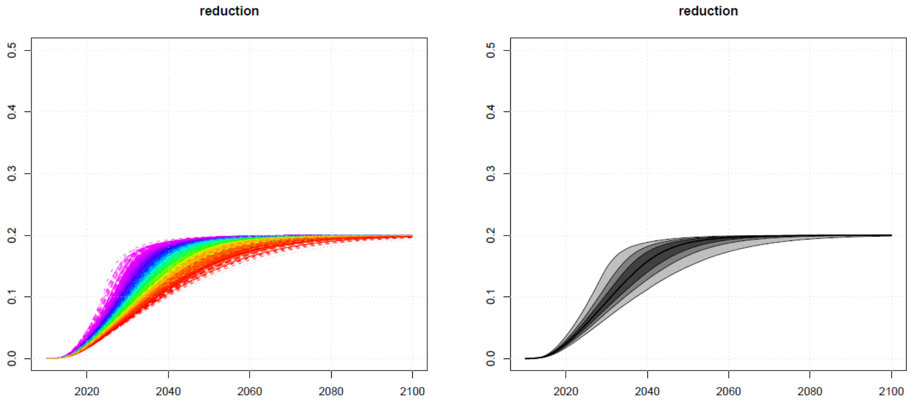

Figure 3.11: Total percentage reduction

limited amount of hours during the year. Therefore, a shift in consumption that smooths load curves may give the possibility to delay capacity expansion and to better use the available capacity, lowering overall plant and capital cost requirements. Indeed, even if customers are not subject to real-time pricing, the utilities that provide them the service, need to buy electricity at whole-market prices, that generally depend on the marginal cost of the most expensive generator that is injecting energy into the grid. This means that when demand peaks, even the most inefficient generators are able to enter the market increasing electricity prices. If demand is instead shifted to lower-demand periods, efficient generators are favoured as they are able to increase their market share. This will reduce the volatility of electricity prices (reducing both high and low peak prices) and, possibly, enable to exploit efficient production opportunities during low-demand times, for generation that is not programmable, such as that with wind and solar energy.

We have tried to quantify the potential benefits and costs of the adoption trends identified with our model and described in the previous Section. As a reference value we take the median of the 2500 simulations, whose impacts in terms of percentage consumption shift and reduction - with respect to total residential electricity demand - are reported in Table 3.2.

	2015	2020	2025	2030
Shift	3.28%	12.99%	22.44%	29.56%
Reduction	0.36%	2.45%	5.63%	9.22%

Table 3.2: Percentage of total residential electricity consumption that can be shifted and avoided

Given that the Italian electricity consumption from the residential sector is around 69,353 GWh/year (AEEG, 2011a), we find the that the amount of load that can be shifted is the one reported in Table 3.3. The same Table reports the corresponding level of generating capacity that can be avoided (or deferred in time), given the 11 hours of peak that are defined in the current tariff structure, and given a power plant capacity factor of 85%. Note that we are interested in evaluating the possibile sostituability with respect to fossil fuel or nuclear power plants. As a reference, consider that 76% of Italy's thermoelectric power plants are under 800 GW, and that a reference nuclear power plant is in the order of 1 GW.

In addition to the generation capacity savings, consumption management enables to avoid, or defer in time, also transmission capacity expansions; though these benefits are not accounted for in this analysis.

	2015	2020	2025	2030
Peak load reduction (GWh/y)	2273	9009	15561	20498
Peak capacity reduction (GW)	0.93	3.70	6.38	8.41

Table 3.3: Peak load reduction potentials by shifts in consumption

A2A, 2010 reports the amount of CO_2 emissions and the system costs that could be avoided if all Italian households were to shift ten percent of their consumption in the cheaper-tariff time-segment. We use these values to calculate the CO_2 emissions and various cost savings induced by the shifting behaviour adoption dynamic that emerges from our model (Table 3.4), assuming that the marginal effects are constant as the number of household shifting or reducing their consumption increases or decreases. As a reference, note that the Italian objective of emission reduction for the period 2008-2012 is of cutting 13.67 $MtCO_2$/y. Of these, 9.5 $MtCO_2$/y need to be avoided by the electricity sector (Ministero dell'Ambiente, 2007).

	2015	2020	2025	2030
CO_2 emission reduction ($MtonCO_2$/y)	0.15	0.58	1.01	1.33
CO_2 emission costs reduction (M€/y)	2.95	11.69	20.19	26.60
Fuel costs (M€/y)	26.22	103.92	179.50	236.44
Plant costs (M€/y)	39.34	155.88	269.24	354.67

Table 3.4: Avoided CO_2 emissions and costs by shifts in consumption

These benefits should be added to the 500 million € that Enel is saving each year because of remote operations on smart meters. The related benefits include remote-meter reading, reading-error reduction, real-time information on low-voltage loads, remote activation/deactivation of service, customer messaging, outage and tampering detection.

A more efficient use of the system infrastructure induces savings for the operators of the system and will enable, in time, also bill savings for all customers. The households that actually change consumption pattern and shift their demand to the low-peak segment will also benefit from direct immediate economic savings. These savings, evaluated on the basis of the average annual consumption of an Italian household and on the current tariff structure, are 2.73 €, 6.99 €, 11.18 € and 12.15 € for a shift of 9%, 23%, 36.8%, 40%, respectively. Aggreagate savings over time are reported in Table 3.5. For now, savings are low, as the price difference between the two segments for the consumer is very low, around 10%, but it will increase from 2013 when the tariff structure will be updated to follow more closely whole-market prices (A2A, 2010).

	2015	2020	2025	2030
Aggregate savings (M€/y)	20.0	79.4	137.1	180.6

Table 3.5: Aggregate households bill savings by shift in consumption with the 2010-2012 tariff scheme

Additional economic and environmental benefits are induced by electricity consumption reduction. Recall that our analysis evaluates reductions with virtually no loss of comfort for the household members, indeed we refer to savings of wasteful power like vampire loads and/or automated reduction of consumption. Table 3.6 reports the load demand reduction that may be achieved by means of a more conscious use of electricity in everyday behaviour, and the relative size of generating capacity. Note that here we spread the consumption reduction over all the 24 hours of the day. Also the impact on CO_2 emissions is evaluated on average emissions and not on peak load emissions. The Table also reports an estimate of the generating cost savings calculated on the basis of the average cost in 2011 (GME, 2011).

	2015	2020	2025	2030
Peak load reduction (GWh/y)	250	1700	3906	6391
Peak capacity reduction (GW)	0.03	0.23	0.52	0.86
CO_2 emissions reduction (MtonCO_2/y)	0.14	0.98	2.25	3.68
CO_2 emission cost reduction (M€/y)	2.88	19.58	44.99	73.62
Generation cost reduction (M€/y)	19.65	133.64	307.05	502.40

Table 3.6: Peak load reduction potentials by reduction in consumption, maintaining constant comfort levels

Bill savings, for consumers that decide to reduce their electricity consumption, in percentage terms correspond to the percentage of consumption savings; while aggregate savings in absolute terms are reported in Table 3.7. We report range-values between a minimum and a maximum, as savings depend also on the total consumption of the household, i.e., tariffs are differentiated not only for time-of-use, but also for the level of aggregate household consumption.

	2015	2020	2025	2030
Min aggregate savings (M€/y)	27.6	187.2	430.1	703.8
Max aggregate savings (M€/y)	67.2	456.2	1,048.3	1,715.4

Table 3.7: Aggregate households bill savings by reduction in consumption with the 2010-2012 tariff scheme

At the household level, bill savings range between: 19-46 €/hh/y for a 5% reduction, 38-93 €/hh/y for a 10% reduction, and 76-185 €/hh/y for a 20% reduction. As a reference, recall that vampire-loads in the EU are estimated to correspond to 10% of total residential consumption (ACEEE, 2008).
Notice that consumption reduction has a much stronger economic saving potential for the consumer with respect to the shifting saving potential. Consumption shift away from peak time segments is efficient in allowing economic, environmental and capacity savings for the system, while economic savings for the customer - with the current tariff scheme - are very low, even if they are prospected to grow after 2013.
Savings due to consumer engagement are high, especially if we consider that they have no (or very little) generating costs, indeed the costs are mostly in terms of effort by the consumer. Here emerges the importance of engaging with the consumer, to make him more empowered and conscious of the multi-level impacts of its consumption decisions.

Figure 3.12 shows the cumulative savings over time compared to the costs of installing the smart meters. We do not include savings by the consumer as these are revenue losses[7] for the electricity providers and, therefore, they are neutral for the whole system. Instead, we depict the latter cumulative savings with respect to total cost for installing smart meters in Figure 3.13, as these costs in Italy are ultimately paid by consumers on the bill. Note that these values do not take into account the possible bill savings that can arise from lower generating costs due to the comparative advantage of distributed generation in certain vulnerable areas of the network. These graphs show that the investment costs for installing the smart metering infrastructure are balanced by the related benefits that accrue in the following years, the investment is repaid in a short amount of time (4-10 years depending on what cost savings are considered).
Note that these evaluation are only indicative as they extend current values in the future, and they take into account only a sub-set of benefits induced by smart meters. For example, outage reduction strongly reduces system costs, though we do not currently have this data for Italy; in the US, outages shrink

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[7] In the current rewarding system.

by 24.5% the revenues of the electric power sector (ISGI, 2010). Recall also that these results are based on the dynamics of a first application of our model based on the data available up to now.

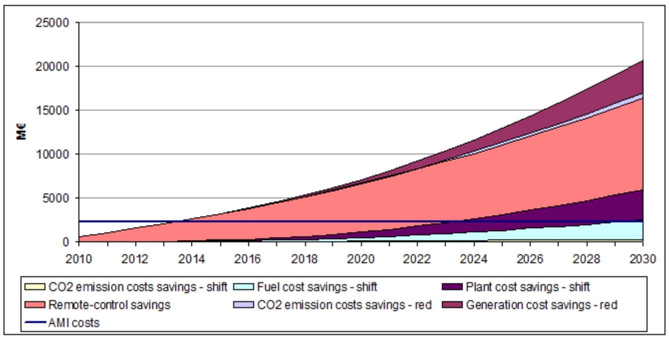

Figure 3.12: Advanced-Metering-Infrastructure costs and power system cost-savings

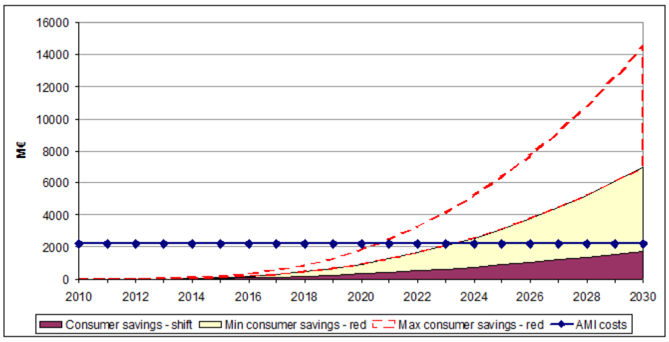

Figure 3.13: Advanced-Metering-Infrastructure costs and aggregate consumer bill savings

The contribution of consumers by shifting or reducing consumption may help increase the energy efficiency of the system, that is one of the objectives of the 20 20 20 EU strategy. Indeed, if we consider its classical definition, energy efficiency is improved because shifting and/or reducing peak load favors the most efficient power producers. Moreover, if we consider the end product, i.e., the energy services demanded by customers, consumption shift and/or reduction - keeping comfort levels constant - are able to provide the same amount of services with lower consumption of electricity (and consequently: lower consumption of primary sources, lower emissions and lower costs).

For what concerns demand response, customers enroll in these rewarded load curtailment programs, that become active at critical times, by reducing the electricity services available. The consumer benefit is a monetary reward

in exchange of the possibility of a loss in comfort for a limited number of times during the year. On the other side, the system is able to react to critical peaks in demand without service interruptions and both society and utilities are able to face lower peak prices. Demand response contracts are useful for dealing with temporary emergencies, but could be also used as a more regular management option for avoiding expensive additional capacity expansion needed just for a very limited amount of hours per year. Current demand response programs in the US (that include also commercial and industrial activities under preplanned prioritazation schemes) count 5 million customers and are potentially able to reduce peak load by 41 GW, that correspond to a six percent peak-load-reduction (FERC, 2008). Our results are only indicative, because in Italy no demand response program for residential customers has been proposed, but from the literature we can verify that adoption trends similar to the ones we find could have very important effects on the power system (GE, 2010; FERC, 2008). For example, in the US, a 3% reduction in peak demand for the 100 more expensive hours of the year would generate 145-300 million $ per year of savings (Brattle, 2007). Moreover, the annual costs for power interruptions in the US is estimated in 80 billion $ per year relative to a total annual sector revenue of 326 billion $ (ISGI, 2010). The previous figures do not take into account the "social" cost of service interruptions: in the US, the willingness to pay to avoid black-outs is evaluated to be around 5$ to avoid one hour of outage (Watch, 2010).
The minimum target of the 2010-2012 AEEG tariff structure in Italy is to distribute consumption in the following way: 1/3 in higher price/cost/impact segment and 2/3 in the other. Therefore, given the demand response adoption rates identified in the previous Sections, the maximum demand response potential linked to residential customers in Italy is reported in Table 3.8.

	2015	2020	2025	2030
Enrolled Households (Millions)	1,644	4,788	8,298	11,215
Potential load reduction (GW)	0.78	2.26	3.91	5,29

Table 3.8: Residential customer demand response potentials

The other main source of emission reduction for the electric sector induced by consumers is related to self-generation with micro electricity generators based on renewable sources of energy. With respect to the other options for consumers some adoption data are already available. The extrapolation of a trend to use for future years is quite complicated as the ones available are the initial installation rates of a new emerging phenomenon, and also because they are strongly related to the high PV incentives that are available for residential consumers in Italy. Future trends will indeed depend on the evolution of such incentive policies, in addition to that of module prices and consumers energy and environmental awareness.

In any case, if we look at the data in 2011, we can get an idea of the magnitude of the possible impacts. Indeed, from the literature we find that PV generation in Italy is able to reduce emissions by 6.3 Million ton CO_2/year (GIFI, 2011). Of the total installed capacity, 14.6% is again of residential households (GSE, 2011), therefore the impact is of 919,800 ton CO_2/year.

Generation with PV has reduced fuel import by 2Mtep/y; of this, 14.6% is due to residential customers. In addition, there are beneficial effects also on the local economy (75% of the costs of installation are in favor of local producers), employment and also state tax revenue (GIFI, 2011).

In Italy, incentives cost 1.5% of the total electricity bill, which is about 1/5 of what consumers finance with the A3 component of the bill, that includes financing also for other types of generation, R&D, and benefits for other sectors.

Moreover, a study by APER shows that as of 2013 bill cost saving should be visible for the Italian consumers, due to the lower cost of distributed PV generation in the most vulnerable areas of the power network. Assosolare, 2011 calculates the benefits to be around 1.9 €/MWh of average reduction of the national unit price of electricity (PUN).

3.4.5 Sensitivity Analysis

An additional interesting analysis is to investigate, at a first order approximation level, the ultimate effect of each single model parameter on the dynamic of the system and, in particular, on the impacts that can be generated on residential consumption (i.e., Aggregate Shift, Aggregate Reduction, Demand Response adoption).

This sensitivity analysis is carried out by means of OLS regression. Figures 3.14, 3.15, 3.28, report the scatter plots of Aggregate Shift, Aggregate Reduction, and Demand Response adoption in 2020[8] versus the corresponding values of the model parameters, for the 2500 simulations. Point colours are the same as those used for the simualtion curves of the Figures of Section 3.4.3. Moreover, in each scatter plot the corresponding univariate-regression line is depicted with the corresponding R^2 index. From these plots it is already possible to identify some strong positive dependencies (e.g., Infectivity, Contacts, other informational channels efficacy, etc.) and some negative ones (e.g., opt-out percentage).

A more precise analysis of these dependencies can be carried out by looking at Tables 3.17, 3.18, 3.19 , where for each model parameter some indexes of the corresponding uni-variate regression are reported: estimate of the β coefficient, its standard deviation, t-statistic, significance of the t-test. In

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[8] This year has been chosen as a reference year for the sensitivity analysis as it is one of the years in which the differences among the 2500 simulations is stronger

these tables, the model parameters are ordered accordingly to their significance. The corresponding ranking can be considered as a marginal sensitivity ranking.

More interestingly for extracting policy implications is a ranking based on a *ceteris paribus* sensitivity analysis, since in real-life applications policy-makers may be interested in knowing the effect of varying the level of one parameter keeping the other unchanged. This kind of sensitivity has been carried out by means of a multivariate linear regression. This regression model allows to overcome the masking effect due to the high number of regressors. Figures 3.20, 3.21, 3.22, report the scatter plots of the residuals of the regression of Aggregate Shift, Aggregate Reduction, and Demand Response adoption with respect to all model parameters, except for the one under examination, vs. the value of the same parameter.
In Tables 3.23, 3.24, 3.25 the results of the regression are reported. Also in these tables, the model parameters are ordered accordingly to their significance. As expected, due to the unmasking effect, more variables turn out to be significant. For this type of linear regression model, it is known that the regression coefficients represent the average effects on the response associated with a unit increment of the regressor, if the other regressors remain unaffected. Therefore, for example, we can expect a percentage point increment in the word of mouth infectivity to generate an increment in the aggregate consumption shift at 2020 of 1.28 percentage points, if the other model parameters remain unaffected, and so on.

Our results show that for the Shifting behaviour, infectivity is by large the most effective parameter, followed by contacts, information-campaign efficacy and demand-side-management efficacy. The parameters relative to the Demand Response and *eea* are uninfluent, coherently with the model configuration.
For consumption reduction, we have very similar results. Note that here *eea* is significant as there is a considerable difference between the redution level of the SSRa box compared to that of the EEA box.
For the demand response adoption, infection confirms its primary role; information-campaign efficacy, specific demand-side-management efficacy, contacts and the discomfort level due to load curtailments are also important. Also here, the parameters that result not significant are those that do not interact with this branch of the model.

In synthesis, even if in all cases all the parameters relevant to the model branch result influent, we can see hoe the most important parameters are those that govern the word of mouth effect and the other informational channels, suggesting that these should be the ones targeted by policies.

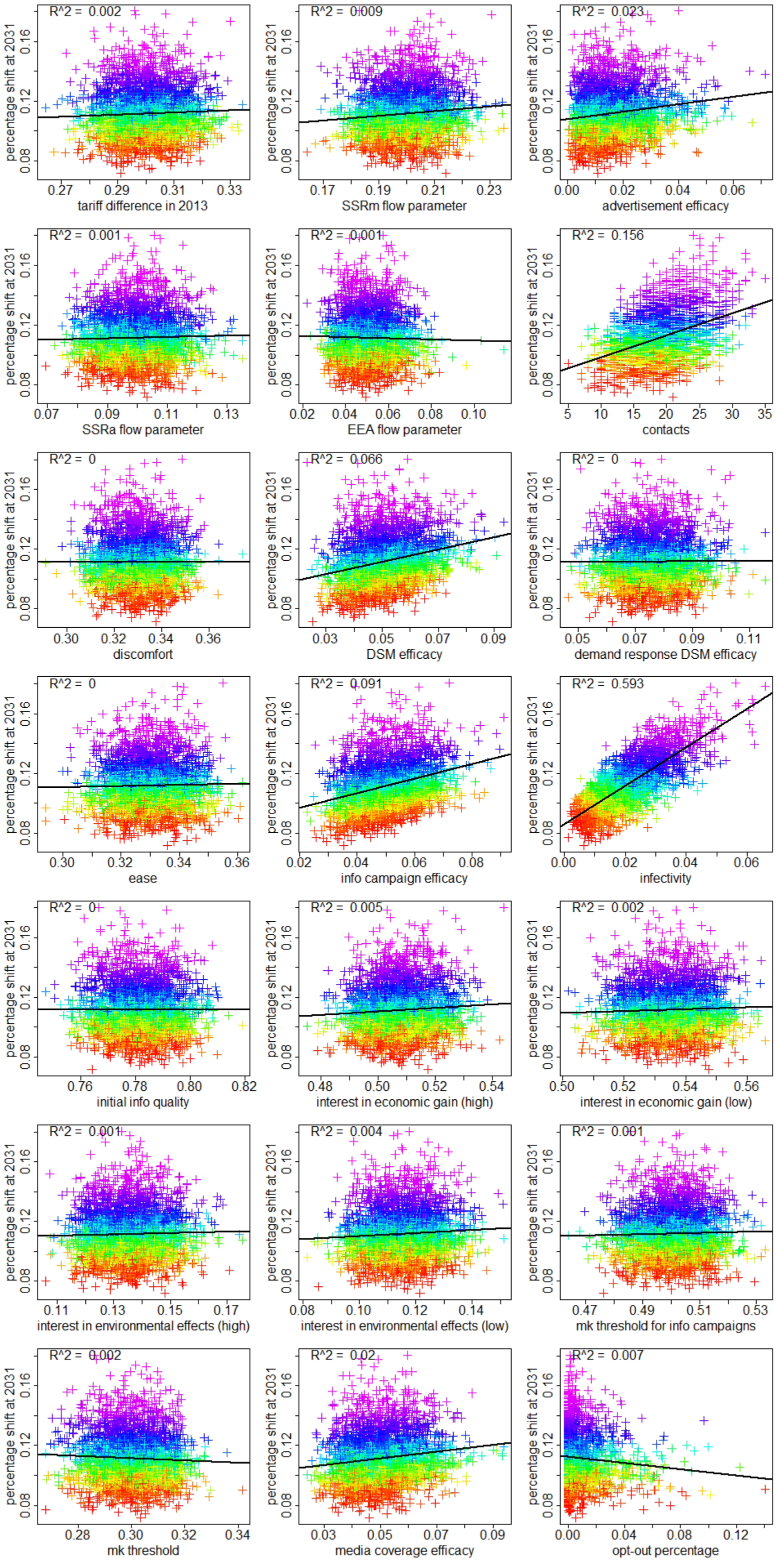


Figure 3.14: Scatter plot of Aggregate Consumption Shift vs. model parameters - univariate regression

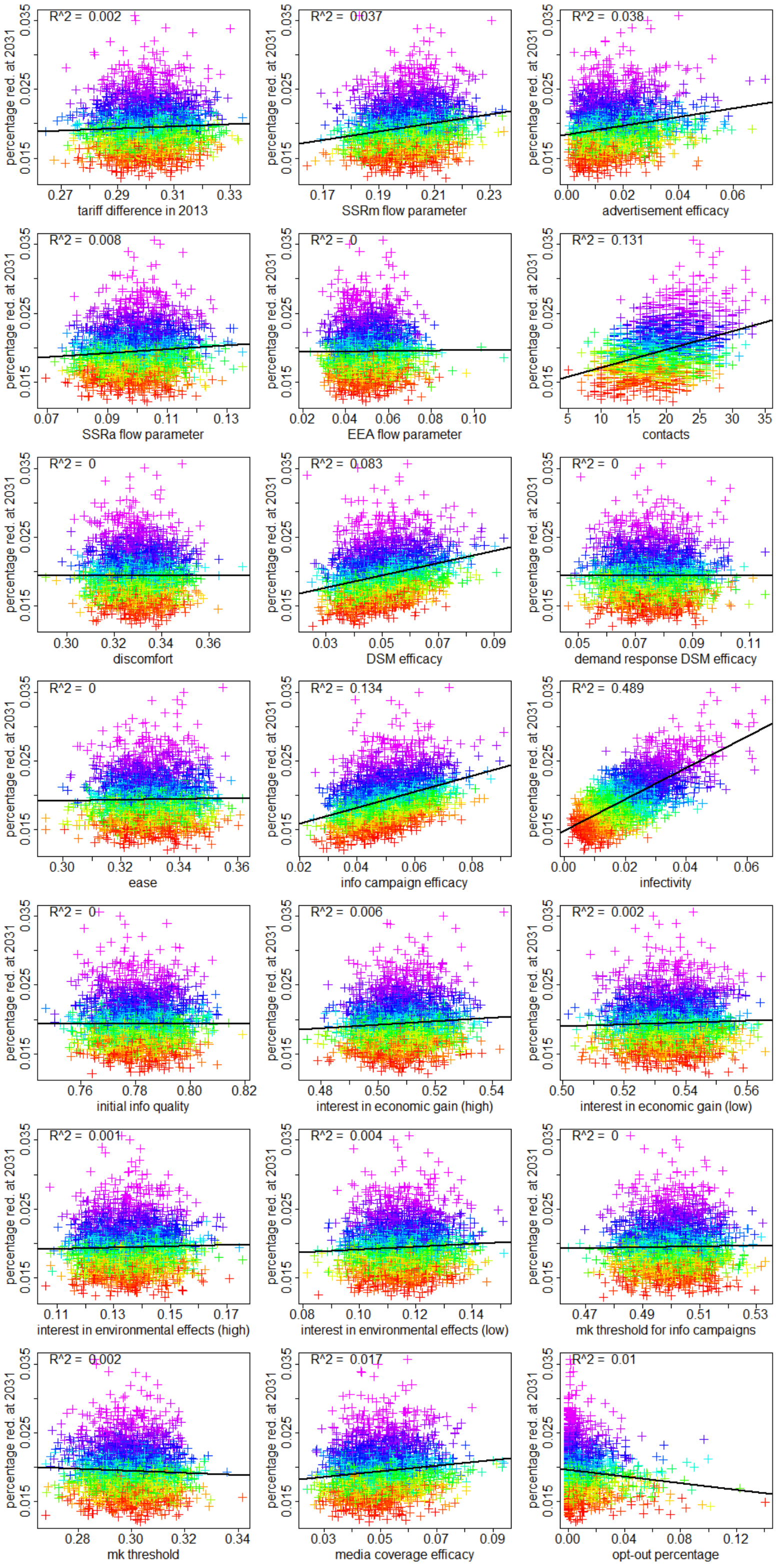


Figure 3.15: Scatter plot of Aggregate Consumption Reduction vs. model parameters - univariate regression

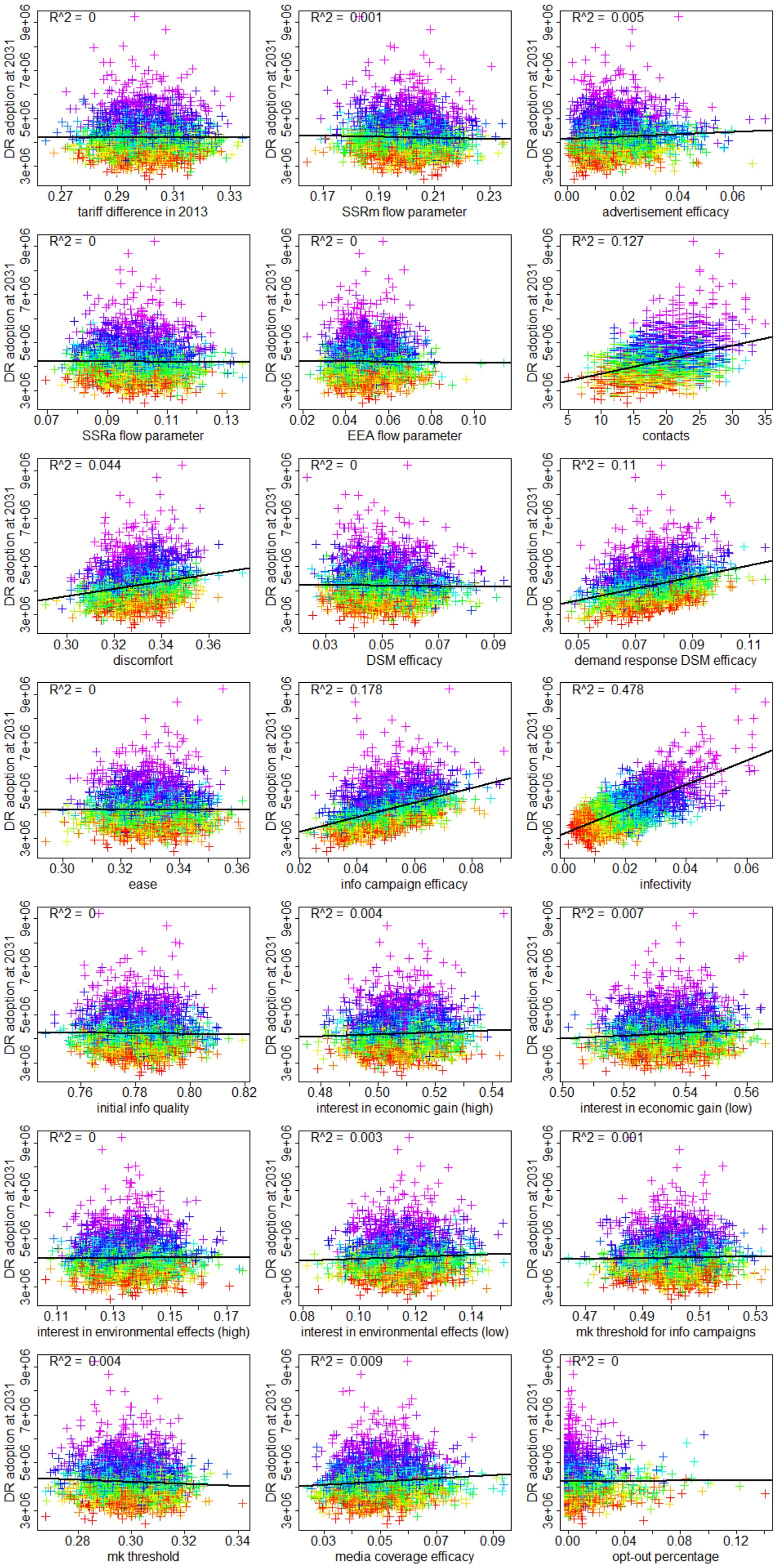
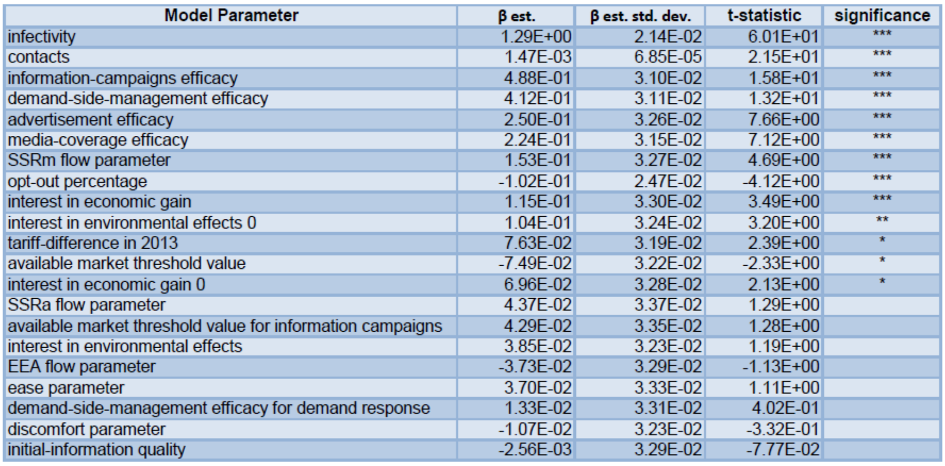
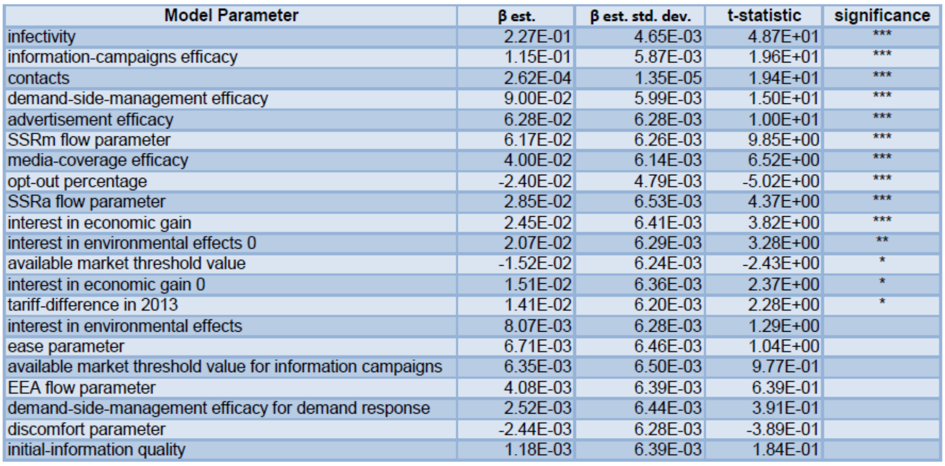


Figure 3.16: Scatter plot of Demand Response adoption vs. model parameters - univariate regression



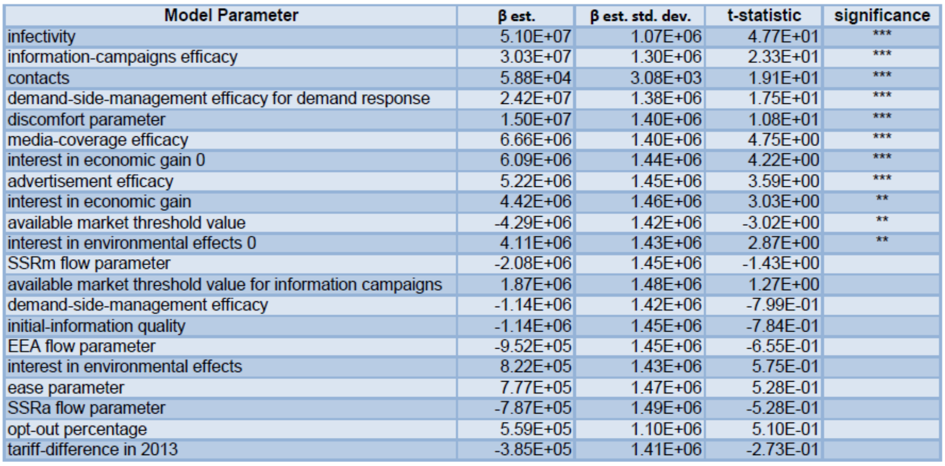
Model Parameter	β est.	β est. std. dev.	t-statistic	significance
infectivity	1.29E+00	2.14E-02	6.01E+01	***
contacts	1.47E-03	6.85E-05	2.15E+01	***
information-campaigns efficacy	4.88E-01	3.10E-02	1.58E+01	***
demand-side-management efficacy	4.12E-01	3.11E-02	1.32E+01	***
advertisement efficacy	2.50E-01	3.26E-02	7.66E+00	***
media-coverage efficacy	2.24E-01	3.15E-02	7.12E+00	***
SSRm flow parameter	1.53E-01	3.27E-02	4.69E+00	***
opt-out percentage	-1.02E-01	2.47E-02	-4.12E+00	***
interest in economic gain	1.15E-01	3.30E-02	3.49E+00	***
interest in environmental effects 0	1.04E-01	3.24E-02	3.20E+00	**
tariff-difference in 2013	7.63E-02	3.19E-02	2.39E+00	*
available market threshold value	-7.49E-02	3.22E-02	-2.33E+00	*
interest in economic gain 0	6.96E-02	3.28E-02	2.13E+00	*
SSRa flow parameter	4.37E-02	3.37E-02	1.29E+00	
available market threshold value for information campaigns	4.29E-02	3.35E-02	1.28E+00	
interest in environmental effects	3.85E-02	3.23E-02	1.19E+00	
EEA flow parameter	-3.73E-02	3.29E-02	-1.13E+00	
ease parameter	3.70E-02	3.33E-02	1.11E+00	
demand-side-management efficacy for demand response	1.33E-02	3.31E-02	4.02E-01	
discomfort parameter	-1.07E-02	3.23E-02	-3.32E-01	
initial-information quality	-2.56E-03	3.29E-02	-7.77E-02	

Figure 3.17: Summary indexes of Aggregate Consumption Shift vs. model parameters - univariate regression



Model Parameter	β est.	β est. std. dev.	t-statistic	significance
infectivity	2.27E-01	4.65E-03	4.87E+01	***
information-campaigns efficacy	1.15E-01	5.87E-03	1.96E+01	***
contacts	2.62E-04	1.35E-05	1.94E+01	***
demand-side-management efficacy	9.00E-02	5.99E-03	1.50E+01	***
advertisement efficacy	6.28E-02	6.28E-03	1.00E+01	***
SSRm flow parameter	6.17E-02	6.26E-03	9.85E+00	***
media-coverage efficacy	4.00E-02	6.14E-03	6.52E+00	***
opt-out percentage	-2.40E-02	4.79E-03	-5.02E+00	***
SSRa flow parameter	2.85E-02	6.53E-03	4.37E+00	***
interest in economic gain	2.45E-02	6.41E-03	3.82E+00	***
interest in environmental effects 0	2.07E-02	6.29E-03	3.28E+00	**
available market threshold value	-1.52E-02	6.24E-03	-2.43E+00	*
interest in economic gain 0	1.51E-02	6.36E-03	2.37E+00	*
tariff-difference in 2013	1.41E-02	6.20E-03	2.28E+00	*
interest in environmental effects	8.07E-03	6.28E-03	1.29E+00	
ease parameter	6.71E-03	6.46E-03	1.04E+00	
available market threshold value for information campaigns	6.35E-03	6.50E-03	9.77E-01	
EEA flow parameter	4.08E-03	6.39E-03	6.39E-01	
demand-side-management efficacy for demand response	2.52E-03	6.44E-03	3.91E-01	
discomfort parameter	-2.44E-03	6.28E-03	-3.89E-01	
initial-information quality	1.18E-03	6.39E-03	1.84E-01	

Figure 3.18: Summary indexes of Aggregate Consumption Reduction vs. model parameters - univariate regression



Model Parameter	β est.	β est. std. dev.	t-statistic	significance
infectivity	5.10E+07	1.07E+06	4.77E+01	***
information-campaigns efficacy	3.03E+07	1.30E+06	2.33E+01	***
contacts	5.88E+04	3.08E+03	1.91E+01	***
demand-side-management efficacy for demand response	2.42E+07	1.38E+06	1.75E+01	***
discomfort parameter	1.50E+07	1.40E+06	1.08E+01	***
media-coverage efficacy	6.66E+06	1.40E+06	4.75E+00	***
interest in economic gain 0	6.09E+06	1.44E+06	4.22E+00	***
advertisement efficacy	5.22E+06	1.45E+06	3.59E+00	***
interest in economic gain	4.42E+06	1.46E+06	3.03E+00	**
available market threshold value	-4.29E+06	1.42E+06	-3.02E+00	**
interest in environmental effects 0	4.11E+06	1.43E+06	2.87E+00	**
SSRm flow parameter	-2.08E+06	1.45E+06	-1.43E+00	
available market threshold value for information campaigns	1.87E+06	1.48E+06	1.27E+00	
demand-side-management efficacy	-1.14E+06	1.42E+06	-7.99E-01	
initial-information quality	-1.14E+06	1.45E+06	-7.84E-01	
EEA flow parameter	-9.52E+05	1.45E+06	-6.55E-01	
interest in environmental effects	8.22E+05	1.43E+06	5.75E-01	
ease parameter	7.77E+05	1.47E+06	5.28E-01	
SSRa flow parameter	-7.87E+05	1.49E+06	-5.28E-01	
opt-out percentage	5.59E+05	1.10E+06	5.10E-01	
tariff-difference in 2013	-3.85E+05	1.41E+06	-2.73E-01	

Figure 3.19: Summary indexes of Demand Response adoption vs. model parameters - univariate regression

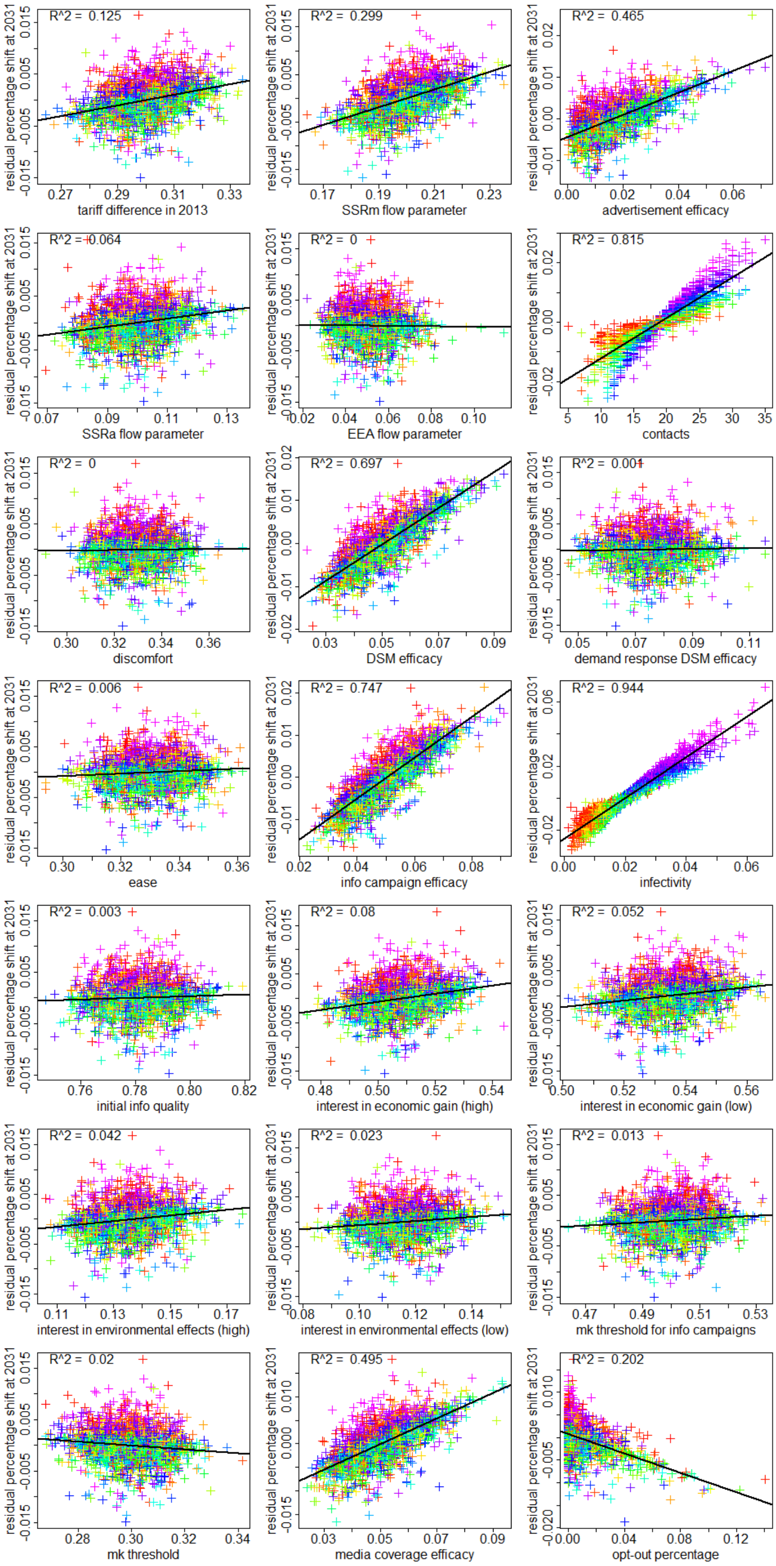


Figure 3.20: Scatter plot of Aggregate Consumption Shift vs. model parameters - multivariate regression

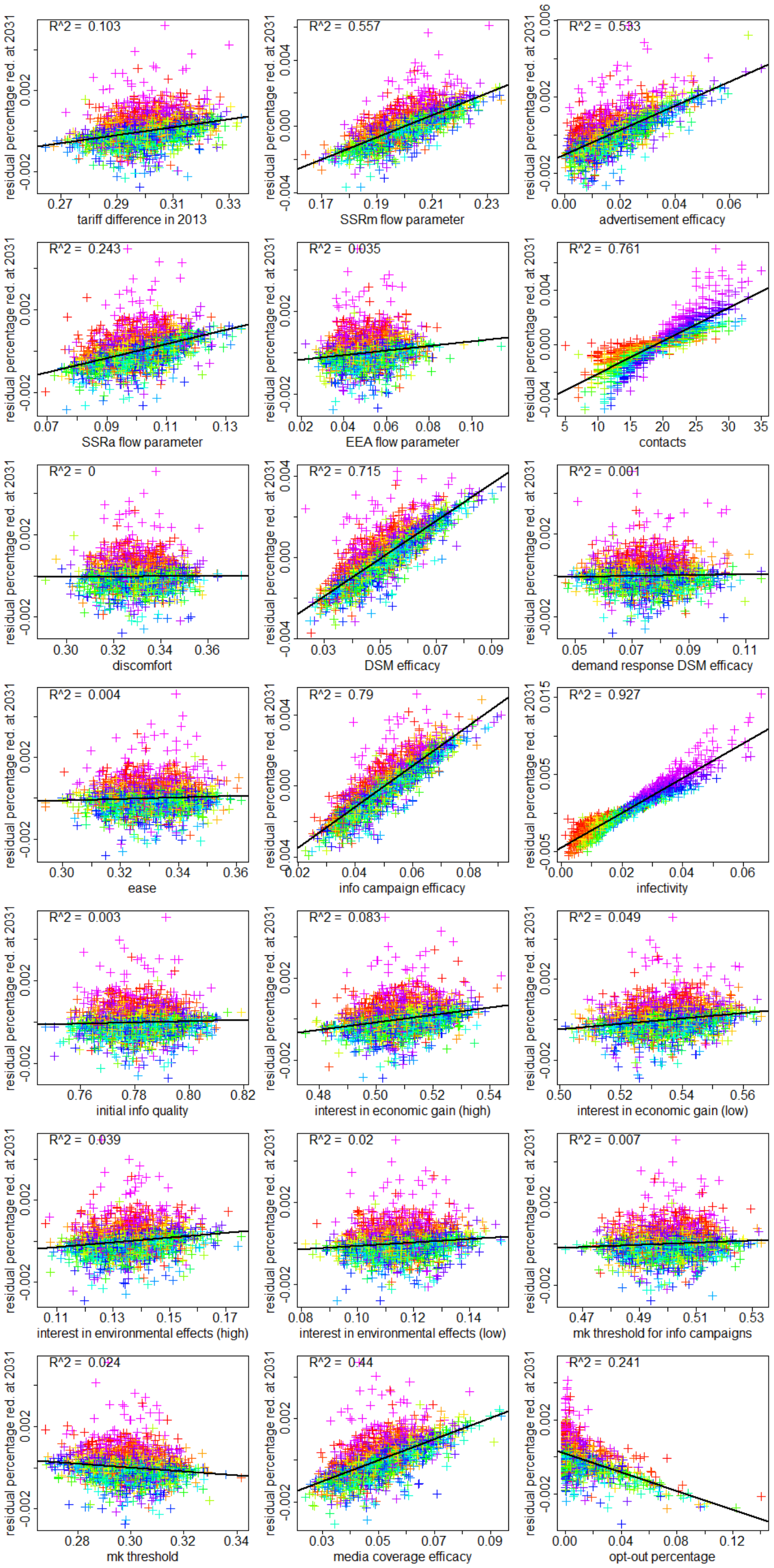


Figure 3.21: Scatter plot of Aggregate Consumption Reduction vs. model parameters - multivariate regression

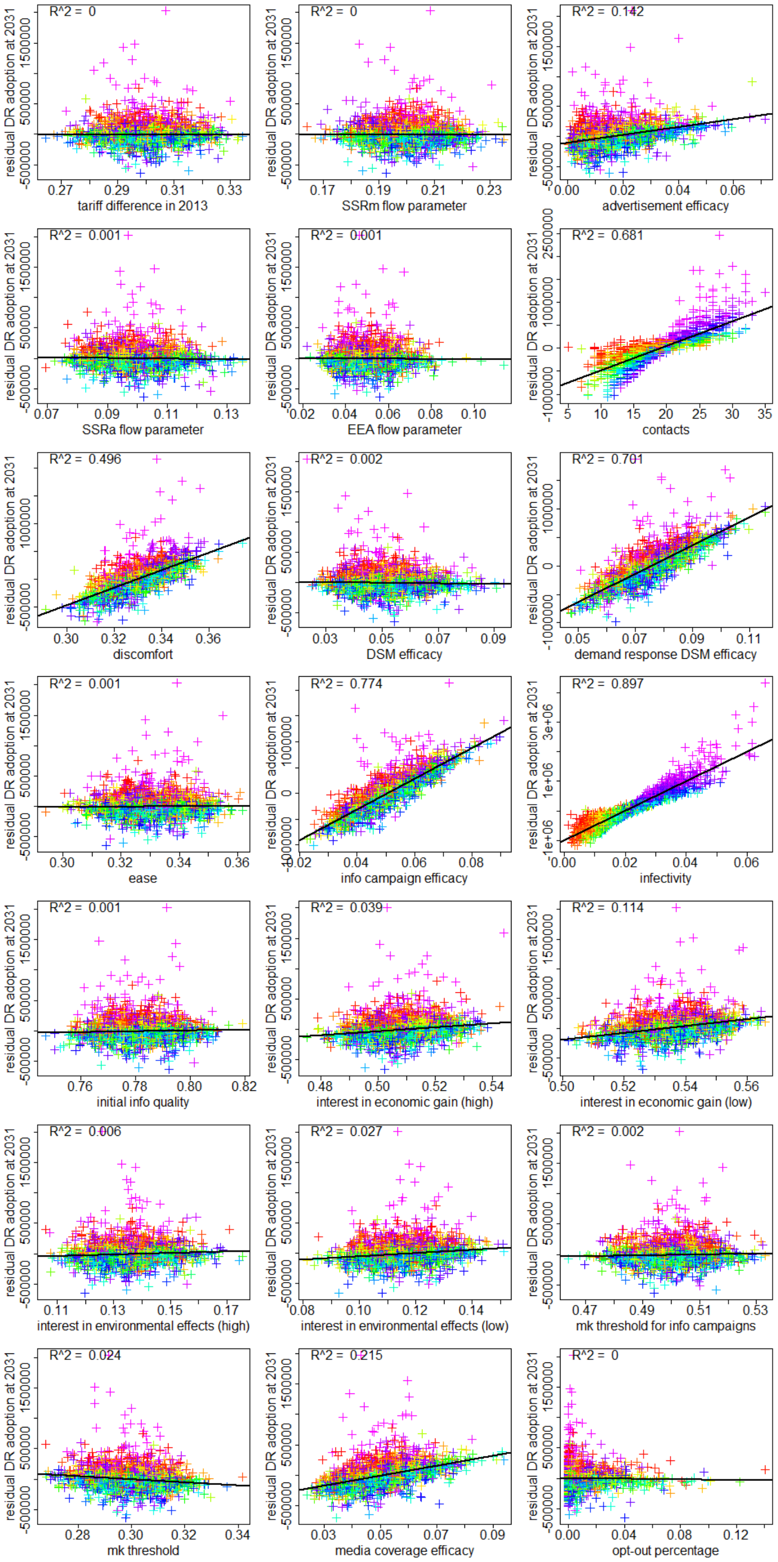


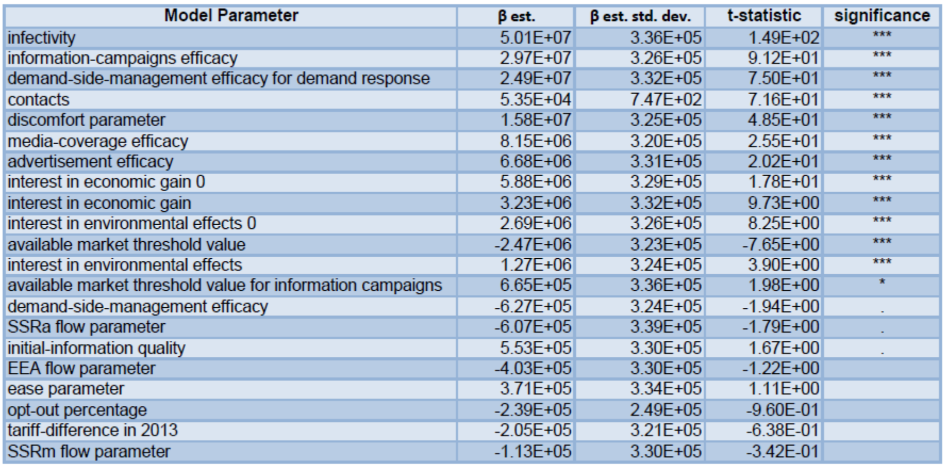
Figure 3.22: Scatter plot of Demand Response adoption vs. model parameters - multivariate regression

Model Parameter	β est.	β est. std. dev.	t-statistic	significance
infectivity	1.28E+00	5.97E-03	2.14E+02	***
contacts	1.36E-03	1.33E-05	1.02E+02	***
information-campaigns efficacy	4.85E-01	5.79E-03	8.38E+01	***
demand-side-management efficacy	4.26E-01	5.75E-03	7.42E+01	***
media-coverage efficacy	2.72E-01	5.68E-03	4.80E+01	***
advertisement efficacy	2.68E-01	5.88E-03	4.56E+01	***
SSRm flow parameter	1.88E-01	5.87E-03	3.20E+01	***
opt-out percentage	-1.07E-01	4.42E-03	-2.42E+01	***
tariff-difference in 2013	1.02E-01	5.71E-03	1.79E+01	***
interest in economic gain	8.34E-02	5.89E-03	1.42E+01	***
SSRa flow parameter	7.44E-02	6.03E-03	1.24E+01	***
interest in economic gain 0	6.85E-02	5.85E-03	1.17E+01	***
interest in environmental effects	5.80E-02	5.76E-03	1.01E+01	***
interest in environmental effects 0	4.33E-02	5.79E-03	7.48E+00	***
available market threshold value	-3.91E-02	5.73E-03	-6.82E+00	***
available market threshold value for information campaigns	3.32E-02	5.97E-03	5.57E+00	***
ease parameter	2.28E-02	5.94E-03	3.84E+00	***
initial-information quality	1.48E-02	5.87E-03	2.51E+00	*
demand-side-management efficacy for demand response	7.79E-03	5.90E-03	1.32E+00	
EEA flow parameter	-4.33E-03	5.86E-03	-7.39E-01	
discomfort parameter	4.18E-03	5.76E-03	7.26E-01	

Figure 3.23: Summary indexes of Aggregate Consumption Shift vs. model parameters - multivariate regression

Model Parameter	β est.	β est. std. dev.	t-statistic	significance
infectivity	2.27E-01	1.25E-03	1.81E+02	***
information-campaigns efficacy	1.15E-01	1.22E-03	9.47E+01	***
contacts	2.42E-04	2.79E-06	8.68E+01	***
demand-side-management efficacy	9.35E-02	1.21E-03	7.75E+01	***
SSRm flow parameter	6.76E-02	1.23E-03	5.49E+01	***
advertisement efficacy	6.45E-02	1.24E-03	5.22E+01	***
media-coverage efficacy	5.10E-02	1.19E-03	4.28E+01	***
SSRa flow parameter	3.44E-02	1.27E-03	2.72E+01	***
opt-out percentage	-2.52E-02	9.28E-04	-2.71E+01	***
tariff-difference in 2013	1.91E-02	1.20E-03	1.60E+01	***
interest in economic gain	1.80E-02	1.24E-03	1.45E+01	***
interest in economic gain 0	1.39E-02	1.23E-03	1.13E+01	***
interest in environmental effects	1.17E-02	1.21E-03	9.68E+00	***
EEA flow parameter	1.12E-02	1.23E-03	9.10E+00	***
available market threshold value	-9.04E-03	1.20E-03	-7.51E+00	***
interest in environmental effects 0	8.39E-03	1.22E-03	6.90E+00	***
available market threshold value for information campaigns	5.13E-03	1.25E-03	4.09E+00	***
ease parameter	3.95E-03	1.25E-03	3.17E+00	**
initial-information quality	3.16E-03	1.23E-03	2.56E+00	*
demand-side-management efficacy for demand response	1.79E-03	1.24E-03	1.45E+00	
discomfort parameter	7.68E-04	1.21E-03	6.35E-01	

Figure 3.24: Summary indexes of Aggregate Consumption Reduction vs. model parameters - multivariate regression



Model Parameter	β est.	β est. std. dev.	t-statistic	significance
infectivity	5.01E+07	3.36E+05	1.49E+02	***
information-campaigns efficacy	2.97E+07	3.26E+05	9.12E+01	***
demand-side-management efficacy for demand response	2.49E+07	3.32E+05	7.50E+01	***
contacts	5.35E+04	7.47E+02	7.16E+01	***
discomfort parameter	1.58E+07	3.25E+05	4.85E+01	***
media-coverage efficacy	8.15E+06	3.20E+05	2.55E+01	***
advertisement efficacy	6.68E+06	3.31E+05	2.02E+01	***
interest in economic gain 0	5.88E+06	3.29E+05	1.78E+01	***
interest in economic gain	3.23E+06	3.32E+05	9.73E+00	***
interest in environmental effects 0	2.69E+06	3.26E+05	8.25E+00	***
available market threshold value	-2.47E+06	3.23E+05	-7.65E+00	***
interest in environmental effects	1.27E+06	3.24E+05	3.90E+00	***
available market threshold value for information campaigns	6.65E+05	3.36E+05	1.98E+00	*
demand-side-management efficacy	-6.27E+05	3.24E+05	-1.94E+00	.
SSRa flow parameter	-6.07E+05	3.39E+05	-1.79E+00	.
initial-information quality	5.53E+05	3.30E+05	1.67E+00	.
EEA flow parameter	-4.03E+05	3.30E+05	-1.22E+00	
ease parameter	3.71E+05	3.34E+05	1.11E+00	
opt-out percentage	-2.39E+05	2.49E+05	-9.60E-01	
tariff-difference in 2013	-2.05E+05	3.21E+05	-6.38E-01	
SSRm flow parameter	-1.13E+05	3.30E+05	-3.42E-01	

Figure 3.25: Summary indexes of Demand Response adoption vs. model parameters - multivariate regression

3.5 Discussion

Our results show that consumers can be successfully involved and that they do respond to appropriate stimuli.

The speed of the diffusion of the different smart energy behaviours is strongly influenced by the actions of policy makers and electric power providers. Indeed, policies can be targeted to both consumers - for example with awareness campaigns - and utilities - for example by imposing best practices or price schemes, like it has happened in Italy with the differentiated tariff by the electric energy and gas authority (AEEG). Moreover, the role of electricity providers in promoting the diffusion of such behaviours is also crucial, as they can decide to implement the minimum activities imposed by regulation or to design proactive initiatives to take advantage of the new opportunities of interaction with the end-user. An example of these two kind of approaches can be seen in the Italian market, where certain providers are designing and using the new options, and encouraging consumers to take on an active role in the electric system, offering (*i*) information and tips on how to reduce wasteful consumption, (*ii*) services to install solar panels in residential dwellings, and (*iii*) taking part in various research projects on innovative functionalities of smart grids and demand response programs. On the contrary, other providers advertise the opportunity to enroll in flat tariff schemes, favoring consumer passivity, although this constitutes a “voluntary passivity”.

Literature shows how the use of smart metering and price signals, and the diffusion of distributed generation brings about benefits to all parts: consumers, utilities and society.
In this direction, there is a value to be attached to electric self-sufficiency. This self-sufficiency is not intended in a pauperistic way, but follows the idea of taking advantage of local opportunities to reduce environmental impacts and increase economic opportunities within communities, in connection with the global system, that has the role of integrating ’local energy ecosystems’.

These new options affect a market that is in equilibrium, therefore, in order to modify it (by integrating more renewable and distributed real and virtual generation sources supported by Smart-Grids) there is the need of an outside “push” (low carbon policies, low risk energy strategies, etc.). Indeed, there is a strong risk of contrast between small smart and active prosumers and large utilities that aim at maximising their revenue. Policy need to be developed so that these two realities can synergically interact, for example changing the reward system for utilities in a way that revenue is not only influenced by the quantity of customer consumption, but also the quality of consumption (energy efficiency, self-generation, shift and reduction of consumption with respect to previous years, interaction with customers and services provided for load management, etc.).

There are, indeed, in current literature, many proposals to completely automatize also the load management, i.e., the demand side of the phenomenon, putting therefore the consumer out of the game. We also consider automation to be a positive aspect to reduce effort and increase efficacy, though the automation included in our model is one available to the consumer, and therefore a voluntary, programmable and reversible automation on specific actions, at specific times with specific criteria. The more diffused engineering approach is most likely easier to administer, but it looses the chance to take advantage of the social and cultural implications that the technological advancements of the power grid may have. We instead consider the opportunity of a qualitative change in the end-user's role to be very important.

3.6 Conclusions

The aim of the paper is to analyse the system effects of Smart-Grids in the light of climate change mitigation policies, with particular attention to the new opportunities and behavioural changes available to end-users, that can now become active and "Smart" electricity users/"Prosumers".

We simulate the adoption of Smart-Grid enabled behaviour by consumers within a System Dynamics model, that considers ten possible behavioural stages. The stylized behavioural stages modelled include various combinations of the following actions: (*i*) no change in consumption patterns, (*ii*) shift in electricity consumption, (*iii*) reduction in electricity consumption, maintaining similar comfort levels, (*iv*) home automation and energy efficiency improvements, (*v*) enrollment in demand-response programs, and (*vi*) electricity generation. The flow of households from one stage to the others is influenced by many factors; the motivational drivers that are modelled are (*i*) economic savings and (*ii*) environmental and societal benefits; while the main informational channels included are: (*i*) information campaigns, (*ii*) demand-side-management policies, (*iii*) word of mouth, (*iv*) media coverage, and (*v*) advertising. Our System Dynamics model builds on Bass, 1969 and the Susceptible-Infectious (SI) models applied in epidemiology and is used to simulate the diffusion process of what we define as "Smart energy behaviours".

More in detail, we firstly propose a conceptual model that can be used as a prototype to estimate models for local evaluations, and secondly simulate a first application to the case of Italy, where the largest deployment of Smart-meters has taken place, up to now. Data availability is still quite scarce as the phenomena involved are at their very early stages, but the model can be easily updated once more specific data are available; in any case, the emerging trends and qualitative adoption dynamics appear to be quite stable to small variations in the parameter values (For details, see Section

3.4.3).

Our simulations show the quantitative importance of the effects of consumer behavioural changes. Indeed, we find that, on average, consumer involvement may induce an aggregated shift in total residential electricity consumption of 13.0% by 2020 and of 29.6% by 2030; and reduction in residential electricity consumption (just by reducing wasteful consumption) of 2.5% by 2020 and 9.2% by 2030. These consumption changes may have strong impacts on the system operating costs (in the order of 380 M€/y by 2020, 1203 M€/y by 2030), on the CO_2 emissions (in the order of 1.56 $MtonCO_2/y$ by 2020, 5.01 $MtonCO_2/y$ by 2030), and on customer savings (ranging between 266-535 M€/y by 2020 and 884-1896 M€/y by 2030, in aggregate terms).

These results show that the smart energy behavior epidemic does spread, i.e., the consumer can be successfully involved in the better management of the power system, using appropriate signals (Information, Communication and Knowledge). Indeed, consumer engagement can generate important effects in the short and medium term.

The most important factors in promoting consumer adoption are the parameters that define the strength of the word-of-mouth effect and the efficacies of the other informational channels. This may help policy makers design effective policies to accelerate the adoption process.

The previous result confirms the importance of modelling the phenomena using a tool that is able to capture the many interdependencies and the epidemic-kind dynamics.

Finally, our results confirm the relevance of consumer involvement and the importance of developing marketing strategies able to engage with the different types of consumers, to take advantage of the different “prosumer” preferences and in order to increase the system management improvements and the climate change mitigation opportunities.

3.7 Future developments

Future developments of this work will deepen the analysis of the styles of electricity consumption by end-users (“Smart” and “Non-Smart” users) and of the new contracts that are arising, in order to better analyse the evolution of the roles of the various players on the energy system and their impacts.

It will also extend the analysis with respect to the impacts and potentials of distributed micro-generation, and analyse the contribution of public buildings, and of commercial and non-energy related industrial activities.

When specific data will be available, the model will be calibrated with real data to improve the calculations of the diffusion phenomena and of the impacts, costs and benefits of different policies.

It will also explore the potentials of citizen aggregation to go beyond the individual physical limit of space/"roof" availability

3.8 References

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3.9 Appendix A

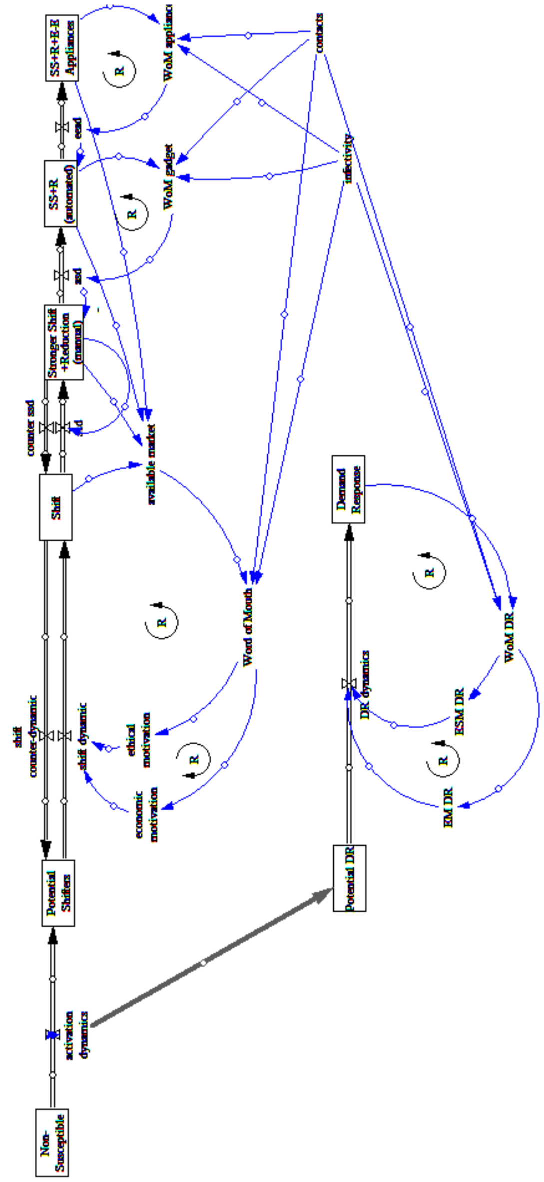

Figure 3.26: Word of Mouth feedback loop

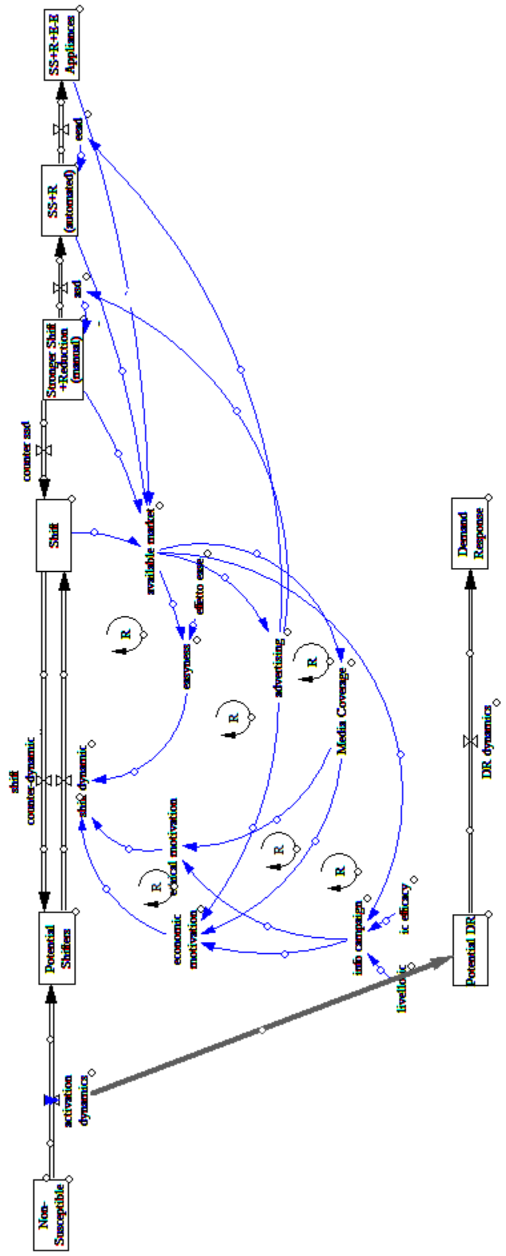

Figure 3.27: Available Market Ease Media Coverage - Advertising feedback loops

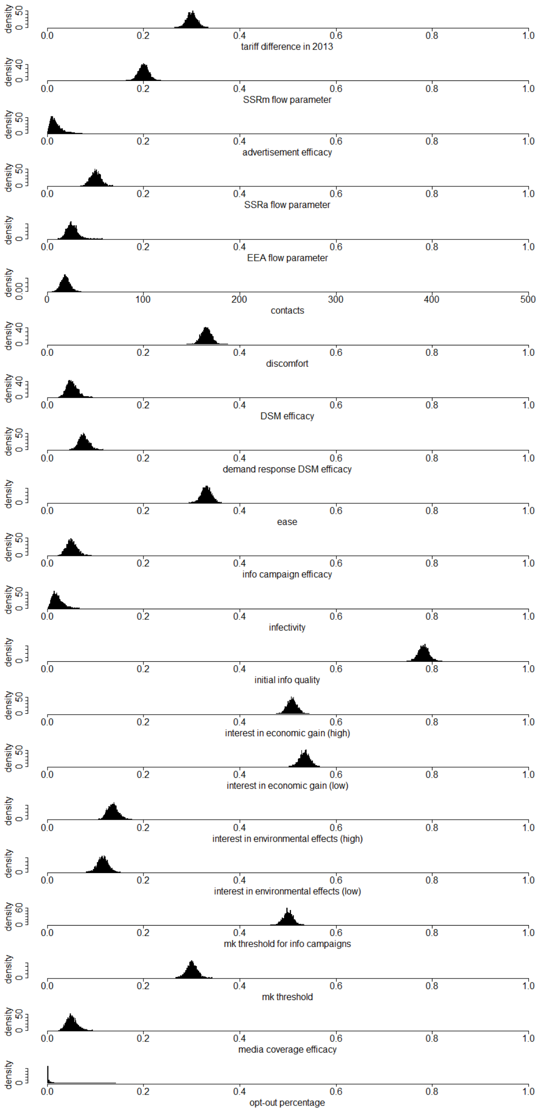

Figure 3.28: Parameter sample densities

Chapter 4

Super & Smart Grid integrated investment scenarios. Green Energy Management Strategies for sustainable scenarios

Abstract

We extend the WITCH model to consider the possibility to invest in power grid innovation, under both technological options of Super and Smart Grids. Super Grids allow to produce and trade electricity generated by large scale concentrated solar power (CSP) plants in highly productive areas that are connected to the %demand centres through High Voltage Direct Current (HVDC) cables; Smart-Grids allow: i) to increase the share of renewable power manageable by the power network, ii) to reduce the costs of customer relationships via Smart Meters; iii) residential consumer to generate electricity via micro-photovoltaic plants, and iv) residential consumer to generate virtual electricity via consumption management. We find that it becomes optimal to invest in grid innovation, in order to start gaining the management benefits and taking advantage of consumer generating opportunities (of electricity and "nega-watts"), starting in 2010 and to exploit the increased possible penetration of renewable energy sources from 2035. Long-distance CSP generation becomes optimal only from 2040, and trade from 2050; but it reaches very high shares in the second half of the century, especially when penetration limits are imposed on nuclear power and on carbon capture and storage operations (CCS). On the whole, climate policy costs can be reduced by large percentages, up to 48%, 34%, 24%, 64%, 55%, for the USA, Western Europe, Eastern Europe, MENA and China, respectively, with respect to corresponding scenarios without the grid innovation via Super and Smart Grid option and with limits on nuclear power, CCS, and CSP import. The analysis is then extended to compare these options considering, at least qualitatively, the differentiated impacts on the environment, technology, organization, society, local and national economies and geopolitics.

Keywords: Smart-Grids, Climate Policy, Integrated Assessment, Renewable Energy, Residential Power Generation, Demand Side Management Concentrated Solar Power, Super-Grids, Electricity Trade

4.1 Introduction

The aim of this paper is to conclude the analysis of the effects of the innovation of the electric power network via Super-Grids and Smart-Grids, started in the first paper through simulations with the WITCH Model of the dynamics and impacts of long distance CSP powered Super-Grids, and continued, in the second paper, with the analysis of Smart Grids in a System Dynamic framework simulating the dynamics of the adoption of "smart" energy behaviour by the emerging new "smart user".

More specifically, this paper aims at analyzing the integrated system effects induced by the innovation through both types of technologies, trying to answer to the question about the importance of the grid-innovation in climate change mitigation policies and in supporting a large expansion of renewable energies in the power system. We are interested in studying the economic feasibility of this expansion as renewables seem to be today the only available power source if we want to reduce the use of both: (i) CO_2 intensive power sources for climate change reasons and (ii) nuclear power for social acceptability and risk-related reasons, and if Carbon Capture and Storage (CCS) operations are also hindered by acceptability, regulatory and economic issues.

To this aim, the paper integrates the results of the two previous papers for an analysis that firstly takes into account the economic and climate implications of the implementation of Super and Smart Grids within the WITCH Model, and then, secondly, extends the scope of the evaluation beyond the economic perspective taking into consideration many multiple issues relevant in the evaluation of energy and climate policies.

More in general, one of the hypotheses is that the innovation of the grid may align the electric power system to the new services and processes of the Knowledge Society. Indeed: (*i*) Smart Grids - and in particular Smart Metering - open new interaction channels between users and providers of

the electricity network and give a new role to the end-user that can - via a smarter grid - decide to become an active player of the energy system.
Moreover, (*ii*) Super-Grids, with their capability of bulk and long distance transmission, allow new electricity networks to arise and significant reorganizations of existing ones.
These changes induce many important effects on society and on the electric system itself at different levels (economic, environmental, organizational, geopolitical, etc.) that are often undervalued. In other words, the implementation of Smart and Super Grids is capable of producing a qualitative change in the power network and in the energy market itself.
The focus on the innovation of the power grid is related to the fact that this is the infrastructure that enables to integrate the different electricity sources and services and that will (or will not) allow to sustain and manage the transformation of the electric power system, towards one with a greater and more sophisticated use of renewable sources and of consumer empowerment.
The nature in itself of renewable power is different with respect to other power technologies; indeed, its primary energy sources are much more diffused and the technologies needed for power generation are very scalable, therefore, the possibility of a power network that allows distributed generation can take advantage of this qualitative difference. If this option will take off and reach considerable levels of market penetration, it will change quite significantly the system's framework and influence society, as it has often happened in the past. Moreover, it will be one of those cases where quantity may enable also strong qualitative changes to the system (from a centralized distributive system to one that integrates local systems).

More in detail, we aim at evaluating within the WITCH model (*i*) the economic attractiveness of the innovation of the power network via Super and Smart Grids, (*ii*) the optimal time and sizing of investments in all of the different options newly available, (*iii*) the implications for the optimal mix of the electric power sector, and (*iv*) its impacts on the climate change stabilization-policy costs.
The analysis is then extended, in the second part of the paper, by (*v*) carefully discussing the qualitative differences between the two types of grid innovation, and (*vi*) disentangling the differential impacts, at various levels, that these two types of evolution might have, separately or in an integrated way. To this aim, we build a multi-dimensional evaluation function to compare the performance of different power system development strategies on the environment, technology, economics, organizational structures, society and geopolitics. For now, the analysis is only qualitative, but future work will include the development of quali-quantitative indices that will enable a full multi-criteria analysis.

The rest of the chapter is structured as follows. Section 4.2 illustrates the methodology for the first part of the analysis, Section 4.3 reports the main technical assumptions and data sources, Section 4.4 describes the scenarios under evaluation, while Section 4.5 reports the simulation results. Section 4.6 presents the multi-dimensional analysis of the impacts of Super and Smart Grid integrated investments. Section 4.7 summarizes and discusses the main results, while Section 4.8 illustrates future research work.

4.2 Methodology

To carry out this integrated analysis we build on the two models of the previous two chapters. The first part of the analysis is an economic evaluation, under different climate and energy policies, able to compare the relative attractiveness of Super and/or Smart Grids with respect to other mitigation options in achieving climate policy targets. Indeed, we extend the WITCH Model - in the version that includes concentrated-solar-power powered Super-Grids (CSP-SG) - so that it is able to take into consideration, even if in an approximated manner, also the option of investing in Smart-Grids. In the second part of the analysis, we try to compare qualitatively the characteristics of the two grid innovation options to be able to grasp different impacts that have not been analysed much in the literature, and that the economic-energy-climate model is not able to capture to their full extent.

Note that, although both types of innovation may sustain different power technologies, we focus on their potential when linked to renewable sources, and in particular to solar power.

4.2.1 Modelling assumptions

Super-Grids are modelled, as described in Chapter 2, Section 2.3, by allowing *i*) CSP generation in high irradiance areas located distantly from demand centres; *ii*) its transmission over long distances with HVDC cables; *iii*) and its trade across regions.

Smart-Grids are modelled through four main model extensions. Qualitatively, the idea is that if investments are dedicated to the innovation of the power network, four options arise.

The first two are related to the technological aspects of the Smart innovation of the power network: (a) the first is the relaxation of the constraint on the use of domestic renewable sources due to technical limits of the power network; (b) the second is the introduction of the efficiency gains in the management of a smarter grid. The third and fourth dimensions are instead more related to the potential effects of consumer engagement. More specifically, we consider the addition of two new generation sources, namely

(c) a "real" source, such as residential photovoltaic (PV) generation, and (d) a "virtual" source that is consumption reduction through demand-side-management policies.
Note that these modelled aspects correspond to those identified by the EU (European Commission, 2011; European Commission, 2009) as being the most important, as described in the previous Section. In addition, to these, the EU highlights the importance of electric vehicles which will be the next step of our research, once transportation will be explicitly included in the model.

In our modelling framework, investments in the "smartening" of the power grid (I_{SMART}) accumulate as follows:

$$SMARTCUM(n,t+1) = SMARTCUM(n,t) + 5 \cdot I_{SMART}(n,t) \ .$$

For each region and at each time step, the level of innovation of the power system is evaluated with an index that ranges between [0,1]:

$$INNOV(n,t) = \frac{SMARTCUM(n,t)}{SGI(n,t)} \ ,$$

where SGI is the estimated cost for a complete "smartening" of the power grid. The index $INNOV$ is used as a signal that progressively activates the options that are induced by Smart-Grid investments, proportionally to the level of innovation.
Indeed, the bound on domestic wind and solar power ($W\&S$) that was included in the model of the first paper, due to the difficulties of the current power systems to manage non-programmable supply, has been modified so that it can be relaxed as the network is smartened:

$$W\&S(n,t) = TOT_{ELEC}(n,t) \cdot (0.25 + \phi \cdot INNOV(n,t)) \ ,$$

where TOT_{ELEC} is the total amount of electricity consumption.
The other mainly technological impact of Smart-Grids is represented by the benefits of remote management (AVC), that lowers the costs of operating the system. These are added to the budget constraint equation (Equation 4.1) as they correspond to a reduction in the expenditure, that can be employed elsewhere.
The other two additions to the model are related to consumers. More specifically, we have added a new technology that is residential micro-PV generation, i.e., generation by micro photo-voltaic plants of 3kW, that is the size generally associated with household generation. The next step will be to add also commercial, industrial and public buildings, with small-medium size plants.
The amount of PV electricity supplied to the grid by consumers (EL_{PV}), in each region and at time period, is determined combining in fixed proportions the generation capacity accumulated (K_{PV}) multiplied by the number

of yearly full-load hours that a PV plant in the region may provide (μ_{PV}), and the operation and maintenance costs ($O\&M_{PV}$), subject to the constraint on EL_{PV}:

$$\begin{aligned} EL_{PV}(n,t) &= min\left\{\mu_{PV,n} \cdot K_{PV}(n,t); \theta_{PV} \cdot O\&M_{PV}(n,t)\right\} \ , \\ EL_{PV}(n,t) &< maxEL_{PV}(n,t) \cdot INNOV(n,t) \ . \end{aligned}$$

The power generation capacity in residential PV accumulates as most other technologies in the model do:

$$K_{PV}(n,t+1) = K_{PV}(n,t)(1-\delta_{PV}) + \frac{I_{PV}(n,t)}{SC_{PV}(n,t)} \ ,$$

where I_{PV} represents the investments in PV capacity and SC_{PV} the relative investment costs. The latter decreases as world installed capacity increases (TK_{PV}), via a learning-by-doing effect:

$$SC_{PV}(n,t+1) = SC_{PV}(n,t_0)\frac{TK_{PV}(t)}{TK_{PV}(t_0)}^{-\alpha} \ .$$

Such investments, together with the operation and maintenance costs, enter the budget constraint (Equation 4.1).

We consider consumption management as another source of electricity, even if virtual (EL_{dsm}). The second paper has showed how consumers may allow a better exploitation of the electricity generation installed capacity. In future work, we will also model the effects of demand response programs, where consumers get paid to reduce their load at specific times. We model consumer "nega-watts" as an additional generation technology as currently demand-response aggregators, such as Enernoc in the US and Kiwi Power in Europe, are entering the electricity market by bidding for the supply of power, that is actually "nega-power", as it is produced by programmed and contracted load reduction.
The cost for consumption management (C_{dsm}) is estimated from the literature regarding demand-side-management, as described in Section 4.3, and it is, again, detracted from the budget constraint:

$$\begin{aligned} C(n,t) &= Y(n,t) - I_c(n,t) - \sum_w p_w Z_w(n,t) - I_{SMART}(n,t) - I_{PV} + \\ &\quad + AVC(n) \cdot INNOV(n,t) - EL_{dsm}(n,t) \cdot C_{dsm}(n) + \\ &\quad - O\&M_{PV}(n,t) \ , \end{aligned} \tag{4.1}$$

where Y is net output of the economy, I_c is the investment in the final good sector, $\sum_w p_w Z_w$ is the expenditure for investments in the energy sector - including that for Super-Grids -, in R&D and other expenses that are detailed in Bosetti et al., 2006.

Also generation by demand side management policies is limited by an upper bound:

$$EL_{DSM}(n,t) < maxEL_{DSM}(n,t) \cdot INNOV(n,t) \ .$$

These two additional power generation sources have been added to the CES function as new branches of the electricity tree, at the level of fossil fuels, nuclear power and renewables. Even if, especially for residential PV, the name and the source recall that of generation with renewable sources, the generation method is drastically different from a qualitative point of view, therefore, we have decided not to put them in the same node as renewables, but in a separate nodes, at the level where the main types of generation are combined.

The results emerging from the second paper, extended to be applied to Europe, allow us to impose an upper bound to the use of these power sources according to the adoption dynamics identified. We also run simulations with no bounds to see what it would be optimal to generate, and then discuss how to enhance consumer participation, so that the optimal values for the WITCH model may be reached.

4.3 Technical assumptions and calibration

Technical assumptions and data sources for the Super-Grid modelling are reported in Chapter 2, Section 2.4.

We model the possibility to invest in Smart-Grids in Western Europe, Eastern Europe and USA. These are, indeed, the regions where most of the discussion is focused, but other regions will be added in future work.

Even restricting the geographical scope to these three regions, data on the costs for the “smartening” of the power grid are scarce. We try to overcome this problem by running our simulations over a range of values, to see what are the maximum values for which investments in these new options are optimal and how paths are influenced. Though, we choose as a reference value - for when we test different climate or energy strategies - 45, 60 and 23 billion $ for the USA, Western and Eastern Europe, respectively. Calculations are based on the costs projected by Iberdrola for Spain (King, 2011) adjusted for population size. The benefits on the system operation costs induced by smart metering have been calculated on the basis of the reduced costs and payback period of Enel in Italy, again, adjusted for population size. Enel in Italy has incurred a 2.2 billion € cost for the installation of 32 million smart meters, and is currently saving about 0.5 billion €/y, with a payback period of just over 4 years (Dolin, 2010). Note that these values do not take into account the additional savings related to the better management of outages in a sensitive network.

The costs for residential rooftop generation are set to 6734 \$2005/kW in 2005, so that in 2010 they reach a central value of range of costs reported in Bruckner et al., 2011 for 2009, though, we will test also the maximum and minimum values indicated (3700-6800 \$/kW), we also test the cost curve proposed by IEA, 2010.
Operation and maintenance costs are set to 1% of the initial investment costs (Bruckner et al., 2011; Breyer et al., 2009; IEA, 2010).
The progress ratio for the learning-by-doing effect is set to 0.90, i.e., investments costs are reduced by 10% at every doubling of the installed capacity. Learning rate estimates in the literature range from 10% up to 47% (IEA, 2010; Neij, 2008; Reich et al., 2011).

For what concerns the full load hours of operation of these micro-PV plants for the different regions, we have set the values to 1600, 1200 and 1000 h/y for the USA, Western and Eastern Europe, respectively (Adapted from Gerlach et al., 2011; EPIA and Greenpeace, 2011).

The costs for Demand-Side-Management (DSM) policies is set to 0.04\$/kWh, this is the cost for DSM programs used in Ehrhardt-Martinez, Donnelly and Laitner, 2010. This low value is coherent with our framework, where the costs for smart-meters are already accounted for in I_{smart}.

The maximum penetration values for PV residential generation and DSM are adapted from Chapter 3 and Paidipati et al., 2008. The share of residential consumption of electricity in the US and in the EU is taken from EIA, 2011 and Bertoldi and Atanasiu, 2009.
Moreover, the additional penetration level that can be reached by wind and solar domestic power (ϕ) has been set to 0.2, but it can be modified once more specific literature is developed.
Data on elasticity of inter-fuel substitution considering residential micro-PV generation or virtual generation by consumption management is not available yet. Therefore, we have decided to use the same relative elasticity functions as those of renewable sources. the model has been calibrated to replicate the situation in 2005.

4.4 Scenario design

The climate policy scenario we have chosen to analyse for our simulations is a stabilization scenario at 535ppm-CO_2eq by 2100. This is not a very stringent policy as it is meant to bring to an increase in the world global mean temperature of 2.41°C above pre-industrial levels, and it is therefore slightly over the 2°C target that is often cited in the international political debate and that is meant to avoid "dangerous climate change" (Metz et al., 2007). Though, the idea is to demonstrate that even with a relatively weak

climate target, given the current situation, it is important to aim at increasing the share of renewable resources and the participation of consumers in the mitigation processes, and, therefore, to innovate the power grid.
Moreover, we assume a global climate agreement whose policy tool is a global carbon market, in which carbon allowances can be traded among regions without limits. The allocation of the emission permits follows a "Contraction and Convergence" rule, which assigns global emissions targets to each region, initially in proportion to current emissions and then, progressively, in proportion to each region's population, with the aim of reaching similar per-capita emissions by the end of the century. These values will be compared to those of the business-as-usual ("Bau") scenario, where no climate policy is enacted, and, therefore, no cost is attached to GHG emissions.
In this context, we also analyse different possible energy policy scenarios with different assumptions on the evolution and expansion of various electricity generation technologies. More specifically, we evaluate:

- Unconstrained Scenario, where no limits are imposed on the penetration of any technology[1] (namely, "U-Stab") ;
- CSP import constrained scenario, where the import of CSP power via Europe-MENA Super grid is limited to 15% maximum of total electricity consumption in Western and Eastern Europe (namely, "IC-Stab");
- Nuclear constrained scenario, where nuclear power generation cannot exceed 2005 levels (namely, "NC-Stab");
- CCS constrained scenario, where CCS operations are not allowed (namely, "CC-Stab");
- all constraints: limit on nuclear power, on CSP import and on CCS (no CCS operations), (namely, "INCC-Stab").

We model all of the above energy scenarios for both the business as usual scenario (namely, "Bau") where no climate policy is enacted and for the stabilization policy.
In addition to the above scenarios, we model the corresponding ones without the possibility to invest in the innovation of the power grid to use as benchmarks in order to evaluate the value of the additional options.

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[1] Except for the technical limit on traditional wind and solar sources already discussed in Section 4.2.1

4.5 Simulation results

4.5.1 Optimal timing and size of investments

Our results show that for Western Europe it is optimal to invest in the innovation of the electric grid starting from the very beginning of the simulation period, under all energy policy scenarios. Once investments on grid innovation start, all the options that are made available by such investments are exploited, except for the release of the constraint on domestic renewable sources that is not binding until 2035-2050 (depending on the assumptions on the expansion possibilities of other generation technologies).
Management benefits, PV and virtual generation all drive investments in grid innovation, though the former is the most important driver that allows to reach the full innovation of the power network by 2020. Without this driver, the grid is innovated at a slower pace. Nevertheless, domestic photovoltaic generation and demand side management policies expand more if the grid is made smarter at a faster pace.

If we where to consider only the effects on promoting the use of renewable sources, investments would still be optimal, but only starting from 2040-2050 (with the grid starting to be smarter in 2045-2055) depending on the assumptions on the expansion possibilities of other generation technologies. Nevertheless, the expansion of domestic large-scale wind and solar power above 25% becomes optimal from 2030-45 if the grid is made smarter due to other drivers.
These results are in line with what is happening in Europe, where for example Enel in Italy has started to install smart meters from 2001 with a 2.2 billion $ investment that should have a 4 year pay-back period. Our results are also in line with the European Union directive (Electricity Directive 2009/72/EC) that imposes full deployment of smart metering systems by 2022 (with 80% by 2020).
The USA follows a very similar path, while for Eastern Europe the innovation of the power grid starts to become optimal later on and is completed only by 2055.
Figure 4.1 shows the residential micro-PV deployment paths for the three regions, under different climate and energy policy scenarios.
Generation increases over time and as more constraints are imposed. Indeed, a small level of production is optimal also in the Business-as-usual cases, with or without the limit on the expansion of other technologies. For all regions, climate change stabilization policies increase the optimal level of generation, but the larger difference is caused by imposing, in addition to the climate policy, a limit on nuclear power. For the USA, the two simulations with a limit on the latter power source have an exponential growth of PV generation until just before mid-century, when long distance CSP enters

the market. In Europe, imported CSP has less of an effect, i.e., there are no early peaks on DG expansion, as it enters the market later and at lower levels than in the US. The simulation scenario with all constraints (on nuclear, CCS and imported CSP) generates a demand for DG that, by the end of the century, is more than double that of the other scenarios. The largest amount of distributed residential PV generation is in Western Europe; Eastern Europe, although at very lower levels, follows similar trends to those in Western Europe.

Trends in the optimal deployment of virtual generation by consumers following demand side management policies are quite similar in qualitative terms and depicted in Figure 4.2. Expension possibilities are limited by the upper bound that is indeed binding under all scenarios. This confirms the optimality of taking advantage of consumption management by households, and suggests that further policies should be implemented to enhance and accelerate consumer adoption of “smart energy behaviour”.

4.5.2 Investments and cost dynamics

The previous Section described the optimal timing for the innovation of the electric grid and for the deployment of PV generation and “virtual” generation by demand side management policies, for the different scenarios analysed in our work. The annual investments needed in order to have such deployment paths are in the range of 0.3-5.9 Billion$ for the USA and of 0.7-8.7 Billion$ for Western Europe, except for the case with limits to nuclear power, CCS and CSP import where they reach values of 22.2 Billion$. Annual investments for Eastern Europe are much lower.

Investment patterns follow a different trend with respect to generation and installed capacity, that increase over time, due to the learning-by-doing effect, that, for example in the all-constraints scenario, makes the higher generation of the end of the century cost less than the lower early production. Indeed, investment costs for residential photovoltaic systems decline as global capacity increases.

We have modelled an endogenous Learning by Doing effect with costs declining as capacity increases. We obtain the cost curve depicted in Figure 4.3, where costs are reduced by about 30% in the first five years and continue to drastically decrease untill 2030 and then stabilize at around 2000 $/kW.

We find that, even if costs decrease substantially, they do not reach the levels estimated in the literature. This is coherent with the fact that we are modelling household generation only in three regions of the world and that the learning-by-doing is only related to residential-size PV systems, while the costs for the latter are most likely going to be affected also by other size plants. Therefore, we also model the case where the investment costs follow the projected costs by IEA, 2010. In these simulation the costs stabilize

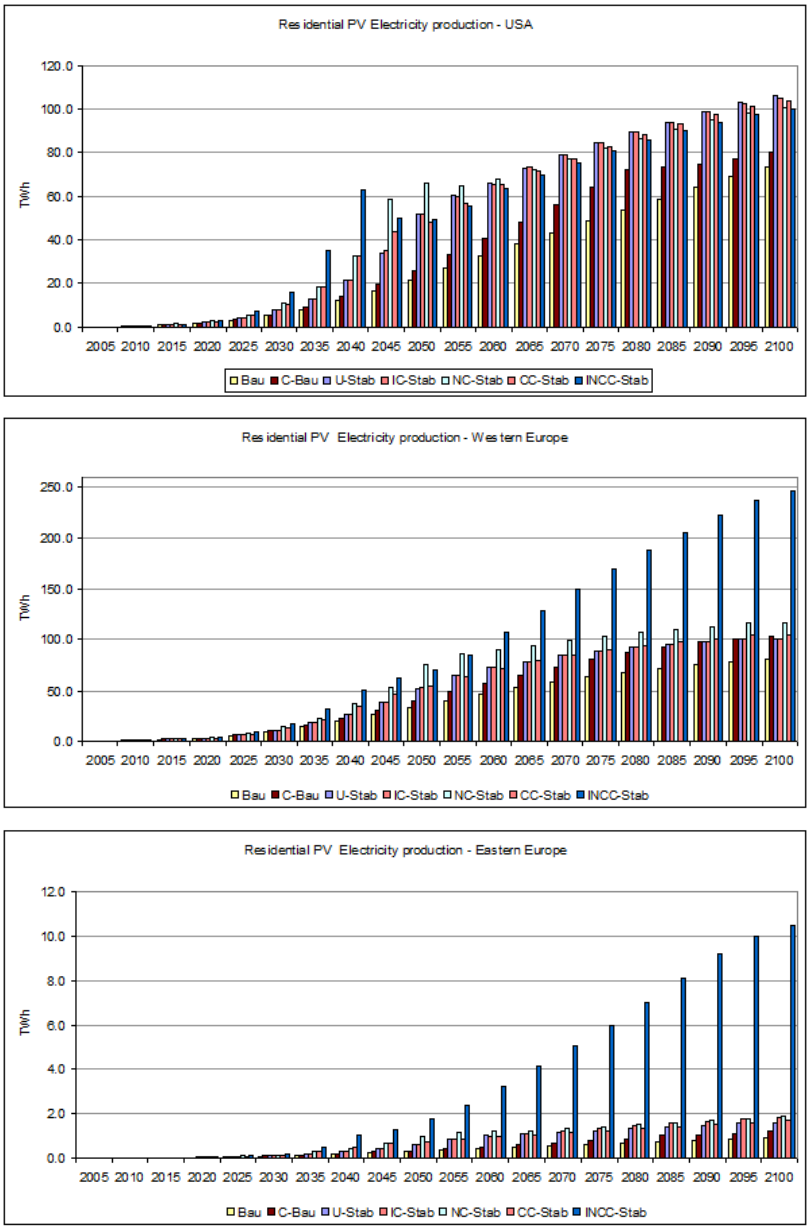
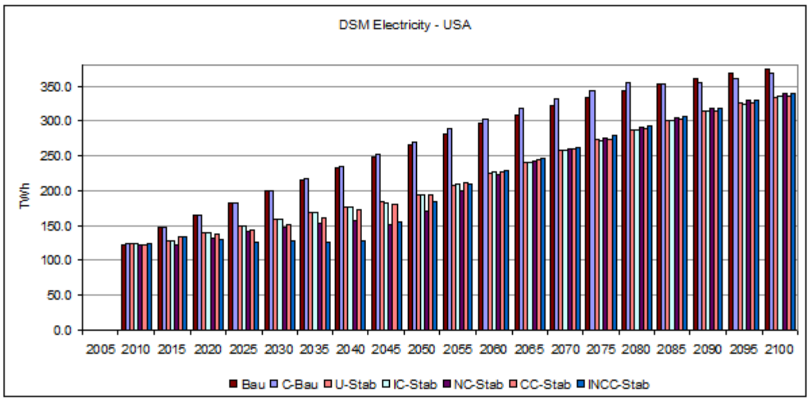
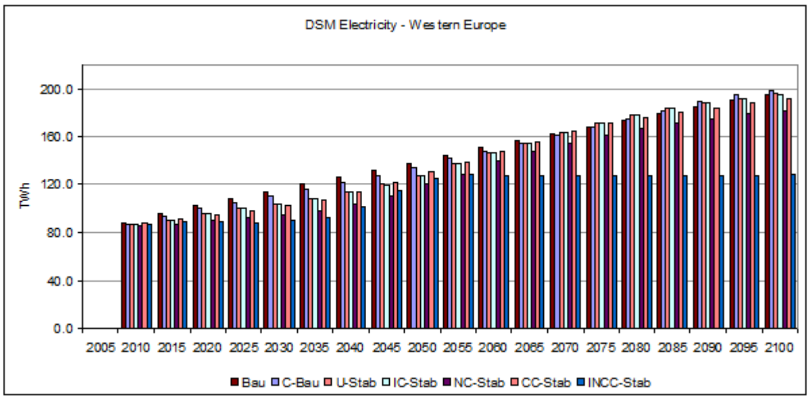


Figure 4.1: Optimal timing and generation by residential micro-PV plants





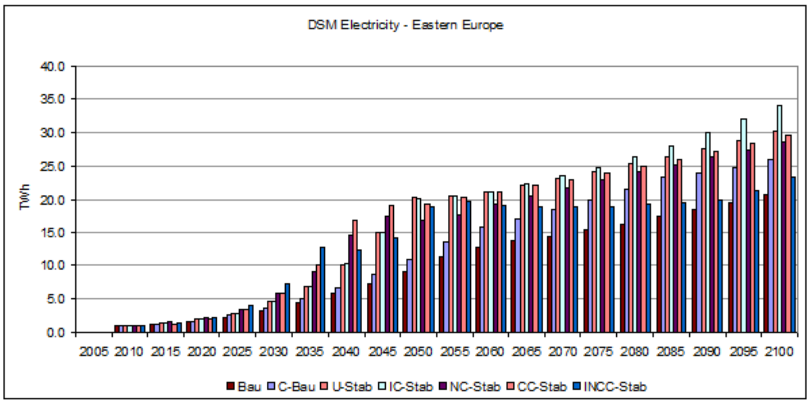


Figure 4.2: Optimal timing and generation by residential consumption management

at around 1000 $/kW. Generation values change accordingly, with values toward the end of the century that are doubled, when the price is lower.

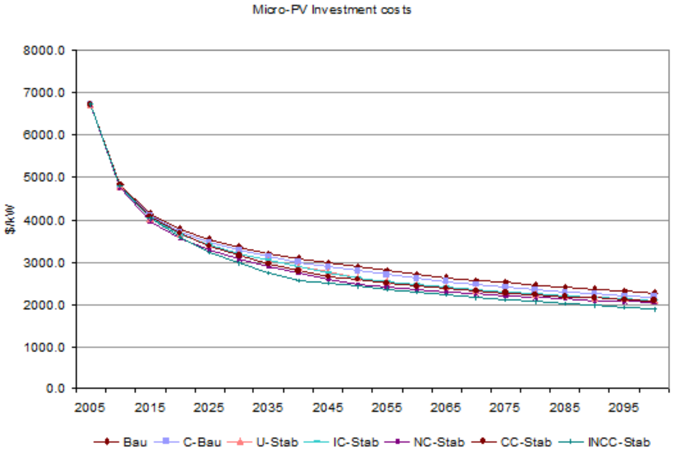


Figure 4.3: Residential micro-PV investment costs

Investments in grid innovation by allowing a greater exploitation of domestic large-scale renewable power sources induce also a reduction in the cost of the latter. Indeed, for these technologies, the WITCH model takes into consideration both a learning by doing effect and a learning by researching effect that leads the cost to decrease to about 570 $/kW by the end of the century.

4.5.3 Electricity mix impacts

The relaxation of the bound on large-scale domestic wind and solar power plants affects Western Europe for which the 25% of total generation bound is binding starting from 2035-2050, depending on the limits imposed on the penetration of other technologies. With investments in Smart-Grids, that enable a better management and monitoring of the power system, this bound can be extended. In these simulations, we relax it up to 45% of total electricity generation.
This option is exploited in all simulations, including the Bau scenarios, and the new bound at 45% becomes binding in the second half of the century, for the stabilization scenarios. Future work will try to account for the integration of supply by different sources and storage opportunities (that are for now included only for long-distance CSP), and possibly relax the bound further.

For the other regions, the bound at 25% was not binding, therefore, the relaxation does not impact their electricity mix. Figure 4.4 reports the electricity mix of the three regions with and without the option of investing in Super and/or Smart Grids.

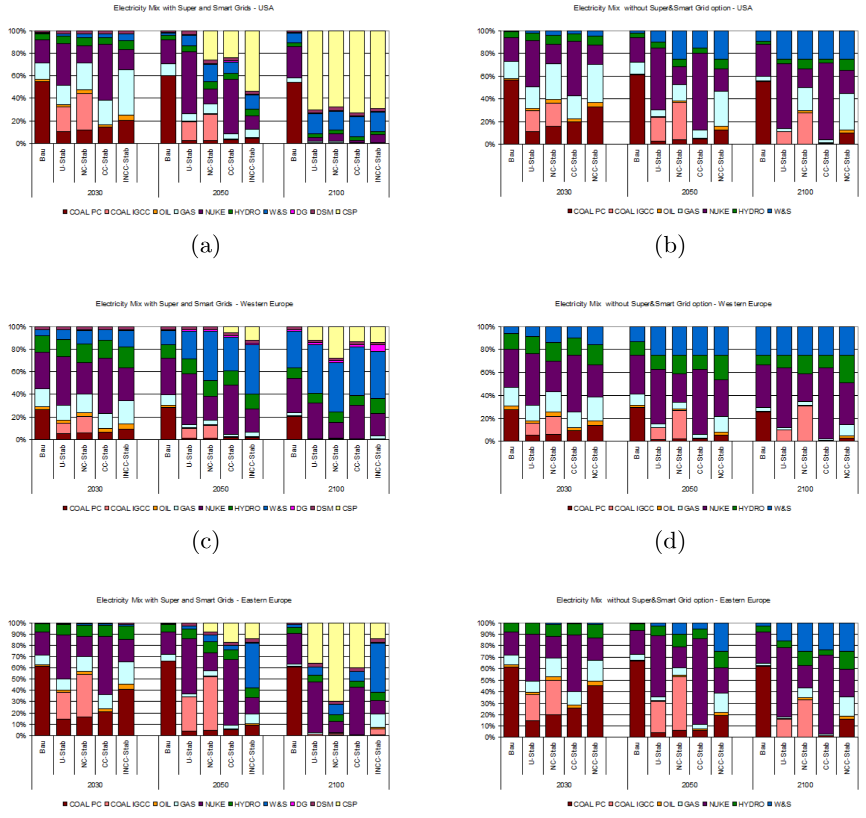
The introduction of real and 'virtual' distributed generation at the household level reduces the use of CSP, to a different extent depending on the country, but leaves its optimal deployment timing largely unaffected. Producing regions, such as China, MENA and the USA, reduce generation by between 1 and 15%; Eastern Europe does not change its import patterns much (reductions are in the range of 0-7%); while Western Europe, that is indeed the region that more exploits the options induced by Smart-Grids, reduces imports of CSP from MENA by between 11-68% (depending on the time period and on the simulated scenario), with values stabilizing between 30-44% depending on the energy policy under evaluation. The electricity mix (Figure 4.4-c) is not drastically modified by the generation of electricity by consumers, as it would be expected. Though, this new 'source' of electricity does appear in the Western European electricity mix, and ranges - depending on the time period and on the simulated scenario - around values of 0.1-5.4% for PV and up to the limit imposed on virtual generation, which for the simulations reported in the graphs is 2.8%.

The electricity mix, in Europe, is instead quite strongly influenced by the additional penetration of large-scale domestic wind and solar power plants. Indeed, the innovation of the power grid, considering both options of Super and Smart-Grids together, enables renewable sources to become dominant in the electricity mix.

In particular, in Western Europe, total renewable source generation in 2020 reaches or exceeds the 20% share that is part of the 20-20-20 EU target, and even the bau levels are around 19%. By mid century, large-scale domestic wind and solar, imported CSP, residential PV, and virtual generation, plus hydro-electric power reach between 25-73% of total generation, and between 44-85% by 2100 (depending on the assumptions on the expansion possibilities of other technologies).

In the US (Figure 4.4-a), distributed PV and virtual generation reach shares of 1.4% and 2.8%, respectively, though total renewable source generation, in stabilization scenarios, ranges between 19-75% at mid-century, and between 91-97% by 2100. Shares at the end of the century are so high in all scenarios because, in the US, CSP becomes cost competitive with nuclear power even in the absence of limits on the expansion of the latter.

In Eastern Europe (Figure 4.4-e), electricity generation by consumers ranges between 0.1-1.3% for residential PV and between 0.1-2.8% for DSM; while, on the whole, renewable sources range between 14-66% at 2050, and between 52-88% by the end of the century.



(a) (b)

(c) (d)

(e) (f)

Figure 4.4: Regional Electricity Mix with and without Super and Smart Grids

4.5.4 Impacts on the emission permit market

We are also interested in evaluating the impacts of the innovation of the power network on the global market of GHG emission permits. Figure 4.5 reports the price of the GHG emission permits over time for the four different stabilization policy scenarios. Compared to the case where Super and Smart Grids are not available, our simulations show a strong reduction in the size of the emission permit market. This is related to the fact that very large emitters such as the USA, China and Europe have an additional mitigation option, that towards the end of the century, in the presence of a significant diffusion of the technology, becomes economically interesting. This is reflected in the price, that is lower compared to the corresponding cases without Super and Smart Grids.

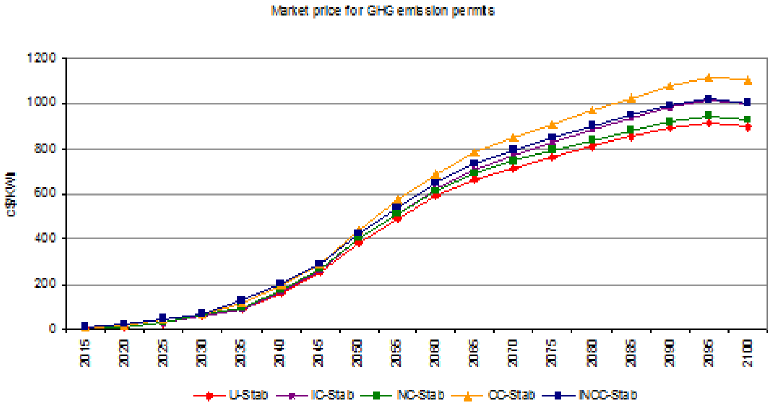


Figure 4.5: Market price for GHG emission permits under the different stabilization scenarios

4.5.5 The option value of the innovation of the power network

Literature shows that climate change stabilization policies come at a cost. How this relates to the actual benefits that it induces is not completely clear, but the precautionary principle leads us to prefer - if anything - a larger reduction than necessary rather than a smaller one, due to the irreversibilities that are part of climate change processes. A drastic reduction of GHG emissions, after the recent events regarding nuclear power - that will most likely limit its diffusion, at least in the close future and at the current state of technology - seems to be even more difficult. Our simulations show that the innovation of the power grid might give the opportunity to develop renewable sources and new organizational structures that can reach the stabilization targets with supportable losses and without the need of a drastic reduction of efficient electricity use/economic activity. Impacts of Super plus Smart-Grids on the climate change stabilization policy costs are quite large (Figure 4.6), and similar to those reported in Chapter 2. With respect

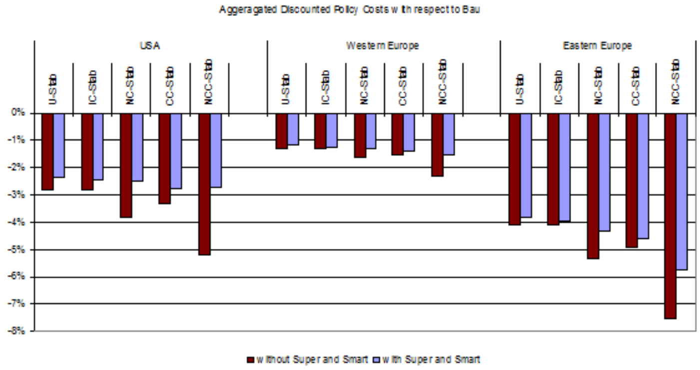


Figure 4.6: Stabilization option value of Super and Smart Grids

to the policy cases without the option of Super and Smart-Grids, cost reduction range between 13.4-47.9% for the USA, 6.5-33.8% for Western Europe, and 4.2-24.1% for Eastern Europe. The additional reduction in policy costs enabled by Smart-Grids and consumer involvement, for the scenarios that are comparable, ranges between: 3.1-5.2% in Western Europe, 0.2-0.9% in USA, and 0.1-1.1% in Eastern Europe. For MENA, instead, the costs of the stabilization increase slightly if Smart grids are introduced in Europe (and the US), as less CSP is sold to Europe, though these still remain much lower than without the Super-Grid option.

4.6 Multi-Criteria Analysis

Summarizing what has emerged in the previous part of the analysis, it seems that under all scenarios it is optimal to invest in the innovation of the power grid in order to be able to increase the share of renewable energy in the electricity mix, to better manage the power system and to engage with consumers opening new "micro-mitigation" opportunities.

The innovation of the power grid, especially of the smart grid type, will allow the power grid to follow the trends emerging in current society, where citizen empowerment is the centre of a qualitative evolution of the new services and dynamics of the Knowledge Society.

In this second part of our analysis, we develop the quali-quantitative analysis further. In the previous Section we were able to integrate economic, energy, climate and geopolitical issues within the WITCH model; here we

want to extend this analysis also to other aspects. To this aim, we put forward the proposal of a general assessment method for the evaluation of the differential impacts that different climate change mitigation strategies can have. It is mainly thought for energy related strategies, but it can ultimately be applied to any type of analysis that aims at taking into account the full set of costs, benefits and changes of different options. In particular, in this work we use it to evaluate the different system effects induced by the innovation of the power grid via Super and Smart Grids.
This methodology, that we denominate GEMS, i.e. Green Energy Management Strategies for sustainable scenarios, is based on a multi-dimensional evaluation function that aims at accounting for the various facets of the processes involved. Indeed, each strategy is evaluated on the basis of its performance with respect to the following dimensions: Environment, Technology, Economics, Organizational Structures, Society, Geopolitics.
This multi-level sustainability function:

$$GEMS = f(Env, Tech, Ec, Org, Soc, GeoP) \ ,$$

tries to take into account many aspects of investments and mitigation strategies that are usually not captured by economic models. This further step is done in a qualitative way, but the aim is to develop, in future work, quali-quantitative indices that will enable a quantitative multi-criteria analysis.

Environment

From an environmental point of view, Super-Grids and Smart-Grids both allow for an increase in the profitable use of renewable electricity sources. For quantitative results please refer to the previous Sections. Though, the electricity is generated and distributed very differently and this generates a qualitative difference that produces different local and global ("glocal") effects.
More specifically, these technologies involve different areas/"surfaces", very different scales and different infrastructure needs. Indeed, Super-Grids connect large distant plants with HVDC cables, while Smart-Grids allow generation also by micro-small systems, possibly placed over existing surfaces, with no additional consumption of land. Micro residential installments do not even need additional cables for distribution.
Moreover, a sensitive (via Smart) and integrated (via Super and Smart) network can allow to aim at local self-sufficiency of local energy ecosystems - integrated with the national power system - taking advantage of the specific local opportunities and conditions.

Compared to electricity generation with fossil fuels, an innovated power network capable of enhancing the role of small and large scale renewable sources is able to reduce the GHG emissions of the power sector. This aspect was included in the simulations of the previous section. In addition to this benefit, there are also other aspects that should be taken into consideration and that where not included in the simulation model. Indeed, local air pollutants are not emitted and therefore health and food safety risks are reduced. This kind of generation and transmission also does not suffer problems related to hazardous waste, although a full Life Cycle Analysis needs to be performed in order to get a full picture.

Land occupation is also an important aspect to take into consideration; indeed, micro generation on roofs or other already occupied surfaces does not create any additional competition for land, but on the contrary allows the latter to be of more than one use. Large renewable energy plants, especially solar or wind, do instead pose land use issues. Though, as these plants do not pose any health related hazards, they do not need a security area around the plant, making the occupied surface less important.

These considerations can be quantified, for example, by looking at the social costs for local pollutant emissions, and at the opportunity cost of land.

Technology

The same subdivision of quantitative and qualitative impacts also applies to the other arguments of the evaluation function.

For example, from a technological perspective, both Super and Smart Grids relay on existing technologies that, however, need to be improved. In order to reach performance optimization, investments are needed. Again, the technological improvements needed are qualitatively different. Super Grids need improvements that are markedly (purely) engineering and aim at the increase of the transmission efficiency. These investments and improvements involve large power plants or transmission lines and, consequently, large industries, in a very centralized system. Smart Grids require investments also in information and communication technologies, that aim at transforming qualitatively the power system in a sensitive network, favoring, in this way, a greater interaction with the end-users and allowing to trigger innovative processes that are in line with the evolution of the Knowledge Society. The innovation still requires the study of some very engineering components, but also of software and services that can be developed and installed by small enterprises. The latter kind of developments may also have positive spillovers in other sectors where similar innovations can be applied.

Moreover, additional investments are also needed for renewable generation technologies; and both Smart and Super Grids, by allowing an increase in renewable energy opportunities, can participate at the demonstration and diffusion processes of these technologies, further allowing for a decrease in their costs and a consequent increase in their spread/deployment.

Indeed, both options allow to invest in technologies that most likely will be prominent in the future, thus increasing the value of the knowledge and capacity built, and less on technologies that are currently more diffused but may have a decreasing role over time. The differential impacts may be evaluated through, for example, literature review and expert elicitation regarding the possible spillovers and their value, and concerning the value of investing in promising technologies in terms of competitive advantage and avoided stranded costs.

Economy and Finance

Even from an economic point of view, impacts are different. Super-Grids favour an evolution with a more classical flavour, related to large investments for and by (for/by) large national or international enterprises, in a very centralized system. Smart-Grids put forward a more innovative evolution, that shifts from the canonic system structure towards trends that are emerging in other sectors, favoring:

- the participation of a greater number of agents/stakeholders;
- the emergence of a greater variety of roles;
- the engagement with agents of different sizes, including local and small-size operators.

Indeed, the role of the end-user is rethought. End-users move out of their passive stance and have the opportunity to become more conscious and active. This opens to a greater variety of behaviour, that can go from small every-day actions to new economic and financial opportunities. Active participation and revenue-making in the power system is now open also to small residential consumers (now “prosumers”).

Moreover, the economic activity induced by investments that favor an opening of the market is very different. Business opportunities arise for many more agents, that are of different sizes and that were already or not in the business, most likely increasing the share of national enterprises in the market.

The skills needed to develop both Smart and Super Grids - linked with renewable energy sources - may also constitute an opportunity for increasing competitiveness of national industries and may have positive spillovers also in other sectors, first of all those of other commodities, such as natural gas and water. Indeed, as the consumer gets used to be more empowered with respect to its electricity consumption choices, he will most likely require more sophisticated services also in other domains.

From a financial point of view, capitals for investments in Super-Grids infrastructure and related power plants, necessarily come from large holdings, while for smart grids there is the possibility to draw alongside these also capitals from medium, small and micro agents. The latter can indeed invest in their own electricity self-sufficiency, enhancing the value of their activity and/or property, and gaining a business opportunity. New financial investments opportunities may arise also for those agents that are not able to produce themselves, but can, for example, finance local and cooperative projects.

A crucial point from a management and policy point of view, is the ability to find ways for these different agents to interact positively and avoid conflict.

Organization

From an organizational point of view, Super-Grids replicate past models, mainly centralized and top-down, while Smart-Grids offer the opportunity to change the system structure, enabling to integrate and manage different types of sources at different scales, up to the micro-residential level, and to take advantage of local characteristics and opportunities.

With both types of innovation, the power network will gain greater importance within the electric system. The management of such system will largely depend on the grid capabilities. Super-Grids will allow the power network to increase in size, while Smart-Grids will allow it to become more sensitive. Both these advancements will enable the network to have a greater integration role as opposed to only a passive distributive one.

As already highlighted in the previous paragraphs, the innovation of the power grid is able to trigger a reorganization of the whole sector, with additional new agents, new services and kinds of behaviour, and business opportunities. Residential consumers, small and medium size enterprises can now change their consumption patterns and exploit behavioural/production process changes or electricity generation opportunities to reduce their costs and, possibly, generate revenue. Other businesses can arise to favour and help the latter exploit their real and virtual generation opportunities.

These are organizational models that can open to prospects and changes that go well beyond the power system.

Society

From a social point of view, Super-Grids tend not to modify the passive role of the consumer; the only social impact that can be induced is the possibility to supply the renewable energy necessary for climate change stabilization reasons and to respond to the demand for renewable electricity coming from a niche of consumers. This may indirectly generate a diffusion process of sensitivity to environmental-energy related issues.

Smart-Grids, instead, promote an active role of the end-user and of its empowerment opportunities. This process starts with a greater diffusion of information and knowledge, that together with tariff policies, allows the consumer to take more conscious consumption decisions and continues with more services and opportunities that enable the end-user to become an active component of the electric power system. An interesting application of such trends is emerging in the so-called "Smart-Cities", where citizen are gaining a more central and active role.

In order to exploit the full potential of Smart-Grid investments, citizens need to be given the tools to be able to become active agents of the electric power system, these include both technologies, economic choices and knowledge. Indeed, the empowerment of the consumer will need electricity providers and businesses to offer consumption management and generation opportunities to their customers; but it will also need the diffusion of an environmental and energy culture among citizens. The ability of consumers to evaluate the environmental footprint of their consumption patterns, will also have impacts on citizen's environmental awareness, and, possibly, the diffusion of behavioural changes also in other aspects of consumer choices.

From a societal point of view, Smart Grids give the chance to take advantage of local generation and storage opportunities creating new economic and organizational bonds/relations between members of the same community, that may become energy-ecosystems with the aim of becoming, at least partially, energy self-sufficient. These need to be integrated with the centralized system, and possibly interconnected by Super-Grids, to maintain stability and quality of service, but they allow to develop local economic opportunities and to reduce some environmental impacts related to electricity generation and transmission.

Geo-politics

From a geopolitical point of view, Super-Grids may have strong impacts, due to their ability to transmit large quantities of electricity over large distances. If the sources of the transmitted electricity are national (like for example for the USA and China, in our simulations) this may increase national energy independence and, thus, security. In this direction, a large exploitation of national renewable sources that where up to now not economically advantageous could have an impact on trading patterns and relationships.

On the contrary, if the electricity transmitted is imported, like in the case of Europe in our simulations, Super-Grids may still increase the share of renewable sources, but also reduce the energy independence of the region. Though, innovative models of international cooperation may generate new equilibria, able to take advantage of relative resource distribution, by in-

troducing perspectives that go beyond administrative barriers to exploit geographical proximity that can favor all parts.
Furthermore, a large development of local micro-generation opportunities and the diffusion of different-sized energy self-sufficient ecosystems, may increase the energy independence and security of a country. The diffusion of these ecosystems will be enabled by Super-Grids that may constitute the back-bone of the system that integrates single self-sufficiencies.

Indeed, these are two types of innovation that apparently aim at the same goal, that is to favour the development and diffusion of electricity generation via renewable sources, but that present very different characteristics that are able to trigger different multi-level impacts. Indeed, the organizational, social and economic "games" that follow an innovation *via* Super-Grids or *via* Smart-Grids are quite different. This can potentially generate situations of conflict (of interest): large vs. small economic agents, local vs. long-distance supply, etc.
It is important to develop policies that are able to avoid conflict and take advantage of both innovation opportunities. To do so, it is crucial to have available an integrated and multi-criteria assessment tool, able to support policy-makers identify strategies and business models that allow a harmonious and synergic evolution of Super and Smart Grids.

4.7 Conclusion

Our results confirm the important role of renewable sources in future energy scenarios. Indeed, scenarios with high penetration levels of renewable sources seem to constitute the only way foreword if we want to limit the use of fossil fuels for climate change concerns and of nuclear power for security and long-term waste management issues, without large losses for the economy. In our simulations, scenarios without a large expansion of renewables, indeed, consume less electricity and suffer much larger economic losses compared to the scenarios where renewables, but with limits on CO_2 emissions and on the expansion possibilities of nuclear power and coal with CCS, are extensively used (differences range between 1% and 38%). Indeed, renewable energy in this kind of scenarios allows economic development (with no additional emissions of CO_2).

The innovation of the power grid may have, in this context, an important role in enabling a large deployment of renewable electricity generation. Indeed, both Super and Smart Grids can play a crucial role, even if with different timings.

The management efficiency benefits induced by the transformation of the power grid in a sensitive network make it optimal to invest in grid "smartening" starting from now (investments from 2005 and power generation from 2010). The consequent deployment of smart meters makes consumer engagement - through real and virtual power generation - optimal from 2010 too. Note that the relative size of generation from end-users may not be large compared to other "sources", but it is qualitatively very different and it may have powerful spillovers in other domains. Residential consumers account for about 30% of total power demand, depending on the region, therefore consumption management and demand-side-management affect a percentage of this share. For what concerns residential micro-generation, there is a limit with respect to space, but this will be relaxed as the efficiency of solar panels improves and as the aggregation capabilities of consumers increase. Moreover, the relative impact of these generating opportunities may expand significantly if commercial activities and public building are included in the analysis.

Moreover, the innovation of the grid also allows - Europe in particular - to increase the penetration of renewable sources in the electricity mix due to better managing capabilities. In our simulations, this becomes relevant starting from 2035 when the share of (domestic) wind and solar generation exceeds 25% (that is the limit that was imposed in the first paper to simulate the technical limitations of the "old" obsolete power network).

The other main enabler of a large increase in the share of renewable sources is the implementation of super grids that allow bulk transmission over long distances (with relatively low losses) enabling the exploitation of efficient renewable sources located far away from demand centres, and also the interconnection of power systems for smoothing the supply from renewable sources. In our work, we specifically look at bulk long-distance transmission within or across power systems, leaving to future work the simulation of the domestic balancing opportunities; though, our results suggest that an intra-regional super grid-network within Europe, able to connect and integrate different domestic renewable source potentials (for example, North-South), is likely to be optimal, possibly before the import of CSP electricity from MENA.

These results depict quite well the current situation, where investments in Smart-Grids and smart-meters are already taking place, while projects for a Europe-MENA power connection are discussed but further away from being implemented. This "picture" is most likely dependent on the size of the investments involved and on the uncertainties of an international trade of electricity, that need to be resolved before any deployment may become credible (On this topic see also Chapter 2).

Renewable sources - here intended as hydroelectric, large-scale wind and solar power, long-distance domestic or imported CSP and consumer distrib-

uted generation - reach, under all scenarios and in every region, very high shares in the electricity mix; indeed, shares range between 11-26% at 2020, 14-75% around 2050 and 52-97% by 2100.
More specifically, we find that the innovation of the power grid, in the form of Super and Smart Grids, has a high option value in reducing the costs for the climate change mitigation (or GHG stabilization) policy, especially if there are no limits on imported CSP or if there are limits on nuclear power and/or CCS. Cost reductions, with respect to the corresponding cases without the grid innovation option, range between 13.4-47.9% for the USA, 6.5-33.8% for Western Europe, and 4.2-24.1% for Eastern Europe.

These values, that emerge from the economic model, are evaluated as GDP differences for the different electricity mix scenarios, therefore, they reflect the differential costs for technologically achieving the climate targets. The second part of the analysis, instead, emphasizes the additional benefits or criticalities that the different technological scenarios may have, focusing on the option of Super-Grids and Smart-Grids.

This second type of analysis is carried out performing a multi-criteria evaluation aimed at capturing the multi-level impacts of energy strategies. The multiple arguments of our sustainability evaluation function concern the impacts on: environment, technology, economics, organizational structures, society and geopolitics. We extend the variables of the analysis as the problem needs not to be solved in a narrow (mono-dimensional) cost minimization way, but indeed the concept of cost needs to be extended to take into account also social, environmental, geopolitical (etc.) costs. This is in line with policy-making that does not only consider differences in investment and operating costs, and with the instances that promote a broadening of concept of state performance beyond GDP.

In this direction, the WITCH model is already able to take into account externalities related to GHG emissions[2], that is the most prominent issue for mitigation; though, the innovation of the power system, and mainly the introduction of Smart-Grids, introduces the possibility to go further as the relative generation opportunities are qualitatively different from the traditional power technologies studied up to now.
Indeed, a smartening of the grid can (*i*) change the system structure and, therefore, (*ii*) open to new relational structures between the systems components, that have multi-level impacts. In particular, the decentralization of a previously very centralized system (*iii*) modifies the roles of the agents; indeed, in this framework, end-users can become sources in addition to being sinks. Moreover, (*iv*) new players can enter the market, at different levels. New players that are not necessarily very large companies, but also medium and small size ones. Even (*v*) investments in the innovation and

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[2] or in the case of nuclear power, waste management issues

future management of the system may come from smaller financial players. Indeed, even citizens can enter the market, as active managers of their own electricity demand, as small electricity producers, or as financial promoters of generation opportunities; in this way, they may become 'micro-mitigation' opportunities (For quantitative evaluations please refer to Chapter 3 - Section 3.4.4 and Chapter 4 - Section 4.5.1).

(*vi*) The level of complexity of the system's management is increased because the variable of human behaviour is introduced in the system. This evolution is new for the power sector, but it has already been experimented in other sectors, like those of IC&T and telecommunications, where consumers have proved to be able to manage their empowerment.

Our analysis has shown that (*vii*) these processes and structural changes may have impacts on the environment, on society, on the local and national economies, and possibly also in other sectors.
The increased complexity and variety of options and players urges new models to evaluate, and then manage, energy strategies. We propose a multidisciplinary methodology to go beyond the concept of “grid parity”, unless the parity concerns a full internalization of costs and benefits at the various levels. The methodology proposed here is only qualitative, but future work will aim at extending it and identifying quali-quantitative indices that will enable a full multi-criteria analysis, that could be denominated 'Green Energy Management Strategies' (GEMS) for sustainable scenarios.

Moreover, our qualitative evaluation has highlighted that, in the context of the innovation of the electric power grid, (*viii*) it will be crucial to develop policies that will enable Super and Smart Grids - i.e., large and small players - to interact in a synergical way and to avoid a conflict between these innovation strategies. Indeed, these changes are in a market that would in itself be stable and that is urged to change by reasons outside of the market, i.e. climate change issues or safety concerns regarding electricity generation. Thus, it is unlikely that existing large players will welcome the changes that may potentially reduce their market share; therefore, a push from outside is needed to develop policies to favour a healthy interaction, like for example the development of a reward system that is not only based on quantity but also on quality of the power and/or energy services provided. In other words, (*ix*) there is the need for the regulatory agencies (that already exist) to design new electricity integration rules and rewarding systems able to promote a synergic and more efficient system.

To take advantage of the full potential of an innovated power network, it is important to engage with the consumer; the consumer needs to be 'technically' empowered - indeed power utilities need to take advantage of the new interaction channels made available by smart meters and inverters, and offer consumption management and self-production opportunities - but also empowered with knowledge. Indeed, it will be crucial to diffuse not only information but also knowledge concerning the power system and its multilevel impacts, and the consequences of the consumer every-day consumption decisions. Therefore, there is the need for a promotion of diffused and distributed environmental and energy culture, that goes well beyond current environmental communication, with the aim of favoring the recognition and internalization of the complexity and multi-facet nature of the processes.

To conclude, this second type of analysis has allowed us to highlight the joint additional effects that may be induced by the different processes that may be chosen to reach the common goal of reducing GHG emissions. Additional impacts that are not"secondary" in terms of importance and effects.

4.8 Future developments

Future work will try to extend the simulation of the effects of Smart-Grids on the power system within the WITCH Model, by firstly considering the option of Demand Response and other consumption management options in lowering the costs of the system management and in producing additional "nega-watts". Secondly, we are going to make investments in grid innovation affect the buffer capacity of power systems and, thirdly, we are going to also include the storage option given by electric vehicles. The impact of current and future-work smart-grid options will be extended to take into account the potential that lies within commercial activities, public buildings and non-electricity related industries.

Furthermore, we would like to introduce some geographical space differentiation within the regions, in order to be able to describe the renewable energy different potentials within regions and test the optimality of the Super-Grid option of connecting them. Especially for Europe, this will be interesting for evaluating the relative benefits and costs of domestic renewable generation versus import from North Africa. This will also allow a greater integration of the two modelled options (Super and Smart Grids).

The Europe-MENA case in particular, highlights the importance of improving the multi-disciplinary analysis of the second part of our study. Indeed, we will identify quali-quantitative indices to quantify the relative performance of the different electricity generation and distribution strategies with respect to the environment, technology, economics, organization, society and geopolitics. This will make the comparative evaluation more complete and relevant for policy recommendations.
More in general, the GEMS multi-level sustainability function may be applied in other domains, where electricity generation and distribution strategies will be very important in future scenarios that are affected by constraints on

GHG emissions and by the complete life-cycle and risk assessment of generating technologies. Particularly interesting cases, where we will test our approach, are those of Smart-Cities and the Agricultural and Agri-business sector. Both, indeed, may benefit by the implementation of smart-grids that favors distributed generation and the pro-activity of the end-users, that are able to become a more prominent part of the system.

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Chapter 5

Final remarks and future developments

The thesis approaches the topic of the innovation of the power network in the light of climate change mitigation objectives.

The hypothesis at the basis of the thesis - developed in in three papers:

First Paper (Chapter 2) New electricity generation networks and climate change: the economic potential of national and trans-national Super-Grids powered by Concentrated Solar Power.

Second Paper (Chapter 3) Smart-Grids and climate change. Consumer adoption of smart energy behaviour: a system dynamics approach to evaluate the mitigation potential.

Third Paper (Chapter 4) Super & Smart Grid integrated investment scenarios. Green Energy Management Strategies for sustainable scenarios.

- is that the innovation of the power network, *via* Super-Grids and Smart-Grids, is an opportunity for a qualitative transformation of the power system that may allign it to the new organizational spaces/times that are emerging in the processes towards a sustainable and knowledge-based society. The drivers of this transformation, as we have tried to highlight in the thesis, are together economical, technological, environmental, organizational, social and geopolitical. This implies the need to develop a multi-criteria objective function to optimize all aspects jointly.

Future energy strategies that may allow the migration towards a low-carbon society and economy constitute a very topical theme in continuous evolution. Indeed, during the development of this thesis, technologies have changed in their relative importance on the international debate agenda. For example, at the beginning of this work, nuclear power was considered as a necessary base technology to reach climate change mitigation targets. Now, after the recent incidents in Japan, the political rethinking concerning nuclear power developments by some governments decreases the role of this power source in the short-medium term, and leaves the "burden" of low-carbon development to renewable power technologies.

This evolution is generating a change in perspective that goes in the direction of promoting the development and enhancement of renewable sources, that still require additional R&D investments to become cost competitive with other generation options. Even if such development is being and will be influenced by the global and European economic crisis, its direction should not change drastically, but instead it should be able to promote a more conscious and careful management of energy strategies. The results of the discussions in Durban confirm that the process for reaching a global agreement on climate change is still ongoing.

Important change is currently visible also among consumers and power providers, that are starting to change attitude and taking into consideration new styles of management of the electricity consumption patterns implied by everyday behaviour. This transformation is highly noticeable looking at the new marketing strategies of large power providers and at the emergence of many new "green" providers. Indeed, marketing strategies of the power sector are today aiming at consumer engagement, exploiting the new technological opportunities made available by the innovation of the power network (via Super and Smart Grids). This engagement is appearing to follow two different directions: on one side, a more pro-active role of the consumer is favored and stimulated, on the other, there is the promotion of a more "hands-off" one, reproposing in this way the traditional patterns characterized by a passive role of the end-user. In any case, the development and proposal of many differentiated contracts that may appeal to consumers with very different preferences, with the aim of making the consumer look for a tailored offer, is evident. This is a change that is going in the direction of offering more advanced and tailored services as it has happened for example in the telecommunication market. Indeed, Smart-Grids, in particular, and the innovation of the power network, more in general, could represent the opportunity for the power system to align itself with the new trends and processes of the new knowledge-based society that enhances consumer empowerment.

The thesis has highlighted the importance of the qualitative transformation of the power network taking advantage of (*i*) the potentials of increasing the use of renewable power sources and of (*ii*) the greater variety of possible relations among the actors of the system, that opens to individual, group or organizational empowerment processes; both of which offer mitigation opportunities. The innovation of the power network opens the challenge of rivisiting the concept of spaciality in the power system, to make the power network become "glocal", i.e., able to integrate and jointly optimize locally and over long distances.

In this context of ongoing evolution and with new emerging trends and opportunities, we are interested in developing further the results of the thesis - described in detail in the three chapters - along different lines of research:

1. **Spatial Glocalization -** Extend the analysis of the integration of Super and Smart Grids, introducing some variability within the macro-regions to be able to capture the opportunities induced by domestic variability in the consumption and generation of electricity, thus favoring the synergies among sources. More in detail, adding some spacial variability within the macro-regions of the WITCH Model will enable to investigate more deeply into the optimal location problem of power generation on the basis of: production efficiency, distance from demand, land availability and opportunity cost. With these model extensions, it will be possible to better model the balancing possibilities of connecting separate sub-regions within the regional networks and to compare domestic opportunities with import options.
2. **Innovative network opportunities -** Deepen the economic analysis of the technological potentials of Smart-Grids looking at the impacts on buffer capacity sizing and management and storage opportunities (including those related to Electric Vehicles).
3. **Smart prosumers -** Deepen the analysis of the styles of electricity consumption by end-users ("Smart" and "Non-Smart" users) and of the new contracts that are arising, in order to better analyse the evolution of the roles of the various players on the energy system and their impacts.
4. **Energy self-sufficiency in low carbon society -** Improve the evaluation of the effects of distributed micro-electricity-generation and energy-self-sufficiency, analysing also the contribution of commercial activities and public buildings in generating electricity. To this aim, we intend to develop a system dynamic model to simulate the adoption potentials of "smart energy behaviour" by these other new actors, and to include these results in the IAM platform.
5. **GEMS - Green Energy Management Strategies for sustainable scenarios -** Develop the quantitative features of the GEMS sustainability function, in order to be able to apply the model. Applications of this function will be extended also to other important sectors - like agriculture, Smart-Cities, mobility, logistics and transport, etc.

> - with the aim of defining a general model that can be applied in a variety of cases, to allow the comparison among different mitigation strategies in diverse fields.

To conclude, the innovation of the power network appears to be: (*i*) a complex evolutionary process in search of a functional equilibrium; (*ii*) a challenge toward a new type of power-network; (*iii*) a non linear and discontinuous pathway towards innovative system configurations and scenarios, that deal with a multi-level concept of sustainability, capable of integrating jointly many aspects.

In other words, the innovation of the power network is a complex process that must be approached with a multi-disciplinary perspective, that has not yet been fully developed and widespread - among both analysts and actors of the system, including the newly empowered "Smart prosumers" - and that still requires a strong research effort.

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