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The role of energy technologies in achieving climate policies: updates of the WITCH model

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SUMMARY The present report describes the advancements related to GEMINA Work Package 6.2.3 reviewing additional mitigation issues which have been incorporated into different versions of the WITCH model.

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1.1. Introduction

Reflecting an on-going initiative to refine the WITCH model, this report reviews a range of additional mitigation issues which have been incorporated into different versions of the model. With the WITCH model focusing on climate policy, many of the additional mitigation issues chosen for further review are those which involve a greater focus on the provision or use of energy within the economy. The structure of the energy sector is of great importance to the overall emission profile of an economy and the introduction of new technologies provide many of the potential emissions reductions modelled within both the base and the extended versions of the WITCH model. With the model design aiming to track the major actions which impact mitigation (such as R&D expenditures, investments in carbon-free technologies and adaptation), the range of additional mitigation issues that can potentially be covered is broad. Following this, the range of mitigation issues currently developed for inclusion into the WITCH model is diverse and ranges from the early retirement of power plants to changes in the use of fuels within key non-energy sectors. In Section 1.2 there is a review of a range of technology based mitigation options within the energy sector, such as the early retirement of power plants (1.2.1 – Capital Vintaging), additional (or refined) representations of renewable energy options (1.2.2 – Refinement of Renewable Technologies), and the capture/storage of carbon dioxide (1.2.3 – Capturing Carbon). Section 1.3 investigates the changes to policy costs that occur with the addition of oil trade between regions. Section 4 then focuses on the inclusion of a light duty vehicle transport sector to allow for mobility demand and breakthrough technologies in personally owned light duty vehicles.

1.2. Technology Portfolio in the Energy Sector

Within the WITCH model, the energy sector is hard-linked to an economic macro-growth model and separated into electric and non-electric energy use. The modelling of six fuels and seven energy generation technologies allows for a reasonable portrayal of future energy and technology scenarios. The additional abatement options reviewed in different versions of the WITCH model and relevant to the energy sector technology portfolio include: the early retirement of carbon intensive energy generation technologies, refinements to the representation of renewable technologies and carbon capture & storage, as well as the potential for direct air capture of CO2. This is the same order that these abatement options will be discussed within the following subsections.

1.2.1. Capital Vintaging

Capital vintaging has been introduced in the WITCH model to differentiate between the existing power plants in the electricity generation sector and new power plants that possess cutting edge technology. As the average technical lifetime of the power plants is relatively high (varying from 25 to 45 years depending on fuel technology), the characteristics of the existing power plants can be considerably different compared to the new technology options currently available. New technologies tend to be characterised by higher energy efficiency and a higher load factor (representing the number of hours per year that they operate at full capacity). With capital vintaging the residual technical lifetime of the installed power plants at the base year (region and technology specific) is taken into account to reflect some inertia in the transition towards a low-carbon world. In order to achieve this a new index has been created to differentiate the capital (power plants) between old and new technologies. This index allows the existing equations to remain essentially the same, but allows for the incorporation of different data to reflect the relative inefficiency/efficiency between old and new capital. In addition to a new index there is a differentiation of depreciation rates to take into account the average residual economic lifetime of the installed power plants in 2005. While new capital has a depreciation rate that is constant over time, old capital depreciates according to the average residual economic lifetime for each region (and fuel type). To calculate the average residual economic lifetime for each fuel and each region, we have used the data provided by WEO (2008), IAEA, NETL Coal Plant Database and Ecofys (2008).

As a result of the change to the depreciation of old capital, the amount of investments in the electricity generation sector is lower in the short-term when compared to the previous version of the WITCH model. The change in global investments reflects the changes in the depreciation rate and hence tends to be greater in the areas of coal, gas, and nuclear technologies. As the depreciation for old capital is based on the residual technical lifetime of the installed power plants the model provides an improved replication of the actual trends of power plant generation capacity (GW) in the short-term . These residual technical lifetimes change between regions and across technologies and accordingly the changes in investments at a regional level have a similar diversity. For both a business-as-usual and a 550ppm GHG stabilisation scenario, the decrease in investments in coal is the most significant in China followed by India and Transition Economies. With respect to investments in gas the decrease is the most significant in the USA and MENA, followed closely by the EU. For nuclear the decrease in investments the most significant is in the EU, the USA, and CAJAZ. These changes in investments tend to exist between 2005 and 2025 as the majority of the modifications to the depreciation rates have been made to reflect technical lifetimes, which last for a similar time period. An exception to this is the case of notable nuclear expansion in the late 20th and early 21st century in non-OECD nations, such as China, India, and East Asia, where technical lifetimes extend for a greater number of years – up to 35 or 45 years in some cases.

1.2.2. Refinement of Renewable Technologies

Initially the modelling of wind in WITCH was combined with solar and had a combined learning-by-doing effect, which decreased the investment cost of wind and solar from 1500 USD per kWe in 2005 to 667 USD per kWe by 2100. With the extension of the model to specifically model Centralised Solar Power (CSP), the modelling of wind power has been refined as it now stands alone and incorporates a supply curve which maps the marginal costs of different capacity levels (net of learning costs which are modelled endogenously). Hoogwijk et al. (2007) explored the dynamic change of electricity production cost with increasing penetration levels in the USA and OECD Europe. The cost of wind electricity is defined by four components: depletion and learning, spinning reserve, backup capacity, and discarded electricity. The depletion effect increases the cost of electricity due to the declining quality of the resource in terms of power, while there is a learning effect, which decreases the cost of the technology. The WITCH model has taken part of the first cost component into account endogenously through the application of a learning effect. The establishment of a supply curve has the aim of including the other three components of cost. In doing so, a fitted polynomial curve (shown in Figure 1) has been designed to replicate the relationship provided by Hoogwijk et al. (2007) for the USA. In addition, a lower bound on the capacity of wind power installed from 2010 onward has been set to ensure that capacity in 2010 is equal to the levels described within WEO (2010). While depletion is not directly modelled, the maximum technical potential of wind (EJ per year) for each region has been applied with the application of estimates from Ecofys (2008a) and Hoogwijk (2004).

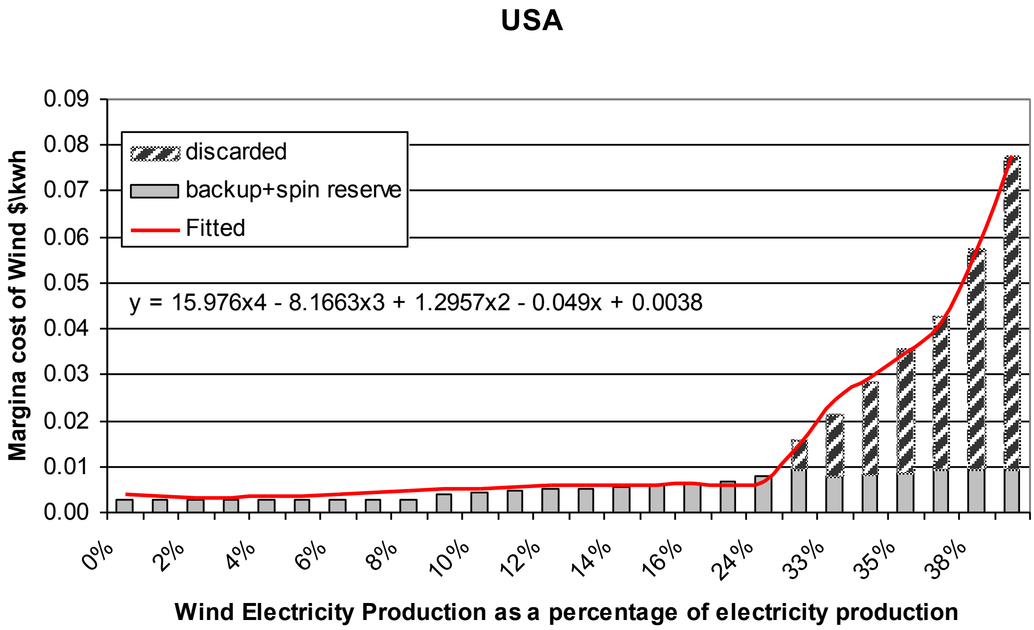

Figure 1. Overall Marginal Cost of Wind (excluding depletion and learning).

Wind, hydro, and solar are not the only renewable technologies that demand interest with respect to climate change policy. Advanced biomass is of interest to integrated assessment models, such as the WITCH model, as they are a fuel source for use during biomass co-firing with coal in IGCC power plants. In addition, they can be used in the production of advanced biofuels for use in the transport sector. It is with these uses in mind that supply curves for woody biomass have been introduced into the WITCH model to define the costs of this input. The supply curves incorporated into the model represent the cost of woody biomass sourced from conventional plantations and short rotation forests for each region. These supply curves have been sourced from the Global Biomass Optimisation Model (GLOBIOM) by harmonising the model with parameters from the WITCH model to determine the supply function for woody biomass with respect to competing land use possibilities; such as managed forests, short rotation tree plantations, and cropland. With wood and food demand being determined by GDP and population changes, regional estimates are produced by GLOBIOM with an allowance for up to thirty-seven different crops and a minimum per capita calorie intake. (Havlik et al., 2010) Given the land use change restrictions imposed in GLOBIOM, short rotation forests are not very sensitive to changes in prices as only cropland and grassland can be converted to plantations. Considering a given year, the change that is observed in the total supply is therefore in great part due to increased woody biomass coming from conventional plantations. Figure 2 reviews the global supply curve and the supply curve for the region with the most abundant biomass resources.

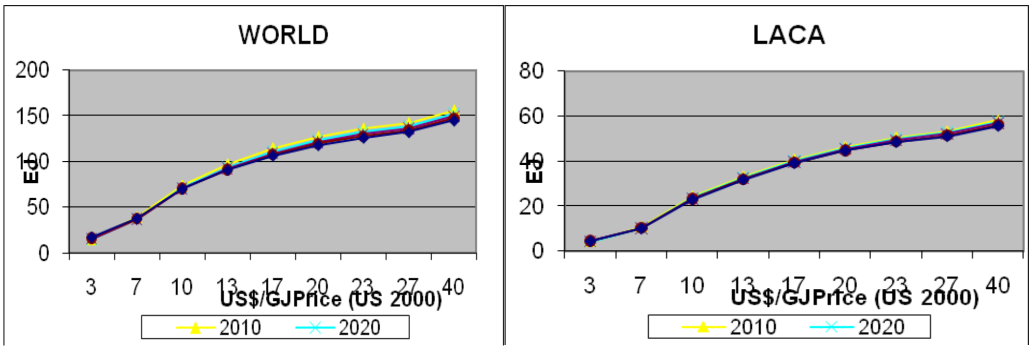

Figure 2.Supply Curves from GLOBIOM – Global & LACA.

Correctly accounting for greenhouse gas emissions is a crucial element in a biomass power production analysis. A common assumption asserts that woody biomass is carbon neutral, in the sense that emissions resulting from its combustion have previously been compensated for by forest carbon sequestration. If bioenergy plantations were to encroach upon natural forests, major land use emissions occurring at this phase would compromise woody biomass carbon neutrality. Accordingly, the curves derived by

GLOBIOM have been constructed using land use change restrictions that guarantee carbon neutrality. As a result, woody biomass is treated in WITCH as a carbon neutral energy. Notwithstanding this, fertiliser use, farming management, harvesting, and transportation imply additional emissions resulting from fossil fuel usage. A rather recent study (Evans et al. 2010) provides a survey on life cycle assessment for electricity production using woody biomass energy sources. While Evans et al. (2010) covers a large number of different electricity generation technologies it leaves out the technology considered in WITCH, for instance co-combustion with coal. Accordingly, the study by Dubuisson and Sintzoff (1998) is utilised as it provides final carbon emission factors for short-run coppices used to produce electricity with this type of technology. The stechiometric coefficient (Mton/EJ) for woody biomass was computed by dividing the carbon content of woody biomass (Million tonnes of C) by the energy supply per unit of biomass (EJ). Life cycle emissions follow Dubuisson and Sintzoff (1998) with CO2 emissions set at 12 Kg/GJ. The maximum biomass potential is 150EJ globally, which corresponds to 3.75 GtC (1EJ=0.026 GtC).

Mitigation options are not limited to generation possibilities and also include innovations within the power network and correspondingly there is a discussion that the development of Super-Grids and Smart-Grids may increase the possibilities for the utilisation of renewable sources (WBGU, 2003; Trieb, 2006; Battaglini et al., 2008; ECF, 2010; IEA, 2010; Jacobson and Delucchi, 2010). While Super-Grids can be coupled to many different power generation plants, the possibility to link them with renewable energy is of interest as it allows for the use of low-carbon energy sources, which are distantly located from energy consumption areas. Deploying High-Voltage Direct Current (HVDC) cables to form a Super-Grid can provide a network for large-scale and long-distance electricity transmission. This becomes possible as HVDC cables are characterised by relatively low transmission losses. Hence, Super-grids powered by Concentrated Solar Power (CSP) have been included within the WITCH model as it provides a renewable source of power that when coupled with heat storage is able to produce power that may even be used for base-load power (hence it partially overcomes intermittency problems). The existing regional profile of the WITCH model has been utilised to model long-distance transmission of CSP electricity within the USA, China and also between MENA and Europe.

The type of CSP modelled is the production of solar thermal power using parabolic trough power plants. Such power plants are characterised by arrays of parabolic reflectors that concentrate solar radiation on to an absorber and convert it into thermal energy, which is then used to generate steam for a turbine. Power production with this kind of technology is strongly influenced by solar irradiance and atmospheric conditions. As solar thermal power employs direct sunlight, it is best positioned in areas without large amounts of humidity, fumes or dust that may deviate sunbeams; such as deserts, steppe or savannas (Richter et al., 2009). As a result, the focus of the modelling within this version of the WITCH model focuses on desert areas with high values of Direct Normal Irradiation such as those found in the MENA region, the north of China, and the South-West of the United States (Richter et al., 2009; Trieb, 2009; IEA, 2010a). HDVC cables and the associated conversion stations are costly and in order for a Super-Grid to be installed there is a need for a significant and stable demand for energy. With the infrastructure being modelled to reflect the trade of CSP electricity from MENA to Europe or the transfer of CSP electricity within China or the USA, the requirement of significant and stable demand is not a major modelling problem for a macroeconomic model such as WITCH. More problematic issues are those related to the high investment costs involved and the evaluation of the commercialisation of the technology. In addition the case of trade between MENA and Europe presents complex considerations of supply security and geopolitical issues.

National power grids are dynamic structures with a historical heritage, which provide a constraint on their evolution. Although it is difficult to account for the specific constraints, the WITCH model considers that these systems are not able to take on any design in little time, but need time in order to evolve, as investments in power generation or transmission are long-lived. Within the modelling, the application of a constant-elasticity function (CES) creates a situation where moving away from an established and differentiated energy mix is costly. The model starting values for each region are calibrated on the real situation as at 2005 (Bosetti et al. 2007). Before considering trade, the possibility to produce solar thermal electricity is introduced and then the 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 (such as the case of MENA and neighbouring regions within Europe).

The amount of CSP electricity supplied to the grid of each region is determined through the combination of: (i) the generation capacity accumulated in each region, (ii) CSP plants operation and maintenance costs, (iii) the capacity of the Smart Grid to transmit electricity from remote areas to the local grid; and (iv) operation and maintenance costs for the Smart Grid. In accordance the production function of CSP electricity is represented by a Leontief function[1]. Power generation capacity in CSP accumulates through investments in concentrated solar power plants subject to a CSP capital depreciation rate and the unit investment cost of installing CSP generation capacity. These investment costs follow a one-factor learning curve depending on the cumulative world capacity of CSP power plants and these costs decrease as experience 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[2].

Theoretically, Super-Grid 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. At the macro-model level Super-Grid investments are 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, investments and capital in the Super-Grid infrastructure are modelled in a similar manner to that for other technologies. If investments in transmission infrastructure 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[3] differs from the production function of CSP electricity consumed domestically due to different grid requirements and an additional index to represent exports. Investments in CSP generation and in the

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[1] The Leontief function can be reviewed within equation one in section 2.1 of the appendix.
[2] The functional form of the relationship with a learning curve and the allowance for limited expansion possibilities can be reviewed within equation two in section 2.1 of the appendix.
[3] The Leontief function for exported CSP electricity can be reviewed within equation three in section 2.1 of the appendix.

Super-Grid infrastructure enter the budget constraint[4] together with O&M costs. The equilibrium of the international market of CSP electricity requires that demand and supply are equal for each time period. The market clearing price is the price that determines the trade flows. The revenue/expenditure for CSP electricity is added/subtracted from the regional output[5].

The modelling of CSP is based on parabolic trough power plant technology, with nominal capacity of 50MW each, 100% solar share and equipped with integrated thermal storage units for 7 hours (Kaltschmitt et al. 2007). 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). The resulting simulations suggest that an extensive use of CSP both for domestic consumption or export will only occur in the second half of the century. The introduction of the CSP option allows stabilisation policy costs to be reduced, and while policy is still costly (in terms of GDP loss compared to a business-as-usual scenario), the addition of CSP significantly decreases such losses in areas with high solar irradiance (such as MENA). Note that a more detailed review of the results related to the integration of CSP into the WITCH model can be found within Massetti and Ricci (2011). Future developments of the WITCH model will expand the number of regions that can invest profitably in CSP, will explore more stringent stabilisation targets and will also describe the optimal geographical location of CSP plants with greater precision.

1.2.3. Capturing Carbon

One technology that has received particular attention in the recent past is carbon capture and sequestration (CCS). CCS is a promising technology but is still far from large-scale deployment. Costs increase

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[4] This budget constraint can be reviewed within equation four in section 2.1 of the appendix.
[5] This relationship with regional output is represented as equation five in section 2.1 of the appendix.

exponentially with the capacity accumulated by this technology. Having introduced a supply of woody biomass as a possible feedstock within the WITCH model, the capacity for its use within co-fired coal IGCC power plants has been established as an additional CCS option. Globally, experience with biomass (or waste) co-firing with coal covers about 150 power plants which are either at the pilot test stage or are used for commercial use (IEA Bioenergy, 2007). Biomass co-firing with coal requires relatively small changes at power plants already equipped with CCS technology and it also ensures some level of fuel flexibility. Currently biomass is co-fired in coal-fired power plants with a 10% fuel share (on energy basis) (NETBIOCOF, 2006) and there are only few examples with higher shares reaching 20%. Since IGCC power plants are equipped with the technology for capturing and storing the emissions produced from the combustion of both coal and biomass, biomass energy with CCS can yield negative net emissions. In accordance, woody biomass with CCS tends to be a key technology within the portfolio of CCS technologies within stabilisation scenarios.

The utilisation of existing CCS structures and technology is not limited to co-firing with waste or biomass. Technologies aimed at the capture of decentralised CO2 emissions will also require the services of carbon sequestration. The development of Direct Air Capture (DAC) envisions the development of a technology, which absorbs CO2 by passing polluted air over sodium hydroxide within a structure similar to a cooling-tower (Bickel and Lane, 2009 and APS, 2011). In comparison to carbon removal from flue gas, DAC allows the process of carbon capture to employ economies of scale as it can be located amongst existing power generating systems (Keith et al., 2006). Since DAC can limit the cost of a stringent climate policy scenario and decreases the need for near-term mitigation, it can be an important additional abatement option in the middle of the century when the marginal abatement cost notably increases. This is the case under a 450 ppm GHG concentration target aimed at keeping the global temperature increase at 2°C. Accordingly the WITCH model has been modified to review the impacts of implementing DAC and its impact on marginal abatement cost and energy use patterns. Having built a benchmark system based on current technological capabilities, APS (2011) released a report on the cost of DAC and its potential role within climate mitigation. The report concludes that while there is potential for the capture of decentralised CO_2 emissions, “at least for the next few decades, unless there are dramatic cost reductions, direct air capture can be expected to be substantially more expensive than many other currently available options". (APS, 2011: iii) In applying the cost assessment developed within APS (2011), the WITCH model reviews both the relative cost of DAC in comparison to other CSS options and its effectiveness given the technology's need for electricity and the storage of captured carbon.

With no changes made to reflect technological improvements, the WITCH model applies the non-energy costs (such as capital costs and non-energy operating costs) and the electricity/non-electricity consumption levels sourced from the APS (2011) study for the whole century. With energy prices set to those derived by the WITCH model, the total cost of the technology allows for competing sources of electricity and the trade-off between supplementing and complementing existing CCS technologies. Note that an upper limit on the penetration rate of DAC has been set to 50% of the total carbon captured by other CCS technologies in the previous five-year period. DAC, like other forms of CO2 absorption, consumes both electricity and non-electric energy. Electricity is used to power the fans and facilities associated with passing air over the sodium hydroxide and produce a cross-reaction with carbon hydroxide to form calcium carbonate. Non-electric energy is used for the heating of the calcium carbonate within a natural gas fuelled kiln to capture the released CO2, which is then stored with the sequestered carbon from other CCS technologies. Reflecting the issue of net-carbon reductions, the WITCH model sources the electricity used to fuel DAC from the existing low-carbon or zero-carbon energies within the model (such as nuclear, renewables and carbon-intensive energy coupled with CCS facilities).

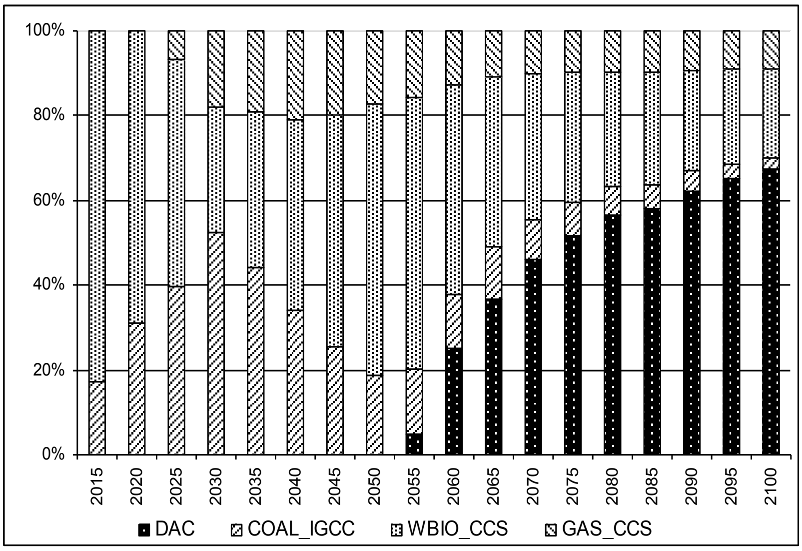

Figure 3. Composition of Carbon Sequestration.

As shown in Figure 3 woody biomass CCS accounts for the largest share of carbon sequestration in a 450 ppm scenario while DAC becomes commercially viable in the middle of the century. DACs share of carbon sequestration increases to over 60% of the total amount of carbon sequestration in the late part of the century. By capturing several gigatonne of CO2 each year (rising from approximately 8 gigatonne in 2070 to approximately 17 gigatonne in 2010), the emergence of DAC results in a decrease in the carbon price of about 73% at the end of the century, down from \$4000/GtCO2 to \$1000/GtCO2. The total policy cost (calculated using the percentage loss of GDP in comparison to the business-as-usual scenario) starts to reduce in comparison to the standard WITCH 450ppm scenario and this corresponds with DAC coming online in 2055. A sharp reduction in the policy cost can be explained by a higher prevalence of the cheaper carbon-intensive energy sources, in comparison to the standard 450ppm stabilisation scenario. Upon comparing the composition of world energy consumption, as in in Figure 4, the total energy consumption increases by more than 300 EJ at the end of the century. The most prominent difference is the consumption of oil, which in 2100 is 8 times more than the case without DAC, while investments in nuclear and renewables are also increased due to the decreased demand for CCS technologies.

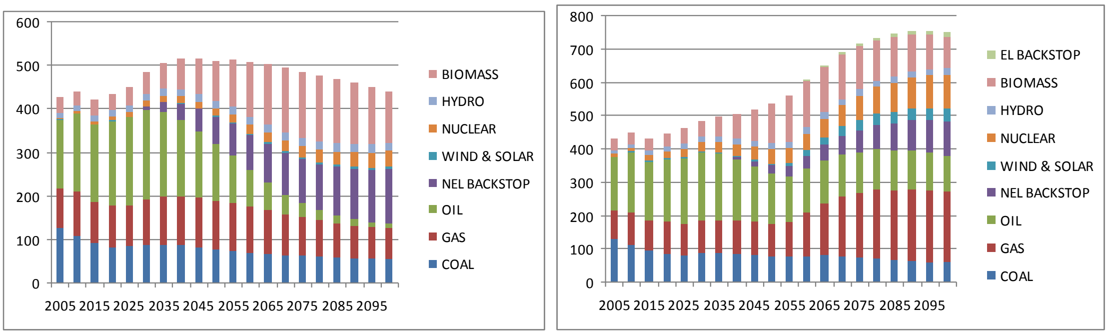

Figure 4. Composition of Energy Consumption (Left: w/o DAC; Right: w/ DAC).

Without the deployment of DAC, the achievement of a 450ppm target within the WITCH model is difficult when the carbon market is incomplete or when the largest emitters are absent from the abatement agreement. While the carbon price is higher in this scenario (reaching almost $1500/GtCO2), the potential importance of DAC in the long-term is reflected in the stabilisation of GHG concentrations at the 450 ppm level without the contributions of India and China. The results of incorporating DAC into the WITCH model are complementary with those of the APS (2011) report as the analysis in both cases show that the DAC deployment should occur in parallel with other CCS technologies, that its deployment will occur slowly and is likely to occur in the latter half of the century with stricter policy reactions to climate change (such as a 450 ppm stabilisation target).

1.3. Policy Costs and the Trade of Oil

Commonly the WITCH model is used to assess the policy costs (and the underlying dynamics) of either a 535ppm or 450ppm CO_2-eq GHG stabilisation target for 2100. Over the century this would require a substantial decrease in carbon emissions with the global peak in CO_2 emissions being identified by the IPCC to be between 2010-2030 (in the case of 535-590ppm) or 2000-2015 (in the case of 445-490ppm).

(IPCC, 2007) The emergence of a low-carbon world (such as that implied by either GHG stabilisation scenario) would mark the end of an “oil age” and provide widely unexplored economic, technological, and geopolitical implications. It is with this in mind that the WITCH model has been extended to incorporate an oil sector that evolves endogenously across all twelve regions. This oil sector is modelled for eight categories of oil, reflecting extraction costs and emissions related to oil extraction for each category. The production of oil is a function of extraction capacity built through endogenously determined investments. The cost of additional oil extraction is also endogenous and depends both on a short-term component, which mimics cost spikes when expansion capacity grows too fast, and on a long-term component, which reflects oil scarcity. Thus, the total expenditure in the oil sector is also endogenous. Once extracted, oil can be used for domestic consumption or it can be traded internationally. The price of oil emerges endogenously as an outcome of a Nash game among the all of the WITCH regions.

The model is calibrated to replicate base year oil production as well as imports and exports. We assume that oil traded internationally is homogeneous and therefore we have a unique international oil price. The cost of additional oil capacity is region-specific and accounts for both long-term exhaustibility and for short-term frictions that might arise in the supply chain when too much capacity is installed in a short-time period. Crude oil is used both in the electric and in the non-electric sector in WITCH. Oil demand is covered by means of domestic production of each category of oil and/or by means of net oil imports from the international oil market. In oil-exporting regions, domestic production of oil is greater than domestic consumption and net imports are negative. Oil production in a given year cannot exceed the extraction capacity cumulatively built in the country. Equilibrium in the international oil market requires that excess demand of oil is equal to zero at any given time period. National Net Gross Domestic Product can be decomposed into oil and non-oil GDP. Equation six (within section 2.1 in the appendix) shows that net non-oil GDP is equal to gross non-oil output net of the climate feedback, the expenditure for oil and the expenditure on other fuels. Equation seven shows that net oil GDP is equal to the value of oil production, valued at the international price of oil. Oil is valued at international market prices for regions and a mark-up is added to account for local factors that affect the cost of oil for final users and this mark-up can be greater or lower than zero. Consumption is equal to what remains of the economy net output, after subtracting investment in all technologies, other expenditures, investments in additional oil capacity extraction and O&M costs. (Refer to equation eight within section 2.1 for the functional form of this relationship.) Investments for oil extraction are equal to the expenditure for financing the expansion of oil capacity and are both region and time specific. We assume that labour is not necessary to extract oil. This is a simplification that does not bear relevant implications since the oil-extraction sector is highly capital intensive.

Oil resources are derived from Rogner (1997) and they are assumed not to grow over time. Oil resources are separated into eight categories. In Table 1 they are aggregated into two categories: conventional oil (categories I-IV) and non-conventional oil (categories V-VIII). In 2005, non-conventional oil production is negligible and concentrated only in a few regions: Canada (CAJANZ aggregation), Brazil and Venezuela (LACA aggregation), and the USA. Oil imports and exports in the base year are calibrated using data provided by Enerdata (World Energy Database). In 2005, the USA is the largest oil importer (4.83 Billion Barrels per year), followed by WEURO, CAJAZ and CHINA. The largest oil exporter is MENA (7.6 Billion Barrels per year) followed by TE, LACA and SSA in decreasing order. An overview of the oil sector is given in Table 1.

	USA	WEURO	EEURO	KOSAU	CAJAZ	TE	MENA	SSA	SASIA	CHINA	EASIA	LACA
Resources (Bln. Barrels)												
Conventional (Cat I-IV)	347	120	13	15	59	538	1341	130	20	186	76	445
Non Conventional (Cat. V-VIII)	1749	416	39	989	1823	1336	3007	331	32	1737	269	3848
Production (Bln. Barrels)												
Conventional (Cat I-IV)	2.1	1.8	0.0	0.2	1.0	4.1	10.1	1.9	0.3	1.3	0.9	3.9
Non Conventional (Cat. V-VIII)	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.1
Net Exports (Bln. Barrels)	-4.8	-2.8	-0.5	-1.0	-1.5	2.4	7.6	1.6	-0.8	-1.4	-0.6	1.7
Consumption (Bln. Barrels)	7.0	4.6	0.5	1.2	2.6	1.7	2.5	0.3	1.1	2.7	1.5	2.3

Table 1. Oil Overview in 2005.

Under a business-as-usual scenario, world consumption of oil doubles during the century (in comparison to consumption in 2005), while the volume of oil traded internationally increases only by 60%. This is explained by the exploitation of vast non-conventional oil resources in countries with high domestic demand. The value of oil traded internationally, measured as the volume of oil times the price that emerges from the market, continues to increase due to the growing price of oil. The stabilisation scenario is constructed assuming that all regions agree on a global trajectory of emissions to stabilise GHGs concentrations in the atmosphere at 550ppm CO2-eq at the end of the century. The regional outlook of the oil sector changes dramatically in the stabilisation scenario. Oil consumption drops substantially in all regions, with respect to the BaU scenario. With respect to 2005, aggregate consumption of Transition and Developing economies grows until 2025, while consumption in high-income economies peaks as early as 2015. The production of oil also changes substantially under climate policy. Non-conventional oil is extracted only in minimal quantity and MENA along with TE are able to supply all oil needed until the end of the century. Between 2040 and 2085 international oil trade is dominated by two macro-regions: the Middle East and North Africa and Transition Economies. The pattern of oil production triggered by the stabilisation policy entails that Western Europe, CHINA and the USA increase their reliance on foreign oil to supply their domestic consumption over the century. However with total demand of oil decreasing substantially, MENA, LACA and TE dominate a market that rapidly shrinks and this leads them to being net losers. In addition, their grip on the energy systems of Europe, the USA, and China vanishes under such stabilisation scenarios. At the global level, the cost of the stabilisation policy are quite sensitive to assumptions on the availability of the least cost non-conventional oil. The results of a sensitivity analysis within Massetti & Sferra (2010) reveal a need for an accurate description of fossil fuels extraction sectors to assess the macroeconomic consequences of a stabilisation policy. In conclusion, it should be noted that introducing a detailed description of the oil sector into the WITCH model results in an increase in policy costs and the regional distribution of these costs shift towards oil-exporting regions. With climate policy expected to reshape the geo-politics in oil rich areas of the world, oil-rich countries will have a strong incentive to undermine climate agreements, unless they are adequately compensated for their losses.

1.4. Demand for Mobility and Transport Options

With forecasts of transport demand in less developed and fast growing nations being approximately three times the rate of the OECD, considerable potential for growth in travel within even the most conservative economic scenarios is expected (Kahn Ribeiro et al., 2007). In order to analyse long-term trends in transport and their repercussions on the rest of the economy a transport module representing the use and profile of Light Duty Vehicles (LDVs) has been introduced into the WITCH model. LDVs have been selected as the vehicle type of interest as they have been identified as being one of the most favoured modes of transport and also one of the most damaging (Chapman, 2007). The addition of the transport module into the WITCH model allows for the evaluation of how the choice between LDVs will affect emissions as well as how these choices are likely to be impacted by climate change policies. The incorporation of the LDV transport sector has been conducted in a manner which allows for a range of emission mitigations to be possible, this includes: increased fuel efficiency, the introduction of alternative fuels and vehicle types, as well as curbed demand through decreases in the amount of kilometres travelled.

Demand for vehicles has been set exogenously based on the assumption that constant travel patterns correspond to given levels and growth rates of GDP and population. The relationship between vehicle ownership and national income has been established within Dargay and Gately (1999) and applied to forecasting within WBCSD (2001). This assumption is important, as the demand for private transport will likely continue to be high and have a strong correlation with national income – unless a significant change in the provision of public transport occurs. With its current framework the model reviews the continuation of constant travel patterns and the constraint that this will place on the achievement of emissions reductions. This means that increased LDV travel (in terms of kilometres travelled per vehicle) as well as the costs of the vehicle and fuel expenditure directly impact utility through the corresponding effect of decreasing consumption on other goods and services. The model separates consumption in transport from the rest of consumption, which allows for the direct modelling of the costs involved in switching between vehicles and fuels for a given demand of mobility. Investments in vehicle capital and supplementary costs decrease the level of consumption. A Leontief function combines exogenous costs of vehicles with fuel costs and O&M costs. Fuel costs depend upon the vehicle chosen and the price of fuel derived in the energy sector, where the fuel demand for oil, gas, biofuels and electricity directly compete with other electric and non-electric uses of fuels.

Having set out the general structure of the model, we will now clarify the description provided with a review of the main equations in the model. Equation nine (shown in section 2.1 of the appendix) represents the distinction between the aggregate level of consumption and the level of consumption net of transport, as the ultimate budget constraint is set to consumption net of output, transport expenditure and investments. With the utility function defined, we can turn our attention to the modelling of the transport sector itself. Starting with the level of investments in vehicles in time period one, the subsequent period's capital stock of LDV is equal to the level of capital remaining after depreciation and the additional capital implied by investments undertaken at the prevailing investment cost of vehicles. With an exogenous estimate of the amount of mobility and hence the vehicle capital demanded in each region, a constraint is placed on the amount of capital in each period for each region. The amount of fuel demanded by each vehicle has been defined in equation ten (shown in section 2.1 of the appendix) as a function of the average fuel efficiency of the vehicle for the amount of kilometres travelled per year using the different fuel technologies, *e*, and the amount of fuel efficiency improvements (FEIs) to date. The amount of fuel efficiency improvement is derived as a function of time (defined as the number of 5-year time spans that have passed) and a fuel efficiency factor. The average fuel efficiency variable has been set to the 2005 level for each vehicle type and applying different fuel efficiency factors produces different FEI curves. The fuel efficiency factor adopted in the base scenario has been set to intersect the US EIA forecast for fuel economy in the USA for the year 2030. The amount of fuel is defined using terawatt hours for direct comparability across fuel types and is linked to the existing WITCH model structure for each of the energy technology types. The amount of fuel also feeds into equation nine as it is multiplied by the fuel cost to become the fuel expenditure variable. The range of vehicles, *ldv*, introduced into the model has been selected to provide a representative overview of the type of vehicles expected to come into contention for successful market penetration in the medium to long-term future. While each of these categories have different fuel economy and vehicle cost levels, the results are discussed in the following terms: Traditional Combustion Engine vehicles (TCEs), hybrid vehicles (HYBRIDs), biofuel vehicles (BIOFUELs), advanced biofuel vehicles (ADV BIOFUELs), Plug-in Hybrid Electric-drive Vehicles (PHEV) and Electric Drive Vehicles (EDV)s.

Figure 5 shows the cost of three key vehicle types across six different time periods for the USA and compares these to that vehicle's share of global sales within the LDV transport sector. (Note that the price of EDVs in the USA is representative of those in all other regions – except for the fuel and carbon cost components.) A decrease in the share of TCE vehicles within 2020 and 2030 is due to the use of biofuels as an alternative fuel source. In 2050 a further decrease occurs with the introduction of EDVs in the US, which are primarily fuelled by electricity from woody biomass with IGCC. With respect to this it should be noted that depending on the fuel source chosen for the corresponding electricity demand, fuel cost, and carbon cost can be very low – with CCS options and traditional gas being the sources predominantly chosen by the model. The introduction of EDVs within the USA in 2050 corresponds with higher vehicle costs, but is offset by considerable emissions reduction possibilities compared to the alternatives. Hence the USA tends to buck the trend of having HYBRID vehicles come in first (or simultaneously in the case of the Rest of the OECD) with the introduction of EDVs following after further cost reductions. After 2050 there is a gradual move towards battery fuelled technologies with EDVs dominating worldwide in 2100. Focusing on the fuels used to provide electricity for electric drive vehicles, natural gas tends to dominate in most of the regions (Europe, Rest of OECD, and Rest of Non-OECD), while there tends to be a significant use of woody biomass with CCS in the USA, China, and post-2090 India. Figure 5 shows that for the USA, the cost of carbon and the price of oil lead to the cost of employing TCE vehicles increasing in the latter half of the century. At the same time, the cost of an EDV is stabilising at a level below that of TCE vehicles from 2090 onwards.

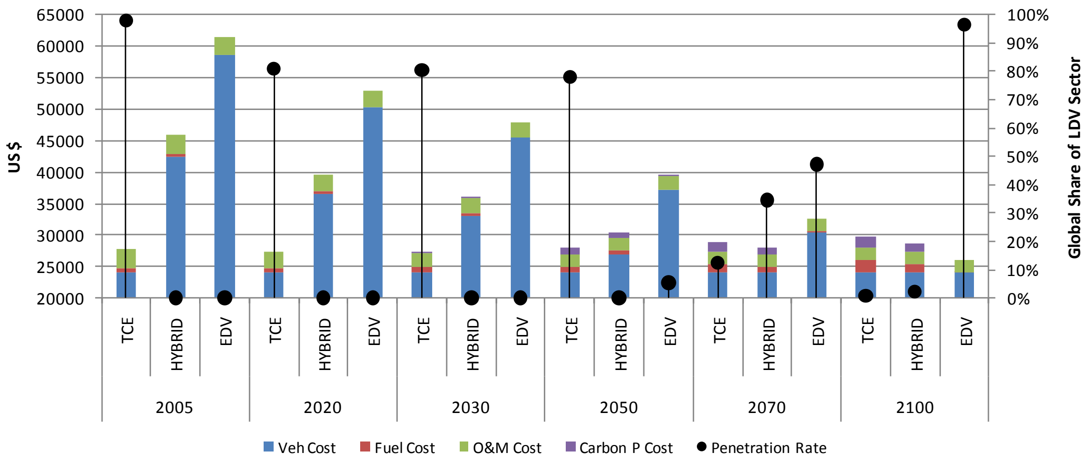

Figure 5. Cost of New Vehicle – Cost of a New Vehicle in the USA and % Share of Global Vehicles.

The sensitivity of the model to the existence of EDVs can be explained once we consider the amount of aggregate emissions from within the LDV transport sector for two additional stabilisation scenarios and compare the global carbon prices. Figure 6 highlights the sensitivity of the carbon price to higher aggregate emissions (attributed to a scenario with no EDVs – entitled the 'No EDV' scenario) and the insensitivity of the carbon price to lower aggregate emissions from within the LDV transport sector (attributed to a scenario with an earlier introduction of EDVs due to lower battery costs, entitled the 'Bat Cost' scenario). Within the 'No EDV' scenario the energy sector has had to compensate for continued reliance on fossil fuels and no decrease in the amount of travel performed or the amount of vehicles purchased. Indeed, a range of scenarios show a similar trend over time and a stabilisation of world concentrations of GHGs at 550ppm CO2-eq at a cost of approximately US $650 per tonne of carbon in 2100. The case of 'No EDV' diverges in the middle of the century, with the price of carbon steadily increasing until approximately US $1173 per tonne of carbon. This matches the trends in the global costs of climate policy (as a percentage of discounted GDP). In all scenarios, except for the 'No EDV' and 'Bat Cost' scenario, the World policy cost tends to be 2.6% of global GDP. For the 'No EDV' scenario the policy cost is approximately 3.5% of global GDP. This confirms that the electrification and decarbonisation of the LDV transport sector is a notable issue with respect to the achievement of a cost effective climate policy. The case of improvements in battery costs result in policy costs of 2.2% of global GDP and reflects the relative insensitivity of the policy cost to lower emissions from the LDV transport sector. In addition to the carbon price, the cost of having no breakthrough in EDVs also impacts the world oil price. An increase in the oil price within the 'No EDV' scenario results in a mark up of approximately 50% of the STAB scenario price in 2100. Already significant, these costs are sure to rise in the complementary case of no electrification within freight transport, a sector of interest that has yet to be directly modelled within WITCH.

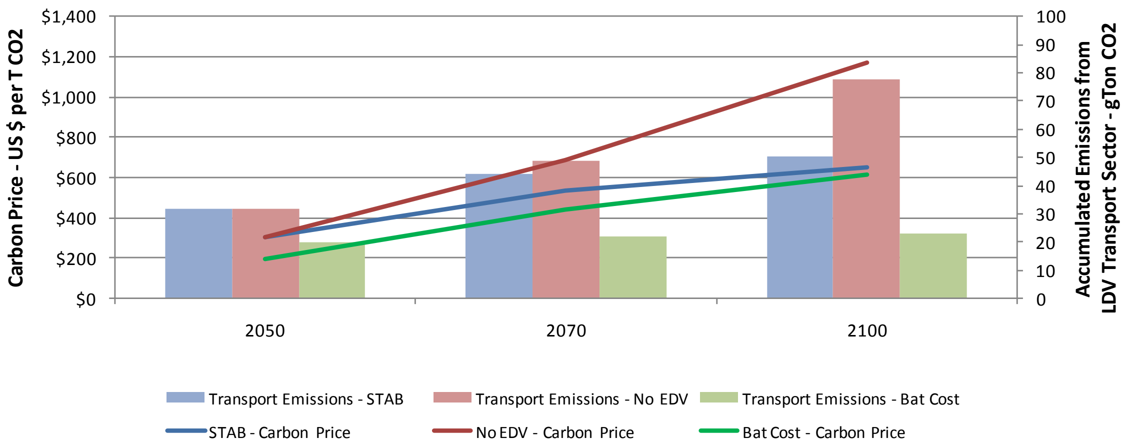

Figure 6. Carbon Price Comparisons.

1.5. Conclusion

With the WITCH model design aiming to track the major actions which impact mitigation, the range of additional mitigation issues modelled and considered as potential candidates for modelling is continually expanding. Within this report, there has been a review of some key developments that are being integrated into WITCH at the time of writing. We acknowledge the contributions of Carlo Carraro, Chen Chen, Enrica De Cian, Emanuele Massetti, Elena Ricci, Renato Rosa, Massimo Tavoni and Valentina Bosetti. Each section has been constructed using contributions from the researchers involved in developing the different model versions. In addition, section 2.2 utilises materials sourced from Massetti and Ricci (2011) and section 3 utilises materials sourced from Massetti and Sferra (2010).

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2. Appendix

2.1. List of equations

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

(1)

$$SC_{CSP}(n,t+1) = SC_{CSP}(n,t_0)\frac{TK(t)}{TK(t_0)}^{-(\alpha)}\left(1+\left(\frac{\left(\frac{I_{CSP}(n,t+1)}{SC_{CSP}(n,t+1)}\right)}{\beta}\right)^{\gamma}\right) \quad (2)$$

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

(3)

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

(4)

$$Y(n,t) = \frac{GY(n,t)}{\Omega(n,t)} - \sum_{q} p_q V_q(n,t) + EL_{CSP,X}(n,t) P_{CSP}(t) \qquad (5)$$

$$Y_{NONOIL}(t,n) = \frac{GY_{NONOIL}(t,n)}{\Omega(t,n)} - OIL(t,n)\left[P_{OIL}(t) + MKUP_{OIL}(t,n)\right] - \sum_z P_z(t) X_z(t,n) \qquad (6)$$

$$Y_{OIL}(t,n) = \frac{1}{\Omega(t,n)} \sum_{g} OIL_{prod}(n,t,g) P_{OIL}(t) \qquad (7)$$

$$C(t,n) = Y(t,n) - \sum_j I_j(t,n) - \sum_g I_{OILCAP}(t,n,g) - \sum_g OILCAP(t,n,g) O\&M - \sum_k W_k(t,n) \qquad (8)$$

$$C(n,t) = CG(n,t) - \sum_{ldv} I_{ldv}(n,t) - \sum_{ldv} O\&M_{ldv}(n,t) - \sum_{ldv,e} FE_{ldv,e}(n,t) \qquad (9)$$

$$Fuel_{ldv,j}(n,t) = FEI_{ldv,e}(t) * AFE_{ldv,e} * K_{ldv}(n,t) \qquad (10)$$

2.2. List of variables

$EL_{CSP,prod}(n,t)$ = Total electric energy produced with CSP

$\mu_{CSP,n}$ = Full load hours for a CSP power plant in region n

$K_{CSP}(n,t)$ = Stock of capital in CSP

θ_{CSP} = Conversion factor to turn US Dollars into energy units for CSP

$\mu_{grid,n}$ = Full load hours for the domestic Super-Grid in region n

$O\&M_{CSP}(n,t)$ = Operation and maintenance costs associated with CSP generation

$K_{grid}(n,t)$ = Stock of capital in the whole Super-Grid infrastructure

θ_{grid} = Conversion factor to turn US Dollars into energy units for the Super-Grid

$O\&M_{grid}(n,t)$ = Operation and maintenance costs associated with the whole Super-Grid

$SC_{CSP}(n,t)$ = Investment costs for the construction of CSP plants

$SC_{CSP}(n,t_0)$ = Investment costs for the construction of CSP plants in the initial period

$TK(t)$ = Cumulative world capacity in CSP power plants

$TK(t_0)$ = Cumulative world capacity in CSP power plants in the initial period

α = Rate of learning by doing (set equal to 0.15 for CSP)

$I_{CSP}(n,t)$ = Investments in CSP plants

β and γ =Parameters of the cost related to a costs increase when there is a limited supply of intermediate goods

$EL_{CSP,X}(n,t)$ = Electric energy produced with CSP for export

$\mu_{n,CSP}$ = Full load hours for a CSP power plant in region n

$K_{CSP}(n,t)$ = Stock of capital in CSP

$\mu_{n,X}$ = Full load hours for export in region n

$K_{grid,X}$ = Stock of capital in the Super-Grid infrastructure for export

$C(n,t)$ = Consumption

$Y(n,t)$ = Gross Domestic Product

$I_c(n,t)$= Investments in Consumption goods

$\sum_w p_w Z_w(n,t)$= The expenditure on investments in the energy sector, in R&D and other expenses

$GY(n,t)$= Gross output

$\Omega(n,t)$= Climate damage feedback on the economy

$\sum_q p_q V_q(n,t)$ = Sum of expenditures of non-CSP related expenditures

$P_{CSP}(t)$= Price of the traded CSP power

$Y_{NONOIL}(t,n)$ = Non oil GDP

$GY_{NONOIL}(t,n)$= Non oil GDP net of climate change impacts

$OIL(t,n)$ = Total consumption of oil

$P_{OIL}(t)$ = International price of oil

$MKUP_{OIL}(t,n)$ = Regional Mark-up on international price of oil

$\sum_z P_z(t) X_z(t,n)$= Vector of prices for the input vector XZ

$Y_{OIL}(t,n)$ = Oil Gross Domestic Product

$\sum_g OIL_{prod}(n,t,g)$ = Domestic oil production (summed across grades of oil, *g*)

$I_j(t,n)$ = Investments in final good

$\sum_g I_{OILCAP}(t,n,g)$ = Investments in additional oil capacity (summed across grades of oil, *g*)

$\sum_g OILCAP(t,n,g) O\&M$ = Oil sector O&M costs (summed across grades of oil, *g*)

$\sum_k W_k(t,n)$ = Welfare

$CG(n,t)$ = Gross Consumption

$I_{ldv}(n,t)$= Investments in Light Duty Vehicles (LDVs)

$O\&M_{ldv}(n,t)$= Operation and maintenance costs for LDVs

$FE_{ldv,e}(n,t)$= Fuel Expenditure for LDV and technology e

$Fuel_{ldv,e}(n,t)$= Fuel consumed per year

$FEI_{ldv,e}(t)$= Fuel efficiency improvement

$AFE_{ldv,e}$ = Average fuel efficiency of LDV

$K_{ldv}(n,t)$= Stock of LDV capital