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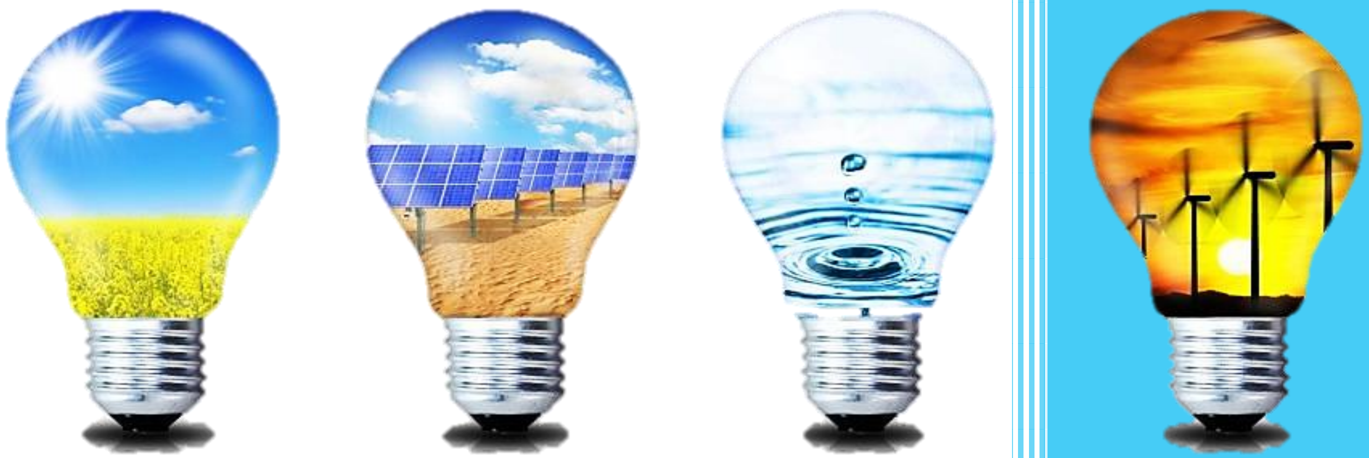
Policy instruments on mitigation options for a low-carbon economy in the Netherlands in 2050



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Policy instruments on mitigation options for a low-carbon economy in the Netherlands in 2050

Using a System Dynamics modelling approach

MSc. Thesis by K. Dekkers

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ABSTRACT

This study aims to address how market-based policy instruments could be deployed to support technological mitigation options (e.g. energy savings, production of CO_2-neutral electricity, electrification, production of bioenergy and Carbon Capture and Storage) in order to achieve a low-carbon economy in the Netherlands in 2050. A low-carbon economy indicates a CO_2 emissions reduction of at least 80 percent compared to 1990. A System Dynamic model is built including the demographic economic, the energy and the environmental system of the Netherlands. Next to the Business-as-Usual scenario, there are four policy scenarios simulated from 2010 to 2050. In all policy scenarios a carbon levy is imposed on non-renewable energy in order to finance subsidies on mitigation options. Results show that imposing a carbon levy additional to the ETS-price to finance subsidies on the mitigation option renewable energy is most effective.

Keywords: *low-carbon economy, CO_2 emissions reduction, market-based policy instruments, mitigation options, System Dynamics, The Netherlands*

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1. INTRODUCTION

1.1 Problem definition

The United Nations (UN) climate change conference in Paris (2015) (COP21) resulted in a mutual agreement between 196 international leaders to limit the global temperature increase to a maximum of 2°C compared to pre-industrial levels[1], and promised to pursue efforts for just a 1.5°C temperature increase (UNFCC 2015). According to EEA (2010), a global temperature increase that rises above the mentioned 2°C will result in passing the Earth's biophysical boundaries. For Europe, that can result in increased risk of inland floods as well as coastal floods, increased erosion, extreme weathers, a higher sea-level, the melting of glaciers, a decreased land productivity and loss of biodiversity. Figure 1 displays the deviation of the temperature mean and as one can see, as of 1880, the world average temperature is increased by 0.85°C (0.65 to 1.06 uncertainty range) in 2015 (CLO 2016).

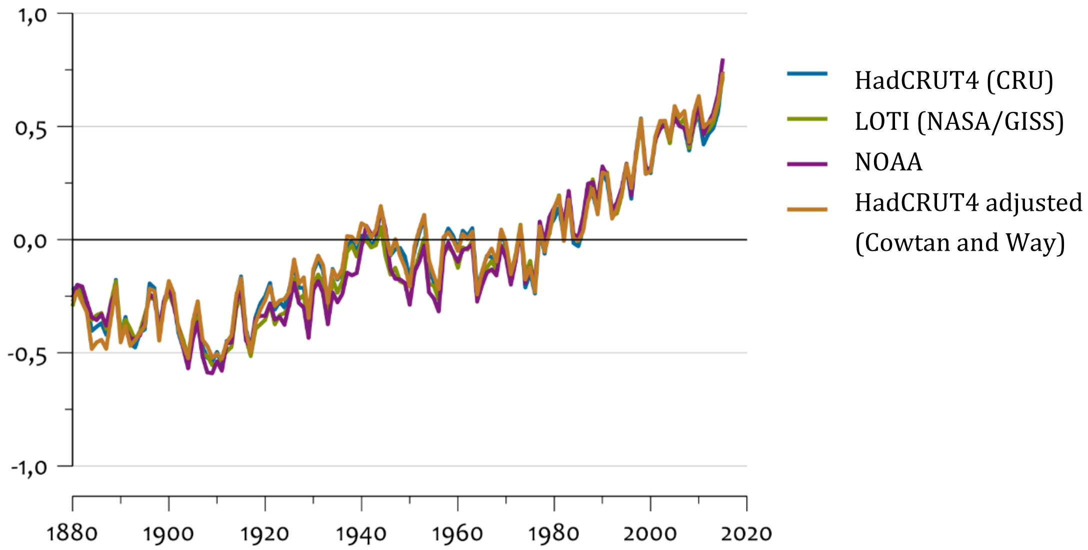


Figure 1 Deviation of global temperature mean 1880-2015. The mean is approximately 15°C, based on the average temperature of 1960-1990. (three temperature datasets are put together by CLO (2016), the so called HadCRUT4 dataset of Climate Research Unit (CRU) and Hadley Centre, the so called LOTI-dataset of the NASA Goddard Institute for Space Studies in New York, the NOAA-dataset of American national climate datacentre National Oceanic and Atmospheric Administration (NOAA) and an adjusted HadCRUT4 – dataset of Cowtan and Way (2014).

According to the IPCC Fifth Assessment Report (Knutti 2013), a direct relationship between CO_2 emissions and temperature rise exists. Therefore, in order to comply with the 2°C goal, the CO_2 concentration in the atmosphere must stop rising. The more ambitious the temperature goal, the earlier the world must produce net-zero CO_2 emissions. Scenarios performed by the International Institute for Applied Systems Analysis, the Potsdam Institute for Climate Impact Research and the Massachusetts Institute of Technology claim that in order to achieve the 2°C goal, the world must be net-zero of CO_2 emission in 2070, and if the 1.5 °C goal is pursued, the world needs to be net-zero in 2050, followed by net-negative emissions after 2050 (SI 2001).

The Netherlands, as one of the countries that signed the Paris agreement, have agreed to develop a low-carbon economy in 2050. A low-carbon economy implies that CO_2 emissions are reduced by 80-95% in 2050 with 1990 as reference year (UNFCC 2015; EZ 2016). In 2015, total greenhouse gases (GHG) in the Netherlands were approximately 200MtCO_2–equivalents per year, whereas the total GHG emissions declined as of 1990, the CO_2 emissions increased (CLO

[1] The explicit definition of pre-industrial levels is not defined by either the UNFCC (2015) report, or the IPCC Fifth Assessment Report (Knutti 2013), however the latter report used 1850-1900 as a historical baseline. Therefore, in this study, it is assumed that pre-industrial levels are conform the historical baseline of the IPCC report.

2017), see Figure 2. In absolute terms, the Netherlands must diminish their GHG emissions to a level of at least 44Mt of CO_2-equivalents per year in 2050(ECN and PBL 2015).

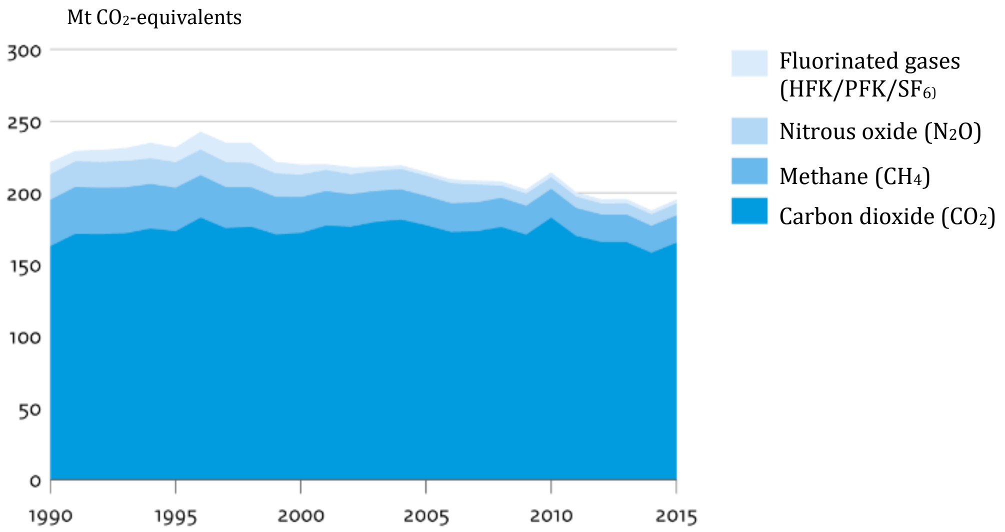


Figure 2 Greenhouse gas emissions development in the Netherlands 1990-2015 (CLO 2017)

1.2 Mitigation options and policy instruments

The question that rises is how to realize such a low-carbon economy. Several studies addressed this issue, from global (OECD 2012; WEC 2013; Shell International 2016) to European (European Commission 2012) to national level (Ros et al. 2011; CPB and PBL 2015; PBL 2016a). A recurrent subject from the aforementioned studies is the potential contribution of the particular technological mitigation options to reduce CO_2 emissions: energy savings, production of CO_2-neutral electricity, electrification, production of bioenergy and Carbon Capture and Storage (CCS). To put it even more strongly, Ros et al. (2011) and PBL (2016) argue that all five technological mitigation options need to be implemented simultaneously if the Netherlands desires to become low-carbon in 2050.

The mitigation option e*nergy savings* covers technologies that use energy more efficiently, meaning to be able to do the same (economic) activity but with less energy use. It is the innovation in products and processes that lead to a higher energy efficiency level (PBL 2016). In this option energy savings resulting from behavioural changes are also taken into account. *Production of CO_2–neutral electricity* option covers technologies that are able to generate power from renewable energy sources: wind, solar, biomass, hydropower, geothermal power, tidal and wave power. *Electrification* simply means an increase in demand of electric power due to more use of electric appliances (European Commission 2016a). This option makes it possible to increase the use of CO_2-neutral electricity. The option *bioenergy* covers all technologies that are able to convert any organic matter into either fuel, electricity or heat. Organic matter for bioenergy conversion can be organic waste streams (e.g. animal waste, municipality (organic) waste and wood waste) and energy crops (e.g. corn, soybeans, hemp and grass). This particular mitigation option provides a solution where CO_2-neutral alternatives are currently lacking, especially in the aviation and shipping sector and most likely for long-distance freight transport (PBL 2016). Lastly, the mitigation option of *Capture and Storage of CO_2 (CCS)* covers technologies that are able to capture CO_2 emissions at production sites and store it to prevent CO_2 from flowing into the atmosphere. Storage in the Netherlands is possible in the North Sea or in an underground geological formation (e.g. empty gas and oil fields). Nevertheless, at the moment there is no social acceptance for storage under main land (PBL 2016). In practice, the development of mitigation options consists of numerous emerging technologies; a list of examples of such technologies is presented in Appendix A.

Nevertheless, future projections show that if the Netherlands continues as they do, the carbon target in 2050 is far from reached (European Commission 2016a; CPB and PBL 2015). The acceleration of implementation of technological mitigation options is too slow. The European Emissions Trading System (EU ETS) is perhaps the largest initiative to enhance cost-effective CO_2 emission reduction in Europe. The system forms the central pillar of European climate policy and aims, by means of a cap-and-trade system, to establish such a carbon price that incentives to invest in low-carbon technologies are created. However, at the present time, the carbon price, established on the market, is not able to create sufficient incentives to reduce carbon emissions for the Netherlands. The European Commission (2016a), PBL (2016) and EZ (2016) expect that this situation does not change till at least 2030.

An additional carbon amount in form of a tax of levy might be the solution to the problems with the EU ETS. At the same time, the money collected with such a carbon tax/levy could be used for subsidies to further foster technological innovation. Cap-and-trade system (EU ETS system), carbon taxes/levies and subsidies are all market-based policy instruments (MBI). The great advantage of these kind of policy instruments is that they provide dynamic incentives for technological change and innovation (Perman et al. 2011; Snyder et al. 2003). This will challenge companies to find (technological) solutions that lower emissions, for example by investing in CCS technology. Same goes for energy consumers, taxes and subsidies on for example energy prices could lead to behavioural changes on short term, such as less energy use and on the long term, consumers could switch to for example more economical devices (PBL 2016).

1.3 Aim and research questions

To sum up, the Netherlands is committed to become low-carbon in 2050, essential technological mitigation options are identified and additional market-based policy instruments, in this study, carbon levies and subsidies, can be deployed to accelerate the implementation of these particular mitigation options. However, how policy instruments should be deployed to support effectively the implementation of technological mitigation options remains unknown. Therefore my study aims to answer the central research question:

How can market-based policy instruments be deployed to encourage the implementation of technological mitigation options in order to establish a low-carbon economy in the Netherlands in 2050?

By means of the following sub questions the central research question is answered:

1. What is the effect of implementing market-based policy instruments on the implementation of mitigation options?
2. What is the best combination of mitigation options supported by market-based policy instruments?

Answer to the first sub research question will give insight in how mitigation options respond to market-based policy instruments. The aim is not to establish the optimal carbon levy value or subsidy amount, but rather to evaluate the degree of government intervention needed to accelerate the implementation of certain mitigation options such that a low-carbon economy is reached in 2050. The degree of government intervention is indicated by the level of the carbon levy. The answer to the first question will help me to obtain an answer to the second research question. This particular answer will say something about the necessary contribution of mitigation options in the transition towards a low-carbon economy. This leads to a combination of mitigation options, supported by policy instruments, which might then be the best solution to develop a low-carbon economy. In my thesis, I consider the best combination of mitigation options as the combination whereby the degree of government invention is at its minimum but yet still able to develop a low-carbon economy in 2050.

Altogether, both answers contribute to improve understanding in how policy instruments can be deployed to support implementation of mitigation options in order to develop a low-carbon economy in the Netherlands in 2050. It is not about obtaining explicit values but rather to see the movement of an economy that is subjected to major changes in the upcoming years. This information is in particular useful for decision makers but also for other stakeholders such as enterprises, non-governmental organizations or individuals.

When policy instruments are mentioned is this study, it is meant as an aggregated name for carbon levies and subsidies unless stated otherwise. When mitigation options are mentioned, the technological mitigation options: energy savings, production of CO_2-neutral electricity, electrification, production of bioenergy and Carbon Capture and Storage (CCS) are meant.

1.4 Method

To be able to answer the sub research questions a System Dynamic (SD) model is built. System Dynamics is a top-down modelling approach developed by Jay W. Forrester (1961) among others, initially to study complex behaviour in social sciences. It became popular among a diverse range of sciences such as life sciences (Sušnik et al. 2013; Simonovic 2002) and engineering sciences; in particular in the field of energy science (Naill 1992; Dyner, Smith, and Peña 1995; Kibira, Shao, and Nowak, S. 2010; Ahmad et al. 2016). This is due to the model's ability to cope with the complexity of energy systems (Ahmad et al. 2016; Forrester 1961). Moreover, SD is able to integrate different systems (e.g. social, economic or ecological) into one model and capable of showing relationships and interdependencies between and within these systems. One of the characteristics that make SD modelling attractive is the cause-effect perspective approach, the ability to deal with feedback effect, time delays and non-linearity (Ahmad et al. 2016; Forrester 1961; Ford 2010). In the end, SD modelling gives insight in the (non-linear) behaviour of systems for the ultimate purpose of assisting decision-makers. SD modelling is a suitable approach for dealing with major system changes, such as the transition of economies to low-carbon economies. (Roberts et al. 1983; Richmond 1993; Kelly et al. 2013; Ford 2010; Ahmad et al. 2016).

The SD model in this study includes the demographic economic system, the energy system and the environmental system of the Netherlands. A Business-as-Usual scenario is built including all already implemented policies regarding energy issues before December 2014. These include renewable energy policies, energy efficiency policies and the EU ETS system. There are three policy scenarios that each covers a carbon levy to subsidize the implementation of a mitigation option. Simulation results of these policy scenarios answer the first research question. Subsequently, the best distribution of subsidy amount for all mitigation options is researched and is the answer to sub research question two.

1.5 Literature review

More studies have addressed the issue of CO_2 emissions reduction by means of different policy instruments and mitigation options using a SD model. A selection from the literature: Liu et al. (2015) used SD to analyse different scenarios for forecasting energy consumption and CO_2 emissions in China for 2020. They aimed to explore the effect of several policy factors and economic growth rates on the consumption of energy and CO_2 emissions. A similar study is done by Xiao et al. (2016), this study focusses only on the carbon intensity target of China, and analyzed mitigation options to lower China's carbon intensity by 45 per cent. Three options were investigated: a stimulation policy of new energy sources (i.e. hydro, solar and wind), a carbon tax policy and an integrated policy. Feng, Chen, and Zhang (2013) conducted a study exploring urban energy consumptions and CO_2 emissions trends in China for 2005-2030. Simulations showed a great importance of the structure of the energy transition. Dyner et al.

(1995) did a specific study towards the behaviour of households and researched how they manage their energy demand and how to increase energy efficiency at a household level. Dyner et al.'s model supports policy makers in energy efficiency measures and allows for calculations on energy savings under different circumstances. Another study on energy consumption is conducted by Ansari and Seifi (2013). They analysed demand, production, energy consumption and CO_2 emissions. They aimed to simulate the energy demand of the Irian cement industry and how subsidies effects consumption in the long term.

To my knowledge, no SD modelling study exists regarding CO_2 emission reductions by means of policy instruments and mitigations in the Netherlands. The aforementioned studies helped me to design the energy system in this thesis and to get familiar with SD thinking and modelling.

1.6 Structure thesis

The structure of this thesis is presented as follows: Chapter 2 explains the model building process; explaining causal loop diagrams and stock-flow diagrams. Chapter 3 discusses data used in the model and associated assumptions. Chapter 4 touches upon the scenario and sensitivity analysis. Chapter 5 is the discussion and chapter 6 concludes.

2. A SYSTEM DYNAMICS ENERGY POLICY (SDEP) MODEL

A System Dynamics Energy Policy (SDEP) model is developed in this study. In this chapter all model building steps are discussed. The relationships between variables are explained and the assumptions regarding the SDEP model are discussed.

2.1 System dynamic modelling approach

The SD approach follows a certain roadmap and is presented in Figure 3. The process starts with identifying the problem definition to clarify boundaries of the model. Thereupon a (qualitative) causal loop diagram (CLD) is drawn where major variables are linked including their feedback effects. Then, the approach shifts from qualitative to quantitative, where a stock-flow diagram is presented for simulation purposes. The next step is to estimate parameter values, in this study, parameters are either obtained from the literature, calibrated or estimated. Subsequently, a reference mode, i.e. business as usual (BaU) scenario, obtained in order to see the general behaviour of a model (Ford 2010). Afterwards, sensitivity analysis on key parameters is performed and assessment of policy scenarios is conducted (Ford 2010; Ahmad et al. 2016).

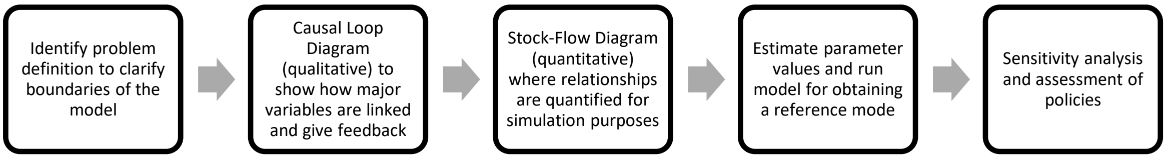


Figure 3 Roadmap SD approach

2.2 Causal loop diagram of the SDEP model

Three mitigation options are included in the SDEP model whereof one is an aggregation of bioenergy sources and CO_2-neutral electricity under renewable energy, the second one is energy savings and the last one is CCS. Due to lack of sufficient information, the mitigation option electrification is not explicitly built in the SDEP model, although implicitly incorporated in the data (more details in section 3.4). As from now, when spoken about mitigation options, renewable energy, energy savings and CCS are meant.

Figure 4 displays the causal loop diagram (CLD) of the SDEP model. The purpose of a CLD is to display the main variables and relationships in this SDEP model and the nature of these relationships. The plus sign indicates a positive relationship meaning that it if a variable changes, the related variable will change in the same direction. If the relationship is negative, a change in one variable causes the other variable to change in the opposite direction. When there is no polarity sign presented[2], the connector reflects either a negative or a positive relation.

Key is primary energy demand (PED), determined by Gross Domestic Product (GDP) and energy intensity (i.e. energy per euro), and breaks down in renewable energy (RE) and non-renewable energy (NRE) production. The latter energy source produces CO_2 emissions. By means of levies or subsidies, the government can intervene and impact either RE production via energy prices, or stimulate energy savings (ES) or CCS, i.e. the mitigation options. In this model, money for investment, in form of subsidies, for one of the three mitigation options is restricted by how much government revenue is generated via carbon levies. In this way, the government is always budget neutral.

[2] Unfortunately, the program (i.e. Stella Software) that I used to make the CLD was not able to include a +/- sign.

For simplification, the SDEP model is divided into three sub-models: the demographic economic sub-model, the energy and the environmental one. Creating sub-models is a method to deal with complexities of systems (Dyner et al. 1995). Furthermore, five *sectors* are defined; households, industry and energy sector, agricultural sector, services sector and the transport sector (see Appendix B for sector specifications). Furthermore, the energy mix exists of two energy sources, RE and NRE sources. This forms the basis for building the quantitative SDEP model.

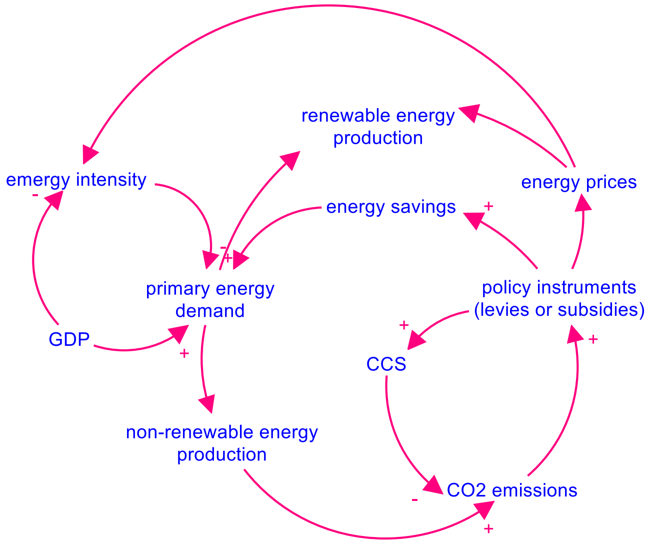


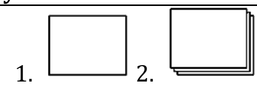
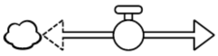
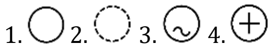
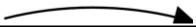
Figure 4 Causal Loop Diagram of the SDEP model

2.3 Stock flow diagrams of the SDEP model

The next step in the SD process is building the quantitative SDEP model in software program Stella Professional (Isee Systems 2017). Stella is widely used by SD modellers for simulation purposes (Feng et al. 2013). Beneficial is the user-friendly interface to visually build the SDEP model.

In order to understand stock flow diagrams one must know the four building blocks of Stella: *stocks, flows, convertors* and *connectors* (see Table 1). A stock represents the level of any variable, it can either be tangible (e.g. natural capital) or not (e.g. information) and accumulates over time. Flows are connected to stocks and display the inflows or outflows of a stock. Convertors are either values or parameters created by a combination of different information sources in the SDEP model or exogenously determined values. Finally, the connecters link all building blocks, reflecting causality within the model (Ford 2010; Ahmad et al. 2016).

Table 1 The four building blocks of Stella with symbol (Ford 2010; Ahmad et al. 2016; Isee Systems 2017)

Building block	Symbol	Description
Stock		A stock (1) is a variable accumulating over time. An arrayed stock (2) contains a multidimensional variable e.g. energy demand per sector.
Flow		Changes stock level by inflow or outflow.
Convertors		A normal convertor (1) connects stocks and flow by providing information or intermediate calculations. The dashed convertor (2) is a copied version of the original convertor, only to keep a visual overview. The graphical convertor (3) contains a graphical function. This can either be a variable depending on time or on another variable. The summed convertor (4) can be a summation of any variable.
Connectors		Connects all building blocks, showing causality in the model.

Each stock equation is a finite difference equation, Stella solves such an equation by initialization and iteration. The initialization phase consists of creating a list of all equations in the suited order and then calculates all initial values for stocks, flows and convertors. Then iteration follows: first the change in stocks over interval DT (delta time) is estimated and new values for stocks are generated based on these estimates, then the new values of stocks are used to calculate for flows and converters and lastly the simulation time is updated by an increment of DT. Stella is equipped with multiple algorithms for iteration. Euler's method is the default method in Stella, and used for simulation of the SDEP model (Isee Systems 2017).

At last, some key settings of Stella before explaining the individual sub-models: start time is 2010 and stop time 2050, where DT is 1 and units are in years.

There are two arrays created: one for all sectors and one for energy sources (NRE and RE). Arrays are simply used for the ease of modelling and to keep a clear visual overview of the SDEP model. Sector specifications are in Appendix B, the stock-flow diagram of the complete SDEP model is given in Appendix C and equations in Stella Syntax are in Appendix D.

2.3.1 Demographic economic sub-model

Key variables in the demographic economic sub-model are household (HH) income and sectoral added values (AV), see Figure 5. The initial stock value of *total HH income* is HH income (per capita) multiplied by total population (*POP*) in 2010. The *HH change* represents the *total HH income* stock accumulation whereby the *HH income (per capita) growth rate* and *POP growth rate* together with the stock value of *total HH income* in t=*0*, establishes the new stock value in t=*1*.

Each sectoral *Added Value* is depending on individual *AV growth rates*; these growth rates times *Added value* stock in t=*0* establishes the *Added value* stock value per sector in t=1, this is captured in *AV change*. The household incomes and sectoral added values are among other variables determinants of PED; this is further detailed in the next section. The formulas of the demographic economic sub-model (eq. 1 to 9), displayed in Stella syntax, can be found in Appendix D.

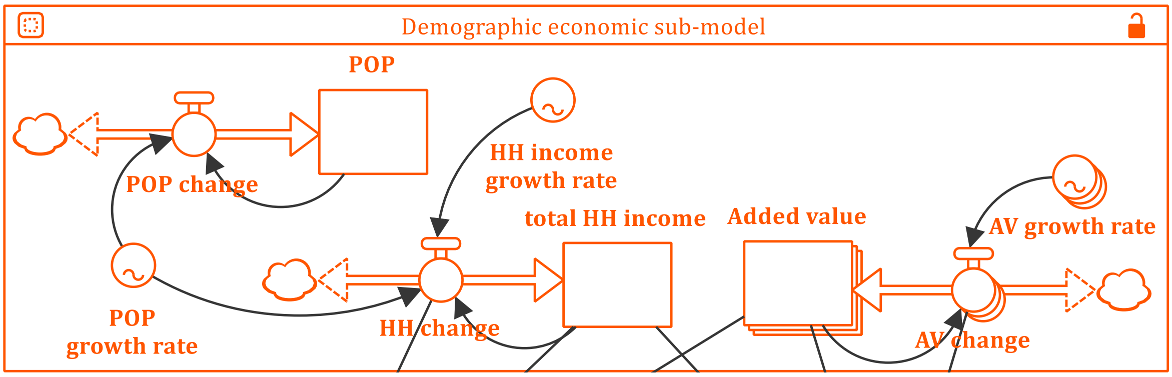


Figure 5 Demographic economic sub-model in Stella (the connectors that leave the demographic economic sub-model are linked to the energy sub-model, to see all the connections see the complete model in Appendix C)

2.3.2 Energy sub-model

I consider two energy sources: RE and NRE. RE are sources that cannot be depleted by use, for example: heat sources (e.g. heat pump and geothermal heat), solar, wind, hydro, and bioenergy (European Commission 2016a). In contrast to NRE, which are fossil energy sources (i.e. oil, coal and natural gas) and nuclear energy[3] (PBL 2016; CBS 2017a). The stock flow diagrams of the energy sub-model are displayed in Figure 6 and formulas (10 to 25) are given in Appendix D.

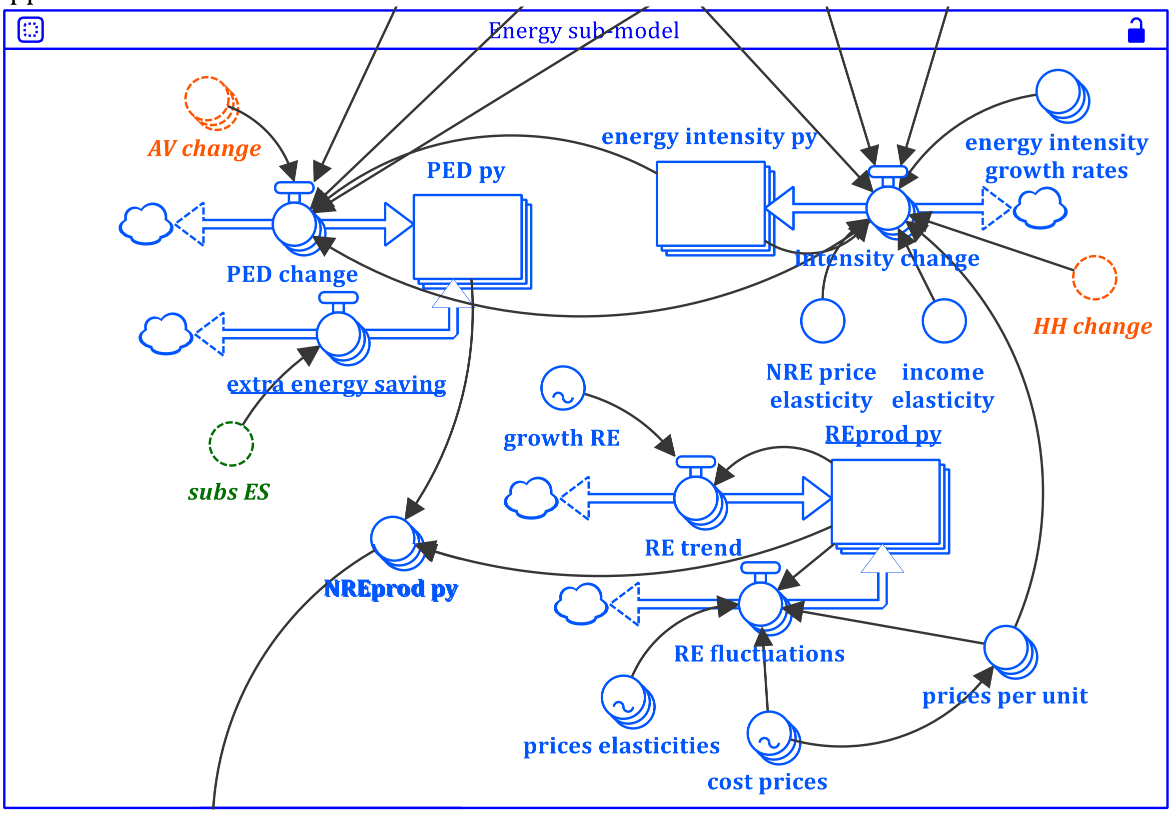


Figure 6 Energy sub-model in Stella (the arrows that are entering the figure from above represent the connections with the demographic economic sub-model and the arrow leaving the figure is the connection to the environmental sub-model, to see all the connections see the complete model in Appendix C)

[3] One might argue that nuclear energy is a CO_2-neutral source that could help to establish a low-carbon economy, however due to risk related to nuclear waste this source of energy is not socially acceptable in the Netherlands (PBL 2016). Therefore, I decided to make a division depending on their renewability.

Energy intensity py (per year), defined as units of energy per euro income, is one of the major driving forces of PED, together with *total HH income* and *Added values*. The initial stock value of *energy intensity py* per sector follows from *PED py* per sector divided by *total HH income* for HH; sectoral added value for SE, AR, IE and TR. The change in energy intensity per year, i.e. *intensity change*, consists of three components. The first component captures the effect of a change in NRE prices. This component is based on the following price elasticity formula (Marshall 1890):

$$\Delta Q = \varepsilon * \Delta P * \frac{Q}{P} \ (derived\ from\ \varepsilon = \frac{\Delta Q}{\Delta P} * \frac{P}{Q})$$

In this case, the epsilon stands for the *NRE price elasticity*, delta P is the difference between NRE prices in t=1 and t=0 and Q is *energy intensity py* and delta Q represent the *intensity change*. The same accounts for the second component of the intensity change equation, but now reflects the effect of a change in income of sectors i.e. *HH change* and *AV change*. Using the price elasticity formula again: epsilon is now *income elasticity*; delta P covers the difference of income of sectors in t=1 and t=0; Q and delta Q are again *energy intensity py* and *intensity change*, respectively. The third component captured everything that is not caused by the former two in *energy intensity growth rates* of sectors. The effect of RE prices on energy intensity is left out because the SDEP model assumes that in case of RE use, the incentive to save on energy use/consumption vanishes.

Accumulation of stock *PED py*, i.e. *PED change*, is subsequently determined by: income change (i.e. *HH change* and *AV change*), income levels (i.e. *total HH income* and *Added value*), *intensity change* and *energy intensity py*. Suppose, income of sectors increases in t=1, then PED would increase by the difference in income in t=1 and t=0 (i.e. income change) times the *energy intensity py* in t=0. Suppose now that only *energy intensity* increases in t=1, then PED would increase by the difference of *energy intensity* in t=1 and t=0 (i.e. *intensity change*) times income in t=0. If both energy intensity and income increase, the aforementioned effects need to be taken into account plus the product of income change and intensity change to capture the whole increase of PED as a result of income and energy intensity change. Furthermore, the PED change function is delayed by one time period, this in order to influence the order of execution of Stella such that PED change reacts to changes in income and energy intensities and not vice versa. Additionally, if subsidy for ES is activated, a certain amount of energy will be subtracted captured in the flow of *extra energy savings*. It is called *extra energy savings* because the energy savings is next to the autonomous dynamic development of less energy demand (more about in section 3.2).

RE production (*REprod py)* stock deals with multiple inflows: an inflow representing the trend of RE production (based on an exogenous growth rate) and an inflow representing fluctuations of the RE trend that arise as a result of changes in prices per unit of energy. The latter inflow captures two effects: the effect of change in price per unit of NRE and the effect of change in price per unit of RE. Both parts are modelled according to the price elasticity formula (Marshall 1890) given earlier in this section, whereby now the epsilon stands for either NRE cross price elasticity or RE price elasticity (captured in arrayed variable *price elasticities*), delta P for the difference in prices per unit and cost prices of either NRE or RE in the same time period; P stands for cost prices of NRE or RE; Q for *RE production* and delta Q for *RE fluctuations*. The inputs of this inflow function is delayed by one period in order to influence the order of equation execution in Stella, making this inflow delayed means that changes in RE production, i.e. *fluctuation RE*, is a reaction on the established prices of the previous period. Hereby assuming that RE production is not able to immediately react to price changes in the same year but the year after. To clarify, (cost) prices of energy sources in t=1 determine the inflow fluctuation RE in t=2.

If there is no government intervention influencing energy prices per unit, RE production solely grows with an exogenous determined growth rate, i.e. *RE Trend*. Under these circumstances *prices per unit* are the same as *cost prices* of energy. Only a carbon levy per unit

NRE or a subsidy per unit RE can make a difference between prices per unit of energy and cost prices of energy.

Furthermore, the SDEP model represents a closed economy, so that supply meets the demand of energy in the Netherlands. In order to comply with such assumption, total NRE production is a result of total PED and total RE production.

2.3.3 Environmental sub-model

Figure 7 displays the environmental sub-model in Stella and equations (25 to 31) are given in Appendix D. There are two methodologies regarding CO_2 emissions accounting: the traditional production-based accounting and consumption-based accounting (OECD 2012). The former only takes CO_2 emissions resulting from indigenous production into account where the latter takes all CO_2 emissions related to the total PED into account. Consumption-based CO_2 emissions accounting is used in this model in order to avoid carbon leakage[4].

To continue, CO_2 emissions is, matter of course, an effect of NRE production (*NREprod py*). The annual NRE production together with an average *carbon intensity* (CO_2 content per ktoe), calculates the total *CO_2 produced py*. For simplification, RE is assumed to be always CO_2-neutral. Thus only NRE energy related CO_2 emissions are taking into account in the SDEP model.

In addition, carbon can be captured and reused (*CCU py*) in chemical and construction sector; and CCS is a mitigation option and thus depending on subsidies from government (*subs CCS*). Once subsidy is activated CCS technologies capture CO_2 and stores it underground. CCS can also be autonomously developed, so the CCS talked about in this study is seen as extra CCS.

So, total CO_2 emissions produced each year corrected by CCU and CCS gives total CO_2 emissions that actually enter the atmosphere since CO_2 absorption is not included.

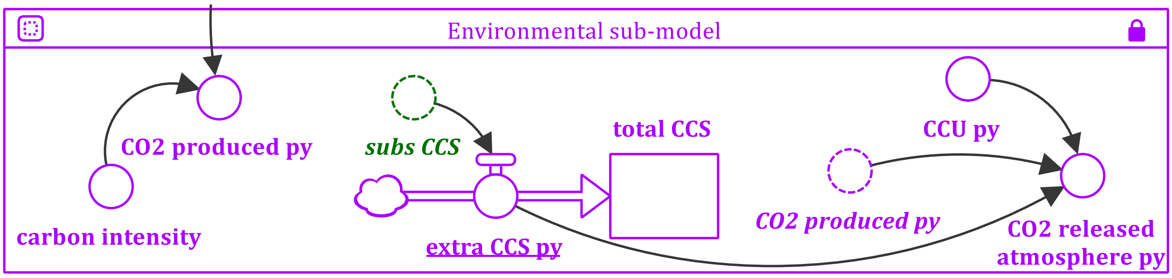


Figure 7 Environmental sub-model in Stella

[4] Carbon leakage occurs when climate change policy or regulation regarding CO_2 emissions reduction in one country leads to increasing CO_2 emissions in another country, so that in the end the intended overall environmental effectiveness is undermined (OECD 2012).

3. DATA

This chapter will elaborate on data requirements per sub-model, data sources and main assumptions regarding the use of data. The European Reference Scenario 2016 (REF2016) (European Commission 2016a) served as main data source for this study. European Commission (2016a) gives trend projections regarding transport, energy and GHG emissions till 2050 for each member state of the European Union, so as the Netherlands. REF2016 is constructed on statistical data from Eurostat. Nevertheless, not all data that was required by the SDEP model was obtained from European Commission (2016a). Other data sources and literature studies are consulted if necessary. However, in order to be consistent with data, I aimed to collect as many data from one reliable source, in this case from European Commission (2016a) because of their large availability of data.

3.1 Demographic economic sub-model

Data for the Netherlands from 2010 to 2050 regarding GDP (including sectoral value added and household income) and population are taken from the 2015 Ageing Report (European Commission 2014). The initial stock values for the aforementioned variables are values for 2010, since this is the start year in the SDEP model, see Table 2. The 2015 Ageing Report stated values in 2013 price level, using CBS (2017a) for price levels in 2013 and 2010, the initial stock values were converted to the 2010 price level, the same act was done for all values that were not in 2010 price level.

Additionally, the growth rates associated to the stocks differ per 10 years, thus in total four growth rates are obtained from the 2015 Ageing Report, see Table 3.

Table 2 Initial stock values (price level=2010) Bln is billion and mln is million. Ktoe is kilo tonne of oil equivalent (1ktoe= 41868 Gigajoule= 11360Megawatthour)

Initial stock values	**Unit**	**Initial value**	**Source**
Household income per capita (HH income)	Bln euro	0.000015735	(European Commission 2014)
Population (POP)	Mln people	16.6	(European Commission 2014)
Added value services sector (SE)	Bln euro	333	(European Commission 2014)
Added value agricultural sector (AR)	Bln euro	10.6	(European Commission 2014)
Added value industry and energy (IE)	Bln euro	136.8	(European Commission 2014)
Added value transport (TR)	Bln euro	114.6	(European Commission 2014)
Primary energy demand per year [HH]	Ktoe	11518.4	(European Commission 2016a)
Primary energy demand per year [SE]	Ktoe	8822.0	(European Commission 2016a)
Primary energy demand per year [AR]	Ktoe	4302.0	(European Commission 2016a)
Primary energy demand per year [IE]	Ktoe	29402.3	(European Commission 2016a)
Primary energy demand per year [TR]	Ktoe	14984.7	(European Commission 2016a)
Initial CCS	Ktoe	0	(PBL 2016)

Table 3 Annual exogenous growth rates of sector incomes, population (European Commission 2014) and renewable energy production in the Netherlands (European Commission 2016a)

Growth rates	**2010-2020**	**2020-2030**	**2030-2040**	**2040-2050**
Household income growth rate	0.7%	1.1%	1.5%	0.19%
Population growth rate	0.3%	0.2%	-0.05%	-0.05%
Added value services sector growth rate	0.8%	1.1%	1.4%	1.6%
Added value agricultural sector growth rate	1.1%	0.6%	-0.2%	0.1%
Added value industry and energy sector growth rate	1.2%	0.8%	1.3%	2.2%
Added value transport sector growth rate	0.8%	0.9%	1,1%	0.5%
Renewable energy primary production	10.5%	1.4%	1.2%	1.2%

3.2 Energy sub-model

3.2.1 Primary energy demand

The initial PED per sector in 2010 in the Netherlands is obtained from European Commission (2016a) as well, see Table 2. PED consists of final energy consumption of end-users (i.e. all sectors except for the energy sector) plus the energy demand from the energy sector itself (including transformation and distribution losses) and it excludes energy carriers for non-energy purposes (European Commission 2016a). Figure 8 illustrates the composition of total primary energy demand and supply (example is from energy demand and supply in 2015 of the Netherlands).

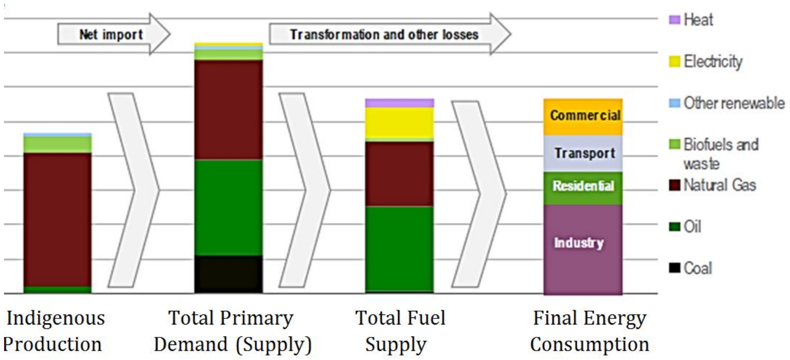


Figure 8 Illustration of energy demand and supply composition: Indigenous Production plus net import is similar to Total Primary Demand (Supply), this minus the energy the energy branch uses for transformation and other losses, is the Total Fuel Supply which is the same as the Final Energy Consumption. Based on a figure of IEA (2010)

As discussed in section 2.3.2, PED is driven by income and energy intensity and if subsidies are activated for ES, an amount of absolute energy is deducted as a result of ES.

Energy intensity is a stock on itself, whereby the initial stock values per sector are determined by the initial values of PED and sectoral income. The initial energy intensity growth rate per sector of the European Commission (2016a) is corrected for the effect of income and NRE prices on energy intensity development. The energy intensity of NRE prices elasticity was initially estimated using energy intensity developments as given by European Commission (2016a), and NRE prices, however it did not give the expected elasticities, same occurred to the energy intensity of income elasticity. This is probably due to several other autonomous developments that are accounted for in the change of energy intensity over time in REF2016 projections. The values for aforementioned parameters as given in Table 2 are reached through calibration on the basis of BaU projections for PED in 2050.

If subsidy for ES is activated, a certain amount of energy is subtracted from total energy demand. To convert subsidies for ES to actual energy saved, a conversion factor was needed. European Commission (2016b) calculated how much direct efficiency investment costs Europe needs if they strive for more ES than in their baseline scenario. They calculated that 30 billion euro annually was needed for 518Mt (megatoe) extra saving, hence the 579 million euro per ktoe per year in Table 4.

Table 4 Parameter values

Parameter values	Initial value	Source
Energy intensity growth rate [HH]	-0.0012	Calibrated
Energy intensity growth rate [SE]	-0.0012	Calibrated
Energy intensity growth rate [AR]	-0.0133	Calibrated
Energy intensity growth rate [IE]	-0.0078	Calibrated
Energy intensity growth rate [TR]	-0.01	Calibrated
Energy intensity elasticity of income	-0.0816	Calibrated

Energy intensity elasticity of NRE prices	-0.281	Calibrated
Carbon intensity ($MtCO_2$/ktoe)	0.002655	(European Commission 2016a)
Direct energy efficiency investment cost per ktoe (mln €)	579	(European Commission 2016b)
Costs CCS per MtCO2 (mln €/MtCO2)	50	(PBL 2016)
CCU (ktoe)	3	(PBL 2016)

3.2.2 Primary energy supply

Primary energy supply (PES) covers all energy that is needed in order to fulfil PED (see Figure 8). As discussed before, energy sources in the SDEP model are divided into RE and NRE. The initial RE production in the Netherlands is obtained from European Commission (2016a), meaning that only RE that is indigenously produced, named primary energy production of renewables, is accounted for in the model and abroad RE production is thus excluded. As given in the report of European Commission (2016a), imported (exported) energy carriers are not divided into RE or NRE products leading to the assumption that when an energy carrier is imported (exported), one does not known whether the energy carrier is RE or NRE. Therefore, I included net imports in NRE production. Important to realize is that the Netherlands' import dependency is expected to more than double in 2050 to 69% against 30% in 2010 as projected by European Commission (2016a). The adverse effect of this assumption is that part of net imports that is actually RE is not accounted for in RE production in the SDEP model.

To continue with RE production, RE production accumulation exists of two parts, whereof one is exogenous and obtained from European Commission (2016a) as well and is displayed in Table 3. The high growth rate of RE production in the first decade is a result from the incorporated policies in BaU scenario, more over in chapter 4.

Furthermore, RE production is influenced by fluctuations in prices of NRE energy prices as well as RE prices. These prices solely exist of cost-prices and levies and/or subsidies. Cost-prices of NRE and RE were not given by the European Commission (2016a) and therefore taken from other data sources.

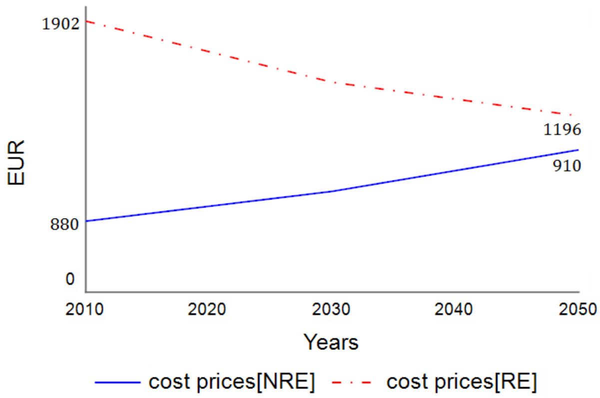


Figure 9 Energy cost prices (euro/toe) per energy source 2010-2050

The cost price of NRE is an average of the pre-tax commodity prices for diesel oil, gasoline, fuel oil, LPG, kerosene, electricity, natural gas, naphtha, solids and other liquids (Capros 2010)[5]. The average NRE price is based on a user-distribution in the Netherlands of 40 per cent natural gas, 40 per cent oil and the rest coal. Capros (2010) estimated price development from 2005 to 2050, whereby is assumed that NRE prices are double in 2050 (from 498 euro per ktoe energy in 2010 to 998 euro per ktoe energy in 2050, see Figure 9). Nevertheless, uncertainty arises in future projections of fossil fuel prices. Several studies have tried to project future prices of fossil

[5] Capros (2010) is a rapport on PRIMES modelling approach and European Commission (2016a) obtained energy prices from PRIMES model, therefor I decided to take these prices as well.

fuels and a large variation of such prices exists. To illustrate, CE Delft (2017) made a comparison of projected fossil fuel prices of different scenarios (e.g. WLO and National Energy Outlook scenarios). Expectations regarding crude oil price ranges from 60 to 126$/barrel in 2030 and from 74 to 149$/barrel in 2050; such wide ranges also occur at future projections of the gas and coal price.

The RE cost price is an average of the cost-price of bioenergy (specifically: H2F and ethanol) (Capros 2010) and the cost-price of CO_2-neutral electricity (European Commission 2016a). The latter are based on a weighted average cost of capital (WACC) of 7.5% real for annual capital cost and average operating hours per year as observed in 2016. The exact discount rate for each specific sector is given in the REF2016 report (European Commission 2016a), on average the discount rate for energy supply sectors is approximately 8%, for firms in demand sectors 9% and for individuals in demand sector around 13%. In addition, RE generation technology is becoming less costly over the years, however to what extent generation costs will decrease is highly uncertain. To illustrate, Fricko et al. (2017) assume cost reductions ranging between 18 to 70% for CO_2-neutral electricity technologies, and 20 to 40% for bioenergy technology between 2010 and 2100. The RE cost prices given by the European Commission (2016a) and Capros (2010) show a cost reduction of 38% from 2010 to 2050, see Figure 9.

The effect of fluctuation of NRE and RE prices on the accumulation of RE production is captured in price elasticities. Price elasticities of specifically NRE and RE were not given by European Commission (2016a) and were non-existed for as far I know. A common price elasticity for energy demand is -0.2 to -0.3 and -0.7 for transport (CE Delft 2014; PBL 2016), however the SDEP model requires a distinction between NRE and RE elasticity, therefor these common price elasticities cannot be used. Cost prices of NRE and RE; and RE production projections from 2010-2050 (European Commission 2016a) are used to calculate the cross price elasticity (captures the effect of NRE prices on RE production) and the price elasticity of RE. The drawback of this approach is that in the dynamic development of RE production also other autonomous developments are in calculated, such as policies creating incentives (European Commission 2016a), this to illustrate that production changes are not solely determined by changes in prices over time. As a result, elasticities are relatively high compared to the common price elasticities, especially in the first ten to twenty years due to inclusion of policies in REF2016 projections. Cross price elasticities of NRE on RE production are in the first twenty years ranging between 4.6 and 2.3 in a decreasing fashion, subsequently going to a stable 0.7 for the last twenty years. RE price elasticities are particular high and variable in the first twenty years (ranging from -8 to -2.30) and stable with a value of around -1.3 for the last twenty years. The first 10 years of relatively high elasticities are not used in the SDEP model because RE production fully runs on exogenous growth of RE, since all policy scenarios start with implementing a carbon levy in 2021.

Another key point is that ETS-prices are accounted for in the exogenous growth. In order to avoid overlap, the ETS price is not explicitly modelled. Another reason I chose not to explicit model the ETS prices is that it would have required more detailed information about how energy and industry sectors pass on ETS prices on to consumers. Under these circumstances, also the existing energy taxes of consumers would have to be implemented. Due to lack of clear overview of prices for different sectors and energy sources, I chose to include a uniform cost price per energy source. Consequently the carbon levy in the SDEP model can be interpreted as value above the ETS-price.

3.3 Environmental sub-model

Only energy-related CO_2 emissions are taken into account in the SDEP model. More specifically: CO_2 emissions from the energy branch and power generation resulting from activities such as: fossil fuels and biomass energy combustion, extraction of natural gas and oil and transport and distribution of energy carriers; and all other CO_2 emissions that are released during the use and consumption of energy. CO_2 emissions from non-energy uses, non-CO_2 GHG emissions and LULUCF are excluded (see Appendix F for definitions). In the SDEP model there is not a distinction made between sectors regarding CO_2 emissions.

Carbon intensity of NRE production is given in Table 4. The carbon intensity is a combination of electricity and steam production intensity; and final energy demand intensity given by European Commission (2016a). Together with the share of electricity and steam production of total energy production, an average carbon intensity is calculated, this value as stated in Table 4 is used in the model.

From the PBL (2016) rapport CCS costs per tonne of CO_2 are taken. The value used, i.e. 50 euro per tonne CO_2, is an average of different CCS technologies where costs are ranging from 10 to 80 euro per tonne CO_2. CCS might also develop autonomously as a respond to a high enough carbon price, although expected by European Commission (2016a) and PBL (2016) to start around 2020-2025. Therefore, the CCS that is talked about in the SDEP model is extra CCS that can be invested in. Furthermore, CCU is a fixed number per year and is not expected to grow in the short run (PBL 2016).

3.4 Other assumptions

Electrification is accounted for in the exogenous growth of RE and is assumed to grow at a rate of 0.56% per year owing to the increase in electricity use for heating and cooling, increase of electric appliances in residential, agricultural and services sector (European Commission 2016a). Additionally, the SDEP model assumes exchange rate from 1.12 $/€ in 2015 to 1.20 $/€ in 2025, at which is assumed to remain constant for the rest of the projection period (European Commission 2016a).

3.5 Model validation

After building the SDEP model in Stella and incorporating all the data, the validity of the model is tested. Since I aimed to rebuild the assumptions of European Commission (2016a) as much as possible, Table 5 therefore, compares BaU scenario results of the SDEP model with REF2016 projections of European Commission (2016a) in 2050. Table 5 compares all endogenous determined stock values of SDEP model, i.e. total PED, individual PED of sectors, energy intensity per sector, total RE production and (energy related) CO_2 produced per year to REF2016 projections. The base year values are also given. As one can see, the error margins are relatively small, i.e. all below 10 per cent, except for PED of AR. This is due to European Commission's (2016a) aggregation of SE and AR under tertiary services while in SDEP model these sectors are separated. An apportionment of AR of tertiary services is only calculated in the start year, and might change over the years but that is not factored in the SDEP model. Nevertheless, if SE and AR were taken together in the SDEP model similar to European Commission (2016a), the error margin would be 9.7 per cent[6]. Under those circumstances all error margins would be less than 10 per cent and therefore I consider the SDEP model as acceptable.

[6] Tertiary services in REF2016 projection demands 10452 ktoe of energy, and tertiary services in SDEP model 9433 ktoe, leading to 9.7 per cent error margin.

Table 5 Model validation results ([1] The REF2016 projection regarding energy intensity is based on exogenous growth rate of REF2016 (European Commission 2016a) together with energy intensity in base year value that is calculated by total PED and HH income or sectoral added value)

Key energy indicators	**Base year 2010**	**REF2016 projection 2050**	**BaU Scenario projection 2050**	**Error margin (% of REF2016 value)**
Energy Intensity[1](ktoe/bln€)				
HH	44	23	21.3	7.4%
SE	28	14	13.7	0.7%
AR	418	202	200.3	0.8%
IE	234	131	123.3	5.9%
TR	139	88	81.4	7.5%
Total PED (ktoe)	69030	59530	59537	0.0%
HH	11518	10645	10554	0.1%
SE	8822	7026	7189	2.3%
AR	4302	3426	2244	34.5%
IE	29402	24790	27104	9.3%
TR	14985	13643	12446	8.8%
RE production (ktoe)	3671	14473	15594	7.7%
CO_2 emissions released per year ($MtCO_2$)	175	112	114	1.8%

4.1 Scenario analysis

The BaU scenario includes all already implemented policies and measures of Europe and the Netherlands (captured in the data that is used to build the SDEP model). Three main policies are incorporated: RE policies, energy efficiency policies and the EU ETS. More details on these policies are given in Appendix E. Beyond 2020 there are no policies incorporated in the SDEP model, except for EU ETS because that is an ongoing scheme. All policy scenarios impose a carbon levy on NRE, starting from year 2021, in order to finance subsidies for different mitigation options. In this way, the government is always budget-neutral. In Table 6 an overview is given of the different policy scenarios where as one can see that number 2, 3, and 4 all include a carbon levy plus subsidy for either RE, extra ES or extra CCS. It is a matter of extra ES and extra CCS because ES and CCS are also incorporated in autonomous developments of the energy system. At last, the integrated policy (IP) scenario where government revenue generated by a carbon levy is divided among the three mitigation options in form of a subsidy. The division of subsidies is determined by the lowest carbon levy that causes the economy to be low-carbon in 2050. All policy scenarios are modelled such that the carbon target of 34MtCO_2 is met in 2050.

Table 6 Overview of policy scenarios

	Mitigation options			**Policy instruments**	
Scenarios	Renewable energy	Extra energy saving	Extra CCS	Carbon levy	Subsidy
1. BaU scenario					
2. RE scenario	X			X	X
3. ES scenario		X		X	X
4. CCS scenario			X	X	X
5. IP scenario	X	X	X	X	X

Figure 17 in Appendix C displays how policy instruments are modelled in Stella. A carbon levy per NRE unit is exogenously established. carbon levy times the total NRE in a year gives the total levy yield, i.e. government revenue. This income can be spend on different mitigation options as explained above. In case of a subsidy for RE, the total amount that is available for subsidy is divided by total RE units to obtain a RE subsidy per unit of RE. To prevent a negative price of RE, it is assumed that the subsidy cannot be larger than the half of the cost price of RE. In case of a subsidy for ES, the total amount available together with a conversion factor determines the extra ES that is subtracted from total PED. Same logic applies to CCS, a conversion factor is used to determine to amount of CO_2 emissions that can be captured and stored each year. Equations (30 to 41) of the policy sub-model are stated in Appendix D.

4.1.1 Business as Usual scenario

In Figure 10 the demographic economic developments are graphically given from 2010 to 2050. The SDEP model simulated that population in the Netherlands grew with 5 per cent in 2050 relative to 2010. Before 2030, population is increasing to a peak level of almost 17.6 mln people in 2030, henceforth slightly decreasing to 17.4 mln people in 2050.

Total household income grew from 260bln euro to 483bln euro in 2050. The total added values doubles in 2050 to a level of 893 bln euro whereof 515 bln euro of services sector, 11 bln euro of agricultural sector, 216 bln euro of industry and energy sector and 151 bln euro of transport sector. Furthermore, total PED is decreased with 14 per cent relative to start year to 59537 ktoe in 2050; whereby the share of RE production of total PED is increased from approximately 5 per cent in 2010 to 26 per cent in 2050, see Table 7. The other 74 per cent of PED, similar to 43944 ktoe of NRE production, produces 113.7MtCO_2 in 2050, which is a CO_2 reduction of 33 per cent compared to 2010.

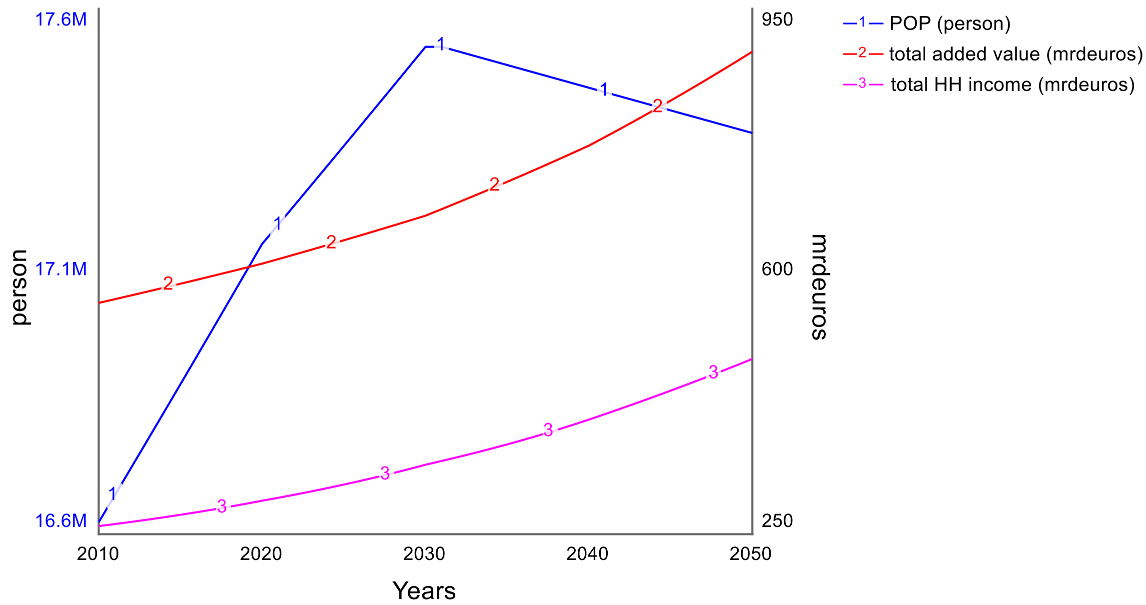


Figure 10 Demographic economic developments 2010-2050

4.1.2 Policy scenarios

In Table 7, the simulation results for total PED, NRE production, RE production, CO_2 emitted and the values for carbon levy per ton CO_2 and total subsidy over 30 years (2020 to 2050) are given. The carbon levies are iteratively explored in Stella, inspired by calculations of CE Delft (2017), who ran calculations on possible additional carbon levies above the ETS-price ranging from one to twenty euros. The run that was able to achieve the carbon target with the lowest possible carbon levy is presented in Table 7. The results of the demographic economic sub-model are already described in the previous section (4.1.1) and applies for the policy scenarios as well since population, household income and added values stocks values were all exogenously determined.

Table 7 Simulation results effect policy instruments and mitigation options on PED and energy mix in 2050 (* accumulated over 2021 to 2050; ** based on 80% of subsidy amount to RE, 10% to ES and 10% to CCS)

	Key energy indicators				Mitigation options			Policy instruments	
Year 2050	Average Energy intensity (ktoe/€ bln)	Primary energy demand (ktoe)	Share RE of total PED (%)	Annual CO_2 (MtCO_2)	RE production (ktoe)	Accumulated* energy savings (ktoe)	Accumulated* CCS (MtCO_2)	Carbon levy per ton CO_2 (€)	Accumulated* subsidy amount (€ bln)
1. BaU scen.	172.6	59538	26.2	114	15594	-	-	-	-
2. RE scen.	87.8	59370	78.8	34	46190	-	-	4.75	9.6
3. ES scen.	87.4	59117	77.8	34	45993	40	-	11.00	22.8
4. CCS scen.	87.5	59182	72.2	34	42751	-	434	10.20	22.1
5. IP**scen.	87.8	59349	77.4	34	45910	2	21	5.30	10.7

Table 7 only displays the absolute values of the key variables in 2050. Table 16, Table 17 and Table 18 (stated in Appendix F) show the dynamic development of key variables, i.e. total PED, total RE and CO_2 emissions, in index numbers with 2010 as base year.

The energy intensities per sector are displayed in Figure 11. The initial values of energy intensities per sector in the SDEP model were 44, 28, 418, 234 and 139ktoe/bln€ for HH, SE, AR, IE and TR respectively. Figure 11 shows the energy intensity per sector in the RE scenario, since this scenario had the lowest carbon levy. The other policy scenarios did not generate much different energy intensities per sector as presented in Figure 11.

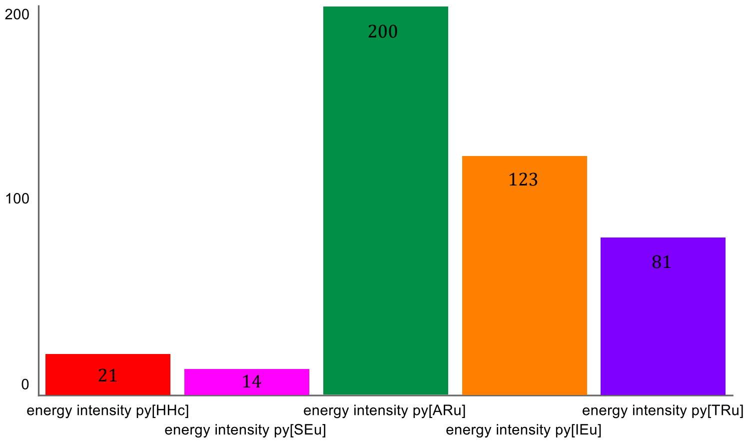


Figure 11 Energy intensities (ktoe/bln euro) per sector in the RE scenario in 2050

Total PED development under different policy scenarios can be seen in Figure 12. In Table 16 in Appendix F the development of total PED in index numbers under different scenarios is given, all scenario including the BaU scenario have 14 per cent reduction of total PED in 2050 compared to 2010.

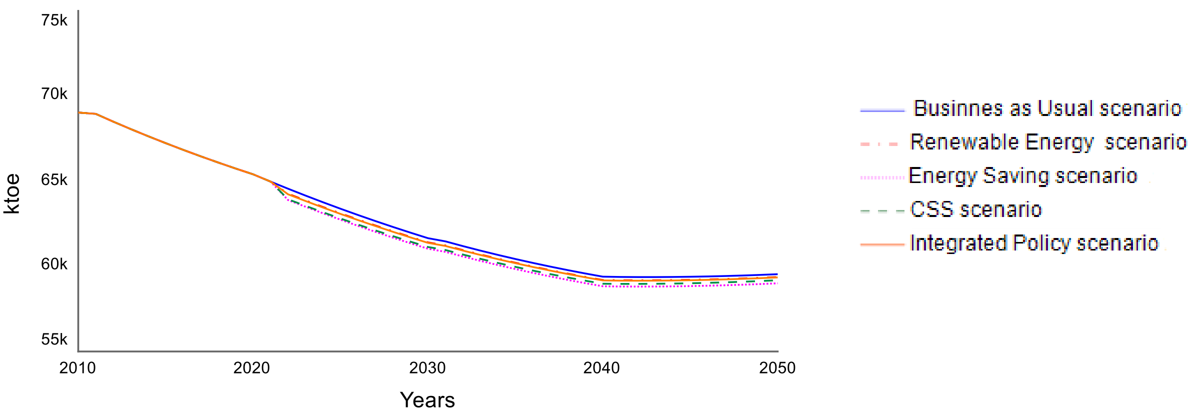


Figure 12 Total primary energy demand per year 2010-2050

To continue, RE production increases the most under the RE scenario to a level of 46190ktoe in 2050, which is similar to 79 per cent of total PED, as can be seen in Table 7. Immediately after 2020 RE production explodes in all policy scenarios, see Figure 13. In the end, RE production grows enormously under all policy scenarios, whereby under RE scenario the most (approx. 1200%) and under the CSS scenario the least (approx. 1100%) (Table 17, Appendix F).

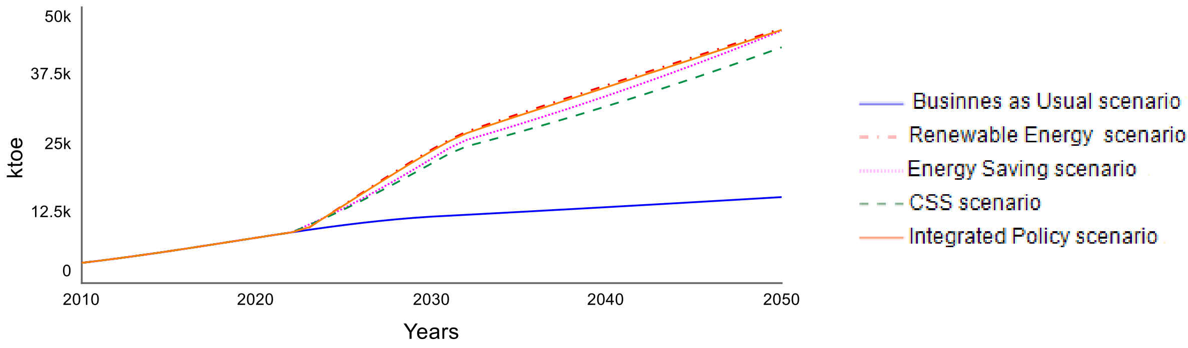


Figure 13 Total renewable energy per year 2010-2050

Table 18 displays the development of CO_2 released in atmosphere per year over the period 2010 to 2050.

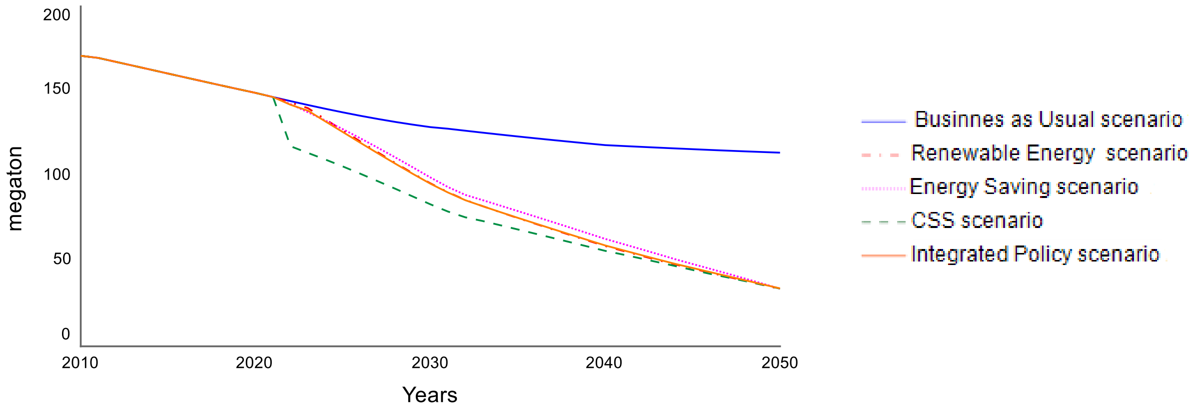


Figure 14 Total CO_2 released per year 2010-2050

A carbon levy of 4.75€ per ton CO_2 generated in total 9,6bln euro of subsidies for supporting RE over the years 2020 to 2050. The second best scenario is the IP scenario, with a carbon levy of 5,30€ and a subsidy amount of 10.7bln euro whereof 80% assigned to RE and 10% assigned to ES and 10% to CSS. For the other two scenarios, i.e. CCS and ES scenario, the carbon levy and total subsidy amount are almost double as high (see Figure 14).

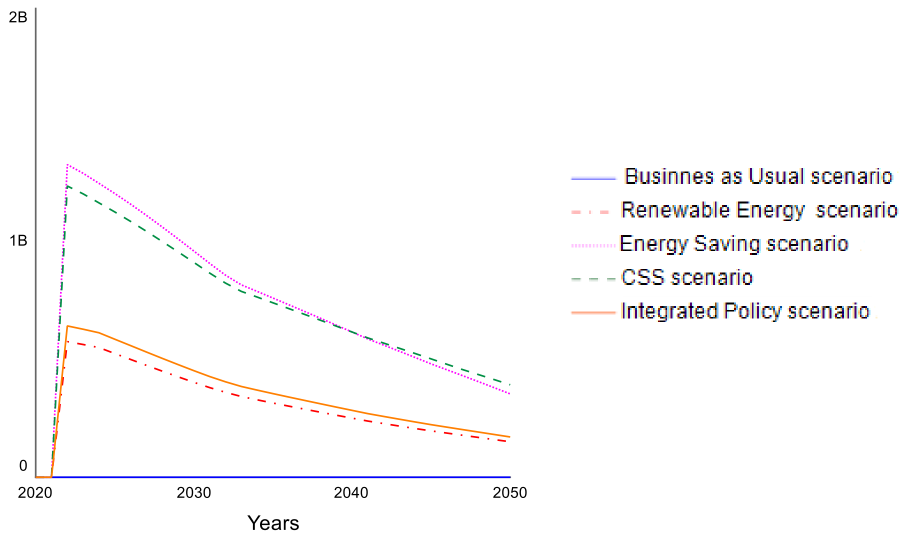


Figure 15 Total subsidy amount in euros 2020-2050

4.2 Sensitivity analysis

In order to check the robustness of simulation results with respect to key parameters, sensitivity analysis is performed on NRE price elasticity of energy intensity (*NRE EI elas.*) and income elasticity of energy intensity (*Income EI elas.*); the cross and normal price elasticity of RE; and the conversion factors of ES and CCS. For sensitivity analysis a range of 25 per cent above and below the initial parameter value is used.

Table 8 and Table 9 present the results of the sensitivity analysis of NRE EI elasticity and income EI elasticity. This particular sensitivity analysis was performed after the BaU scenario and thus before the policy scenarios. In this case, the BaU scenario is run again with one parameter change at the time, ceteris paribus. Since energy intensity is a determinant of PED, the total PED results in 2050 associated with different elasticities are given. The values with an asterisk are the initial elasticity values. Between brackets are the percentage differences relative to the initial value, either elasticity or total PED, a positive value means an increase and a negative value a decrease towards the initial value. As one can see in Table 8, 25 per cent increase in the NRE EI elas. leads to an increase of 5 per cent in total PED, whereas a 25 per cent decrease leads to a 4.5 per cent reduction in total PED. The total PED increase is just 1 per cent as a result of a higher income EI elas. and 0.8 per cent reduction in case of a lower income EI elas (Table 9). Overall, the SDEP model has a weak sensitivity to NRE EI and income EI elasticity.

Table 8 The sensitivity analysis of NRE EI elasticity

NRE EI elas.	Total PED (Mtoe) in 2050
-0.2810*	**59.5***
-0.2110(+25%)	62.4 (+5%)
-0.3510(-25%)	56.8 (-4.5%)

Table 9 The sensitivity analysis of income EI elasticity

Income EI elas.	Total PED (Mtoe) in 2050
-0.0816*	**59.5***
-0.0612(+25%)	60.1 (+1%)
-0.1020(-25%)	59.0 (-0.8%)

The following sensitivity analyses are performed after running the policy scenarios. The effect of different (cross) price elasticities values on total RE in the RE scenario in 2050, ceteris paribus are presented in Table 10. The percentage between brackets reflects the change in comparison to the initial RE scenario results, indicated with asterisk. Furthermore, the row in italics presents the necessary adjustment of the height of the carbon levy to reach the carbon target again with changed price elasticities. Figure 16 displays the change in pathways of RE in case of lower elasticities. In particular, these lower elasticities are of interest because it brings the estimated price elasticities closer to price elasticities as described in the literature. An increase or decrease of one of the price elasticities has a weak direct effect on total RE (percentage difference under 10%) however the indirect effect in the system, reflected by the CO_2 emissions in 2050 was almost three times as high. Furthermore, it shows that an increase or decrease of both the elasticities together with a new carbon levy to reach the carbon target in 2050 again, did not have symmetrical results. Whereas decreased elasticities requires a 33% increase in the carbon levy, increased elasticities only agree with a 20% reduction in carbon levy, this captures the non-linearity behaviour of RE. This kind of information on system behaviour is useful for policy-makers in case of establishing support policies for RE.

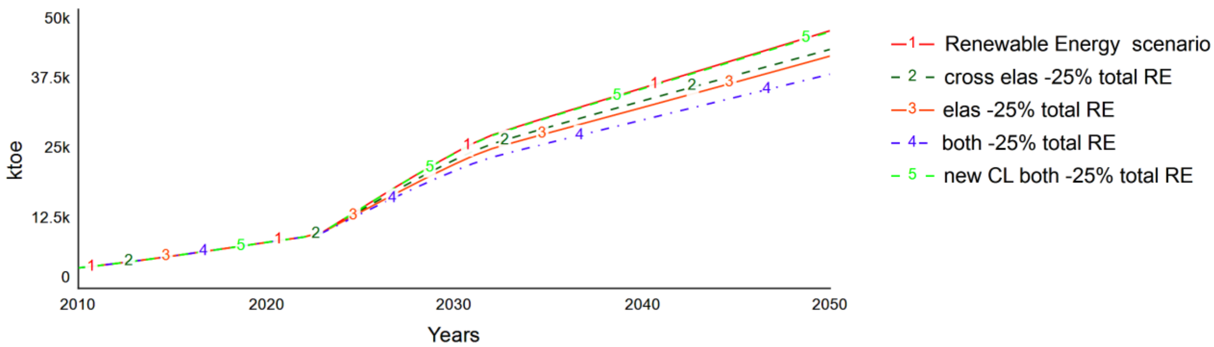


Figure 16 Total renewables subjected to different (cross) price elasticities

Table 10 Sensitivity analysis price elasticities (* is initial simulation result of RE scenario)

Price elasticities		Total RE (Mtoe) in 2050	Annual CO_2 emissions (Mt) in 2050	Carbon levy (€ per ton CO_2)
Cross elas.	**Normal elas.**			
*	*	**46.2***	**34***	**4.75***
+25%	-	49.8 (+7.8%)	24 (-27.6%)	
-	+25%	50.4 (+9.1%)	23 (- 31.5%)	
+25%	+25%	54.1 (+17.1%)	14 (-58.8%)	
+25%	*+25%*	*46.2 (0.0%)*	*34 (0.0%)*	*3.8(-20%)*
- 25%	-	42.8 (-7.4%)	42 (+23.5%)	
-	- 25%	41.6 (-10.0%)	45 (+32.4%)	
-25%	-25%	38.4 (-16.9%)	53 (+55.9%)	
-25%	*-25%*	*46.0 (0.0%)*	*34 (0.0%)*	*6.3 (+33%)*

In addition, the sensitivity of conversion factors of ES and CCS regarding total ES and total CCS, respectively, is also tested (results in Table 11 and Table 12). The analysis shows that the direct effect (on the mitigation options itself) of change in conversion factors is relatively strong (percentage differences ranging from 20 to 80%), however the indirect effect on the annual CO_2 emissions is relatively small (under the 10% range again). This might say something about the strength of the ES and CCS as mitigation options itself in the economy. To illustrate: if costs of CO_2 capture and storage decreases by 25% for example as a result of innovation, the total CCS is then increased by 33.2%, however the annual CO_2 emissions in 2050 only decrease with 8%.

Table 11 Sensitivity analysis of conversion factor ES (Energy savings are accumulated over the entire time period, in contrast to CO_2 emissions which is an amount per year in 2050; *is initial simulation results of the ES scenario)

Conversion factor ES (mln €)	Accumulated energy savings (ktoe)	Annual CO_2 emissions (Mt) in 2050
579*	**40***	**34***
434 (-25%)	52 (+30%)	34 (-0.03%)
724 (+25%)	7 (-82.5%)	34 (0.00%)

Table 12 Sensitivity analysis of conversion factor CCS (CCS are accumulated over the entire time period, in contrast to CO_2 emissions which is an amount per year in 2050; *is initial simulation results of the CCS scenario)

Conversion factor CCS (mln €)	Accumulated CCS (MtCO2)	Annual CO_2 emissions (Mt) in 2050
50*	**434***	**34***
38 (-25%)	578 (+33.2%)	31(-7.9%)
63 (+25%)	347 (-20%)	36 (+4.4%)

5. DISCUSSION

This study performed in total five scenarios, BaU scenario, RE scenario, ES scenario, CCS scenario and IP scenario. All scenarios, except for the BaU scenario, were modelled such that the carbon target of 34MtCO_2 per year in 2050 is reached. In the policy scenarios, a carbon levy on NRE energy is imposed in order to finance subsidies on mitigation options. So, all policy scenarios are budget neutral for the government. The discussion is structured as follows: section 5.1 elaborates on key findings and section 5.2 covers model uncertainties.

5.1 Key findings

5.1.1 Renewable energy scenario versus Business-as-Usual scenario

The energy intensities of sectors in the RE scenario are halved compared to BaU scenario in 2050 (see Table 7). In other words, the number of energy units per euro is significantly decreased. This can be a result of either higher NRE energy prices, economic growth or autonomous development of the overall efficiency level. Higher NRE energy prices might result in energy saving behaviour of users and consumers on the short-term and investment in clean and/or more efficient technologies in the long-term, leading to a downward effect on energy intensity. Economic growth can lead to a lower energy intensity for example because of increased capacity to invest in new technology. A last part of this energy intensity improvement originates from autonomous improvement of the overall efficiency level (European Commission 2016a).

The total PED in the RE scenario does not deviate much from the BaU scenario in 2050. This might be due to the relatively strong autonomous decline of total PED until 2050 in the BaU scenario. Another reason might be that policy instruments and mitigation options intended to reduce CO_2 emissions, do not have a significant impact on total PED. In contrary to the energy mix, whereby the RE scenario results show a major shift from NRE to RE occurs in 2050 compared to the BaU scenario. This is illustrated by the 26% of renewables in the BaU scenario in 2050 to the almost 80% renewables in the RE scenario. This particular shift in the composition of the energy mix tends to be the main driver of CO_2 emissions reduction. According to the BaU scenario, CO_2 emissions would be still at a level of 113MtCO2 per year in 2050, which is 70% more of emissions than the policy scenarios show in 2050.

5.1.2 Renewable energy scenario versus other SDEP policy scenarios

Despite that all policy scenarios reached the carbon target in 2050, they did not follow the same path towards that target. The RE scenario keeps the highest level of total PED, whereby one might expect higher CO_2 emissions, but this effect is offset by the higher share of RE. The ES scenario shows, as expected, with 253ktoe less energy in 2050 compared to the RE scenario, the lowest demand of energy. The CCS scenario has the second lowest PED and the IP scenario thereafter. Moreover, the RE scenario has the highest share of RE compared to the other policy scenarios, which is a logical result when RE is subsidized. The CCS scenario, conversely, has the lowest RE share, which may reveal that the more carbon is captured and stored, the lower the need for RE. This relationship is found by the study of PBL (2016) as well. All policy scenarios obtained relatively high shares of RE in 2050 (ranging between 72 to 79%), this is in line with expectations of previous studies (PBL 2016b; European Commission 2016b, 2012). Furthermore, CO_2 emissions gradual decline towards 2050 in as well the RE scenario as in the ES and IP scenarios, the CCS scenario, however, showed a more abrupt decline immediately after policy implementation in 2021 but eventually convergences to the other policy scenarios in the last decade (Figure 14). The abrupt decline of CO_2 emissions of CCS can be explained by the relatively large availability of NRE in 2021 (still 91% of total PED), leading to a high government revenue to subsidize CCS, resulting in a large amount of CO_2 captured and stored at once that year.

5.1.3 Degree of government intervention in SDEP policy scenarios

Different degrees of government intervention in policy scenarios are needed to enable economy to become low-carbon. I assume that the degree of government intervention and impact on the Dutch economy is indicated by the level of carbon levy of each scenario. This carbon levy can be interpreted as an increase of the European ETS-price, starting from year 2021. Carbon levies in the SDEP model are in the same range as calculations of CE Delft (2017), which also looked at an additional carbon tax above the ETS-price. However, did not elaborate on the purpose of tax revenues such as the subsidies on RE, ES or CCS, in contrast to this study. In this study the government is always budget neutral.

Simulation results (Table 7) show that in case of implementation of RE mitigation options an carbon levy of 4,75 euro per ton of CO_2, and a total subsidy amount of 9.6 bln euro the carbon target in 2050 can be met. More steering of the Dutch government is necessary, indicated by the twice as high carbon levy compared to subsidizing RE, in order to achieve the carbon target with stimulating ES or CCS.

It is no surprise that the scenario with two policy instruments influencing the relative price of energy, i.e. increase of the NRE price (carbon levy) and decrease of the RE price (subsidy), is most effective. The ES and CCS scenarios only had the carbon levy to influence the relative price of energy, whereas the RE scenario that has two policy instruments, e.g. carbon levy per NRE unit and subsidy per RE unit influencing the relative energy price. Several studies (OECD 2012; Snyder et al. 2003; Bailey 2007; PBL 2016) argued that such policy instruments are, among many others, one of the most effective policy instruments in stimulating an economy to reduce CO_2 emissions. Such policy instrument affects the energy consumer/user directly and stimulates in this way, to opt for the greener source, in this case: renewable energy.

The main driving force behind CO_2 emissions reduction is the implemented carbon levy and not per se the implementation of mitigation options in the Dutch economy. This follows from ES scenario results showing that only 40ktoe is a direct result of support of the option energy saving. The rest of the declined energy demand in the ES scenario (compared to BaU) must, then, be induced by the implemented carbon levy. In case of the support of CCS, in total, i.e. an accumulation over 30 years, 434MtCO_2 is captured and stored. This is a considerable amount of CO_2 stored, however not yet close to reaching its potential (approximately 725MtCO_2) in the Netherlands given that a maximum of 25MtCO_2 can be stored in the North Sea each year (PBL 2016). A reason for the relatively limited contribution of ES and CCS to CO_2 emissions reduction might be that implementation of ES and CCS is relatively costly compared to RE, argued by (PBL 2016) as well. It is probably for this reason that the IP scenario resulted in assigning 80% of total subsidy amount to subsidizing RE.

In practise, implementation of mitigation options might be harder than the SDEP model outlines. Every mitigation option copes with challenges of implementation in the Dutch society. All scenarios show high shares of RE in 2050, in this study RE aggregated bioenergy and CO2-neutral electricity. To realise such RE shares, the Dutch has to rely heavily on the import of biomass (PBL 2016), which may, at the same time, decrease the overall environmental effectiveness of environmental policy due to an increase in transport. Nevertheless, CO_2-neutral electricity supply is expected not to be an issue in 2050, it is even projected that the Netherlands is going to export this particular electricity (European Commission 2016a). However, electrification is needed in order to exploit this Dutch CO_2-neutral electricity. A major advantage of RE is that there is no major social resistance, mainly due to the many different existing types of renewables, this is in contrast to CCS. There is reasonable capacity in the Netherlands: in the

North Sea and under main land, however for now, no social acceptance exists regarding storage under main land (PBL 2016). The reason originates from the ignorance of the long-term effects of CO_2 storage. Therefore CCS is limited by the capacity in the North Sea, although the Dutch government may decide to store carbon abroad. To continue, the implementation of ES seems to be a complex one. On the one hand, ES are expected to develop due to improved energy efficient technologies (PBL 2016) whereby extra government intervention tends to have less to nothing impact on the speed of such development, as shown by this study. On the other hand, ES is often offset by other developments. To illustrate: incentives to save energy may vanish when the consumer or user already uses RE; or when energy efficiency improvement in for example electronic devices is offset by the increasing number of electronic devices per household (e.g. from maybe one computer per household to multiple laptops, phones and tablets per household).

5.2 Model uncertainties

This section aims to address model uncertainties divided into three types: uncertainty in model parameters, model drivers and model structure.

Firstly, many model parameters are subjected to a certain extent of uncertainty. The parameters in the SDEP model are the (cross) price elasticity of RE, NRE EI elasticity, income EI elasticity, growth rates of EI of sectors and the conversion factors of ES and CCS. On the calibrated parameters NRE EI elasticity and income EI elasticity the model showed a weak sensitivity given that a 25% change in either one of the elasticity causes 1 to 5% change in total PED. However, a weak sensitivity of calibrated parameters may indicate that numerous values for these parameters are possible (Pianosi et al. 2016). This was indeed the case in the SDEP model. Furthermore, the estimated (cross) price elasticities used in the SDEP model are relatively high compared to the normal energy demand elasticities found in the literature, however they were of key importance for simulation results. Sensitivity analysis (Table 10) showed that changing price elasticities has a relatively small effect on their direct-linked variable, RE in this case, but at the same time, they pass on a relatively strong effect on final CO_2 emissions. Additionally, the conversion factors of ES and CCS were tested. Conversion factors make it possible to convert subsidies to either an amount of energy saved or an amount of CO_2 captured and stored. In other words, it reflects the cost per unit of energy saved or per ton of CO_2 captured and stored. The change in conversion factors did not lead to major changes in final CO_2 emissions, despite the relatively strong effect on the level of implementation of mitigation options.

Secondly, model drivers form important pillars for the SDEP model. Uncertainties mainly play a role at the demographic economic drivers of energy demand and energy prices as drivers for the energy mix. In the SDEP model, demographic economic drivers are population, household income and sectoral added value income. Regarding projection of population, several scenarios studies (PBL 2016b; CPB and PBL 2015; European Commission 2016a) projected approximately the same population size in 2050, therefor relative little uncertainty is involved in this particular driver. This is in contrast to economic drivers, to illustrate the CPB and PBL (2015) who distinguish low and high economic growth for the Netherlands or SSP scenarios by (Fricko et al. 2017), which present five different projections regarding economic activity in Europe.

Furthermore, to what extend economic activity drives the energy demand is subject to debate. Whereas earlier the energy demand used to grow with economic growth, studies now projects energy demand reduction together with economic growth (European Commission 2016a). Parameters reflecting the effect of economic activity on energy intensity and thus energy demand turned out to be small during calibrations in the SDEP model which is thus in line with the decoupling trend of economic activity and energy demand.

Moreover, energy prices are important drivers of the energy mix. As explained before, energy prices are highly uncertain in the future as can be concluded from the broad range of energy price estimations of different studies (CE Delft 2017; Fricko et al. 2017; European Commission 2016a). Besides, the complex international fuel market, the resource uncertainties, the unknown development of technologies make it hard to obtain reliable future energy price estimations (OECD 2012). Despite the different absolute energy price estimations, the dynamic development of NRE and RE prices tend to be more identical in different studies (Fricko et al. 2017; Capros 2010; European Commission 2016a). For this study, the dynamic development and the ratio of RE and NRE prices was more important than the absolute height of such prices.

On purpose some potential model drivers are left out in the SDEP model, this is mainly due to time constraints and to avoid complexity in the model. SDEP could be extended in two ways: energy prices as driver of economic growth and the effect of open borders within Europe on the energy mix. A connection from the energy sub-model to the demographic economic sub-model could have captured the effects of energy prices on economic growth and included the creation of green jobs. This would have closed the system, meaning that all key stock variables would have been endogenously determined. This could have led to for example a lower energy demand as a result of lower income as a reaction to higher energy prices.

The international character of the Netherlands is as well left out in the SDEP model. This might have resulted in missing the effect of economies of scale or comparative advantages of countries in Europe. For example, solar energy in the South of Europe probably yields more electricity than in the North of Europe. Nevertheless, an advantage of modelling a closed economy was the prevention of carbon leakages.

The last source of uncertainty is the model structure. This thesis used a SD modelling approach out of the many modelling techniques that exists. Matter of course, each modelling technique has their advantages and disadvantages. In the light of system understanding, SD is a suitable approach. It is able to display how one change is passed on to the rest of economy, to detect (non-linear) behaviour of system variables and to influence the system with time-dependent variables and time-delays. It gives in particular information about relationships and interdependencies of variables and sub-models. Additionally, it enables you to play with time, for example implementation times of policies. To a certain extent, it is possible to include economical foundations such as finding the lowest carbon levy or working with the supply and demand market. However, SD is not an optimization model, therefore prices must be endogenously modelled in SD. At last, feedback loops might not always be realistic (Kelly et al. 2013).

6. CONCLUSION

This study aimed to address how market-based policy instruments could be deployed in order to achieve a low-carbon economy through the implementation of mitigation options. For all mitigation options, RE, ES and CCS, I considered a combination of a carbon levy and a subsidy on the mitigation options so that the government is budget neutral. Whereby the first research question aimed to find insight in how mitigation options respond to policy instruments. Simulation results show that implementation of RE requires the least amount of government intervention by means of policy instruments compared to implementing ES and CCS. It is rather the carbon levy that enables the economy to go a low-carbon than the implementation of mitigation options. From these findings I aimed to see if there exist a combination of mitigation options that overrules the effectiveness of the dominant RE scenario. Since previous studies argued (PBL 2016b; Ros et al. 2011) that all mitigation options are essential in reaching a low-carbon economy in 2050. The simulation results of this particular scenario could not exceed the strong effect of implementation of solely RE. This raises the question whether indeed all mitigation options are needed as suggested by PBL (2016) and Ros et al. (2011). Then again, their studies did not include an additional carbon levy, or elaborated on the financing of implementation of mitigation options. Imposing a carbon levy to finance subsidies to foster implementation of RE might be the better solution to reduce CO_2 emissions than financing subsidies for a combination of mitigation options. Especially since multiple studies confirmed, as this study as well, that implementation of ES and CCS is costly and difficult. Therefore, I would like to suggest for future energy policy, on the basis of these study results, to focus on establishing an additional carbon levy to the ETS-price in order to subsidize the implementation of RE.

At last, future research regarding the specific price elasticities of RE and NRE could be of great interest of economic-energy models which aim to address the energy transition. Additionally, it would be interesting to look how the implementation of electrification can be supported by means of policy instruments.

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APPENDIX

A. Examples of technologies of mitigation options

Table 13 Technologies examples of mitigation options (examples given by 1= European Commission (2012); 2=RVO and TKI (2017))

Technological mitigation options	Examples of technologies
Energy savings[1]	• Efficient lighting (high efficient light bulbs) • Efficient improvement electric appliances • Thermal integrity of buildings • Efficiency improvement in electricity generation
CO2 neutral electricity[1]	• On and off wind turbines • Solar photovoltaic • Solar thermal • Biomass electricity • Geothermal • Tidal-waves • Hydrogen
Electrification[2]	• Power-to-heat technologies: heat pumps, electric boiler, infrared, plasma heating and induction furnace • Power-to-hydrogen technologies • Power-to-gas technologies • Power-to-chemical technologies
Bioenergy[1]	• Co-firing of biomass in conventional plants • Biogas CHP technologies • Waste technologies
CCS[1]	• Conventional power plants equipped with carbon capture and storage technologies • Biomass conversion with carbon capture and storage technologies

B. Sector specifications

Table 14 Specifics of sectors

Sectors	Energy consumption and use
Households (HH)	All energy consumed for living, such as cooking and heating.
Industry and Energy (IE)	All energy used for the production of industry and energy related products. Inclusive the energy the energy branch consumes. Sectors included: industry, construction industry, energy and landfills. According to the IEA balance definitions sector industry covers: iron and steel industry; chemical and petrochemical industry; non-ferrous metals; non-metallic minerals; transport equipment; machinery, mining, food and tobacco; paper, pulp and print; wood and wood products; construction; textile and leather and other industries (IEA 2017).
Services (SE)	All energy used for services. This also includes the energy that is needed to heat offices. Sectors included: information and communication, financial services, rent and trade of property, business services, government and care; culture, recreation, trade and other services.
Transport (TR)	All energy that is used for any transport activity. It is either passenger transport activity which consists of public road transport, private cars and motorcycles, rail, aviation and inland navigation or freight transport activity which consists of heavy goods and light commercial vehicles, rail and inland navigation. Inland navigation covers waterways and national maritime transport (IEA 2017).
Agriculture (AR)	All energy used for the production of agricultural products. Sectors included: agriculture, forestry and fisheries.

C. Complete model in stock-flow diagrams in Stella

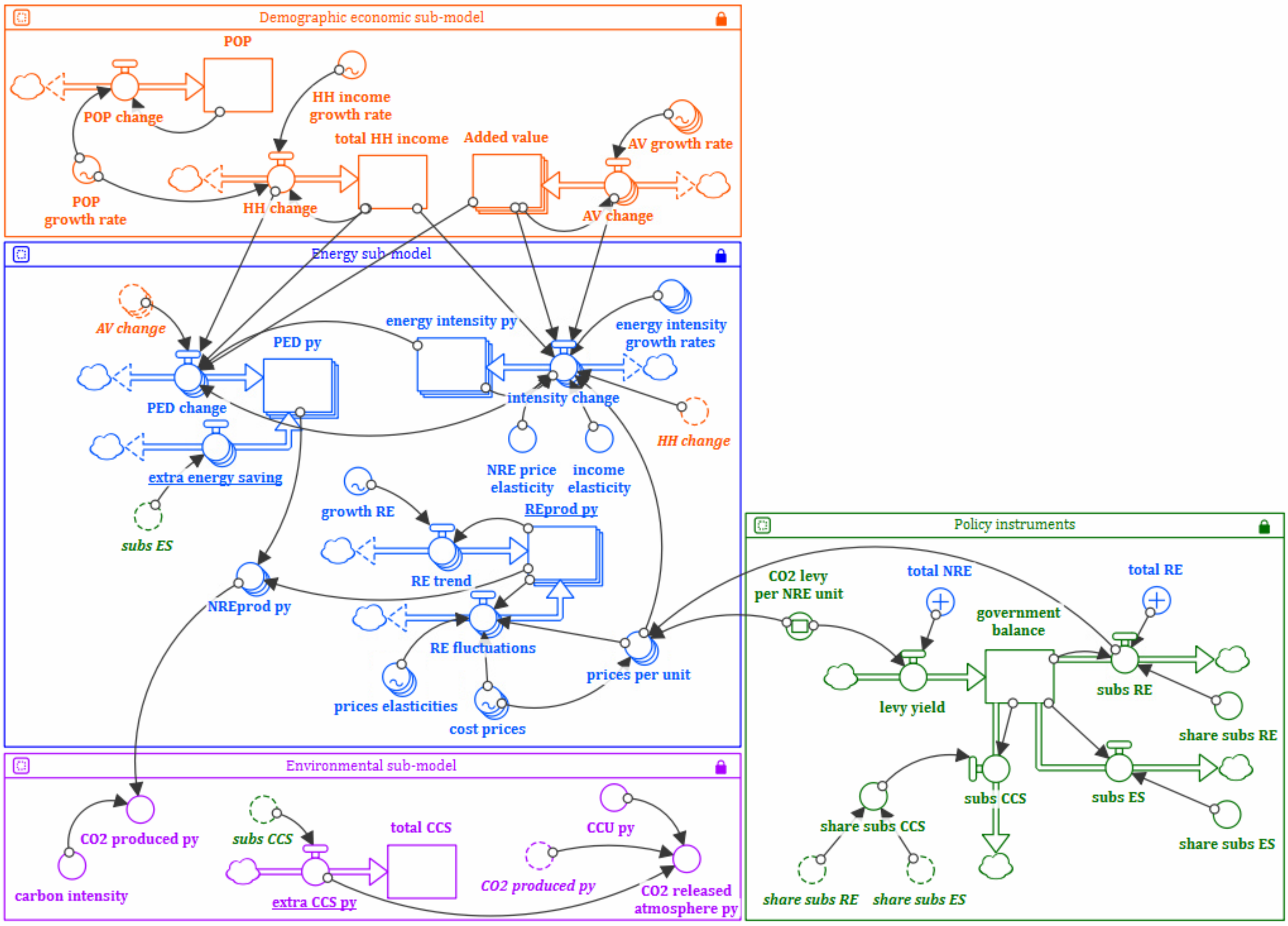

Figure 17 The complete model in Stella

D. Equations in Stella Syntax

S = Stock; I = Inflows; O= Outflows; C = Convertors/conveyors

Demographic economic sub-model

1. S: **Added value[sectors](t)**= Added value[sectors](t - dt) + (AV change[sectors]) * dt
   a. INIT Added value[SE] = 314
   b. INIT Added value[AR] = 10.3
   c. INIT Added value[IE] = 125.8
   d. INIT Added value[TR] = 108
2. I: AV change[sectors] = AV growth rate[sectors]*Added value[sectors]
3. C: AV growth rate[sectors] = GRAPH(TIME)
   a. [SE]: (2010, 0.008), (2020, 0.011), (2030, 0.014), (2040, 0.016), (2050, 0.016)
   b. [AR]: (2010, 0.006), (2020, -0.002), (2030, 0.001), (2040, 0.003), (2050, 0.003)
   c. [IE]: (2010, 0.012) (2020, 0.0085) (2030, 0.0125) (2040, 0.0215) (2050, 0.0215)
   d. [TR]: (2010, 0.009) (2020, 0.009) (2030, 0.011) (2040, 0.002) (2050, 0.002)
4. S: **total HH income(t)** = total HH income(t - dt) + (HH change) * dt
   a. INIT total HH income = (0.00001573545)*POP
5. I: HH change = (HH income growth rate*total HH income)+(POP growth rate*total HH income)
6. C: HH income growth rate = GRAPH(TIME)
   a. (2010, 0.007), (2020, 0.011), (2030, 0.015), (2040, 0.019), (2050, 0.019)
7. S: **POP(t)** = POP(t - dt) + (POP change) * dt
   a. INIT POP = 16574989
8. I: POP change = POP growth rate*POP
9. C: POP growth rate = GRAPH(TIME)
   a. (2010, 0.003) (2020,0.00238) (2030, -0.0005) (2040, -0.0005) (2050, -0.0005)

Energy sub-model

10. S: **energy intensity py**[sectors](t) = energy intensity py[sectors](t - dt) + (intensity change[sectors]) * dt
    a. INIT energy intensity py[sectors] = (INIT(PED py[sectors])/INIT(total HH income OR added value[sectors])
11. I: intensity change[sectors] = energy intensity growth rate[sectors] *energy intensity py[sectors]+(NRE price EI elas*(((prices per unit[sectors, NRE])-PREVIOUS(prices per unit[NRE],INIT(prices per unit[NRE]))))*(energy intensity py[sectors]/prices per unit[NRE]))+income EI elas*(HH change OR AV change)*energy intensity py[sectors]/(total HH income OR Added value[sectors])
12. C: NRE price elas.= -0.281
13. C: Income elas.= -0.0816
14. C: Energy intensity growth rates
    a. [HH] = -0.0012
    b. [SE] = -0.0012
    c. [AR] =-0.0133
    d. [IE] = -0.0078
    e. [TR] = -0.01
15. S: **PED py[sectors](t)** = PED py[sectors](t - dt) + (PED change[sectors] + extra energy saving[sectors]) * dt
    a. INIT PED py[HHc] = 11518.4
    b. INIT PED py[SEu] = 8822
    c. INIT PED py[ARu] = 4302

d. INIT PED py[IEu] = 12208.3+17194
e. INIT PED py[TRu] = 14984.7

16. I: PED change[sectors]=HH change OR AV change*DELAY(energy intensity py[sectors],1)+intensity change[sectors]*DELAY(total HH income OR Added value[sectors], 1)+HH change OR AV change*intensity change[sectors]
17. I: extra energy saving[sectors] = -(subs ES/579000000)
18. S: **REprod py[sectors](t)** = REprod py[sectors](t - dt) + (fluctuations[sectors] + trend RE[sectors]) * dt
    a. INIT REprod py[sectors] = 3671*(INIT(PED py[sectors])/total PED)
19. I: fluctuations[sectors] = (DELAY(prices RE elas[NRE], 1)*((DELAY(prices per unit[sectors,NRE], 1)-DELAY(cost prices[NRE],1))*(DELAY(REprod py[sectors], 1)/DELAY(cost prices[NRE], 1)))) +DELAY(prices RE elas[RE], 1)*(DELAY(prices per unit[sectors,RE], 1)-DELAY(cost prices[RE],1))*(DELAY(REprod py[sectors],1)/DELAY(cost prices[RE], 1))
20. C: cost prices[energy sources] = GRAPH(TIME)
    a. [NRE] = (2010, 498000), (2030, 707000), (2050, 998000)
    b. [RE] = (2010, 1901000), (2030, 1472000), (2050, 1236000)
21. C: prices per unit[NRE] = cost prices[NRE]+(carbon levy per NRE unit)
22. C: prices per unit[RE] = cost prices[RE]-MIN(subs RE/total RE, 0.5*cost prices[RE])
23. C: prices RE elas[energy sources] = GRAPH(TIME)
    a. [NRE] = (2010, 4.60), (2020, 2.90), (2030, 0.70), (2040, 0.70), (2050, 0.70)
    b. [RE] = (2010, -8.40), (2020, -3.80), (2030, -1.95), (2040, -1.30), (2050, -1.20)
24. I: trend RE[sectors] = growth RE*REprod py[sectors]
25. C: growth RE = GRAPH(TIME)
    a. (2010, 0.104), (2030, 0.014), (2050, 0.012)
26. C: NRE prod[sectors] = IF (PED py[sectors]-REprod py[sectors])>0 THEN PED py[sectors]-REprod py[sectors] ELSE 0

Environmental sub-model

27. S: **CCS total(t)** = CCS total(t - dt) + (CCS py) * dt
    a. INIT CCS total = 0
28. I: CCS py = (subs CCS)/50000000
29. C: carbon intensity = 0.002655
30. C: carbon per capita = (CO2 released atmosphere py*1000)/POP
31. C: CCU per year = 3
32. C: CO2 produced py = carbon intensity*SUM(NRE prod)

Policy instruments

33. C: carbon levy per NRE unit = IF TIME>2020 THEN factor*2166 ELSE 0
34. C:CO2 released atmosphere py = CO2 produced py-CCU per year-(CCS py)
35. C: factor = ''carbon levy''
36. S: **government balance(t)** = government balance(t - dt) + (carbon levy - subs RE - subs ES - subs CCS) * dt
    b. INIT government balance = 0
37. I: carbon levy = carbon levy per NRE unit*total NRE
38. O: subs RE = share subs re*government balance
39. O: subs ES = share subs es*government balance
40. O: subs CCS = share subs CCS*government balance
41. C: share subs CCS = 1-share subs re-share subs es
42. C: share subs es = 0; share subs re = 0

E. Incorporated policies

The policies that are implemented before December 2014 are incorporated in the SDEP model (European Commission 2016a). The main policies are listed below:

1. Renewable energy policies: including legally binding targets on renewables in 2020 meaning that 20 per cent share of gross final energy consumption is from RE sources. Note that in the SDEP model primary energy demand is used, not final energy consumption. Also the national blending obligations for biofuels is taken into account. For the Netherlands, the blending obligation is ascending to 10% in 2020 (NEA 2016).
2. Energy efficiency policies: covers policies such as eco-design and labelling, the energy efficiency directive (EED) and the energy performance of building directive (EPBD) are taken into account.
3. European Emissions Trading System (EU ETS): this is a scheme that allows GHG allowances to be traded within Europe. More information about the trajectory of the emission cap of EU ETS, as it is incorporated in the model, can be found in Table 15.

Beyond 2020 there are no policies incorporated in the SDEP model, except for EU ETS because that is an ongoing scheme and national blending obligations which are assumed to be constant post-2020.

Table 15 Trajectory of the European Emissions Trading System (ICAP 2017)

Phases	
Phase one and two (2005-2012)	• EU absolute cap established from aggregating the National Allocation Plans of each European Union Member State. • 100% free allocation through grandfathering • Key sector included: energy, industry and aviation sector.
Phase three (2013-2020)	• The EU-wide cap was stated at 2084 $MtCO_2$–equivalents per year in 2013 • The annual reduction factor of the cap is set on 1.74 per cent
Phase four (2021-2030)	• The annual reduction factor of the cap is proposed to go to 2.2 per cent.

F. Key variables development in index numbers

Table 16 Total primary energy demand development in index numbers (2010 = base year) 2010-2050

	2010	2015	2020	2025	2030	2035	2040	2045	2050
1. BaU scenario	100	97	95	92	89	88	86	86	86
2. RE scenario	100	97	95	91	89	87	86	86	86
3. ES scenario	100	97	95	91	88	87	85	85	86
4. CCS scenario	100	97	95	91	89	87	85	85	86
5. IP scenario	100	97	95	91	89	87	86	86	86

Table 17 Total renewable energy production development in index numbers (2010 = base year) 2010-2050

	2010	2015	2020	2025	2030	2035	2040	2045	2050
1. BaU scenario	100	158	225	287	328	351	375	400	425
2. RE scenario	100	158	225	388	660	837	978	1118	1258
3. ES scenario	100	158	225	371	616	787	928	1083	1253
4. CCS scenario	100	158	225	366	594	751	860	1022	1175
5. IP scenario	100	158	225	388	656	831	971	1112	1254

Table 18 CO_2 released in atmosphere per year in index numbers (2010 = base year) 2010-2050

	2010	2015	2020	2025	2030	2035	2040	2045	2050
1. BaU scenario	100	94	87	81	75	72	69	68	67
2. RE scenario	100	94	87	74	56	44	35	27	20
3. ES scenario	100	94	87	75	59	47	37	28	20
4. CCS scenario	100	94	87	50	36	39	40	32	20
5. IP scenario	100	94	87	74	56	44	35	27	20