Modelling Energy Transition in the Netherlands

Methodology and Experimental Setup

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1 RESEARCH METHOD

The problem statement, literature review and subsequent research question of the project suggest that the energy sector can be considered to be a complex system. Complex systems are characterized by non-linear dynamic relations and feedback loops. In order to answer the sub questions and ultimately the research question a simulated model was created to illustrate the relations among the components of the system.

The model is a method that is used for the exploration of 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. The outline of the process that is followed in order to model the energy sector of the Netherlands is illustrated in figure 1.

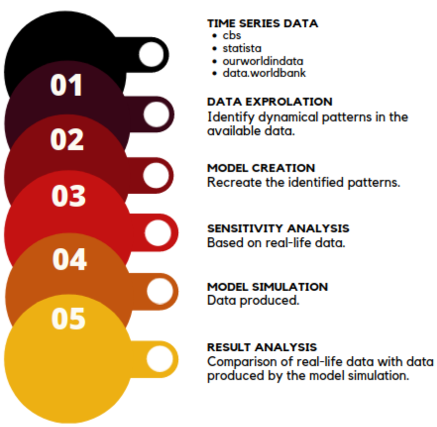

Figure 1: Modelling Process Overview

1.1 Causal Loop Diagram

The first model that was constructed is a causal loop diagram (CLD) that depicts the relations between the different components of the energy sector in the Netherlands. In particular, the CLD diagram is used to establish and depict the existing interactions among the structural elements of the system. The developed model was based on the causal loop diagram proposed by Laimon et al. in [1]. The CLD that was created is illustrated in figure **??** of the Appendix section A.2.

1.1.1 *Diagram Assumptions.*

The appropriate modeling approach to use depends on the assumptions about the stocks and flows in the system that are applicable to a specific purpose.

When writing this part of the report, the assumptions are not yet defined. Therefore, this part is not complete, but will be enriched in the future.

1.2 Stock and Flow Diagrams

The main aim of this thesis is the construction of a generic model that depicts the dynamics within the energy sector. Based on the causal loop diagram, a stock and flow diagram of the energy sector in the Netherlands was constructed. The model simulates the behavior of the system to capture different dynamical patterns. Thus the feedback loops that are present in the CLD (see **??**) were translated into a stock and flow diagram (SFD).

1.2.1 *Formulating a model.*

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 behaviour of the system during each step of the process, could be thoroughly investigated in order to make sure that the foundation of the system was established. Then more components were incorporated by translating the the feedback loops of the CLD into the SFD. In this way, a complex model was created that is able to recreated the expected behavior.

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 2.

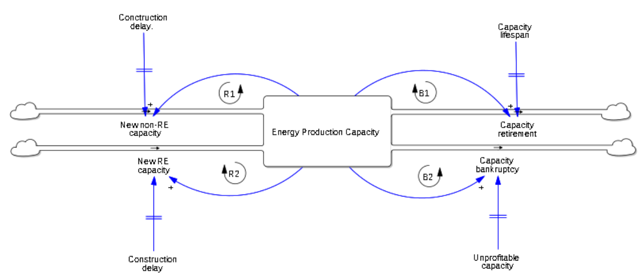

Figure 2: SFD: first iteration

For the next phase of the development process, the addition of the "Capacity under construction" stock. The model that was created during the first step had to be slightly altered in order to incorporate the new component into the system and arrange the feedback loops between the two stocks. The SFD diagram that was produced after the addition of the second stock is presented in figure 3.

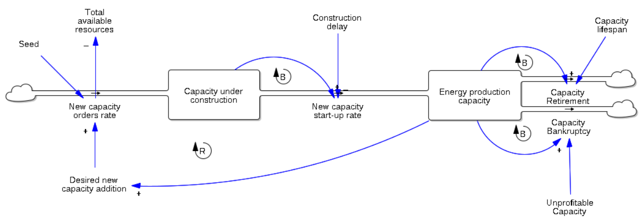

Figure 3: SFD: second iteration

During the next phase of the model development, the stock of the population was added. Firstly, a SFD representing the population of the Netherlands was constructed. In this way, the feedback loops that are related to the population stock can be examined prior to the incorporation of this part in the model. The SFD that was created to illustrate the population of the Netherlands is presented in figure 4.

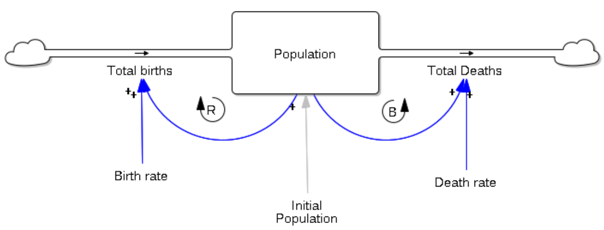

Figure 4: SFD: population of the Netherlands

After the investigation of the population's behavior, it's connection to the system described in figure 3 was established. As suggested in the CLD created ??, the population has a reinforcing relationship with the energy demand. Therefore, in order to establish the connection between the stocks, the required auxiliary variables were defined. In this case, the auxiliary variable "Energy security" bridges the two stocks. Energy security in general , can be seen as ensuring uninterrupted access to energy resources at an affordable price. The SFD that was created after the addition of the population stock and the appropriate alterations is illustrated in figure 5.

1.2.2 Model Coupling. 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 resources extraction for each individual source that contributes to the energy production in the Netherlands was created. The general model is illustrated in figure 6.

The model that was created contains different variables. The list of the SFD's variables is contained in table 1. For each variable the name, type and measurement unit, that are used in the context of the model created, are listed. The parameters that are defined for the stocks and the auxiliary variables of the SFD are gathered in table 3 of the appendix section A.1.

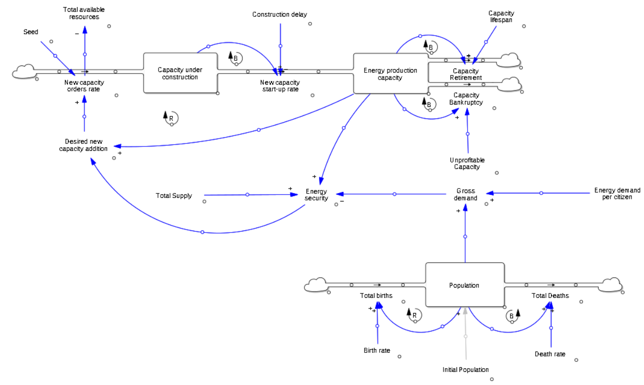

Figure 5: SFD: third iteration

Table 1: Stock & Flow Diagram - Variable List

Variable name	Type	Measurement Unit
Adjustment factor	Constant	
Approved %	Auxiliary	percentage
Birth rate	Constant	per person
Capacity bankruptcy	Auxiliary	GWh/year
Capacity lifespan	Constant	year
Capacity retirement	Auxiliary	GWh/year
Capacity under construction	Level	GWh
Capital expenditure rate	Auxiliary	$/year
Capex costs	Constant	$
Construction delay	Constant	year
Depreciation rate	Auxiliary	$/year
Death rate	Constant	per person
Desired new capacity addition	Auxiliary	GWh/year
Energy demand per citizen	Constant	GWh/year
Energy production capacity	Level	GWh
Energy security	Auxiliary	percentage
Gross demand	Auxiliary	GWh/year
Initial population	Constant	
Investment	Level	$/year
"Min % to invest"	Constant	percentage
"Net profit."	Auxiliary	$/year
New capacity orders rate	Auxiliary	GWh/year
"New capacity start-up rate"	Auxiliary	GWh/year
Population	Level	people
ROIC	Auxiliary	percentage
Total available resources	Auxiliary	
Total births	Auxiliary	
Total deaths	Auxiliary	
Total supply	Auxiliary	GWh/year
Total supply cost	Auxiliary	$/GWh
Wholesale price	Auxiliary	$/GWh
Unprofitable Capacity	Auxiliary	GWh/year

1.2.3 Energy resources extraction model. The SFD created represents each individual energy source. However, in order to be answer to the research question, the examination of all the different energy

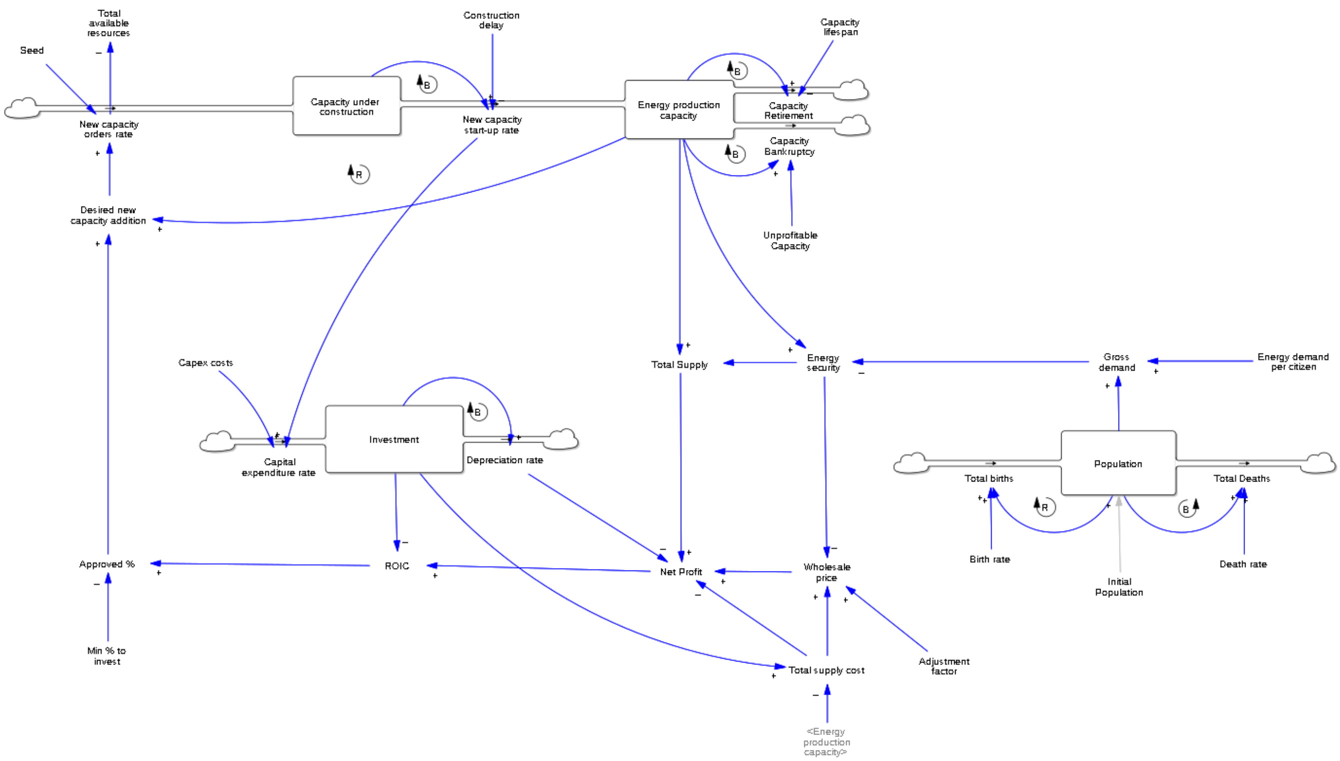

Figure 6: Stock and Flow Diagram: Representation of energy resources extraction

sources should be conducted. This process includes the simulation of the general model presented in figure 6 for the use case of each different source. At the moment, the use case of wind power is examined. During the next steps, a model that includes all the different sources will be constructed. The constituent component for the model will be the existing general model, which will be used for each different energy resource.

2 SIMULATION SETUP

The simulation constitutes an experiment that is performed on a model with the objective to generate insight that enhances the understanding of the behaviour of the system. For the development of the model, specific modelling software was used. The visual models that were created were made in the software package Vensim [1] which is specifically designed for conducting system dynamics analysis. During this process different energy sources were depicted and analysed since Vensim also enables the user to do sensitivity analysis over a large number of variables under different assumptions.

The data used for the sensitivity analysis of the model will be analyzed using the Python programming language [2]. Although, the results of the simulation can be analyzed both in Vensim or Python, the choice of python is made for more intelligent analysis. The PySD [3] module in python is specifically designed to be used on models build with Vensim.

2.1 Condition tuning

The change of the conditions (the experimental frame) enables the analysis of the system for different scenario's. The general model that was constructed can recreate the behavior of different energy resources. Currently, the model was simulated for the use case of wind power. The initial values that were used for the simulation are gathered in table 2.

2.2 Model Validation

The validation of the model created involves structural and behavioural tests. The structural tests evaluate whether the structure of the model represents the real-world system that is described. Then, the behavioral tests determine whether the behaviour of the model recreates accurately the behaviour of the real-life system and whether the output is reasonable according to the assumptions that were defined previously.

With regard to the structural tests, the measurement unit consistency is examined to check that the transition from one component to another is executed correctly. According to the behavioural tests, the comparison between real-life time-series data and the simulated values calculated by the model was realised as the model should recreate the behaviour of the system. However, the validation tests

[1] Vensim
[2] Python
[3] PySD

Table 2: Stock & Flow Diagram - Initial Value List

Variable name	Initial Value
Adjustment factor	1.4
Birth rate	0.097
Capacity lifespan	25
Capacity under construction	5
Capex costs	1600000
Construction delay	10
Death rate	0.088
Energy demand per citizen	0.047972222
Energy production capacity	0.011508
Initial population	1.73E+07
Investment	3.00E+11
"Min % to invest"	10
Population	Initial population

of the model will be further explored throughout the rest of the project.

REFERENCES

[1] Mohamd Laimon, Thanh Mai, Steven Goh, and Talal Yusaf. 2020. Energy Sector Development: System Dynamics Analysis. *Applied Sciences* 10, 1 (2020). https://doi.org/10.3390/app10010134

A APPENDIX

A.1 Stock & Flow Diagram - Parameters List

Table 3: Stock & Flow Diagram - Parameters List

Variable name	Parameter Value
Approved %	ROIC - "Min % to invest"
Capacity bankruptcy	Energy production capacity* Unprofitable Capacity /100
Capacity retirement	Energy production capacity/Capacity lifespan
Capacity under construction	New capacity orders rate-"New capacity start-up rate"
Capital expenditure rate	Capex costs*"New capacity start-up rate"
Depreciation rate	0.02*Investment
Desired new capacity addition	max (0,Energy production capacity * "Approved %"/100)
Energy production capacity	("New capacity start-up rate")-Capacity Bankruptcy-Capacity Retirement
Energy security	Energy production capacity/Gross demand
Gross demand	Energy demand per citizen*Population
Investment	(Capital expenditure rate-Depreciation rate)*Investment
"Net profit."	(Total Supply*Wholesale price)-(Depreciation rate*Total supply cost)
New capacity orders rate	max(1, Desired new capacity addition * RANDOM UNIFORM(1,0.8,Seed))
"New capacity start-up rate"	Capacity under construction/Construction delay
Population	Total births-Total Deaths
ROIC	Net profit/Investment*100
Total available resources	1-"New capacity start-up rate"
Total births	Population*Birth rate
Total deaths	Population*Death rate
Total supply	IF THEN ELSE (Energy security>0,Energy production capacity *(1-Energy security/100),Energy production capacity)
Total supply cost	Investment/Energy production capacity
Wholesale price	Adjustment factor*Total supply cost/Energy security
Unprofitable Capacity	20+PULSE(20, 1)

A.2 Causal Loop Diagram

The CLD that was created is divided into two different figures in order to be readable as it contained many components. The Energy Production Capacity part is included twice in order to provide a clear visualization of the connections within the diagram.

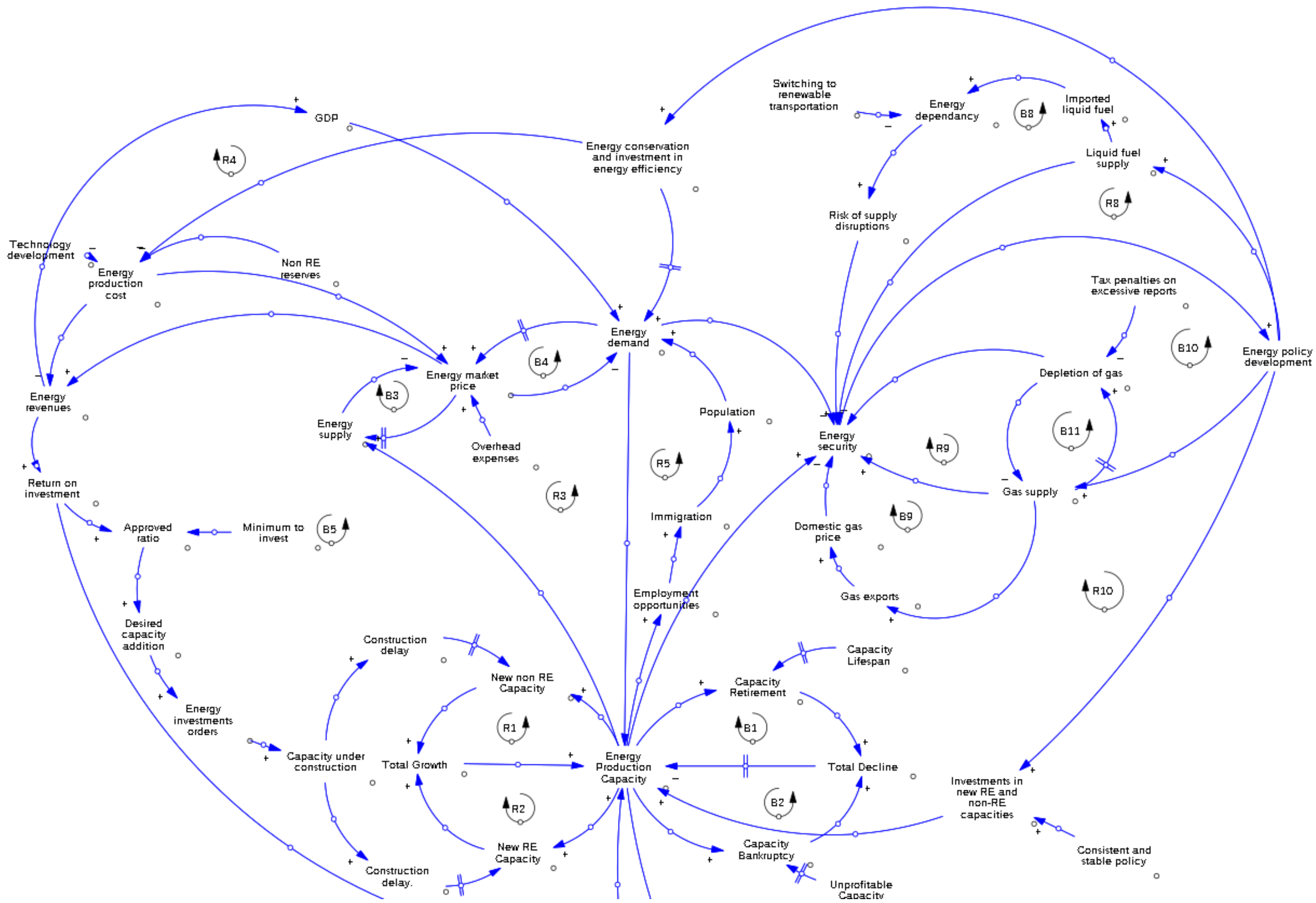

Figure 7: Causal Loop Diagram part 1: Representation of all the constituent components and their relationships, including polarization and the different feedback loops.

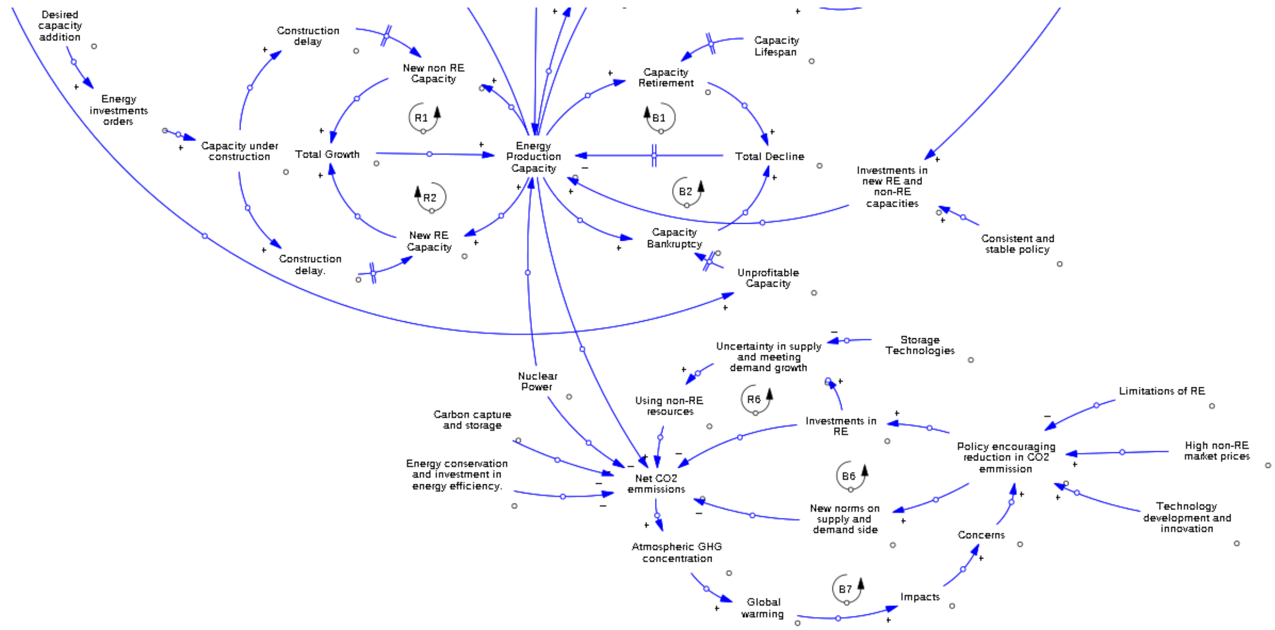

Figure 8: Causal Loop Diagram part 2: Representation of all the constituent components and their relationships, including polarization and the different feedback loops.