Modelling the Energy Transition in the Netherlands

Simulating the effect of energy transition policies in the Netherlands.

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ABSTRACT

Avoiding the uncontrollable climate change and meeting the Paris Agreement targets require designing and implementing the appropriate interventions that constitute a complex challenge for policymakers. The need to transition towards a more sustainable energy sector is urgent. However, the energy sector is a complex, dynamic system with various constituent components and interactions among them; hence its development requires approaches that can adapt to its dynamic complexity. This research proposes a system dynamics approach to design and construct an integrated model that simulates the energy transition in the Netherlands at a country level. Previous studies focus on other use cases and adopt approaches that disregard the dynamics of the energy system, reducing understanding of the system behaviour. The results showcase that keeping current practices will increase the Netherlands' global CO2 footprint. This research simulates different policy scenarios and examines their effects on the system. The energy sector of the Netherlands is used as a case study; however, the model can be applied in other contexts with the appropriate alterations.

KEYWORDS

modelling systems dynamics; energy modelling; energy transition; renewable energy systems; energy policy; CO2 emissions

1 INTRODUCTION

Energy is fundamental for the existence and the development of countries. Thus, the provision of energy that is secure, affordable, clean, environmentally friendly, produced and used efficiently is essential for sustainable development. Ensuring modern energy access for all constitutes one of the "Sustainable Development Goals (SGD)" determined and adopted by the United Nations [3] in 2015 as a universal call to action to eradicate poverty, safeguard the environment, and ensure that everyone lives in peace and prosperity by 2030. The Paris Agreement legally binds the international participating countries and parties to specific commitments on climate change [34]. Since its adoption on 12 December 2015, countries have committed to prioritizing progress for the goals set. The environmental target is to reduce global warming to below 2 degrees Celsius compared to pre-industrial levels. In order to accomplish this goal, countries set targets to reduce the amount of greenhouse gas emissions as soon as possible. The reconstruction of the energy sector towards a low-carbon system requires the integration of renewable energy sources (RES) [21]. Hence, flexibility issues arise when high shares of renewable energy are reached since fossil-based technologies can lead rapidly to fluctuations in energy demand.

The Netherlands has committed to several international agreements on tackling climate change, the core of which is the National Climate Agreement of the Netherlands issued in June 2019 [23]. The aim is a rapid transition due to the urgent need to avoid uncontrollable climate change and the fast increasing energy demand. Although the Netherlands has advanced on its transition to a carbon-neutral economy, it remains heavily reliant on fossil fuels and holds natural gas reserves in Groningen [13]. Furthermore, it is a densely populated country with high energy demands.

The decline of fossil energy resources, the growth of the world's population and the need to fulfil the requirements of the Paris Agreement make the need for a sustainable energy sector more critical. Consequently, concerns such as the growth of energy demands, the threats of carbon dioxide (CO2) emissions and the constraints of the use of fossil fuels unite researchers of diverse fields, governments and decision-makers to design and develop their energy policies sustainably.

The implementation of the Paris Agreement requires economic and social transformation [2]. The formulation of a sustainable energy sector approaches a multi-level problem that interacts with different socio-economic and political interests. The system consists of diverse supply sources, multiple stakeholder involvement with different interests and can be regulated by external and internal factors. Therefore the energy sector constitutes a dynamically complex system with various components and interactions since it is not rooted in one discipline. The energy system ought to meet energy needs, complement the national economy of each country, enact environmental sustainability and mitigate social inequalities.

In order to achieve the energy transition sustainably, a comprehensive understanding and analysis of the energy sector's components and the interactions among them are required. The energy transition in the Netherlands is concerned with cornerstone alterations in the existing systems of production, provision and consumption of energy. Currently, the ability to understand how the system works and design possible interventions to provide leverages that help the transition is limited.

The interdisciplinary nature of the energy sector imposes the need for an approach that can manage dynamically complex systems and examine the components of the system and their interactions. The use of system dynamics quantitative models supports the (re)design of systems and control structures.

1.1 Research Question

As a case study, this thesis will adopt a systems dynamic approach to construct a conceptual model for examining the performance of the energy sector in the Netherlands. The model explores an integrated system's approach towards assessing and implementing the energy transition. In addition, it identifies feedback mechanisms likely to influence the sector's behaviour. In order to achieve this, the following research question is formulated:

> What dynamics result from the distinct influences in the Dutch energy system and how can the energy transition towards sustainability be realised while taking into account the many boundary conditions that apply, as well as the social, economical and ecological aspects?

To facilitate the investigation, we populate intermediate goals underneath this overarching research question which we formulate as follows:

(1) What dynamical patterns can be observed in the data available, particularly in the Netherlands?

(2) What changes to the existing models are required to capture the patterns in the data and describe the energy transition in the Netherlands?
(3) To what extent will the Netherlands be able to fulfill the commitments on climate change based on the Paris Agreement of 2015, given a data-based simulation of the energy transition?

2 RELATED WORK

In this section, a brief background on the related literature is presented. Additionally, insight on approaches to the formulation of a simulation model is provided as well as an overview of the simulation of the Dutch energy transition.

2.1 Background

The energy sector faces serious problems [37]. Limits to growth are fast approaching for reasons such as excessive fossil fuel extraction, high emissions and high energy dependency [19]. Consequently, the prevention of the effects of global warming, the improvement of human well-being and security in accordance with the development of sustainable development are becoming more and more urgent. The transitions towards a more sustainable energy system are considered to be helpful.

Therefore, much interest has been shown in the energy transition from policymakers, governments and academics due to the significant improvements it achieves in the environmental efficiency [35]. Various approaches have been developed to investigate the ongoing energy transition [25]. The distinct approaches focus on different aspects that influence the energy transition. However, many of those have been disapproved due to their limited incorporation and representation of societal factors and socio-political dynamics [27].

In the context of the energy transition, various emerging renewable energy initiatives are introduced in the Netherlands, as well as in other countries [30]. However, it is not made clear whether they make a difference in the influence, direction and speed of the energy transition due to the continuous growth of the size and complexity entailed within the energy sector [29]. During the past few decades, remarkable advances have been achieved in comprehending the dynamics of deeply interconnected systems. Energy systems encompass complex, uncertain behaviour, influenced by various dynamic uncertainties, (non) linear relationships between system variables, delays, and interactive feedback loops [38]. The study of Mutingi et al. [29] presents an analysis and classification of energy policy formulation problems and proposes appropriate archetypal structures for each. Their findings suggest that the decision to form the appropriate energy policies is ambiguous depending on their use. However, the use of archetypes is beneficial in uncertain environments, assisting the decision on which is the suitable policy to apply.

2.2 Energy Transition Simulation Models

Emergent properties constitute a central characteristic of complex systems, where the system itself influences them, its agents, structure and underlying dynamics [24]. In the use case of the energy transition, the focus lies in modifying those properties of the system to meet the Paris Agreement. A system dynamics approach can be adopted to identify their origin and effects.

Energy system modelling supports energy policy while creating and evaluating distinct energy transition approaches [22]. There is a wide, continuously expanding variety of energy models and studies that focus on investigating the energy sector from a specific scope. For instance, Keller organises the models in three different types [1] depending on their functionalities:

(1) Models constructed on proven theories and mathematical abstractions of a real-world target framework.
(2) Models that calculate the responses in hypothetical questions and provide an output (data). The simulations represent the behavior of an actual system that is computed by a set of equations based on theoretical observations. However, the empirically verification of those results is not feasible.
(3) Models that reproduce the performance of entities.

The work of F.G.N. Li et al. suggests a concept of 'socio-technical energy transition' (STET) models [27]. Those quantitative models will include the components of socio-technical transitions. Armands Gravelsins et al. propose a system dynamics modelling approach to the energy transition that combines the techno-economic, and socio-technical analysis [21]. Within this approach, a range of flexibility challenges of the renewable energy sources adoption is analysed. However, further research is required to provide insight into the system dynamics.

A review of the current modelling landscape by Chang et al. [18] proposes that since most of the tools have been created for particular purposes and requirements, there is not a single tool that can combine different scopes.

2.3 Simulating the Dutch Energy Transition

Transition thinking of traditional systems has been researched in the Netherlands [25]. Since the energy sector is a complex system, the Dutch energy transition towards sustainability entails the transition of its constituent subsystems. The effects of a change in one domain of the system will spread to the various disciplines it involves. Therefore, the various practices that can support the energy transition are presented. Geels' socio-technical approach [20], refers to the correlation between society and technology and suggests that they define each other, creating a dependency between them. Rotmans et al., in the transition management approach, argue that transition management establishes a foundation for societal consistency that can support the adoption of sustainable practices [31]. Martens and Spaargaren approach the societal transition and analyse how transition practices are formed in everyday life [28]. Finally, the tradition of reflexive modernisation focuses on the governance of reflexive modernisation as well as the value and belief system of the system's actors [36]. The abovementioned approaches express interest in deepening the understanding of the system's mechanisms while maintaining a co-evolutionary view. However, an integrated approach has not been attempted for the Dutch energy transition.

Laimon et al. [26] develop an integrated model that simulates the behaviour of the Australian energy sector. Contrary to previous efforts, the model of Laimon et al. incorporates and analyses different interconnected components of the energy sector. In this way, an investigation of the system's dynamics and the way CO2 emissions and energy dependency grow can be conducted.

The model that was created during this research was based on the model designed in Laimon et al. [26]. The Laimon et al. model depicts Australia's energy sector development. The appropriate adjustments were integrated into the created model to illustrate the Dutch energy sector.

3 METHODOLOGY

The problem statement, literature review and subsequent research question illustrate that the energy sector can be seen as a complex system. Complex systems are characterised by non-linear dynamic relations and feedback loops that influence the system's behaviour. Due to the difficulty of envisioning the future system's behaviour, the decisions that regulate complex sectors might fail or have unexpected side effects [32].

In order to answer the sub-questions and, ultimately the research question, a simulated model is created. A computational model is a method used to explore complex systems when experiments are costly in resources, technically or physically impossible and have many variables that cannot be controlled. In the case of the energy sector, an experiment is not feasible, and decisions on the definitive actions should be made.

Overview of the modelling process. Firstly, the necessary data is gathered and analysed. The model is created based on the dynamical patterns that are identified within the data. Then, the model simulation follows. After the model simulation, the calibration process follows to quantify the relationships among its elements and explore its projection into the future. Finally, the validity of the model is assessed. The outline of the process that is followed to model the energy sector of the Netherlands is illustrated in figure 1.

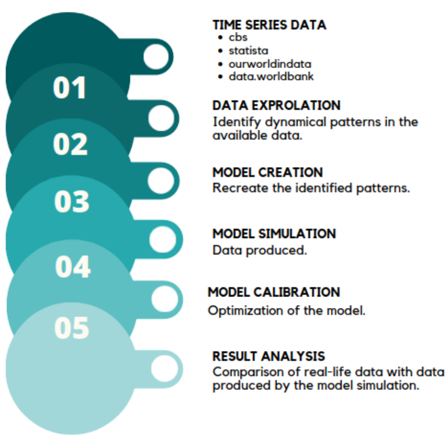

Figure 1: Overview of the modelling process followed throughout this research.

3.1 Model Description

This thesis's main aim is to construct a generic model that depicts the dynamics within the energy sector and the impact of different scenarios; in this case, different ways to achieve the energy transition. The appropriate modelling approach depends on the assumptions about the stocks and flows in the system that apply to a specific purpose. During this case study, two different types of models will be used. The system modelling will be firstly approached by a causal loop diagram and then by a stock and flow diagram. The models that are developed within this project are based on the models designed in Laimon et al. [26].

3.1.1 Causal Loop Diagram. The first model that was constructed is a causal loop diagram (CLD) that illustrates the relations between the different components of the energy sector in the Netherlands. The CLD created constitutes a simplified version of the Australian case, one that establishes an initial structure of the system. It is used to depict the existing interactions among the components of the system. The CLD that was created is illustrated in figure 8 of the Appendix section 6.1.

The feedback loops constitute a significant element of the CLD since the most complex behaviours usually arise from the interactions among the different components of the system and not from their complexity [32]. Within the CLD created, the present feedback loops are identified and annotated as reinforcing or balancing ones. The system's feedback loops are depicted in figure 8. Overall, eight reinforcing (R1-R8) and eleven balancing loops (B1-B11) can be found in the CLD.

The CLD illustrates the main components of the energy sector, such as the energy capacity and production of the different sources, supply and demand in the Netherlands, the financial investments of the energy sector, and emissions. The aforementioned are described in the sections below to explain the origin of the structures in the Dutch context.

- **Energy Production Capacity and Energy Finances Loops.** The feedback loops that illustrate the interconnections between energy production capacity and the financial aspect of the sector include the reinforcing R1, R2, R3 and R4 and the balancing B1, B2, B3, B4 and B5. The loops that describe the energy production capacity development (R1, R2, B1, B2) express both renewable and non-renewable sources. The balancing loops depict total decline resulting from capacity bankruptcy and retirement, while the reinforcing ones describe total growth due to the construction of new capacity. The balance between energy supply and demand is portrayed by two balancing loops (B3, B4), while R4 reflects the positive correlation among energy revenues, GDP and demand. Finally, loop B5 expresses the risk of new investment in the different sectors. In case the expected return on the investment (ROIC) is significant, more new investments will be anticipated. However, the addition of capacity under construction is influenced by other factors that eventually balance the system.
- **Energy Production Capacity and Energy Demand Loop.** The interaction between the energy production capacity and specific social factors that influence the energy demand is represented by the reinforcing feedback loop R5 as shown in figure 8. The increasing population will create an increasing need for energy production capacity. In this way, new employment opportunities will be formed that might increase the social factors.

Energy Production Capacity and CO2 Emissions Loops. The feedback loops B6, B7 and R6, illustrate the interconnections between energy production capacity to emissions. The CLD suggests that in order to reduce CO2 emissions, the Netherlands can invest in nuclear power, renewable energy sources, energy efficiency, carbon capture and storage or introduce new norms on the supply and demand sides. Renewable energy investments are positively affected by market prices and technology development. The limitations of the RE energy supply might lead to the reduction of RE investments. In this way, uncertainty in future RE energy supplies emerges, endorsing the use of non-RE energy sources and increasing CO2 emissions.

Energy Production Capacity and Energy Security Loops. The section of the CLD that describes energy security includes the reinforcing loops R7, R8 and the balancing loops B8, B9, B10 and B11. Energy security, constituting a significant indicator of sustainable development, can deal with the variety of the available national energy sources being in line with economic developments and environmental needs while maintaining the system flexibility to react to disruptions in the supply-demand balance [39]. Energy dependency can be calculated by dividing the national net energy imports by the sum of gross inland energy consumption to determine if the country's energy needs can be met [33]. Increasing energy demand positively influences energy dependency, which then decreases energy security [17]. Within the CLD created, the factors that can positively influence energy security are the increase in energy production capacity or gas supply. Contrary to those, increasing energy demand, risk of supply disruptions, depletion of gas and the increase in gas price decrease the energy security. When maintaining the supply-demand balance, lowering energy demand entails lowering the energy supply.

3.1.2 Stock and Flow Diagram. Although the CLD provides qualitative insight into the sector, its limitation lies in its inability to simulate the system's dynamics over time quantitatively. Based on the causal loop diagram, the stock and flow diagram of the energy sector in the Netherlands is constructed. The components that are present in the CLD (see 8) are translated into a stock and flow diagram (SFD), except for the elements that are presented in red, which were not able to be interpreted in the context of the SFD. The model simulates the behaviour of the system to capture different dynamical patterns.

In order to formulate a full-scale model that recreates the behavior of the energy sector in the Netherlands, a modular approach was followed. In particular, each component of the system was incorporated in different steps. In this way, the system's behaviour during each step of the process could be thoroughly investigated to ensure that the system's foundation was established. Then, more components were incorporated by translating the feedback loops of the CLD into the SFD. This way, a complex model was created to recreate the expected behaviour.

The first phase of the development of the model included the translation of the rate at which new capacity comes on stream. This part contains two reinforcing and two balancing loops, as well as the construction delay entailed in the project. The SFD diagram that was created during the first iteration is illustrated in figure 9.

The second phase of the development process included the addition of the "Capacity under construction" stock to reflect the process of adding capacity thoroughly. The model that was created during the first step had to be slightly altered to incorporate the new component into the system and arrange the feedback loops between the two stocks. The improved SFD has one reinforcing loop that links the energy production capacity with the capacity under construction stock via the desired new capacity addition variable. In this way, the order rate of a sector can be controlled and adjusted depending on each sector's nature. The new version of the SFD does not distinguish between the RE and non-RE sources since the model can apply to both categories. The SFD diagram that was produced after the addition of the second stock is presented in figure 10.

During the third phase of the model development, the stock of the population was added. Firstly, an SFD representing the population of the Netherlands was constructed. In this way, the feedback loops related to the population stock can be examined before incorporating this part in the model. The SFD that was created to approximate the population growth of the Netherlands is presented in figure 11.

After investigating the population's behaviour, its connection to the system described in figure 10 was established. As suggested in the CLD shown in figure 8, the population has a reinforcing relationship with the energy demand. Therefore, the required auxiliary variables were defined to establish the connection between the stocks. The auxiliary variable "Energy security" bridges the two stocks in this case. Energy security, in general, can be seen as ensuring uninterrupted access to energy resources at an affordable price and enhancing the supply-demand balance. The SFD that was created after the addition of the population stock and the appropriate alterations are illustrated in figure 12.

The final structure of the model consists of six linked parts: one energy extraction view for each sector (six in total), the population view and the CO2 emissions view. The final phase of the model development included the addition of the investment stock and the various connections among the existing and new components of the system. Then, a general model that depicts resource extraction for each individual source that contributes to energy production in the Netherlands was created. The general model is illustrated in figure 4.

The constituent component for the model is the existing general model, which will be used for each different energy resource. However, in order to answer to the research question, the examination of the different sources that contribute to the Dutch energy sector is conducted. The energy sectors that are incorporated within the model are wind, solar, hydro, coal, natural gas and oil since they produce the majority of energy in the Netherlands. In figure 4, the use case of wind power is presented however, during the simulation, all the different sources are examined. For each sector, the initial value of the capital employed is aligned with the initial value of the energy production capacity.

Since each view describes a specific part of the energy system, the parts that describe global concepts (i.e. population, CO2 emissions) are segregated from the resources view. The final model illustrates

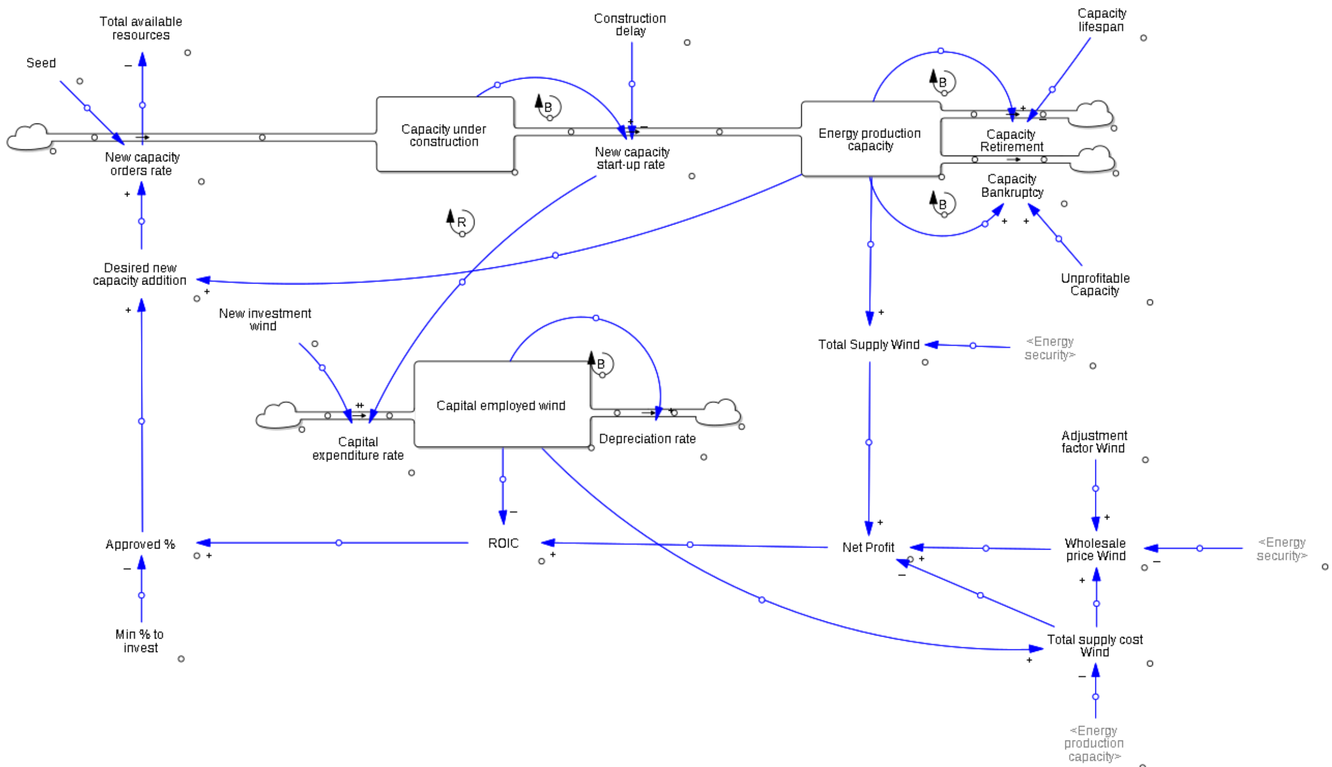

Figure 2: Stock and Flow Diagram: Representation of energy resources extraction view of the model.

the global concepts in a designated view. The connection among the different views is established by shadow variables.

The model that was created contains a range of different variables. The list of the SFD's variables along with their equations is contained in table 2 in the appendix section B.

Population view. The representation of the Dutch population is illustrated in a designated view shown in figure 9. In this view, the positive relation between population and gross demand is formed. In this way, the energy demand per citizen is incorporated, creating a supply and demand balance that is expressed through energy security.

The list of the population view variables and equations is provided in table 3 of the appendix section B.

CO2 emissions view. Some indicators are established to evaluate the simulations for the various policies. One of the requirements of the Paris Agreement is the reduction of CO2 emissions globally. Therefore, the indicator that leads the policy evaluation of the model is the Dutch CO2 emissions footprint. Thus, a designated view that represents the effects of energy production in different scenarios is included in the model. The CO2 emissions view, shown in figure 4, is coupled with sources' views using the energy production capacity variables.

The list of the CO2 emissions view variables and equations is provided in table 4 of the appendix section B.

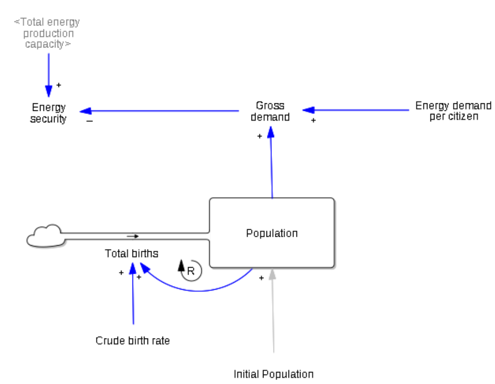

Figure 3: Stock and Flow Diagram representing the population view of the model.

3.2 Simulation Set-up

For the development of the model, specific modelling software is used. The visual models created are made in the software package Vensim[1], which is specifically designed for conducting system dynamics analysis. Vensim also enables the user to do sensitivity analysis over a large number of variables under different assumptions. Although the results of the simulation can be analyzed both

[1]Vensim

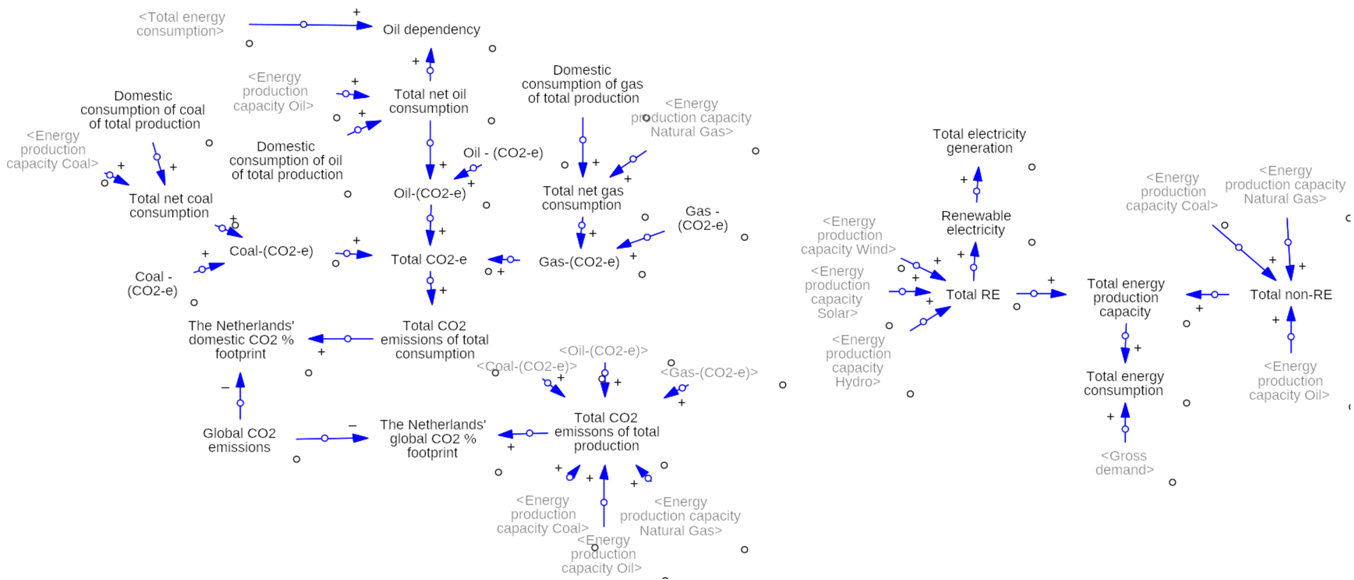

Figure 4: Stock and Flow Diagram: Representation of CO2 emissions view of the model.

in Vensim or Python[2], the choice of Python is made for more sophisticated analysis. The PySD[3] module in Python is specifically designed to be used on models built with Vensim. The materials produced during this thesis can be found on the project's GitHub repository[4].

The mathematical model produced by this thesis has a predictive function since the initial objective is to use the simulated model to guide the energy transition. The simulation constitutes an experiment performed on a model with the objective of generating insight that enhances the understanding of the system's behaviour. The change of the conditions (the experimental frame) enables the analysis of the system for different policy scenarios.

4 ANALYSIS AND RESULTS

This section provides an analysis of the use case and the results. In particular, section 4.1 outlines the specifications of the Netherlands use case and the model's known parameters. Then, the policy implementation is described in section 4.2. Finally, in section 4.3, the results of the simulations are presented.

4.1 Case Analysis

The model is calibrated with the most recent available data for the Netherlands, dating back to 2018. The case could not be simulated for earlier years since the required range of data was not available before 2018.

The stock and flow diagram that was created formulates an energy resources extraction pipeline model for the significant dispatchable and non-dispatchable resources for the Netherlands' energy sector. The energy sources incorporated and examined within the scope of the model are wind power (onshore and off-shore), solar power, hydro-power, power generated from coal, natural gas, oil and other petroleum commodities.

4.1.1 Known Parameters. Table 1 in the appendix section B provides an overview of all the known parameters and their initial values used within the model's scope. This section describes the origin of the initial values.

- **Adjustment factor, Capacity lifespan, Construction delay.** The adjustment factor constitutes the expression of the overhead expenses factor, which is significant in matching supply and demand [26].
  Capacity lifespan expresses the lifetime of the infrastructure and capacity produced from the moment of their integration while functioning under the same conditions.
  Construction delay expresses the delay at which a new capacity is integrated within the existing system.
  The values are gathered from the Australian use case paper of Laimon et al. [26]. The values range depending on the sector of activity, as presented in table 1.
- **Capacity under construction, Energy production capacity.** Capacity under construction and energy production capacity constitutes the main stocks that articulate how new capacity orders are incorporated within the system after the construction delay. The values for each sector are accumulated from the Renewable electricity; production and capacity subject of CBS [12]. The values for the non-renewable energy sectors are retrieved from CBS [12] and IEA fuels and technologies report [6].
- **Capital employed, Minimum to invest.** The investment section of the model (capital employed, new investment, capital expenditure rate, depreciation rate, etc.) expresses the way new investment is introduced into the system and the amount of capital employed so far for each sector. As mentioned in section 3.1.2, the initial values align with the

[2] Python
[3] PySD
[4] https://github.com/kntziora/MSc-SD-for-SET-in-NL

energy production capacity. The initial values for the new investment variables are retrieved from CBS [4], and for the capital employed stock, they are retrieved from IRENA [14–16]. The calculations for the capital employed are conducted using the LCOE of each sector, which is a ratio of the lifetime costs to the lifetime of electricity generation [16].
The minimum to invest was set to 10% for the different sectors incorporated in the model.
- **Initial population, Crude birth rate, Energy demand per citizen.** The model's population view contains information on how the Netherlands population will grow in the future. A crude birth rate is included that can be calculated by subtracting the net death rate from the net birth rate. The incorporation of the crude birth rate was made in order to keep the model as simple as possible and avoid impractical components. The value for the initial population of the Netherlands is obtained from CBS [11]. The information on the crude birth rate is calculated from the birth [9] and death rate [10] in the Netherlands.
- **Domestic consumption of non-RE, Global CO2 emissions.** Global CO2 emissions are a primary indicator of the sustainability of the system's behaviour. The initial value of the CO2 emissions is acquired from Our World in Data[5]. The value for the initial domestic consumption of non-RE sources (oil, natural gas, coal) in the Netherlands is calculated based on insight provided by The Netherlands 2020 Energy Review from IEA [7] and The Netherlands's Effort to Phase Out and Rationalise its Fossil-Fuel Subsidies from OECD/IEA [8].

4.1.2 Calibration of the model. After the specification of the use case, the process of calibrating the model follows, which entails optimizing the model to fit the real-life data. From the beginning of this research, the limitation of having few data points to optimize constitutes a challenge for the model calibration. Several optimization approaches were investigated despite having very few historical data points since the available data date from 2018. Firstly, an attempt to calibrate the model based on the actual value of the wholesale price during 2019 and 2020 was conducted. However, the lack of available data points constituted the approach ineffective. Secondly, we examined introducing new factors that control the total supply cost of each sector and could be optimized. This approach caused a disturbance to the system's dynamics, therefore, considered ineffective. Eventually, the model was calibrated via the adjustment factors to control the variable wholesale price, which positively correlates with the net profit. The first factor that was optimized was the adjustment factor of natural gas due to the sector's importance to the Dutch energy system. The approach followed imitates an intervention of a tax increase that was imposed on the natural gas sector. However, by changing one factor, the system's dynamics are modified since the intervention should be reflected in the system. Hence, the optimization process eventually suggested the factors indicated in Laimon et al. study [26].

4.2 Policy Design

The final sub-question of this thesis research question is whether the Netherlands can fulfil the requirements of the Paris agreement while keeping the recent trends. The simulation of the stock and flow diagram provides insight into the sustainability of the ongoing behaviour of the energy system. This constitutes a no-growth scenario representing the current conditions and no further growth of the current production.

The model's behaviour is also tested over different policy scenarios designed based on the requirements of the Paris Agreement. The main target of the different policy strategies was the reduction of the Netherlands' CO2 footprint. The first scenario that is simulated is the case of reducing the new investment to all the non-renewable energy sectors (coal, natural gas, oil) to 0 at time t=46. The idea is that the transition toward more sustainable energy production requires the abandonment of non-renewable sources. The intervention is accomplished by changing the new investment equation of those sources using the "DELAY FIXED" or "PULSE" function that Vensim provides. The second strategy depicts a more turbulent society that lengthens the construction delay of the projects related to non-renewable sources. In this way, the energy prices of those sectors are expected to increase, making the other sectors profitable. The third policy approach is to reduce the minimum percentage to invest of renewable sources to zero to create more approval and insurance on those. Simultaneously, the minimum percentage to invest in the non-renewable ones is increased to twenty to achieve the opposite effect.

The different policy strategies that were formed are presented in table 5 of the appendix section B.

4.3 Results

In this section, the model and policy simulations are presented. First, the simulation of the model is presented in section 4.3.1. Then, the different policy strategy simulations are reviewed in section 4.3.2.

4.3.1 Model Results. The displayed results correspond to the model simulation with the initial values specified in table 1 while keeping the same energy usage and production patterns. The model was simulated for t = 200 months. In figure 5, the behaviour of each sector's energy production capacity stock is illustrated. However, the behaviour of the sectors that have a smaller magnitude, i.e. hydro, solar, is not expressed in the same plot; thus the energy production capacity graph is provided for each individual sector in figures 16, 20. It can be observed that the capacity of wind and hydro energy follows an exponential growth, to be consistent with the gross demand that follows a similar trend, shown in figure 22. Solar power's production capacity starts with a steep fall and follows a Gaussian distribution. Moving to the non-renewable sectors, although coal and natural gas' energy capacities mark a steep fall due to the quick capacity bankruptcy and retirement, they react following an exponential growth since their technologies have the flexibility to respond to disruptions quickly. The final sector, oil and other petroleum derivatives, follows a steep fall until its capacity reaches zero. The Netherlands mostly depends on natural gas and coal, explaining the difference in the non-renewable sectors' production capacity.

The behaviour of each sector's energy production capacity can be reflected in the correspondent total supply variable, as shown in figure 21 of the appendix section A.3. It can be observed that the

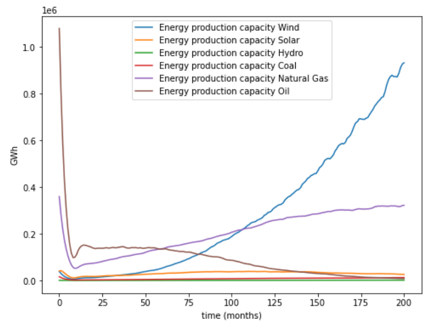

Figure 5: Growth of the energy production capacity of the various energy sectors of the system.

wind and hydro supply graphs follow an exponential growth, the solar one a normal distribution, coal and natural gas an S-shaped growth and oil a decreasing Sigmoid curve. The model results suggest that the Netherlands, at a country level, currently can cover the required power supply with the use of energy produced by coal and natural gas since the supply of those sectors reaches an equilibrium and meets the gross demand. Respectively, the energy security graph, figure 23, indicates that during the first months of the simulation, the Netherlands' total energy capacity was just enough to sustain the population and meet the population demand. However, at some point, the country starts producing more and more energy than the demanded until the system reaches an equilibrium and balances itself.

As mentioned in section 3.1.2, the primary indicator for evaluating the different energy transition strategies is the Netherlands' global CO2 footprint. Since one of the Paris Agreement requirements is the reduction of CO2 emissions, the sustainability of the current energy system can be evaluated based on whether the CO2 emissions are decreased in the future while keeping the same trends. In figure 6, the results of the Netherlands' global CO2 footprint suggest that keeping the same energy production and consumption practices will not achieve the requirement of reducing CO2 emissions. It can be observed that although the CO2 emissions graph decreases during the first 12 months of the model simulation, it then follows an increasing S-shaped curve, surpassing the bounds set to reach the reduction target.

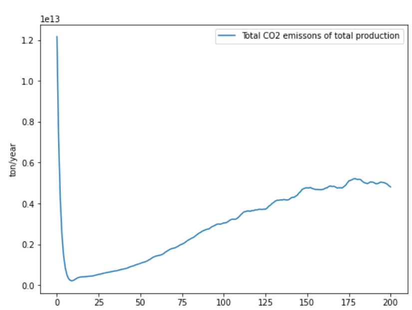

Figure 6: Growth of the total CO2 emissions of the system. The plot includes CO2 emitted from total energy production.

4.3.2 Policy Results. In order to achieve the CO2 reduction required, different practices should be adopted that drive the Dutch transition towards a more sustainable energy system. The policies that were presented in table 5 are simulated to evaluate the different interventions. The model's behaviour over the different policies is presented in figure 7. The results of the policies are discussed in section 5.

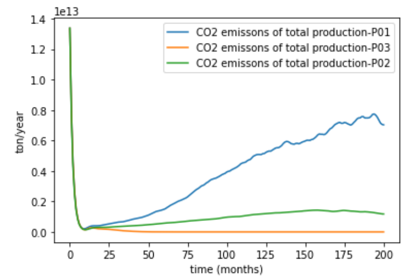

Figure 7: Policy effects on growth of total CO2 emissions of the system. The plot illustrates scenarios P01, P02 and P03.

5 DISCUSSION

The model created is capable of running one version of a situation at a time and may capture the whole variety in the changing values of its variables. The system created depicts the growth of the energy production capacity of each sector and deepens the understanding of its mechanisms and dynamics. When simulating, the model recreates behavioural patterns similar to those identified in real life. To validate the model, data that can be related to observed variables is required. Unfortunately, there is still a lack of accessible data, leading this research into a different verification method, the use of structural and behavioural tests. The structural tests evaluate whether the structure of the model represents the real-world system described. Then, the behavioural tests determine whether the model's behaviour accurately recreates the real-life system's behaviour and whether the output is reasonable according to the assumptions defined previously. The model's different components generated the expected behaviour based on the feedback loops they create. Randomness was added to the model using seed variables to avoid biased results and depict a wide range of experiments. The behavioural tests that were examined suggest that the sectors are sensitive in their dynamics since all of them are interconnected. Changing one of the components of a view affects the behaviour of the rest of the model since the energy sector creates a whole that changes behaviour when a parameter is adjusted. If, for instance, the energy production capacity of coal decreases, the population must adjust and supply more energy from a different sector. This indicates the robustness of the model.

In modelling, there is a classic trade-off between the depth and magnitude of the structure [29]. The magnitude of the model created is large, since at t=0, it already accumulates the energy production capacity and capital employed of each sector historically over the years. The research conducted suggests that the Netherlands energy sector is likely to lead to high CO2 emissions while maintaining the current trends. Presently, the dutch energy sector relies heavily on the extraction of fossil fuels, which does not enhance its sustainability. At the same time, the energy supply exceeds the demand since energy production is larger than the demand. In this way, the Dutch society has low energy security and high energy dependency on the non-renewable sectors, making the future projection of the current approach unsustainable. According to the Paris Agreement, the Netherlands needs to realise net-zero CO2 emissions by 2050 to achieve the target of 1.5°C maximum average temperature increase target over pre-industrial times. The simulation results suggest that CO2 emissions will increase in this scenario, making the target unattainable.

Therefore, the Dutch energy system urgently needs to transition towards a more sustainable energy sector to meet the objectives of limiting the average global temperature. In order to achieve this, the system must be subjected to a fundamental transformation of its constituent components and their interconnections. To gain insight into the effect of different interventions in the energy sector, different policy strategies were simulated, shown in table 5. In the first scenario, P01, the investment in non-renewable sources was reduced to zero after 46 months of the start of the simulation. Although it can be observed that the CO2 emissions are reduced, they do not remain within the required bounds. This means that reducing the non-renewable sources' investment is not enough to achieve the transition. At the same time, the development of renewable sources should be supported. In this way, the Dutch energy sector will adapt its dependency into mainly relying on renewable sources and gradually abandon the non-renewable ones. In the second scenario, P02, the illustration of a disobedient society is simulated by increasing the construction delay of the non-renewable sources' new projects. In this case, the CO2 emissions are reduced, and the system follows limits to growth by adjusting and increasing the energy production capacity from renewable sources. Finally, in the third policy scenario, P03, the minimum percentage to invest is reduced to zero for the renewable sources and increased to twenty for the non-renewable ones. With this intervention, an effort to increase the approval rate of the sustainable sources is enforced to create insurance for those sectors and establish them in the dutch energy system. In this case, the CO2 emissions of the Netherlands are reduced.

During this research, the main target was the construction and exploration of a system dynamics model that depicts the dutch energy sector. This means that the policies created were mainly used to identify their effects and do not reflect a holistic strategy to tackle climate change. In order to drive the energy transition towards sustainable practices, more sophisticated policies should be introduced that recommend specific changes customised to each sector. In this way, the different effects of each change will be investigated before their incorporation into the strategy since the impact of an intervention derives from the system's emergent properties. Emergent properties characterise complex systems and are shaped by the system itself, its individual agents, its structure and dynamics. Therefore, the emergent properties should be thoroughly evaluated to enhance understanding and control over the energy transition policies.

5.1 Limitations of modelling

Every model is a representation of reality and inevitably leaves things out depending on its boundaries. Therefore, realising that the model has a validity domain and only represents part of the energy sector system is essential. The system dynamics approach does not focus on a prediction but on understanding the interactions among the system components that influence the behaviour over time. Consequently, the model's simulation and calibration outputs might not exactly match the available data from the original system. Hence the model might have limited accuracy. Nonetheless, the essence and beauty of modelling lie in its focus on simplicity and dynamics while trying to enhance our understanding of the system.

6 CONCLUSIONS AND FUTURE WORK

The transition towards a low CO2 emissions energy supply that is secure, accessible and reliable constitutes a challenge for the whole world, as well as the Netherlands. Today's energy and climate changes demand the incorporation of socio-technical energy transitions within the model to include the various multi-disciplinary components of the system. During this research, a system dynamics approach was adopted to incorporate the primary system's components, recreate their dynamics and simulate the effect of the different policies on the Dutch energy sector. In the existing literature, there was no evidence of a system dynamics model relevant to the Dutch energy sector as the applicability of the models is restricted in specific context areas. Based on the model from Laimon et al. [26], which refers to the Australian sector, a diagram was created to interpret the Dutch energy sector.

The modelling results showcase that the model's dynamics demonstrate the expected behaviour. However, the magnitude of the model is large due to its limited accuracy. Nevertheless, there is still a shortage of accessible data on the energy sector, restraining modellers from comprehending the effect of emergent properties of the system. In this way, modelling an advanced decision system is restricted since there is no insight into the effect in case uncertain changes occur related to energy supply and demand. Thus, the decision on the appropriate energy transition policies cannot be taken without the required analysis first.

This study examines a range of policies and their effects on the system. The current scenario would not meet the Paris Agreement target of CO2 emissions reduction. Intervening in the non-renewable sources' investment would not lead to a more sustainable future as well. The transition should develop gradually while ensuring at each step that the energy supply after the intervention is enough to sustain the country's population. In the case of adjusting the construction delay in the non-renewable sources or the minimum percentage to invest in all sectors, create better scenarios for a sustainable future. The main advantage of those approaches would be switching the energy dependency from the non-renewable sectors to the sustainable ones.

It can be observed that the model presents different leverage points for forming the energy transition and improving the current system to meet the Paris Agreement requirements. The model implementation equips modellers with the ability to approach these concerns, determine the system's dynamics and enhance their understanding of how different policies can be outlined and developed.

Thus, the required regularisation for the future of the Dutch energy sector can be determined. However, further research is required to allow access to knowledge on the exact improvements that could stimulate the desired system behaviour and drive the transition to a sustainable energy system.

6.1 Future Work

A model constitutes a simpler representation of a real system, with determined boundaries that inevitably leave parts of the real world's complexity beyond its scope. A complete examination of the Dutch energy sector could not be conducted within the time frame of this research. However, the current model can be improved by adding more complexity. In order to provide a more meticulous solution, some parts of the models can be extended. Further research is required to gather more knowledge about the system's socio-technical dynamics and build a more detailed model structure. So far, some feedback loops illustrated in the CLD, figure 8 are not translated into the SFD. Considering all the different feedback loops of the real-world system can support the future model structure. In this way, the model simulation would incorporate the evolution of the social norms.

Accessing more data related to the model's variables would also benefit the accuracy. The optimization of the current model can be achieved by comparing real-life time-series data and the simulated values calculated by the model. In this way, the model's behaviour accurately recreates the behaviour of the real-life system. Therefore, the exploration of a wide range of policies could be conducted to assist modellers in outlining the direction and speed of the energy transition precisely.

Finally, it is essential to recall the highly interdisciplinary nature of the energy sector. The heterogeneity and importance of the sectors involved in the system is not currently reflected in the model leading to a lack of depiction of specific actors that bring about systemic change. The incorporation of the dependence on each sector could provide more insight into the ways of smoothing the transition without disrupting the energy supply-demand balance.

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APPENDIX

A FIGURES

A.1 Causal Loop Diagram

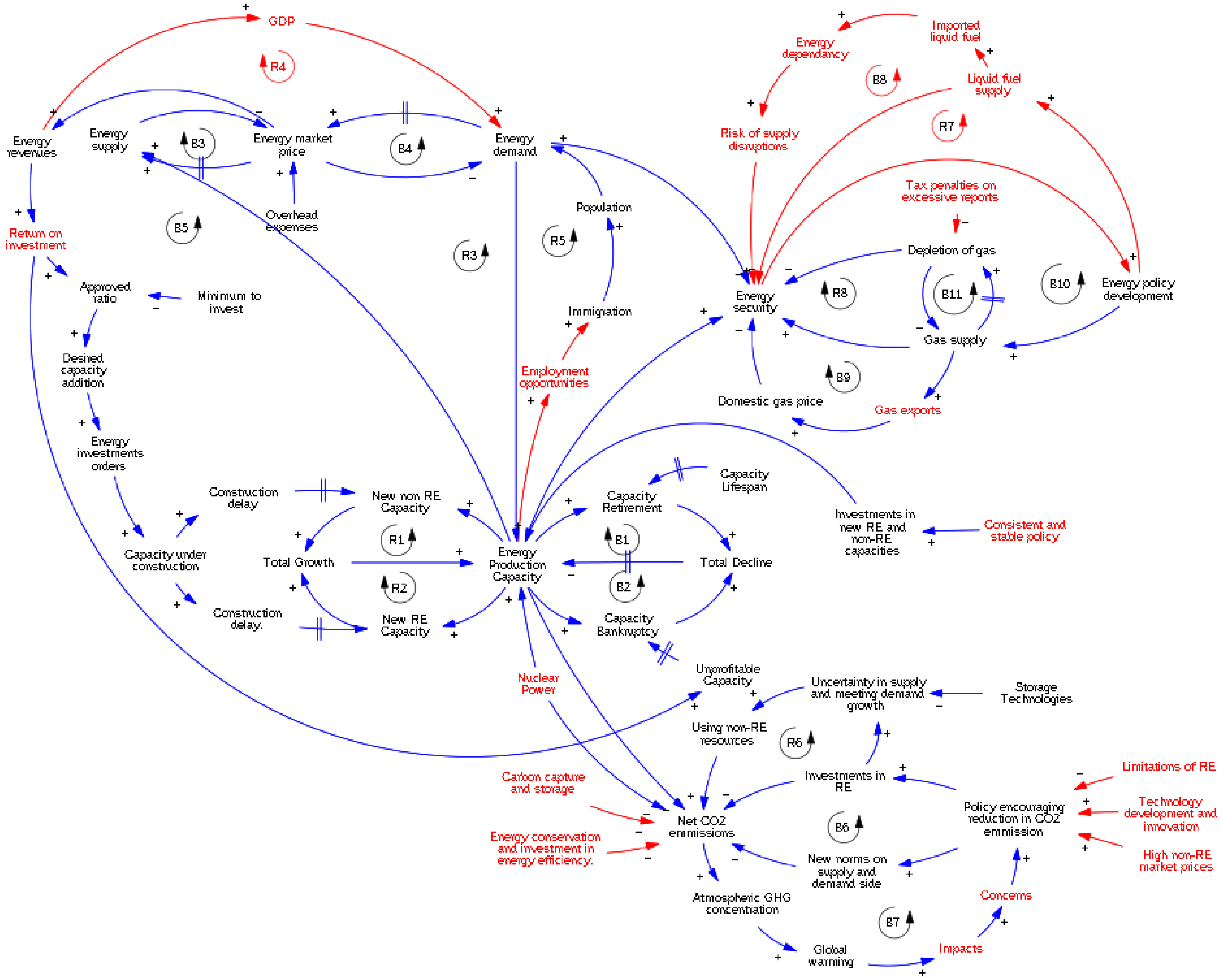

Figure 8: Causal Loop Diagram (CLD): Representation of all the constituent components and their relationships, including polarization and the different feedback loops. The CLD illustrates the main components of the energy sector such as the energy capacity and production of the different sources, supply and demand in the Netherlands, the financial investments of the energy sector and the CO2 emissions. The CLD contains eight reinforcing loops and 11 balancing ones. The sections of the model that are coloured in red are not yet incorporated in the stock and flow diagram created. The CLD is introduced in section 3.1.1 of the main text.

A.2 Formulating a Stock and Flow Diagram stages

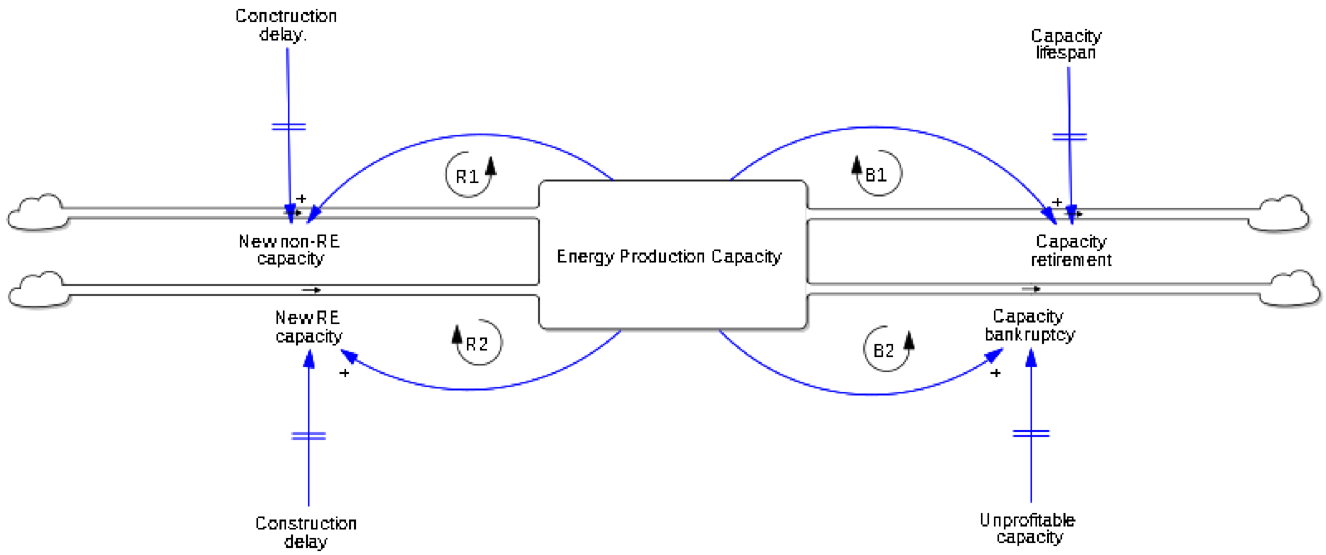

Figure 9: SFD: first iteration of the model formulation process. The model depicts the rate at which new energy capacity comes on stream. The model can illustrate both RE and non-RE sources. The first model iteration is introduced in section 3.1.2 of the main text.

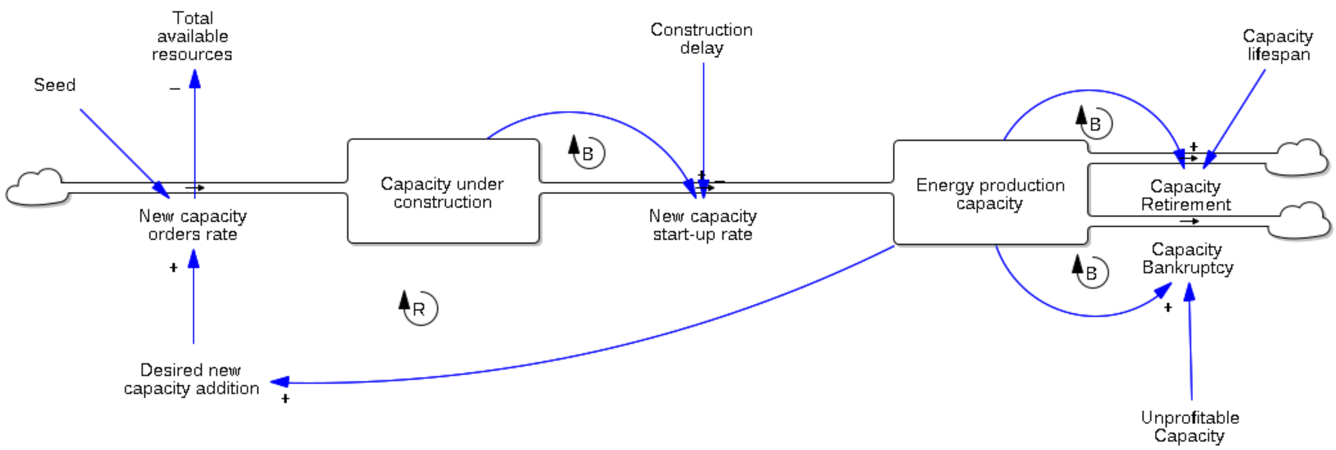

Figure 10: SFD: second iteration of the model formulation process. The model after the addition of the capacity under construction stock. The second model iteration is introduced in section 3.1.2 of the main text.

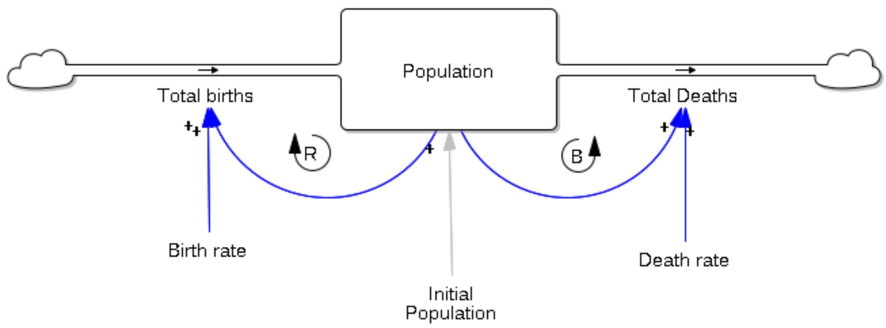

Figure 11: SFD: modelling the population of the Netherlands. The model includes one reinforcing and one balancing loop each one corresponding to the birth and death rate of the population. The population model is introduced in section 3.1.2 of the main text.

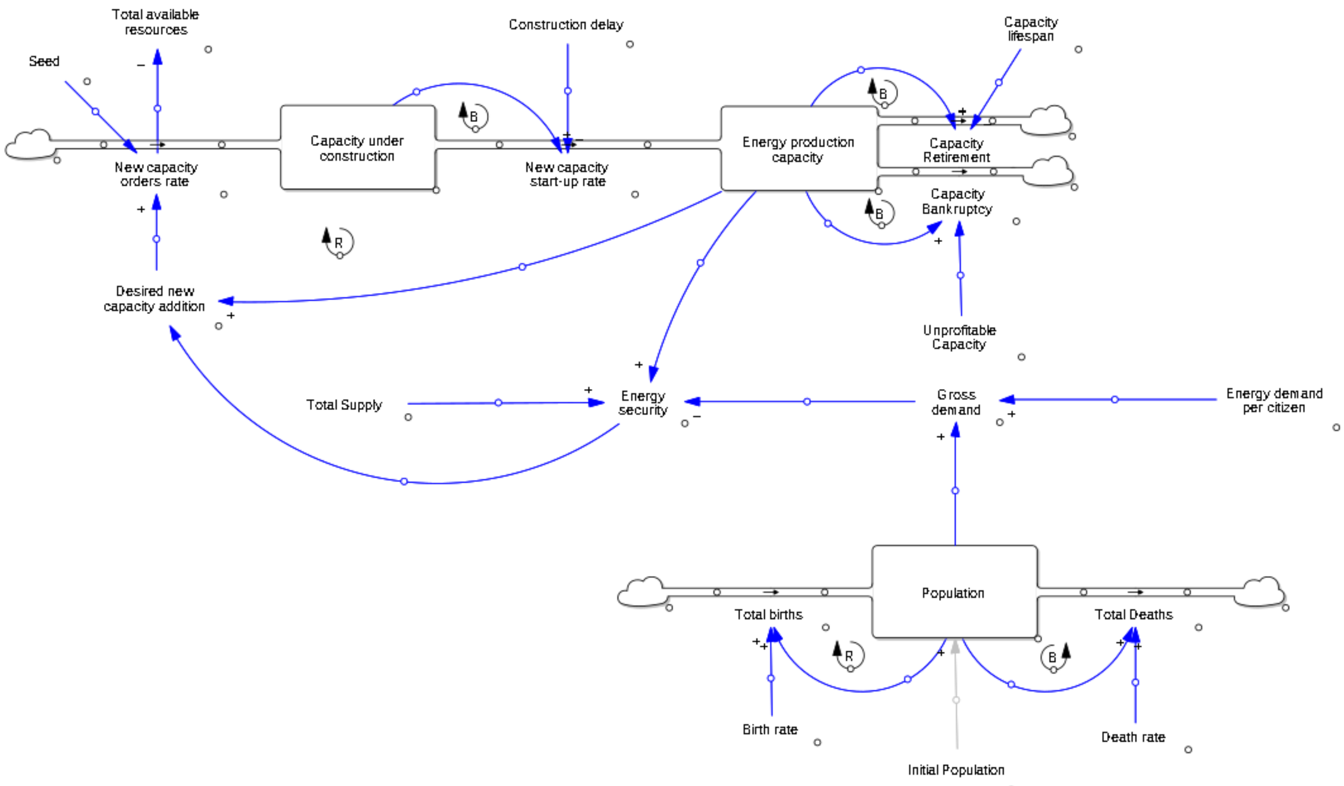

Figure 12: SFD: third iteration of the model formulation process. Connection of models depicted in figure 10 and 11. The appropriate auxiliary variables were added to establish a link between the two models. The third model iteration is introduced in section 3.1.2 of the main text.

A.3 Results Figures

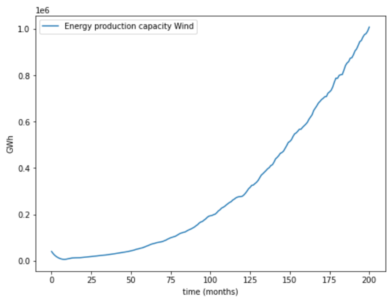

Figure 13: Growth of wind energy.

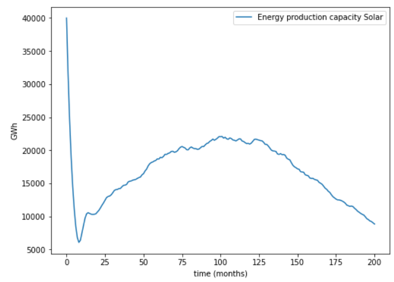

Figure 14: Growth of solar energy.

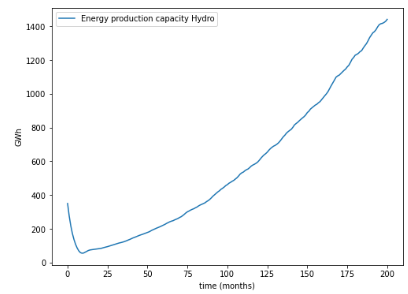

Figure 15: Growth of hydro power.

Figure 16: Energy production capacity plots for the renewable sectors. The diagrams correspond to wind, solar and hydro power. The total supply growth is discussed in section 4.3.1 of the main text.

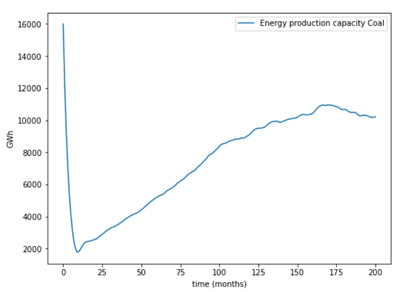

Figure 17: Growth of energy produced by coal.

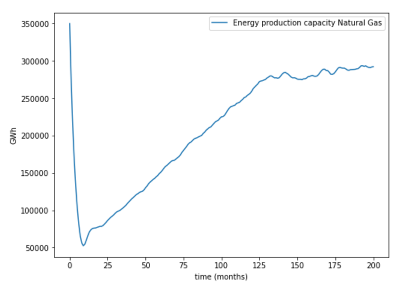

Figure 18: Growth of energy produced by natural gas.

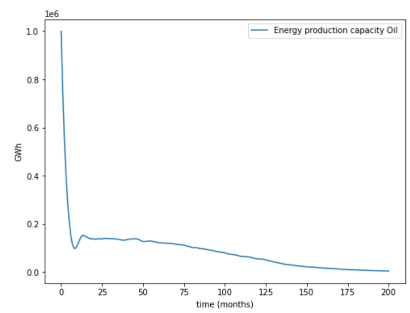

Figure 19: Growth of energy produced by oil.

Figure 20: Energy production capacity plots for the non-renewable sectors. The diagrams correspond to wind, solar and hydro power. The total supply growth is discussed in section 4.3.1 of the main text.

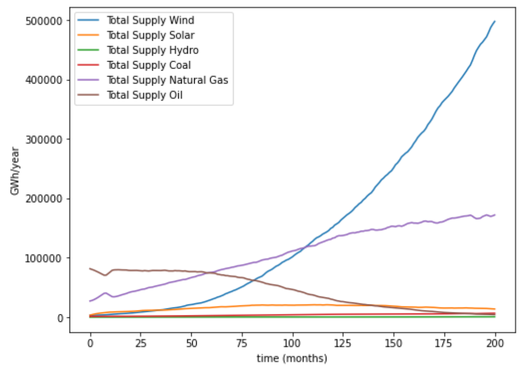

Figure 21: Growth of the total supply of the various energy sectors of the system. The energy sectors that are incorporated into the model are wind, solar, hydro power, energy produced by coal, natural gas and oil. The total supply growth is discussed in section 4.3.1 of the main text.

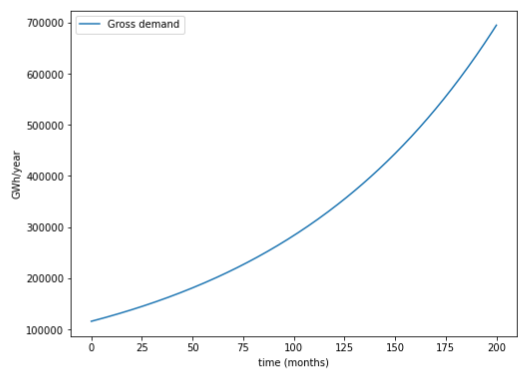

Figure 22: Growth of the gross energy demand. The energy demand growth is discussed in section 4.3.1 of the main text.

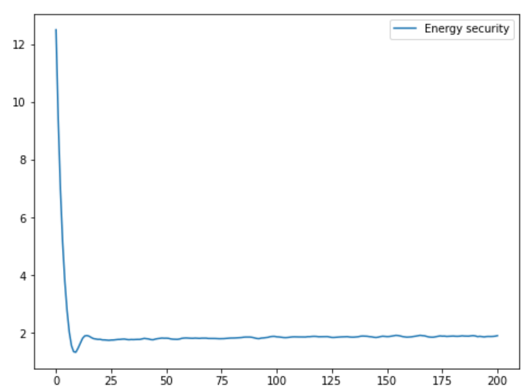

Figure 23: Growth of the system's energy security. The total supply growth is discussed in section 4.3.1 of the main text.

B TABLES

Table 1: Variables in the stock and flow diagram, their measurement units and initial values. The table is discussed in section 4.1.1 of the main text.

Variable name	Measurement Unit	Initial Value
Adjustment factor		1.4 (wind), 1.25 (solar), 1.3 (hydro), 1.35 (coal, gas, oil)
Capacity lifespan	year	25 (wind, solar), 50 (hydro), 22 (coal, gas), 11 (oil)
Capacity under construction (wind)	GWh	800
Capacity under construction (solar)	GWh	2300
Capacity under construction (hydro)	GWh	1
Capacity under construction (coal)	GWh	309
Capacity under construction (natural gas)	GWh	50000
Capacity under construction (oil)	GWh	77000
Capital employed (wind)	$	3.00E+11
Capital employed (solar)	$	2.00E+09
Capital employed (hydro)	$	1.50E+06
Capital employed (coal)	$	2.60E+09
Capital employed (natural gas)	$	4.50E+10
Capital employed (oil)	$	1.00E+08
Construction delay	year	2 (wind, solar, oil), 5 (hydro, coal, gas)
Energy production capacity (wind)	GWh	40000
Energy production capacity (solar)	GWh	40000
Energy production capacity (hydro)	GWh	350
Energy production capacity (coal)	GWh	16000
Energy production capacity (natural gas)	GWh	350000
Energy production capacity (oil)	GWh	1000000
New Investment (wind)	$/year	1.20E+09
New Investment (solar)	$/year	1.90E+09
New Investment (hydro)	$/year	7.40E+08
New Investment (coal)	$/year	5.40E+08
New Investment (natural gas)	$/year	1.40E+09
New Investment (oil)	$/year	1.83E+18
"Min % to invest"	percentage	10
Crude birth rate		0.009
Energy demand per citizen	GWh/year	0.0067
Initial population		1.73E+07
Population		Initial population
Domestic consumption of coal of total production	percentage	0
Domestic consumption of oil of total production	percentage	2
Domestic consumption of gas of total production	percentage	39
Global CO2 emissions	ton/year	36.7 billion
Coal-(CO2-e)	ton/GWh	300
Oil-(CO2-e)	ton/GWh	250
Gas-(CO2-e)	ton/GWh	150

Table 2: Variables of the energy resources extraction view, their measurement units and equations. The table is discussed in section 3.1.2 of the main text.

Variable name	Measurement Unit	Equation
Approved %	percentage	ROIC - "Min % to invest"
Capacity bankruptcy	GWh/year	Energy production capacity* Unprofitable Capacity /100
Capacity retirement	GWh/year	Energy production capacity/Capacity lifespan
Capacity under construction	GWh	New capacity orders rate-"New capacity start-up rate"
Capital expenditure rate	$/year	Capex costs*"New capacity start-up rate"
Depreciation rate	$/year	Investment/Capacity lifespan
Desired new capacity addition	GWh/year	max (0,Energy production capacity * "Approved %"/100)
Energy production capacity	GWh	("New capacity start-up rate")-Capacity Bankruptcy-Capacity Retirement
New Investment	$/year	(Capital expenditure rate-Depreciation rate)*Investment
"Net profit."	$/year	(Total Supply*Wholesale price)-(Depreciation rate*Total supply cost)
New capacity orders rate	GWh/year	max(1, Desired new capacity addition * RANDOM UNIFORM(1,0.8,Seed))
"New capacity start-up rate"	GWh/year	Capacity under construction/Construction delay
ROIC	percentage	Net profit/Investment*100
Total available resources	percentage	1-"New capacity start-up rate"
Total supply	GWh/year	IF THEN ELSE (Energy security > 1, Energy production capacity 2 /Energy security, Energy production capacity 2)
Total supply cost	$/GWh	Investment/Energy production capacity
Wholesale price	$/GWh	Adjustment factor*Total supply cost/Energy security
Unprofitable Capacity	GWh/year	20+PULSE(20, 1)

Table 3: Variables of the population view, their measurement units and equations.The table is discussed in section 3.1.2 of the main text.

Variable name	Measurement Unit	Equation
Energy security	percentage	Energy production capacity/Gross demand
Gross demand	GWh/year	Energy demand per citizen*Population
Population	people	Total births-Total Deaths
Total births		Population*Birth rate
Total Supply	GWh/year	Total Supply Oil+Total Supply Coal+Total Supply Natural Gas+Total Supply Coal+Total Supply Hydro+Total Supply Solar+Total Supply Wind

Table 4: Variables of the CO2 emissions view, their measurement units and equations. The table is discussed in section 3.1.2 of the main text.

Variable name	Measurement Unit	Equation
Renewable electricity		Total RE
Total RE	GWh	Energy production capacity + Energy production capacity 0 + Energy production capacity 1
Total energy production capacity	GWh	"Total non-RE"+Total RE
Total energy consumption	GWh	IF THEN ELSE(Gross demand<Total energy production capacity, Gross demand, Total energy production capacity)
"Total non-RE"	GWh	Energy production capacity 1 0+Energy production capacity 2
"Total CO2-e"	ton/year	"Coal-(CO2-e)"+"Gas-(CO2-e)"+"Oil-(CO2-e)"
Coal-(CO2-e)	ton/year	“Total net consumption” * “Coal-(CO 2 -e)”
Oil-(CO2-e)	ton/year	“Total net consumption” * “Oil-(CO 2 -e)”
Gas-(CO2-e)	ton/year	“Total net consumption” * “Gas-(CO 2 -e)”
Oil dependency	percentage	“Total net oil consumption”/“Total energy consumption” * 100
Total CO2 emissions of total consumption	ton/year	(Energy production capacity 1 0*"Coal-(CO2-e)")+(Energy production capacity 2*"Gas-(CO2-e)")+(Energy production capacity 2 0*"Oil-(CO2-e)")

Table 5: Policy strategies, their description and interventions within the model. The table is discussed in section 4.2 of the main text.

Scenario ID	Policy description	Intervention
P01	Reduction of non-RE (coal, natural gas, oil) sources’ new investment to 0 at time t=46.	Initial new Investment of sector * PULSE(0, 46)
P02	Increase of the construction delay of the non-RE projects.	construction delay of coal, natural gas = 10 years, construction delay of oil = 4 years
P03	Reduction of the minimum percentage to invest of the renewable sources to 0 and increase of the non-RE to 20.	min % to invest RE = 0, min % to invest non-RE = 20