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Super-Grids and Concentrated Solar Power: a scenario analysis with the WITCH model

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SUMMARY 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 to regulate a hypothetic Mediterranean electricity market.

Keywords: Climate Policy, Integrated Assessment, Renewable Energy, Concentrated Solar Power, Power Grid, Electricity Trade

JEL: Q2, Q43 , Q54

1. Introduction

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 recent 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). 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 paper aims at evaluating the changes in the policy costs – and in the electricity mix – when the option of long distance transmission of concentrated solar power (CSP) is added to the portfolio of available technological options. We analyse the issue in a cost-minimization framework, i.e., to look for the least-cost option that allows the achievement of the targeted climate policy.

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 decarbonisation 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 both 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 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

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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.

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 decarbonisation targets will necessarily require the introduction of new technologies and it will be important not to focus only on the different generation technologies, but also on the opportunities induced by the structural transformations of the distribution system and its management.

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.

This work focuses on Super-Grids (SG), that are high capacity wide area transmission networks intended to transmit power over long distances. Although Super-Grids 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. Even if they require the construction of converter stations that are costly and 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

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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).

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

lines; (*vii*) greater control over power transfers, that is important for electricity trade (Heyman *et* al. 2010).

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, as the levels of solar radiation, especially for the Middle-East and North Africa (MENA) region, may be the source of comparative advantages.

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[5] should drastically reduce the demand for water of cleaning operations (Williams 2010). In addition, operating temperatures are quite low – around 400°C – implying a moderate conversion efficiency; central

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[5] This technique is based on sensors that measure the dust on the surface of the panels: when the latter

receiver CSP plants have instead good prospects for reaching higher temperatures, though this technology has not yet been commercially proven (Richter *et* al. 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 optimal profile of investments in a Super-Grid capable of delivering long distance electricity, generated with solar thermal power plants. The optimal timing and quantity of investments both in the grid and in the new power plants will be 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.

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 social effects of the increased availability of (carbon-free) electricity in the MENA region, starting from the possibility of producing

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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.

relatively cheap and low-carbon fresh water, in line with some exploratory work that has appeared in the literature (Trieb and Müller-Steinhagen 2007; Trieb 2009).

The main goal of this paper is to illustrate modelling choices to introduce CSP powered Super-Grids and international trade of electricity in the WITCH model and to review the implications that these technology options have on technological and economic/geo-political issues. On the technological side we are interested in examining (i) the optimal scale of CSP, (ii) the optimal timing of investments in CSP, (iii) the optimal power generation mix, (iv) the implications for non-power energy uses. On the economic/geo-political side we examine (i) the impact of introducing CSP on the cost of achieving a given stabilization target, (ii) the scale of the investments needed and the size of the European Union-MENA (Euro-MENA) electricity trade, (iii) the evolution of investment costs in CSP (iv) the geo-political implications of having a large fraction of electricity in the EU that is imported from the MENA region and (v) we start investigating scenarios where market power is exerted.

Our analysis is the most comprehensive in the literature. Compared to previous policy scenarios analysis we use a solid energy-economy modelling framework (Trieb 2006; Patt *et* al. 2008; Ummel and Wheeler 2008; Jacobson and Delucchi 2010). 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) and the insertion of the Super-Grid option (Section 3), discuss the calibration procedure (Section 4) and then (Section 5) evaluate the costs, benefits and potential effects of the Super-Grid option, to understand if the necessary technological upgrades are economically justifiable. Section 6 evaluates the costs and benefits of an anticipated common deployment of CSP while Section 7 analyses the Euro-MENA trade situation in the presence of market power. Section 8 illustrates the sensitivity analysis and conclusions follow.

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.[6]

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 CH_4, N_2O, SLF (short-lived fluorinated gases), LLF (long-lived fluorinated) and SO_2 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.[7]

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

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[6] 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).

[7] 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

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.

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.

Power production with this kind of technology is strongly influenced by solar irradiance and atmospheric conditions. Solar thermal power, in fact, employs only direct sunlight, therefore it is best positioned in areas, such as deserts, steppe or savannas, without large amounts of humidity, fumes or dust that may deviate the sunbeams (Richter *et* al. 2009).

For these reasons, this paper focuses on desert areas with high values of Direct Normal Irradiation[8] that are found in the MENA region[9], in the north of China and the South-West of the United States (Richter *et* al. 2009; Trieb 2009b; IEA 2010c). 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.

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programs. However, avoided deforestation is not a source of emissions reductions in the version of the model that we used for this study.

[8] Direct Normal Irradiation (DNI) is the amount of solar radiation received per unit area by a surface that is always oriented perpendicular (or normal) to the sun rays. It is usually expressed in kWh/m^2 over a period of time.

[9] Sand storms seem not be a major problem for CSP power plants in the Sahara desert as they are rare. In addition, for power plants that have thermal storage, electricity generation can continue even when the mirrors are protected to avoid damage from the storms.

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.

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.

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.

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 on the real situation at 2005 (Bosetti *et* al. 2007a).

First of all, we introduce the possibility to produce solar thermal electricity. 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 distances with low losses.

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 2005 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 2005 USD, converted into energy units by θ_{grid}. The production function of CSP electricity is synthetically represented by the following Leontief function:

$$EL_{CSP,\,prod}(n,t) = \min\left\{\mu_{CSP,n}K_{CSP}(n,t);\theta_{CSP}O\&M_{CSP}(n,t);\mu_{grid,n}K_{grid}(n,t);\theta_{grid}O\&M_{grid}(n,t)\right\}. \qquad (1)$$

Power generation capacity in CSP accumulates as it follows:

$$K_{CSP}(n,t+1) = K_{CSP}(n,t)(1-\delta_{CSP}) + \frac{I_{CSP}(n,t)}{SC_{CSP}(n,t)}; \qquad (2)$$

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[10] 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:

$$SC_{CSP}(n,t+1) = SC_{CSP}(n,t_0)\,\frac{TK(t)}{TK(t_0)}^{-(\alpha)}\left(1+\left(\frac{\left(\dfrac{I_{CSP}(n,t+1)}{SC_{CSP}(n,t+1)}\right)}{\beta}\right)^{\gamma}\right) \qquad (3)$$

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

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 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:

$$K_{grid}(n,t+1) = K_{grid}(n,t)(1-\delta_{grid}) + \frac{I_{grid}(n,t)}{SC_{grid}(n,t)} . \tag{4}$$

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:

$$EL_{CSP,X}(n,t) = \min\left\{\mu_{n,CSP}K_{CSP}(n,t);\theta_{CSP}O\&M_{CSP}(n,t);\mu_{n,X}K_{grid,X}(n,t);\theta_{grid}O\&M_{grid,X}(n,t)\right\}, \tag{5}$$

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:

$$EL_{CSP,prod}(n,t) = EL_{CSP}(n,t) + EL_{CSP,X}(n,t) , \tag{6}$$

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:

$$C(n,t) = Y(n,t) - I_c(n,t) - \sum_w p_w Z_w(n,t) - I_{CSP}(n,t) - I_{grid}(n,t) - O\&M_{CSP}(n,t) - O\&M_{grid}(n,t) , \tag{7}$$

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 Appendix A.

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:

$$EL(n,t) = \left[EL_2(n,t) + \alpha_{HYDRO}(n) EL_{HYDRO}(n,t)\right]; \tag{8}$$

$$EL_2(n,t) = \left[\alpha_{FF}(n) FF(n,t)^{\rho_{EL_2}} + \alpha_{NUKE}(n) EL_{NUKE}(n,t)^{\rho_{EL_2}} + \alpha_{W\&S}(n) EL_{W\&S}(n,t)^{\rho_{EL_2}}\right]^{1/\rho_{EL_2}}; \tag{9}$$

$$EL_{NUKE}(n,t) = \left[EL_{NUCLEAR}(n,t) + EL_{BACKSTOP}(n,t)\right]; \tag{10}$$

$$FF\ (n,t) = \left[\alpha_{COAL}(n) EL_{COAL}(n,t)^{\rho_{FF}} + \alpha_{OIL}(n) EL_{OIL}(n,t)^{\rho_{FF}} + \alpha_{GAS}(n) EL_{GAS}(n,t)^{\rho_{FF}}\right]^{1/\rho_{FF}}; \tag{11}$$

$$EL_{COAL}(n,t) = \left[EL_{PC}(n,t) + EL_{IGCC}(n,t)\right]. \tag{12}$$

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

In our simulations, electricity from CSP power will enter various nodes depending on the region. Section 4 will give a more detailed description of the various assumptions. For further details on the structure of the model see Bosetti *et* al. (2007a).

3.3. Electricity Trade

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

$$\sum_n EL_{CSP,\,X}(n,t) = 0 \quad \forall t. \tag{13}$$

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*):

$$Y(n,t) = \frac{GY(n,t)}{\Omega(n,t)} - \sum_q p_q V_q(n,t) + EL_{CSP,\,X}(n,t) P_{CSP}(t) \quad , \tag{14}$$

where GY is gross output, Ω the damage function[11] and $\sum_q p_q V_q(n,t)$ the sum of expenditures, as better detailed in Appendix A.

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.

The overall investment costs for such power plants are estimated at 260 million euro, while the operation and maintenance costs amount to approximately 5.1 million euro per year. 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).

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 have modelled a learning by doing effect with a progress ratio of 90% as suggested in Neij (2008) and IEA (2010c). This means that investments costs are reduced by 10% at every doubling of the installed capacity. Estimates in the literature vary from 85% to 92% (Enermodal Engineering Limited 1999; IEA 2003, 2010c; Kearney 2003; Neij 2008).

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.

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[11] Note that, as discussed in Section 2, in this work we do not include the damage function as we take a cost-minimization approach.

For MENA, we consider delocalised production in different sites in the Sahara Desert region as currently discussed (Trieb 2006; Trieb and Müller-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 is taken from Trieb (2009b). Such value for MENA is also available in Kaltschmitt *et* al. (2007).

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 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 ¾ and ¼ 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 1. Parameter assumptions overview

In this first analysis of the impacts of Super-Grids, we have focused on the Europe-MENA case as investment projects and financing options are already taking shape (Trieb and Müller-Steinhagen 2007). We have then added the cases of China and the USA as they are the largest emitters of GHGs and include in their territory highly productive areas for CSP electricity. Domestic SGs have been considered as such electricity markets are likely to remain closed in the next decades. Future work will include Australia, Brasil and Indonesia as these are the other world regions with the most potential for CSP production (Trieb 2009-b).

In our simulations, CSP electricity directly substitutes electricity from Oil and Gas in MENA, as these are its major power generation sources ($EL_{CSP,oil}$ and $EL_{CSP,gas}$ are added to equation 11).

$$FF\ (n,t) = \begin{bmatrix} \alpha_{COAL}(n) EL_{COAL}(n,t)^{\rho_{FF}} + \alpha_{OIL}(n)\left(EL_{OIL}(n,t) + EL_{CSP,oil}(n,t)\right)^{\rho_{FF}} + \\ + \alpha_{GAS}(n)\left(EL_{GAS}(n,t) + EL_{CSP,gas}(n,t)\right)^{\rho_{FF}} \end{bmatrix}^{1/\rho_{FF}} \qquad (11bis)$$

For all other regions, CSP electricity enters in direct competition with nuclear power (EL_{csp} is added to the right-hand side of equation 10) and IGCC power with CCS (EL_{csp} is added to the right-hand side of equation 12) 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.

$$EL_{NUKE}(n,t) = \left[EL_{NUCLEAR}(n,t) + EL_{BACKSTOP}(n,t) + EL_{CSP,nuke}(n,t) \right]\ ; \qquad (10bis)$$

$$EL_{COAL}(n,t) = \left[EL_{PC}(n,t) + EL_{IGCC}(n,t) + EL_{CSP,ccs}(n,t) \right]\ . \qquad (12bis)$$

We model CSP as if it was the backstop technology taking shape. All regions without the CSP option still have the classic formulation of a generic electric backstop technology.

A sensitivity analysis of the key parameters is reported in Section 8.

5. Simulation Results

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 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.

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, 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. 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 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").

The choice of the constrained scenarios relates to the discussion on nuclear power and CCS operations detailed in Section 1. Other studies (ECF 2010, PricewaterhouseCoopers 2010) also include scenarios with no CCS nor nuclear power expansion.

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.[12]

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).

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 1 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. For MENA, it is optimal to generate CSP from 2040 under all stabilization policy scenarios, while for the USA and China it is first optimal for those scenarios where there are limits to the penetration of other low-carbon technologies and only later for the unconstrained stabilization case. In the USA, at the very end of the century, CSP becomes competitive with nuclear and IGCC with CCS and is therefore a viable option under all stabilization scenarios. 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. The costs of electricity production with the different technologies, divided into three cost components related to capital, fuel and CO_2 emissions, that emerge from our simulations, are reported in Appendix B for reference.

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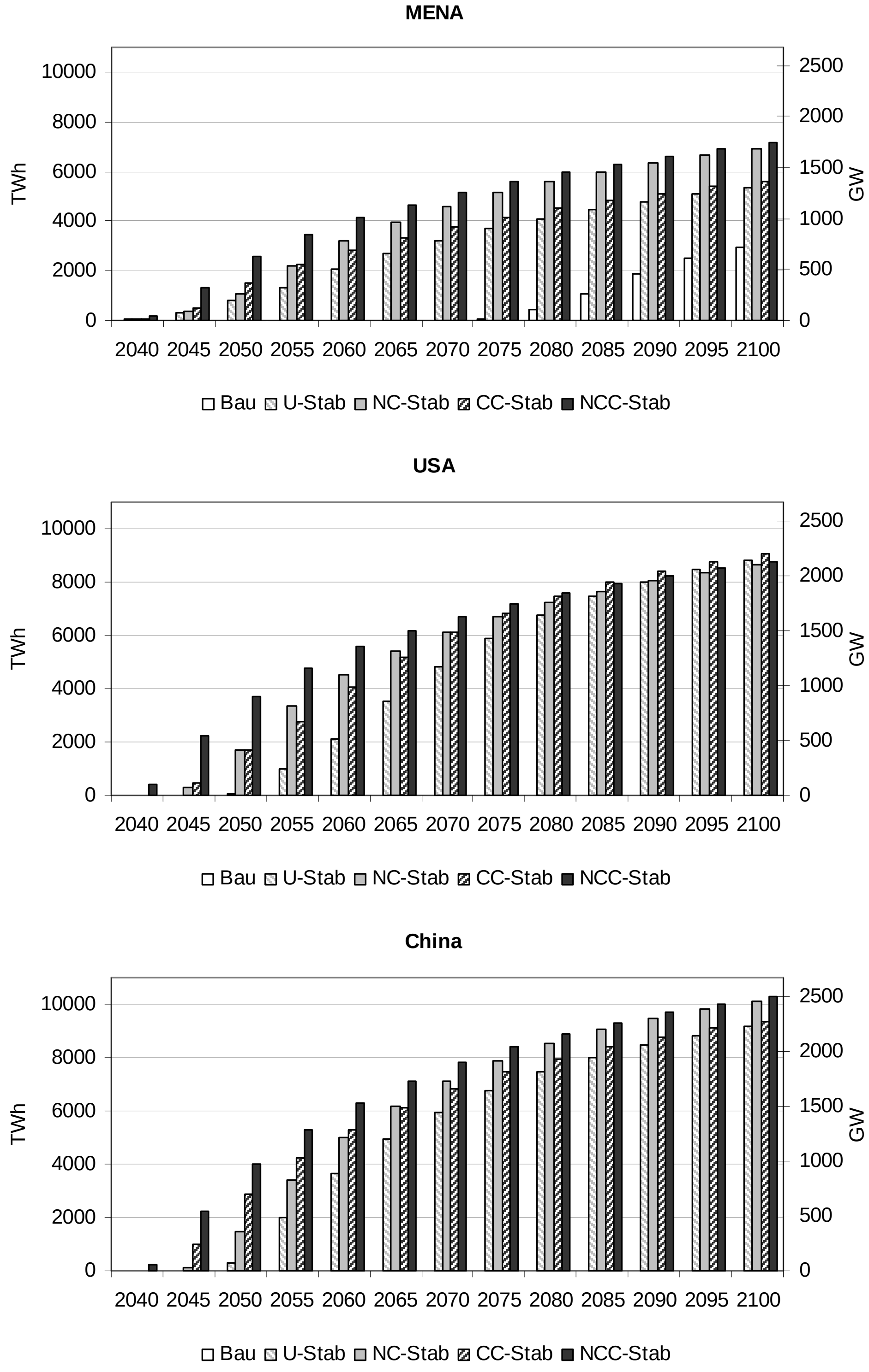
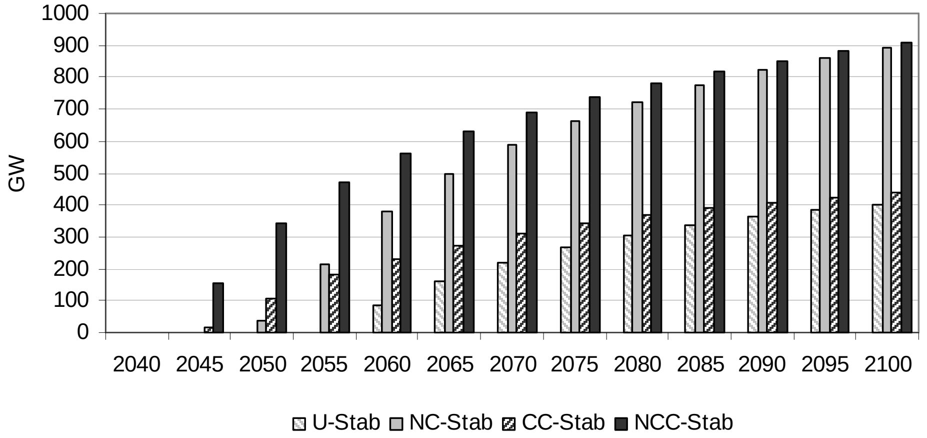
[12] Note that this 25% limit does not apply to the CSP electricity.



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 1. CSP Installed Capacity and Electricity Generation



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. Super-Grid Installed Capacity – Europe-MENA

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 1 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 though, that, domestic consumption of CSP for MENA is not very sensitive to the different policy scenarios (Figure 1); the differences that can be seen in Figure 1 mostly depend on the import demand from Europe.

Figure 2 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 1.

Figure 3 reports the paths of investments 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, investment costs follow a very different trend highlighting the strong 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.[13] Their share increases over time as we have assumed non decreasing investment costs for the Super-Grid infrastructure.

The cost paths depicted in the left panel of Figure 4 represent the weighted average of the costs across regions[14] 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 Eq. 3).

Our results also show that investment projects in a Mediterranean SG that connects the power networks of MENA and Europe are optimal under certain scenario conditions. Figure 5 shows how the total CSP electricity generated by MENA is divided between domestic consumption and exports to Western and Eastern Europe, under the different policy scenarios considered. Indeed, the graph shows that: (*i*) most of the electricity produced is for domestic consumption, and (*ii*) that a market for this electricity and its transmission over long distances does arise. More in detail, it results optimal to invest in such trade projects only in the presence of a stabilization policy and mainly in the second half of the century. We will discuss with greater detail the optimal timing of investments in Section 6.

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.

Both domestic consumption and exports increase over time, but exports seem to be more sensitive to the various policy cases. This is mainly due to the fact that MENA has low levels of generation with both nuclear and IGCC with CCS power plants. Differences in production for domestic consumption by MENA depend on the varying investment costs associated with installed capacity at the world level.

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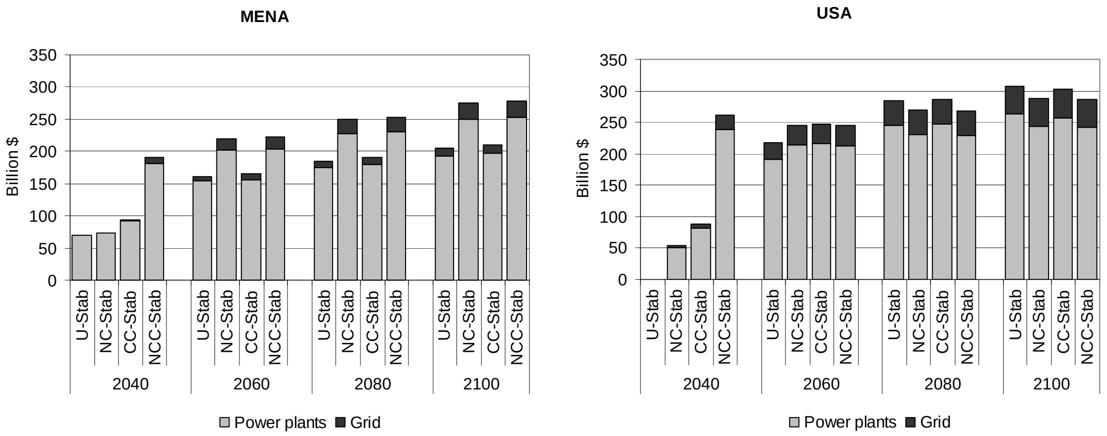
[13] Investments needed to build CSP capacity and the super-grid in China are similar to those needed in the USA.

[14] This is the average of the regional costs weighted by the amount of production of the region.



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 3. Investments for CSP-Plants and the Super-Grid Infrastructure – MENA and the USA

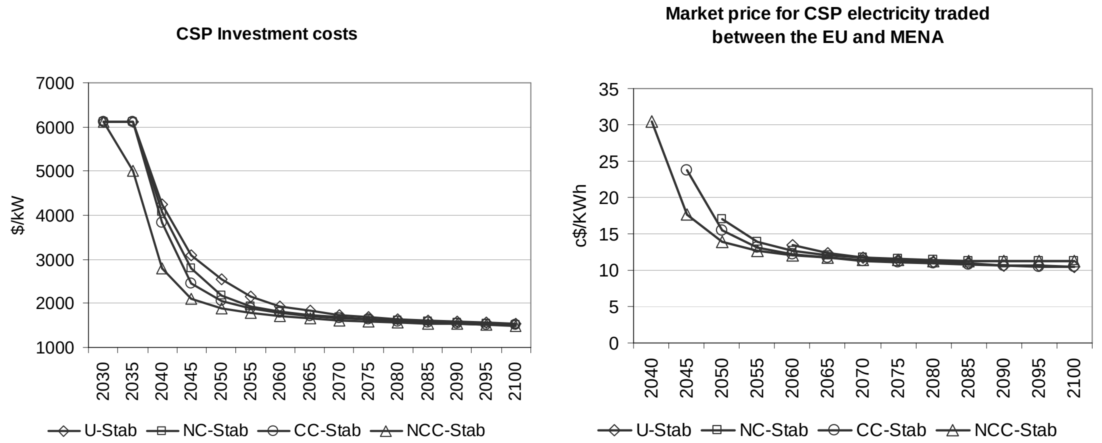


Figure 4. CSP Investment Cost and Market Price for CSP Electricity Trade Between the EU and MENA

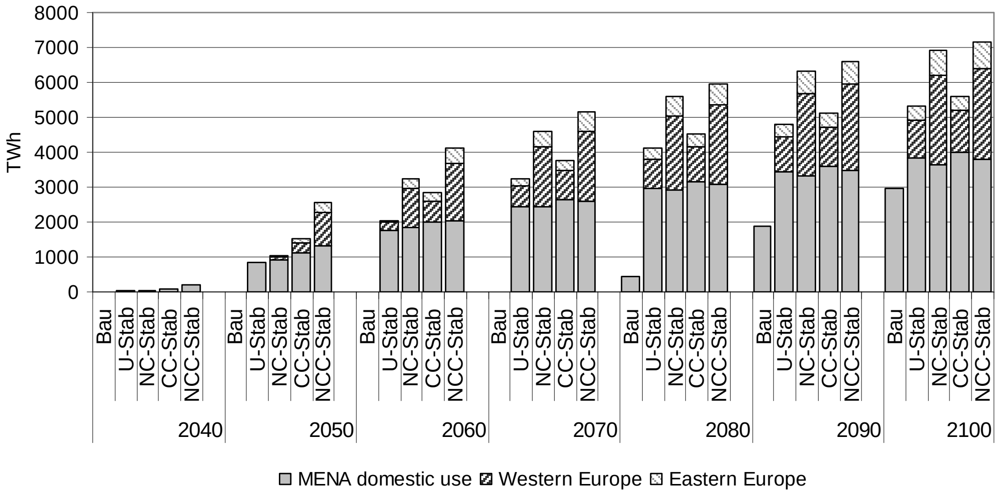


Figure 5. Distribution of CSP Power Produced by MENA.

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%

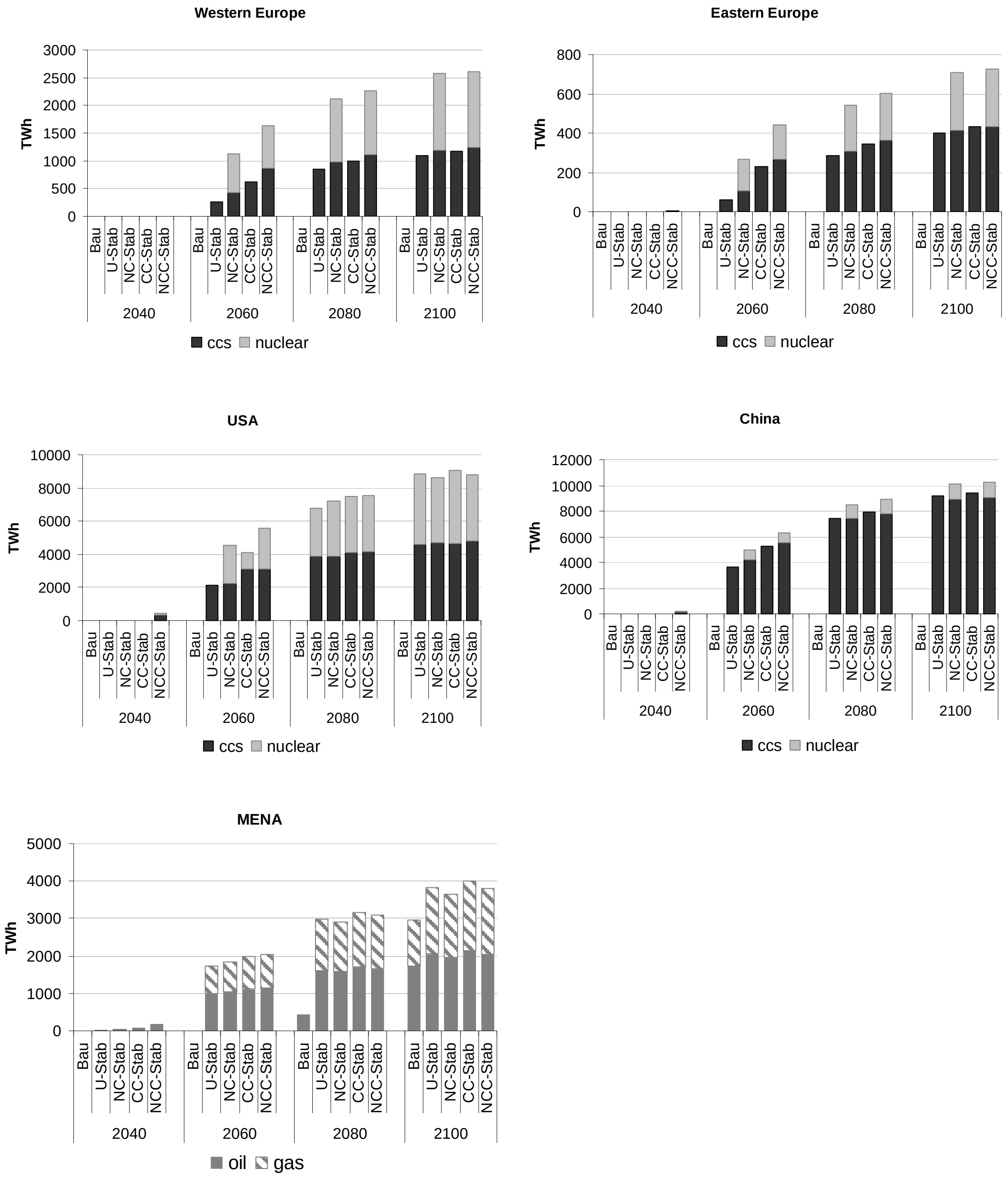
Notes: Bau = Business as usual; U-Stab = unconstrained stabilization; NC-Stab = constrained stabilization with cap on nuclear; CC-Stab = constrained stabilization with no CCS; NCC-Stab = constrained stabilization with cap on nuclear and no CCS.

Table 2 – MENA CSP Export Market Size and European expenditure relative to regional GDP.

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. Indeed, 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 4 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 3.1, investment costs for MENA strongly depend on world cumulative capacity, that is very sensitive to policy and technological penetration limits.

Table 2 indicates the money flows induced by the trade and their relevance with respect to regional gross domestic product (GDP). 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.



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 6. Regional Concentrated Solar Power use

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

Figure 6 shows in what scenarios and how much of the consumption substitutes each of these hydrocarbon sources. 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. 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. Indeed, the availability of the CSP option has quite relevant impacts on the electricity generation mix of the various regions.

Figure 7 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. The introduction of a climate stabilization policy (without technological penetration limits) induces a contraction of all fossil fuel sources – especially coal – and the appearance of IGCC with CCS. There is 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.

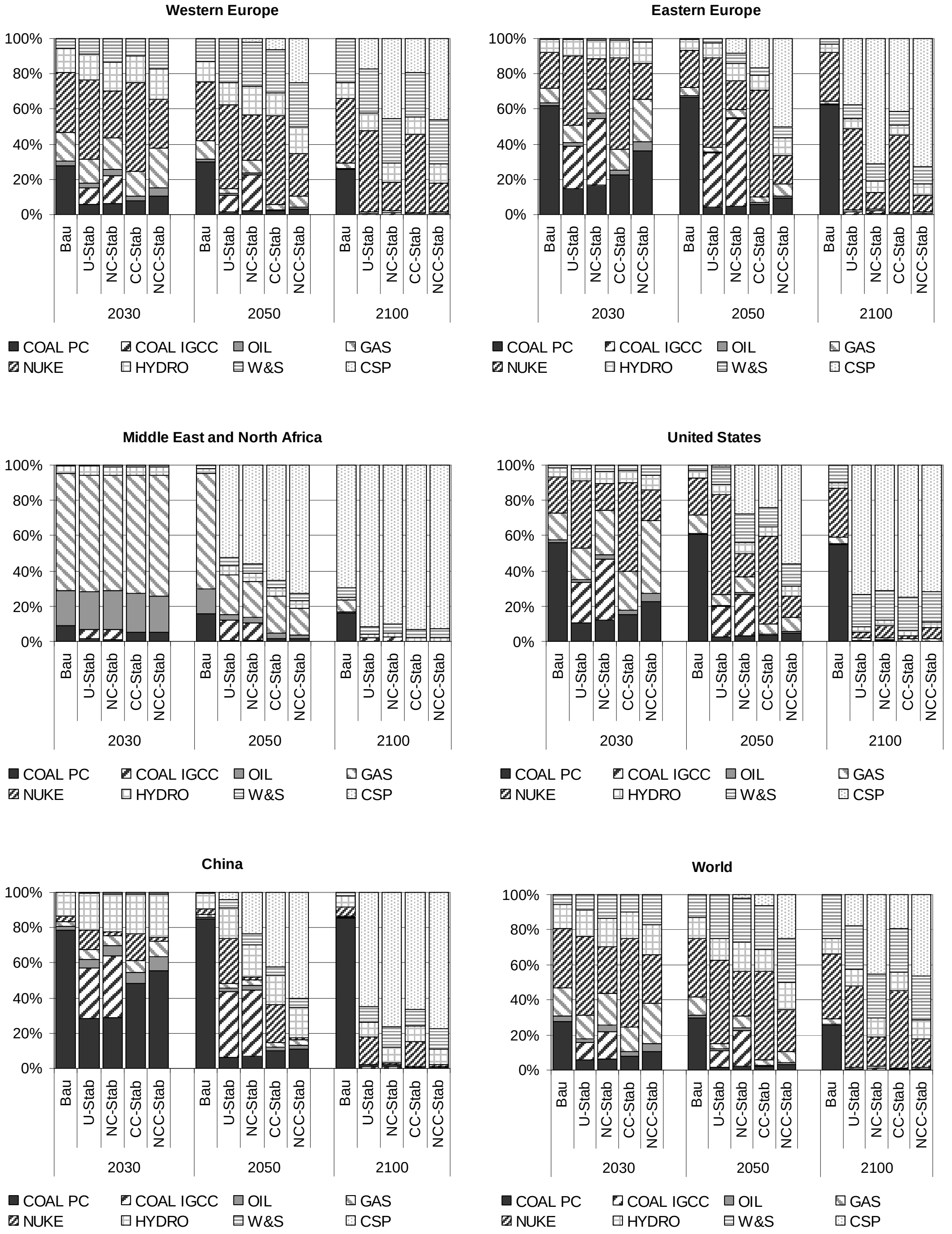
In the scenarios without the CSP import option, the Western European electricity mix is still dominated by nuclear and domestic renewable resources, though a relevant percent is still generated by fossil fuels: mostly IGCC with CCS and gas, i.e. the less carbon intensive fossil fuel sources.

The electricity mix of Eastern Europe is dominated by hydrocarbon generation. In the stabilization cases, this dominance characterises the first part of the century through to mid-century with IGCC with CCS, where available. In the second half of the century the role of imported CSP increases of importance, especially 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. With the introduction of a GHG stabilization target, hydrocarbon generation starts to decline around 2045 and is substituted with CSP production. An increase in the share of IGCC with CCS - where available – and traditional renewable sources is also visible. At the end of the century it is optimal to produce a very large share of electricity with CSP also in the Business as usual scenario. Stabilization scenarios reach 90% generation with CSP. 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 Müller-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.



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 7. Regional and World Electricity Mix

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.

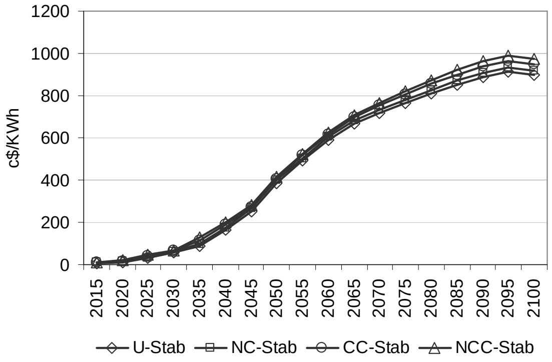
The Chinese electricity mix is instead dominated by coal and hydro-electric power. With a stabilization policy, pulverised coal is substituted by IGCC with CCS and nuclear power, where these technologies are available. Starting form the mid part of the century it becomes optimal to generate electricity 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.

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 7). 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 7 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.

We are also interested in evaluating the impacts of the introduction of the CSP-powered SG on the global market of GHG emission permits. Figure 8 reports the price of the GHG emission permits over time for the four different stabilization policy scenarios. Compared to the case where the CSP-SG option is not available, our simulations show a strong reduction in the size of 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.



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 8. Market price for GHG emission permits

Moreover, we are interested evaluating the role of Super-Grids in lowering the costs of climate policies. Indeed, Figure 9 indicates for each region the difference in the overall discounted[15] policy costs for the four stabilization scenarios, calculated as the loss of GDP with respect to the business as usual scenario[16]. All four stabilization policies entail a loss of GDP for all regions.

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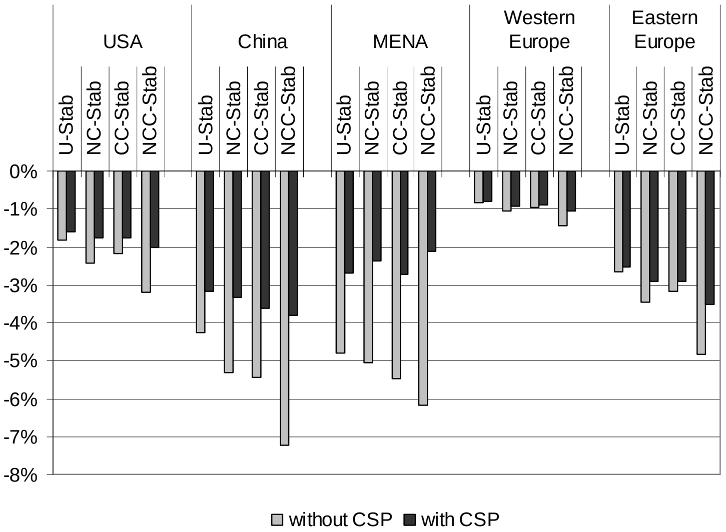
[15] The discount rate used is 5%. In Appendix B we report the results also for a discount rate of 3%.

[16] For the cases with penetration limits, these limits are also imposed on the reference business as usual scenario used for the comparison.

As it would be expected, the scenario with the least number of constraints is the less costly one, except for MENA. This is due to the fact that its domestic demand is little sensitive to limits on nuclear power or CCS activities, but the demand of CSP by Western and Eastern Europe – as that of the USA and China – instead, increases as the technological constraints are added, inducing a larger diffusion of the CSP technology and therefore lower unit costs for the almost stable domestic consumption.

In aggregate 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-SG option. For the USA and China these policy costs are reduced by between 12-37% and 25-47%, respectively. MENA reduces its losses by between 44 and 66%.



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 9. Aggreagated Discounted (5%) Policy Costs with respect to Bau

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 3 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.

	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 3. CSP mirror surface and HVDC cables

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.

Table 3 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.

6. Anticipating investments in CSP

The scenarios discussed in the previous Section indicate that it is not optimal to invest in CSP generation before 2035 for all three producing regions and that significant investments should occur only from 2050 onwards. Many studies and most of the discussion in the literature (Trieb 2006 and 2009; Trieb and Müller-Steinhagen 2007; Ummel and Wheeler 2008; Richter 2009; IEA 2010a, 2010b, 2010c), though, suggest that investments should start much earlier, around 2020.

In Section 8 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 differences with respect to the literature are due to: (1) much lower capital costs of CSP and Super-Grid (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 3).[17]

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). The target remains to stabilize GHG concentrations at 535 ppm CO_2 equivalent by 2100, with no limits to the penetration of nuclear or IGCC with CCS power (indicated as "anticipated-U-Stab" in the graphs).

The new scenario shows that a more rapid expansion of CSP determines a faster contraction of investment costs, due to learning by doing (Figure 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, definitely later than in the literature.

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. In MENA, the discounted sum of consumption increases by 0.16% (5% interest rate) or 0.24% (3% interest rate); all other regions have much lower consumption gains.

Therefore, learning externalities might motivate the introduction of subsidies to invest in CSP all in countries with high production potential. However, they do not suggest that it would be

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

optimal for Europe to import CSP electricity before the second half of the century, if there are not major constraints on the expansion of nuclear and CCS.

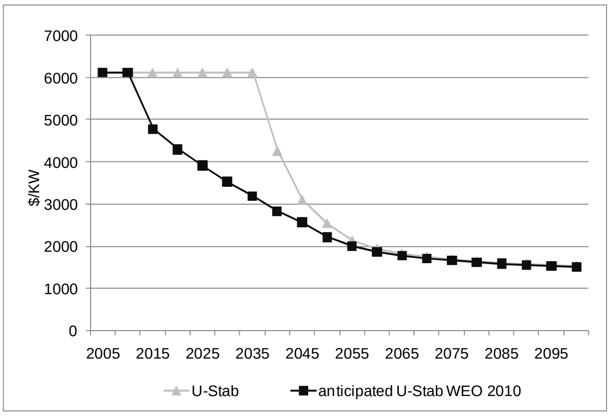

Figure 10. CSP Investments costs for in the unconstrained scenario and in the anticipated investments scenario.

7. 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 only marginally two very relevant issues.

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. CSP electricity covers from 18% to 46% of total electricity consumption in Europe in our scenarios. The Desertec concept foresees 17% of electricity consumption from the MENA region. These large shares of imported electricity represent 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.[18]

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[18] 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 et al. (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 et al. (2006).

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. Unfortunately, the complex institutional aspects of a large Mediterranean grid have not been discussed so far. We believe instead that they should be moved on top of the agenda, before any large investment project starts. The investments in Super-Grids are so high and long-lived that generate a market similar to a bilateral monopoly where there are both monopoly and monopsony features. Therefore, market price and output will, most 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). The rest of this Section is devoted to test this hypothesis.

In the standard 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. Therefore, 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. Figure 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.

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 have tested three intermediate combinations of prices.

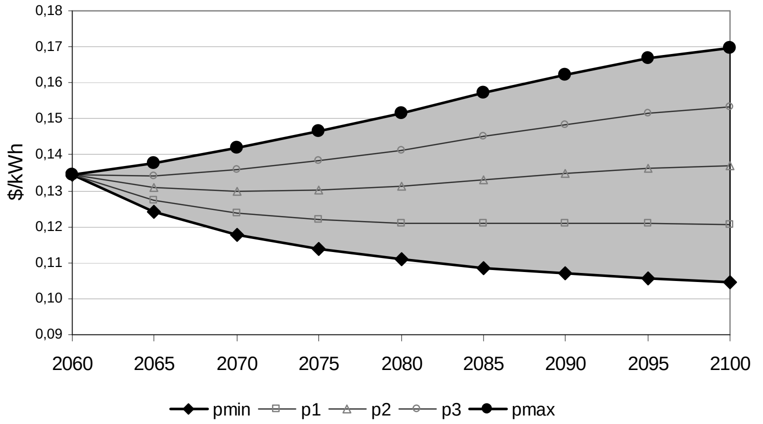

Figure 11. Price for traded CSP Electricity

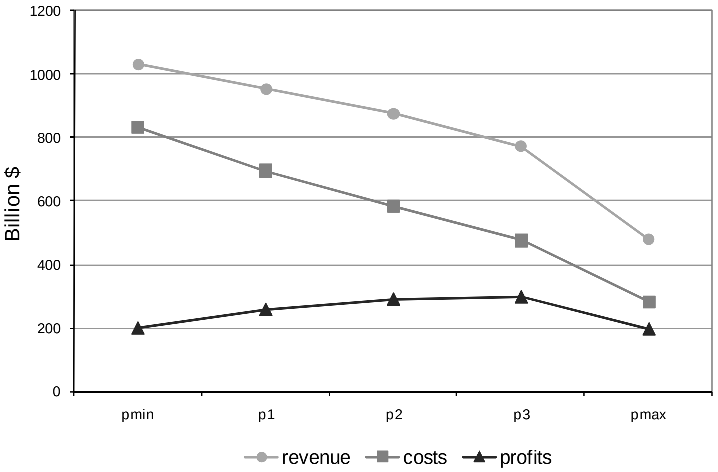

Figure 12. MENA Aggregated costs, Revenue and Profits from CSP Electricity trade

We find that as price increases the quantity traded decreases and therefore both revenues and costs decrease (see Figure 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.

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 Desertec concept does not believe that MENA countries might form a cartel because Europe has the potential to generate CSP domestically and would discourage any monopoly.[19] 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.

8. 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 B 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

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

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.

9. Conclusions

We have analyzed the effects of the introduction of Concentrated Solar Power (CSP) transmitted by means of Super-Grids (SG) in four regions of the world: Europe, Middle East and North Africa (MENA), the United States of America and China. We have evaluated the economic potential of this low-carbon option for electricity generation, under a Business as Usual scenario and under a 535ppm-CO_2eq policy target in the presence of a global carbon market. We tested our results under different assumptions regarding the expansion of nuclear power and coal power with carbon capture and storage (CCS), that, together with renewable power, are 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.

Our simulations suggest that an extensive use of CSP power both for domestic consumption or export, in the case of the Europe-MENA Super-Grid, will become optimal only in the second half of the century.

CSP-powered SG electricity in Western and Eastern Europe and China substitutes production from zero-carbon technologies only when there are penetration limits to the exploitation of the latter. CSP domestic production 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. Therefore, 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.

The price at which the CSP electricity will be traded between Europe and MENA is expected to start around 30c$/KWh, for the most extreme case, and decrease over time to 10-11 c$/KWh as the world cumulative capacity increases triggering the Learning by Doing effect that drastically reduces investment costs for CSP generation. Though, the trading price, will necessarily depend on long-term international agreements. Our simulations have also identified a set of feasible and Pareto-improving combinations of price and quantity exported and the best situation for Europe and for MENA

In the second part of the century the electricity mix of the USA, China, MENA, Western Europe and Eastern Europe will be strongly modified by the additional CSP option that will reach very large shares of electricity generation. Limits to the penetration of this technology or the consideration of the increasing cost of managing the power network with large shares of solar electricity might be needed to make the results more realistic.

The introduction of the CSP-SG option allows stabilization policy costs to be reduced, under all scenarios for all five regions. The stabilization policy is still costly in terms of GDP loss compared to the Business as Usual scenario, though adding the CSP-SG option may decrease such losses up to 66%.

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 a CSP power market. In particular, high attention should be devoted to the mechanisms and rules that will determine the price of electricity. We have shown 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 case of a large deployment of CSP, 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 dependence. Therefore our scenarios, appear to be overly optimistic. Realistically, CSP will be able to contribute only marginally to the European power mix and domestic carbon-free power sources need to be developed. Very large is instead the potential of CSP in China, the USA, and in MENA countries, where the only constraints are technological. Future developments of this work will expand the number of regions that can invest profitably in CSP, will explore more stringent stabilization targets and will describe with greater precision the optimal geographical location of CSP plants and Super-Grids.

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Appendix A

List of Main Equations

In this Appendix we reproduce the main equations of the model. For a full description of the model please refer to Bosetti et al (2007-a; 2009). The website www.witchmodel.org contains useful information on the model. The list of variables is reported at the end of this Section.

In each region, indexed by *n*, a social planner maximises the following utility function:

$$W(n) = \sum_t U\left[C(n,t), L(n,t)\right] R(t) = \sum_t L(n,t)\left\{\log\left[c(n,t)\right]\right\} R(t)\,, \tag{A1}$$

where *t* are 5-year time spans and the pure time preference discount factor is given by:

$$R(t) = \prod_{v=0}^{t}\left[1+\rho(v)\right]^{-t}\ , \tag{A2}$$

where the pure rate of time preference $\rho(v)$ is assumed to decline over time. Moreover, $c(n,t) = \dfrac{C(n,t)}{L(n,t)}$ is per capita consumption.

Output gross of climate change damages, in the non-oil sector, is produced by combining a capital-labour intermediate input with energy services (*ES*) in a constant elasticity of substitution (CES) production function:

$$GY(n,t) = TFP(n,t)\left[\alpha_Y(n)\left(K(n,t)^{\beta} L(n,t)^{1-\beta}\right)^{\rho_Y} + \left(1-\alpha_Y(n)\right) ES(n,t)^{\rho_Y}\right]^{1/\rho_Y}\ . \tag{A3}$$

Total factor productivity $TFP(n,t)$ evolves exogenously with time. The labour force is set equal to population (*L*), which evolves exogenously. Capital (*K*) evolves following a standard pattern:

$$K(n,t+1)\ =\ K(n,t)\left(1-\delta_{GY}\right) + I(n,t) \tag{A4}$$

Energy services are an aggregate of energy (*EN*) and a stock of knowledge combined with a CES function:

$$ES(n,t) = \left[\alpha_{HE}(n) HE(n,t)^{\rho_{ES}} + \alpha_{EN}(n) EN(n,t)^{\rho_{ES}}\right]^{1/\rho_{ES}}\ . \tag{A5}$$

New ideas which contribute to the stock of energy knowledge, $Z_{HE}(n,t)$, are produced using R&D investments, $I_{R\&D}(n,t)$, together with the previously cumulated knowledge stock $HE(n,t)$:

$$Z_{HE}(n,t)\ =\ a\, I_{HE}(n,t)^{b}\, HE(n,t)^{c}\, HKL(n,t)^{d}\ . \tag{A6}$$

The knowledge stock evolves as follows:

$$HE(n,t+1)\ =\ HE(n,t)(1-\delta) + Z_{HE}(n,t) \tag{A7}$$

<u>The Energy Sector</u>

Energy is a combination of electric (*EL*) and non-electric energy (*NEL*):

$$EN(n,t) = \left[\alpha_{EL}(n) EL(n,t)^{\rho_{EN}} + \alpha_{NEL}(n) NEL(n,t)^{\rho_{EN}}\right]^{1/\rho_{EN}}\ . \tag{A8}$$

Each factor is further decomposed into several sub-components that are aggregated using CES, linear and Leontief production functions. In particular:

$$EL(n,t)=[EL_2(n,t)+\alpha_{HYDRO}(n)EL_{HYDRO}(n,t)]; \tag{A9}$$

$$EL_2(n,t)=\left[\alpha_{FF}(n)FF(n,t)^{\rho_{EL_2}}+\alpha_{NUKE}(n)EL_{NUKE}(n,t)^{\rho_{EL_2}}+\alpha_{W\&S}(n)EL_{W\&S}(n,t)^{\rho_{EL_2}}\right]^{1/\rho_{EL_2}}; \tag{A10}$$

$$FF(n,t)=\left[\alpha_{COAL}(n)EL_{COAL}(n,t)^{\rho_{FF}}+\alpha_{OIL}(n)EL_{OIL}(n,t)^{\rho_{FF}}+\alpha_{GAS}(n)EL_{GAS}(n,t)^{\rho_{FF}}\right]^{1/\rho_{FF}}; \tag{A11}$$

$$EL_{COAL}(n,t)=\left[\alpha_{PC}(n)EL_{PC}(n,t)^{\rho_{EL_{COAL}}}+\alpha_{IGCC}(n)EL_{IGCC}(n,t)^{\rho_{EL_{COAL}}}\right]^{1/\rho_{EL_{COAL}}}. \tag{A12}$$

The Super-Grid

We reproduce here the equations that have been illustrated in the main text of the paper for an easy reference:

$$EL_{CSP,prod}(n,t)=EL_{CSP}(n,t)+EL_{CSP,X}(n,t). \tag{A13}$$

$$EL_{CSP,prod}(n,t)=\min\{\mu_{n,CSP}K_{CSP}(n,t);O\&M_{CSP}(n,t);\mu_{n,grid}K_{grid}(n,t);O\&M_{grid}(n,t)\}. \tag{A14}$$

$$EL_{CSP}(n,t)=\min\{\mu_{n,CSP}K_{CSP}(n,t);O\&M_{CSP}(n,t);\mu_{n,grid}K_{grid,D}(n,t);O\&M_{grid,D}(n,t)\}. \tag{A15}$$

$$EL_{CSP,X}(n,t)=\min\{\mu_{n,CSP}K_{CSP}(n,t);O\&M_{CSP}(n,t);\mu_{n,grid}K_{grid,X}(n,t);O\&M_{grid,X}(n,t)\}. \tag{A16}$$

$$\sum_n EL_{CSP,X}(n,t)=0 \quad \forall t. \tag{A17}$$

$$K_{CSP}(n,t+1)=K_{CSP}(n,t)(1-\delta_{CSP})+\frac{I_{CSP}(n,t)}{SC_{CSP}(n,t)}. \tag{A18}$$

$$K_{grid}(n,t+1)=K_{grid}(n,t)(1-\delta_{grid})+\frac{I_{grid}(n,t)}{SC_{grid}(n,t)}. \tag{A19}$$

$$K_{grid}(n,t)=K_{grid,D}(n,t)+K_{grid,X}(n,t). \tag{A20}$$

$$SC_{CSP}(n,t+1)=SC_{CSP}(n,t_0)\cdot\frac{TK(t)}{TK(t_0)}^{-(\alpha)}\cdot\left(1+\left(\frac{\left(\frac{I_{CSP}(n,t+1)}{SC_{CSP}(n,t+1)}\right)}{\beta}\right)^{\gamma}\right). \tag{A21}$$

$$O\&M_{grid}(n,t)=O\&M_{grid,D}(n,t)+O\&M_{grid,X}(n,t). \tag{A22}$$

$$\begin{aligned}C(n,t)=Y(n,t)-I(n,t)-\sum_j I_{R\&D}(n,t)-\sum_j I_j(n,t)-\sum_j O\&M_j(n,t)-I_{CSP}(n,t)-I_{grid}(n,t)\\ -O\&M_{CSP}(n,t)-O\&M_{grid}(n,t)\end{aligned}. \tag{A23}$$

$$Y(n,t) = \frac{GY(n,t)}{\Omega(n,t)} - \sum_f P_f \ (n,t) * X_{f,extr}(n,t) - \sum_f P_{f\,\mathrm{int}}(n,t) * X_{f,netimp}(n,t) - P_{CSS}(n,t) * CCS(n,t) + EL_{CSP,\,X}(n,t) P_{CSP}(t) \quad . \qquad \text{(A24)}$$

Climate Module

Carbon dioxide emissions from combustion of fossil fuels $\left(X_f\right)$ are derived applying stoichiometric coefficients to the total amount of fossil fuels utilised. Emissions associated to non-conventional oil production are also tracked. By using carbon capture and sequestration (*CCS*) it is possible to reduce the amount of CO_2 emissions in the atmosphere:

$$CO_2(n,t) = \sum\nolimits_f \omega_{f,CO_2} X_f(n,t) + \sum\nolimits_g \phi_{g,CO_2} OIL_{prod}(n,t,g) - CCS(n,t). \qquad \text{(A25)}$$

For details on land use emissions and on non-CO_2 gases please see Bosetti et al (2009).

The damage function impacting output is quadratic function of the temperature increase above the pre-industrial level *T*:

$$\Omega(n,t) = 1 + \left(\theta_{1,n} T(t) + \theta_{2,n} T(t)^2\right). \qquad \text{(A26)}$$

Temperature increases through augmented radiating forcing F, moderated by the cooling effect of SO_2 aerosols, $cool(t+1)$:

$$T(t+1) = T(t) + \sigma_1\{F(t+1) - \lambda T(t) - \sigma_2[T(t) - T_{LO}]\} - cool(t+1) \,. \qquad \text{(A27)}$$

List of Variables

Ω = Climate feedback on the economy
δ_i = Depreciation rate
$\mu_{CSP,n}$ = Full load hours for a CSP power plant in region *n*
$\mu_{grid,n}$ = Full load hours for the domestic Super-Grid in region *n*
C = Consumption
c = Per-capita consumption
CCS = CO_2 captured and sequestered
CO_2= Emissions from combustion of fossil fuels
Δ = Additional oil capacity
EL = Electric energy
EL_i = Electric energy use from the i^{th} generation technology
$EL_{CSP,prod}$ = Total electric energy produced with CSP
EL_{CSP} = Electric energy produced with CSP for domestic consumption
$EL_{CSP,X}$ = Electric energy produced with CSP for export
EN = Energy
ES = Energy services
F = Radiative forcing
HE = Energy knowledge
I_{CSP} = Investments in CSP plants
I_{grid} = Investments in the Super-Grid infrastructure
$I_{R\&D}$ = Investment in energy R&D
I = Investment in the final good sector
L = Population
K = Stock of capital in the final good sector

K_{CSP}= Stock of capital in CSP
K_{grid} = Stock of capital in the whole Super-Grid infrastructure
$K_{grid,D}$ = Stock of capital in the Super-Grid infrastructure for domestic consumption
$K_{grid,X}$ = Stock of capital in the Super-Grid infrastructure for export
NEL = Non-electric energy
NIP = Net import of carbon permits
$O\&M_{CSP}$ = Operation and maintenance costs associated with CSP generation
$O\&M_{grid}$ = Operation and maintenance costs associated with the whole Super-Grid
$O\&M_{grid,X}$ = Operation and maintenance costs associated with Super-Grid for domestic consumption
$O\&M_{grid,X}$ = Operation and maintenance costs associated with Super-Grid for export
P_{CSP} = Price of the traded CSP power
p = Price of carbon permits
P_Z = a vector of prices for the input vector X_Z
R = Discount factor
SC_{CSP} = Investment costs for the construction of CSP plants
SC_{grid} = Investment costs for the construction of the Super-Grid
T = Temperature level
TFP = Total factor productivity
U = Instantaneous utility
W = Welfare
X_Z = a vector including inputs that are considered a net loss for the economy
Y = Gross Domestic Product
Z_{HE} = Flow of new energy knowledge

Assigned Values to Key Parameters:

List of key parameters

	μ_{CSP} (h)	μ_{grid} (h)	$\mu_{grid,X}$ (h)	SC_{CSP} ($/kW)	SC_{grid} ($/kW)	$SC_{grid,X}$ ($/kW)	$O\&M_{CSP}$ ($/kW)	$O\&M_{grid}$ ($/kW)	$O\&M_{grid,X}$ ($/kW)
CHINA	4110	4110		6500	329		127.5	6.6	
MENA	3680		3680	6500		336	127.5		6.7
USA	4600	4600		6500	277		127.5	5.5	

Note: the values in $ are in 2007US$ as reported in the original data source (Kaltshmitt 2007), these are then converted into 2005US$ for the model simulations.

	δ_{CSP}	δ_{grid}	α	β	γ
All	0.1	0.1	0.15	380	3

Appendix B

Additional Results

Electricity Costs

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	55,39	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	12,35
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

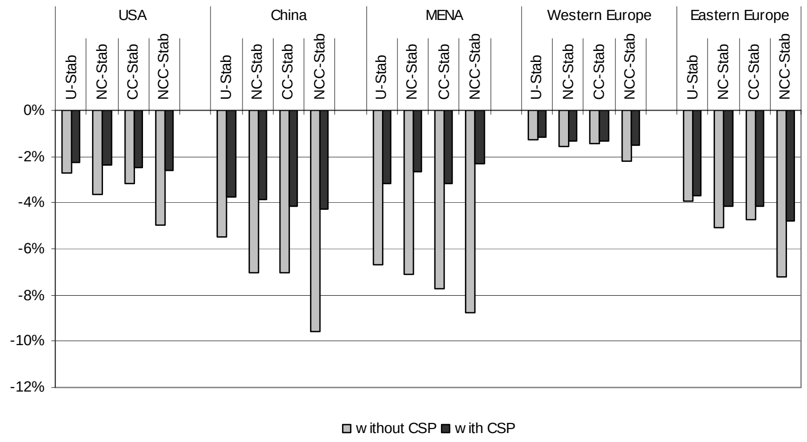
Western Europe	COAL PC			COAL IGCC				OIL			GAS			NUKE		HYDRO	W&S	CSP
	Capital	Fuel	CO_2	Capital	CCS	Fuel	CO_2	Capital	Fuel	CO_2	Capital	Fuel	CO_2	Capital	Fuel	Capital	Capital	Import
2005	2,98	2,98	-	5,54	0,49	2,77	-	2,35	10,54	-	1,85	4,13	-	6,18	0,14	5,71	10,14	-
2010	2,85	2,96	-	5,25	0,49	2,81	-	2,26	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	3,59	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.

The above tables refer to the unconstrained stabilization scenario (U-Stab). Similar tables for all other scenarios are available upon request.

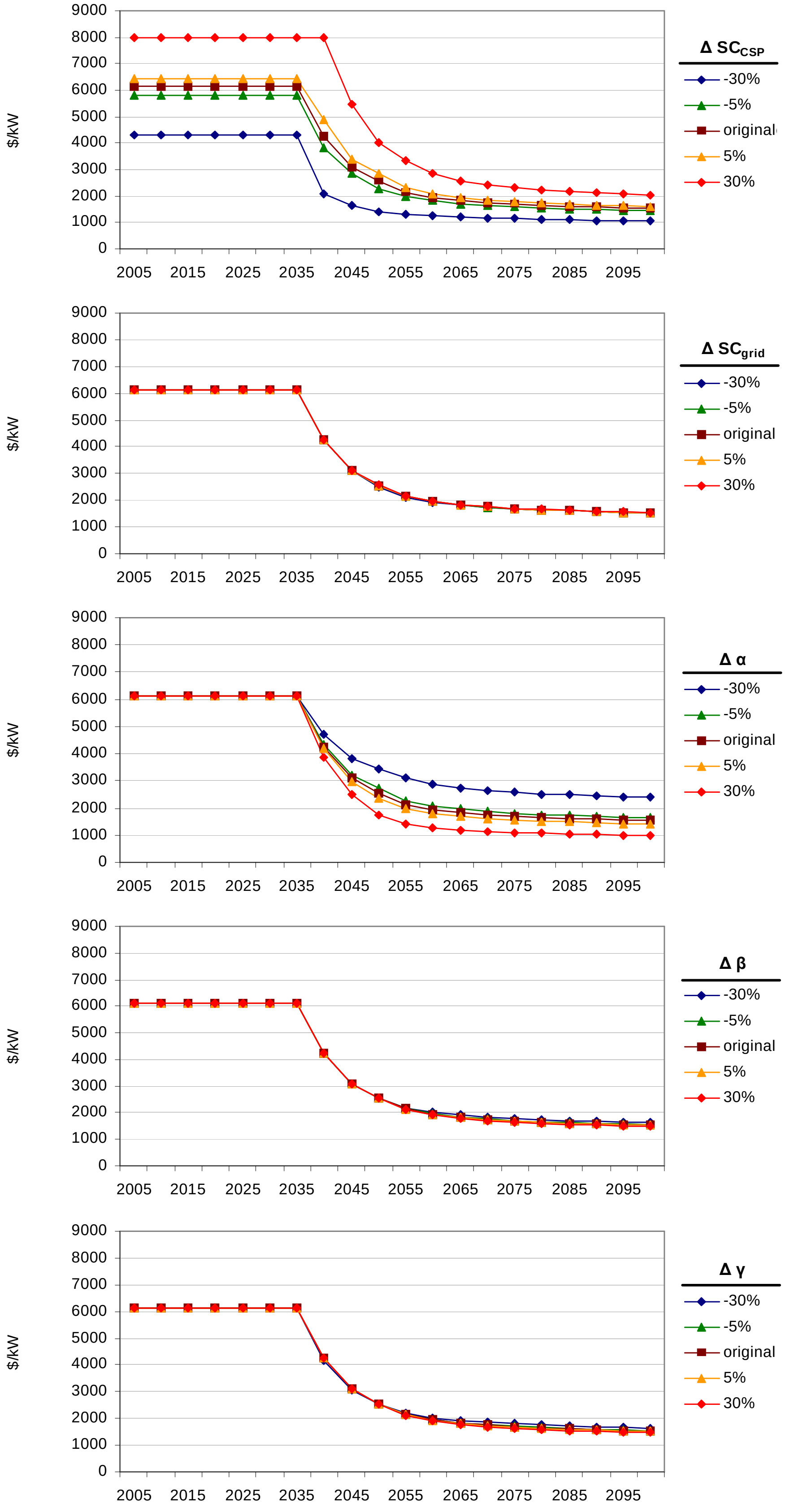
Policy Costs



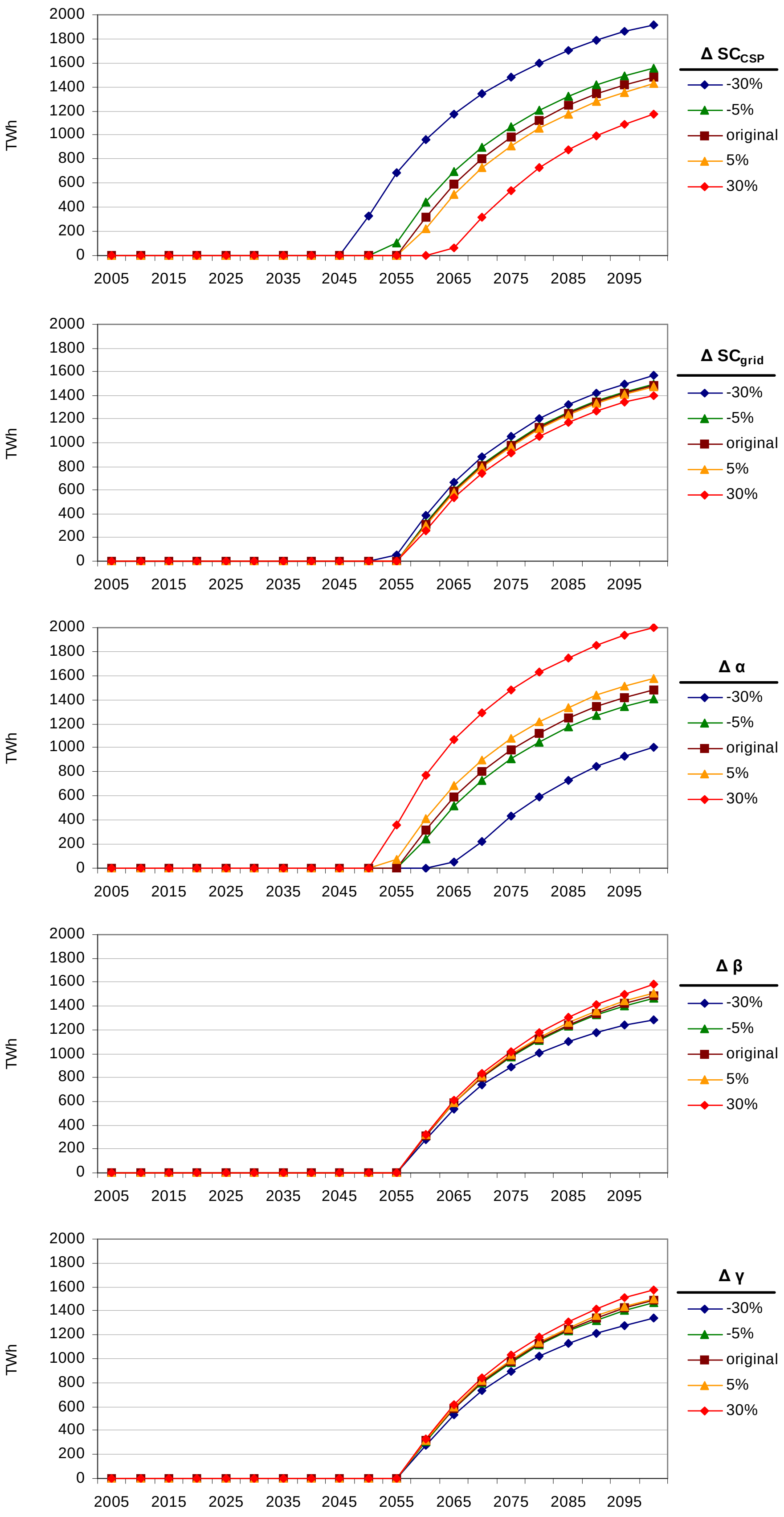
Aggeragated Discounted (3%) Policy Costs with respect to Bau

Sensitivity Analysis

CSP Investment costs



EU-Mena trade of SG-CSP Electricity



CSP World Cumulative Installed Capacity