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# An Integrated Assessment of Super & Smart Grids

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## Summary

We assess the optimality of investments in power grid innovation, under both technological options of Super and Smart Grids, using the WITCH model in the version that includes Super-Grids. Super Grids allow producing and trading of 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. We extend the model to include also Smart-Grids that 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% for the USA, Western Europe, Eastern Europe, 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

**JEL Classification:** C61, Q42, Q54

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# An integrated assessment of Super & Smart Grids

Elena Claire Ricci

## Abstract

We assess the optimality of investments in power grid innovation, under both technological options of Super and Smart Grids, using the WITCH model in the version that includes Super-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. We extend the model to include also Smart-Grids that 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% for the USA, Western Europe, Eastern Europe, 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.

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# 1 Introduction

Current electric power systems are qualitatively the same as they where in the last century; although capacity and efficiency might have been improved, their qualitative structure/rules have remained very similar. Though, today the power network is faced with various challenges such as:

- the necessity to improve its efficiency, security and quality of service;
- the necessity to manage an increased amount of renewable energy sources to face the climate change issues;
- the need to interact with consumers that are becoming used to be more empowered and active.

Indeed, the power network 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, capable of responding to the current societal challenges that require its modernization.

The two types of evolution possible are to include features of Super-Grids and/or Smart-Grids in the national electric power networks. Super-grids are intended to connect, in a more integrated way, electric power systems, facilitating trade between regions and to take advantage of distantly located energy sources. This may enable an increased geo-political diversification of energy sources for energy security issues and also an increased usage of low carbon technologies, reducing the electric power sector $CO_2$ footprint. Smart-grids aim at exploiting local electricity production possibilities in line with “glocalization” trends. Power systems have always been centralized and unidirectional, but the need to increase the share of low carbon energy sources - as required by the most foreword-looking policies - makes distributed and low-scale production relevant. This will require the exploitation of innovative ICT solutions and a different kind of involvement of consumers, who acquire an active role. The induced consumer empowerment - that is in line with the development of contemporary knowledge society - needs to be taken into account and enhanced.

These two options are quite often treated separately or, at the opposite, confused in the literature.Indeed, these two types of innovation are quite different in their philosophy, technology and impacts, though could generate interesting synergies once integrated.

In this direction, 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 takes into account the multi-level impacts of the implementation of Super and Smart Grids using for the economic, technological and climate aspects an integrated assessment model (IAM) - namely the WITCH Model, and extending the scope of the evaluation taking into consideration, qualitatively, also other issues relevant in the evaluation of energy and climate policies, such as organizational changes, local economy, societal and geopolitical issues. This choice is related to the fact that the nature in itself of renewable power is different with respect to other power technologies and therefore could need different assessment tools to capture all relevant aspects. Indeed, its primary energy sources are much more diffused and the technologies needed for power generation are very scalable, therefore, more stakeholder are included in the picture. A power network that allows distributed generation is able take advantage of this qualitative difference (with respect to other power sources). This in addition to changes in the management of the network, to be able to respond to the intermittency problems, is able to entail also new economic games. If renewable sources will take off and reach considerable levels of market penetration also by means of distributed generation, this could change quite significantly not only the electric power system's framework but also influence organisation and society, internationally and locally. Indeed, the connection between power sources and society development has been evident in the past. Moreover, this could 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).

One of the starting points of this work is the idea 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 re-organizations 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.
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.

In the discussion, the analysis of the results is extended 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. The multi-dimensional evaluation is done by comparing 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 paper is structured as follows. Section 2 illustrates the methodology used in the first part of the analysis, that 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. This section reports a brief description of the WITCH Model (2.1), the main modelling assumptions for this analysis (2.2), the technical assumptions and data sources (2.3) and the scenarios under evaluation (2.4). Section 3 reports the simulation results. Section 4 presents the multi-dimensional analysis of the impacts of Super and Smart Grid integrated investments, where the qualitative characteristics of the two grid innovation options are compared 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. Finally, Section 5 summarizes and discusses the main results.

# 2 Methodology

## 2.1 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. National power grids are dynamic structures that have a "histor", tied with economic, technological, social and geo-political preferences, that strongly determines their evolution. In this direction, the use of a constant-elasticity function (CES) to depict the energy sector makes moving away from an established and differentiated energy mix costly. World countries are aggregated in twelve regions on the basis of geographic, economic and technological vicinity. The regions interact strategically on global externalities: Greenhouse Gases (GHG), technological spillovers and, a common pool of exhaustible natural resources. 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, the modelling relies on estimates for reference emissions, and a top-down approach for mitigation supply curves. A climate module governs the accumulation of emissions in the atmosphere and the temperature response to growing GHG 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 GHG 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.

## 2.2 Modelling assumptions

In this paper, 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 this way we are able to give a more complete representation and analysis of the potential role of the innovation of the power network in the climate policy debate. Though it should be noted 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.

Indeed, Super-Grids are modelled, as described in Massetti & Ricci (2013), 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 specific 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, together with electric vehicles, correspond to those identified by the EU (European Commission, 2011, 2009) as being the most important ones related to Smart Electricity Distribution Networks. In our modelling framework, investments in the “smartening” of the power grid ($I_{SMART}$) accumulate as follows:

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

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 Massetti & Ricci (2013), 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 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 ($\mu_{PV}$), and the operation and maintenance costs ($O\&M_{PV}$), subject to the constraint on $EL_{PV}$

$$EL_{PV}(n,t)=\min\{\mu_{PV,n}\cdot K_{PV}(n,t);\theta_{PV}\cdot O\,\&\,M_{PV}(n,t)\},$$

$$EL_{PV}(n,t)<\max EL_{PV}(n,t)\cdot INNOV(n,t)\ .$$

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 1).

We consider consumption management as another source of electricity, even if virtual ($EL_{dsm}$). 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 2.3, and it is, again, detracted from the budget constraint:

$$\begin{aligned} C(n,t) &= Y(n,t) - I_c(n,t) - \sum_w p_w Z_w(t,n) - I_{SMART}(t,n) - I_{PV}(t,n) + \\ &+ AVC(n) \cdot INNOV(n,t) - EL_{dsm}(n,t) \cdot C_{dsm}(n) - O\&M_{PV}(n,t) \end{aligned} \tag{1}$$

where $Y$ is net output of the economy, $I_c$ is the investment in the final good sector, **Errore.** 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:

$$EL_{dsm}(n,t) < \max EL_{dsm}(n,t) \cdot INNOV(n,t).$$

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 node, at the level where the main types of generation are combined.

## 2.3 Technical assumptions and calibration

Technical assumptions and data sources for the Super-Grid modelling are reported in Massetti & Ricci (2013).

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 & 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 *et al.* (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 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 & Atanasiu (2009).

Moreover, the additional penetration level that can be reached by wind and solar domestic power ($\varphi$) has been set to 0.2, but it can be modified once more specific literature is developed. This extends the maximum penetration of domestic wind and solar power to 45% of electricity generation, once the grid is fully innovated. Even if no specific data for this parameter is available, many reports support the idea of renewable power reaching at least 50% of penetration (LLP, 2011; Turkenburg & Usher, 2012; Lund H., 2009).

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.

## 2.4 Scenario design

The climate policy scenario we have chosen to analyse for our simulations is a stabilization scenario at 535ppm-$CO_2$eq 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").

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[1] Except for the technical limit on traditional wind and solar sources already discussed in Section 2.2

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.

# 3 Simulation results

## 3.1 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. 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 follow 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 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.

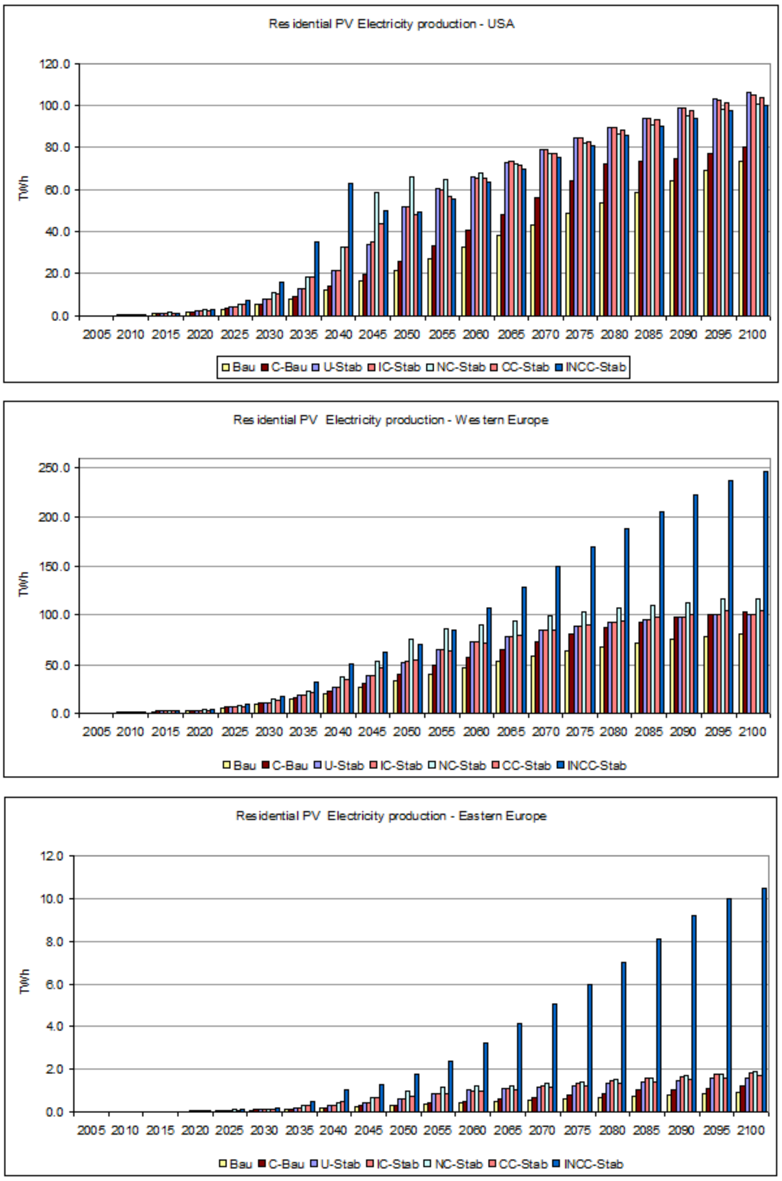

Figure 1: Optimal timing and generation by residential micro-PV plants

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 2. Expansion 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”.

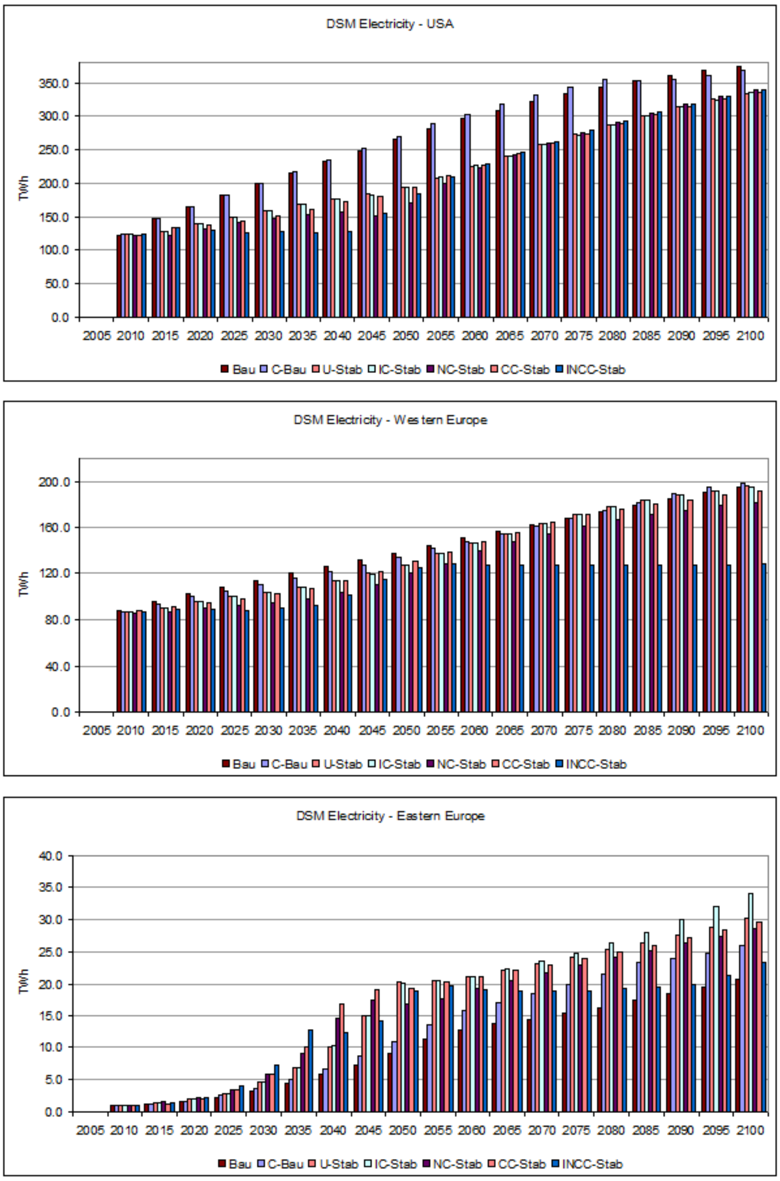

Figure 2: Optimal timing and generation by residential consumption management

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

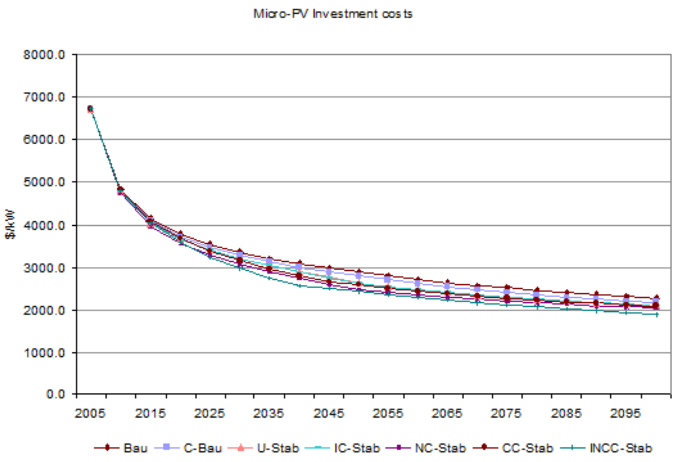

Figure 3: Residential micro-PV investment costs

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.

## 3.3 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% is not binding, therefore, the relaxation does not impact their electricity mix. Figure 4 reports the electricity mix of the three regions with and without the option of investing in Super and/or Smart Grids.

The option of investing in CSP-powered Super Grids has an impact on the electricity mix from m id century. Compared to results of Massetti & Ricci (2013), 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 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 (Figure 4-b), 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 option of increasing the penetration possibilities 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-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-c), 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.

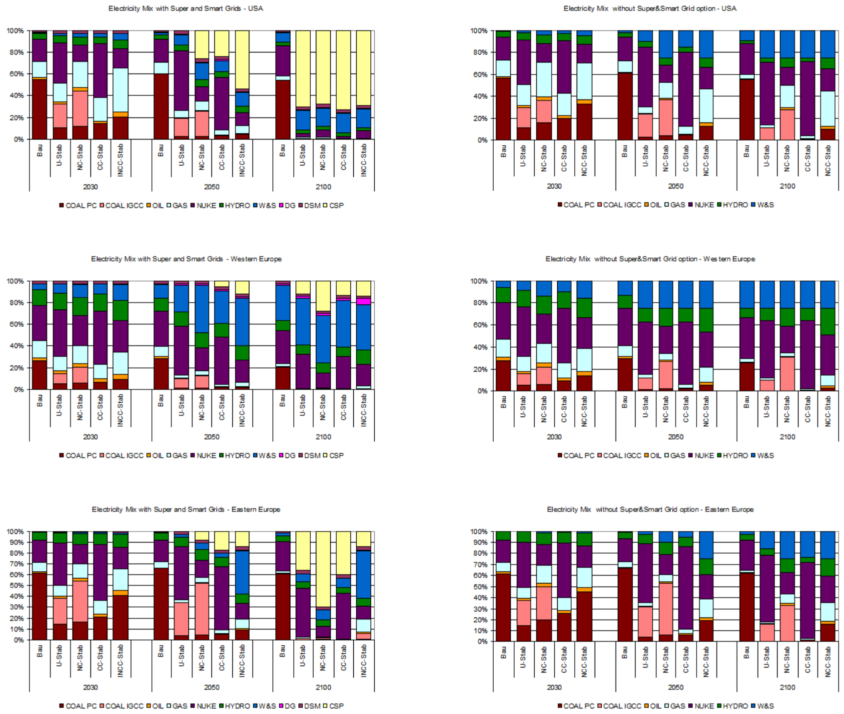

Figure 4: Regional Electricity Mix with and without Super and Smart Grids

## 3.4 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 5 reports the price of the GHG emission permits over time for the four different

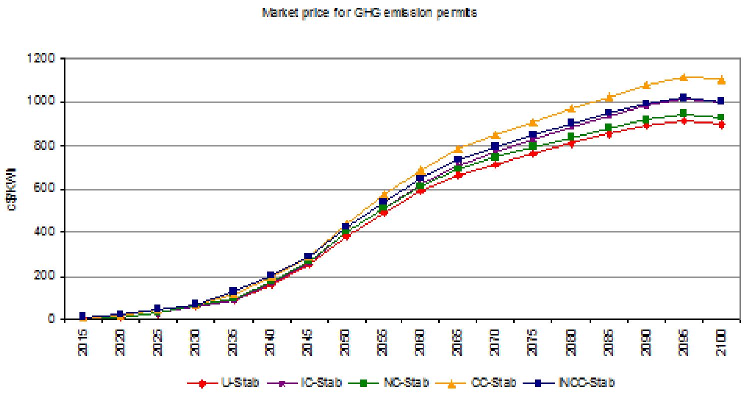

Figure 5: Market price for GHG emission permits under the different stabilization scenarios

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.

## 3.5 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 6).

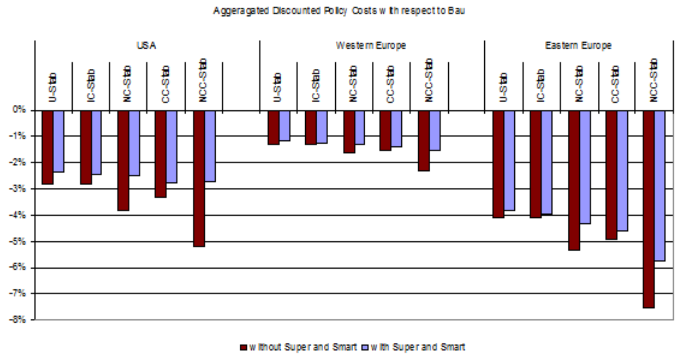

Figure 6: Stabilization option value of Super and Smart Grids

With respect 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, that is the exporter of CSP to Europe, 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 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 introducing 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. that will need to be addressed.
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.

# 5 Conclusions

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 but with limits on $CO_2$ emissions and on the expansion possibilities of nuclear power and coal with CCS, indeed, consume less electricity and suffer much larger economic losses compared to the scenarios where renewables 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 is imposed to simulate the technical limitations of the “non-smart” 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.

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

It should be noted that all previous results are obtained under a moderate climate policy and allowing nuclear power to expand freely or up to current levels (not lower). More stringent scenarios would strengthen the emerging indications.

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 qualitative discusision emphasizes the additional benefits or criticalities that the different technological scenarios may have, focusing on the option of Super-Grids and Smart-Grids.

To capture the different multi-level impacts of different energy strategies, 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 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.

(*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 multi-disciplinary 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

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

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 multi-level 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, our analysis has allowed us to highlight the variety of 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.

Future work will try to extend the simulation of the effects of Smart-Grids on the power system within the WITCH Model, by 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”. The impact of smart-grid options will be also extended to take into account the potential that lies within commercial activities, public buildings and non-electricity related industries.

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