Quantifying the correlation between oil price and CO2 emissions towards 2030

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Abstract

To limit global warming, policymakers focus on substantially reducing greenhouse gases – through policymaking – in all sectors of the economy. However, the uncertain development of external influences to these sectors of the economy could lead to undesired effects, when these influences evolve unexpectedly. The qualitative nature of effects and influences of external forces are mostly known by policymakers, though the quantitative nature is more complex and mostly not known. Through the execution of a System Dynamics approach, a quantification process of the correlation between oil prices and CO2 emissions of the Dutch electricity system towards 2030 is explained. Looking at the future effects of external forces on CO2 emissions, could be helpful to policymakers to design more robust policies.

Keywords: Simulation Modeling, External Forces, Uncertainty, Monte Carlo Analysis, Electricity System

1. Introduction

The European Union as well as the Dutch government have implemented several policy measurements to stimulate sustainable development. Yet, these policies have not lead to the desired effect in both the renewable energy production adoption and the carbon emission reduction. The complex environment, that the policymakers of the EU and the Netherlands try to influence, makes it challenging to design policies that result in the desired effects. Besides, factors – like economic growth and Gross Domestic Product (GDP) – influencing the system, could potentially disarm policies when these factors evolve unexpectedly.

The effect of the oil price developing unexpectedly on among others electricity systems, is questioned by Robert Stavins – Director of the Harvard Environmental Economics program – focusing on policies and renewable energy. In his blog Crude Oil Prices, Climate Change, and Global Welfare (Stavins, 2015) he asks himself: “Is the dramatic decline in oil prices a complete gift to the West because of the enormous funds being saved, or is it an unintended Trojan horse because development of renewable energy as well as new fossil-fuel sources will decline in the West, posing longer new challenges?”. This question triggered the focus on quantifying the effects of oil prices on CO_2 emissions.

By quantitatively understanding the effects of a changing oil price on electricity system – instead of only qualitatively understanding the effects – might help policymakers to design more robust policies. The following research question has been set up to quantitatively understand the relation between oil prices and the behavior of electricity systems better. Next to that, an answer to this research question provides the process to quantify the relationships between external forces and a system.

To answer this question there will be focused on simulating the Dutch electricity system towards 2030.

What is the correlation between oil prices and CO_2 emissions in the Dutch electricity system?

Chapter 2 focuses on the methodology to quantify the effects of external forces. In chapter 3 qualitative knowledge on the Dutch electricity system and its external forces is translated to a conceptual model, which describes the subsystems of the Dutch electricity system and the relations between subsystems and external forces. The conceptual model is converted to a simulation model, where after the simulation results of the Dutch electricity system are provided in chapter 4. Chapter 5 provides a specific analysis on quantifying the effect of oil price to renewable energy development and CO_2 emissions. Finally, a conclusion on the effects of the oil price on the Dutch electricity system is drawn in chapter 6, focusing on providing input for policymakers.

2. Research method

Policy Approach Framework

Complex systems are exposed to dynamical changes within the system that could influence other parts of the system unexpectedly. Therefore, actions (i.e. policy implementations) that are taken by policymakers should be monitored constantly in order to measure whether the policies have led to the desired effect. Warren E. Walker has proposed a *Policy Approach Framework* (Figure 2.1) which identifies the most important elements of the policy analysis process (Walker, 2000).

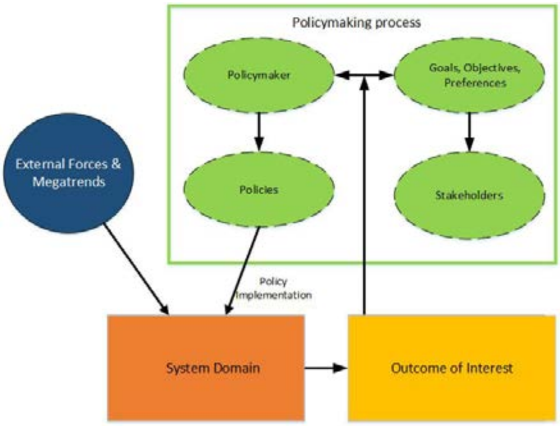

Figure 2.1 Elements of the Policy Approach Framework (adapted from Walker, 2000)

Applying this framework, helps to understand the current situation concerning policies and megatrends influencing the Dutch electricity system. Next to that, it can help to design future policies and it can help to better understand the effects of external forces on the system domain.

The **System Domain** is the core of the Dutch electricity system, containing variables as the installed generation capacity and electricity prices. The **outcome of interest** – for the policymakers – are the CO_2 emissions caused by the Dutch electricity system. The **policymaking process** is the design process of policies and shows the feedback loop in policy design. The external forces and megatrends are external influences – like economic growth – that influence the behavior of the Dutch electricity system, and thus the behavior of the outcome of interest and the policies.

System Dynamics

System Dynamics (SD) – introduced by Jay Forrester in the 1960s – is a well-established simulation modeling methodology for visualizing, understanding and analyzing complex dynamic feedback systems (Forrester, 1969). Elaborating on systems thinking, the methodology is able to analyze the cause-and-effect relationship among elements in subsystems and between subsystems within a dynamical system, based on computer simulation modeling. This is used to quantitatively analyze the structure of an information feedback system and the dynamic relation between function and behavior of a system.

System Dynamics can reflect on the incorporated individual subsystems within a general framework and analyze their interactions. As policy and megatrends responses are taken into account as well, the method could provide an holistic understanding of the entire dynamical complex system.

System Dynamics has been used in many areas, including:

- Urban Industrial Systems (J. W. Forrester, 1969; Jay Wright Forrester, 1971)
- Ecological systems (Kerem & Barlas, 2001)
- Environmental management and policy assessment (Dyson & Chang, 2005)
- Greenhouse Gas (GHG) mitigation (Anand, Dahiya, Talyan, & Vrat, 2005; Kunsch & Springael, 2008)
- Development of the energy industry (Bunn & Larsen, 1992)

Even though, megatrends are part of these executed system analyses, System Dynamics has never been used to specifically analyze megatrends and other external influences. For analyzing the effects of megatrends on the Dutch electricity system, the System Dynamics of Justin Groot is used (Groot, 2015).

System Dynamics explanation

System Dynamics exists of three main concepts; feedback loops and stocks and flows. A feedback loop is a circular causal path of variables, where variables affect previous variables. An example is a population feedback loop, where an increase of births per year leads to an increase of the population, leading to more births per year – Figure 2.2. The causality of this feedback loop is positive as the variables in the feedback loop amplify each variable. If the feedback loop contains a negative causality it represents a negative feedback loop. In a negative feedback loop, an increase of a variable leads to a decrease of another where after it influences the first variable again.

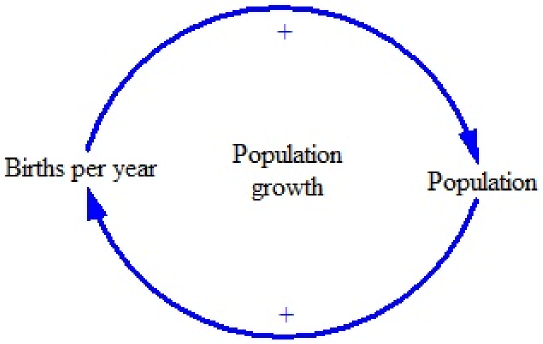

Figure 2.2 Population Feedback Loop

The Policy Approach Framework – in Figure 2.1 – also shows a feedback loop, which will come back in the System Dynamics model.

Figure 2.3 schematically provides an overview of a stock and flow diagram. A starting stock value represents the water level when time is zero. Depending on the inflow and outflow value, the stock will increase or decrease.

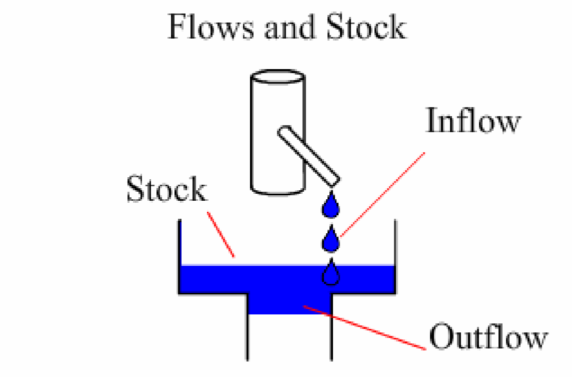

Figure 2.3 Stock and Flow Diagram

The representation of the Dutch electricity system could be modelled by building an extensive network of variables – containing stock variables like installed capacity per generation method and flow variables like the adoption of new production capacity of a certain generation method.

An important note – made by Sterman – is that all models are wrong since it is a simplification of reality (Sterman, 2000). However, it does not mean that models are useless, as it provides an approach to understanding the behavior of the real world. Based on historical data, the usefulness of a model could be determined. A part of the validation process is to compare historical behavior of the system with modeling data. The closer the output of the model to historical data, the better the representation of reality. Another way to test the model is to assess the behavior of the model under extreme conditions. If the model behaves as expected during these circumstances, the confidence level of the model would rise.

External force scenarios towards 2030

For the external forces influencing the Dutch electricity system historical data – for modeling the electricity system between 2005 and 2015

– and scenario data is used – for modeling the electricity system between 2015 and 2030. The defined scenarios for the external forces are based on literature – explained in the report *Exploring the future electricity price in the Netherlands* (Groot, 2015). According to a report of the International Energy Association the oil price will grow to $117 per barrel towards 2030 (Department of Energy & Climate Change, 2013). This scenario for oil price development has been taken into account in the simulation model.

Monte Carlo Analysis

As external forces might develop differently than the chosen scenario, uncertainty factors have been added. Based on the uncertainty factors – and the distribution of these factors – a Monte Carlo Analysis can be executed. A Monte Carlo Analysis is a computational method where simulations are executed a number of times, while random varying certain aspects – e.g. uncertainty factors – in the simulation. In the System Dynamics model, most of the uncertainty factors – like the oil price – follow a random uniform distribution and a variation of 10%. This is assumed in the research of Groot (2015), as supporting literature on uncertainty factors on external forces were not available during its research.

The uncertainty factors are connected with the external factors of the model. By running the model 8000 times and thereby varying the external factors, the uncertain development of the future scenarios have been covered – within the uncertainty range.

3. Conceptualization

The simulation modeling process consists of a qualitative analysis, which results in an identification of the important variables of the Dutch electricity system and the relations between those variables. Also, the simulation modeling process has a quantitative analysis that determines which input data is required, which analysis data is needed and what the mathematical relations between the variables of the system are. Both aspects combined – qualitative and quantitative analysis – lead to a conceptual model design of the Dutch electricity system. Both analyses are provided in chapter 3. The information gathered from this chapter functions as input for the System Dynamics simulation model.

Qualitative representation

This section explains the main components of the core system domain in more detail, focusing on the role of the component within the system domain. The core component is the power exchange as it influences the electricity demand and electricity supply sub systems. The electricity supply arises from the installed capacity of generation capacity. The power exchange determines the electricity prices, which influences the yearly turnover and the available investment budget to adopt new generation capacity.

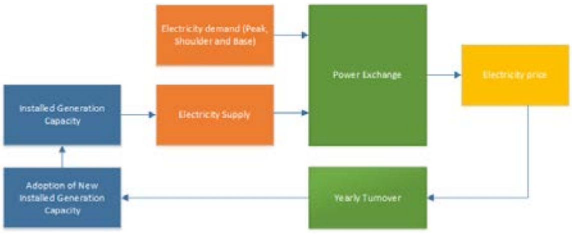

Figure 2.2 Schematic overview of the System Domain in conceptualized model

The **power exchange** determines the hourly electricity price through demand and supply. The **electricity demand** is the desired hourly electricity volume by the Dutch population. The **electricity supply** is the hourly available electricity (produced and imported electricity minus the exported electricity). The **Installed Capacity** is the electricity generation capacity in the Netherlands. The **Yearly Turnover** is the sold electricity volume times the electricity price. The **Adoption of installed capacity** are the made investments in new generation capacity.

In the report *Exploring the future electricity price in the Netherlands* a more detailed qualitative analysis is executed, focusing on the relations between the system components, polices and external forces. It is of great importance to understand which components positively correlate to each other and which negatively.

Based on the conceptualized model of the system domain, it is determined which external forces, megatrends and policies influence each subsystem of the Dutch electricity system. The **availability of wind** and the **cost of electricity production per generation method** are important external forces. The oil price influences the electricity demand. Policies that influence the Dutch electricity system are the **EU Emission Trading Scheme (ETS)** (European Commission, 2014c) and the **SDE+ Subsidy fund** (Rijksdienst voor Ondernemend Nederland, 2014) of the Dutch government. However, this research is focused on the megatrends. The most important megatrends that influence the Dutch electricity system are **Gross Domestic Product (GDP)**, **Population Growth**, **Decentralized electricity production** and **Electric Vehicle (EV) adoption** (Groot, 2015).

Quantitative representation

The data and mathematical relations of the external forces and policies influencing each of these components are determined in this stage of analysis. The focus of this research is how the oil price influences the CO_2 emissions of the Dutch electricity system. To determine the correlation between the oil price and CO_2 emissions of the Dutch electricity system, the System Dynamics simulation model of Groot (2015) is used.

In this simulation model the yearly CO_2 emissions of the Dutch electricity system are calculated through the amount of MWh each generation method has produced over a year. The model determines the required amount of electricity production per generation method based on the electricity demand, which is affected by – among others – the oil price. Demand decreases when oil-, gas-, coal- and nuclear-prices increases, as the marginal cost of each generation method goes up and thus the electricity price goes up. Next to that, the amount of money that households and company could spend decreases when energy prices go up. Naill (1977) has determined the causality between energy prices and electricity demand as -1.1%. This means that the electricity demand will decrease by 1.1% when energy prices increase with 1% (Naill, 1977).

To model the future electricity system towards 2030, scenarios have been set up that describe the expected behaviour of an external force. Figure 3.2 shows the assumed development of the oil price from 2005 to 2030, which is used in the System Dynamics simulation model of the Dutch electricity system (Groot, 2015). The oil price between 2005 and 2014 is based on historical data and the price between 2015 and 2030 is assumed based on literature of the International Energy Association (Department of Energy & Climate Change, 2013).

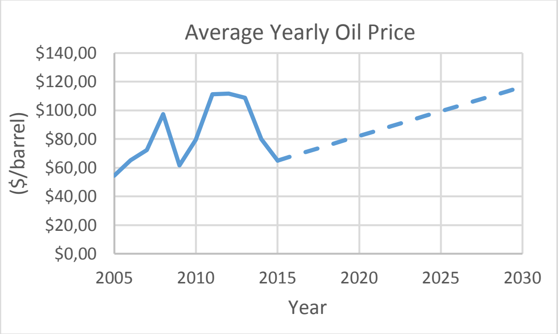

Figure 3.2 Average Yearly Oil Price towards 2030 (Department of Energy & Climate Change, 2013)

In the simulation model, an uncertainty factor of 10% has been connected to the oil price as the development of the price is unpredictable. This factor is random uniformly distributed in the Monte Carlo Analysis.

4. Simulation Results

Policymakers of the Dutch government focus among others on designing policies to reduce CO_2 emissions from the Dutch electricity system. External forces influence the effectiveness of policies.

The designed System Dynamics model by Groot, models the Dutch electricity system between 2005 and 2030. As two different data sets are used – historical data and scenario data – the correlation determine is split into two phases. The correlation between oil price and CO_2 emissions based on historical data is determined as well as the expected correlation between oil price and CO_2 emissions towards 2030 – according to the model.

Modeling results of 2005 – 2015

Historical behavior of the Dutch electricity system is modeled to validate the behavior of the model. Groot has executed a validation by calculating two metrics, the R^2-metric and the MAEP-metric (2015). The R^2-metric provides information on how well the model data fits the shape of the real world data and the MAEP metric calculates the percentage error between the model data and the real world data. Based on these values, Groot states that the designed model is useful to model the Dutch electricity system (the R^2-metric value of the CO_2 emissions is 0.53 and the MAEP value is 7.3%). However, there is room for improvement.

The simulation results between 2005 and 2015 – specifically looking at the oil price and CO_2 emissions – are shown in 4.1.

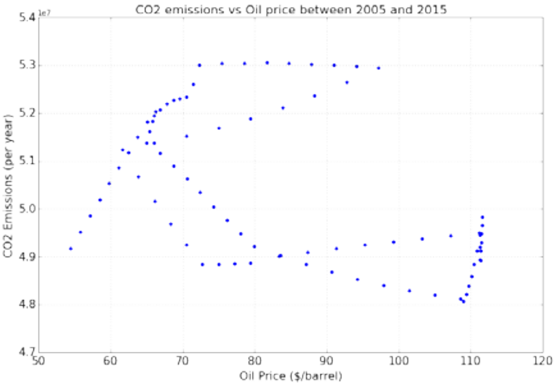

Figure 4.2 CO_2 emissions vs Oil price between 2005 and 2015

Figure 4.1 shows that there is no clear correlation, which is due to the time effect in the results. However when looking at the results in a specific year, a clear correlation is shown (see Figure 4.2 and 4.3).

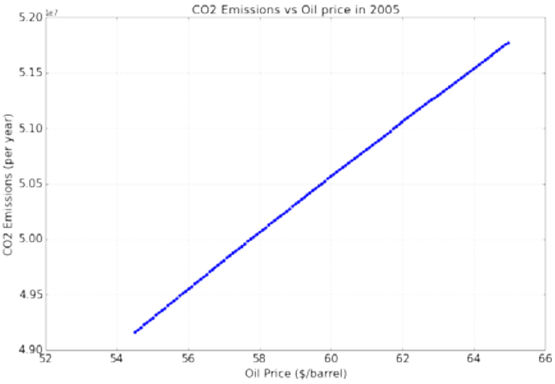

Figure 4.3 CO_2 emissions vs Oil price in 2005

Interestingly, Figure 4.2 shows a correlation in a way that when oil prices go up the CO_2 emissions increase, which is the opposite in Figure 4.3. The results in Figure 4.3 are more likely as literature describes that when energy prices go up, the demand goes down (Naill, 1977) and thus also the electricity production through CO_2 intensive methods. A possible explanation for the result in Figure 4.2, is that other external forces nullified the effect of the oil price in 2005. More research has to be done – focusing on the effects of other external forces on the CO_2 emissions – to verify this statement.

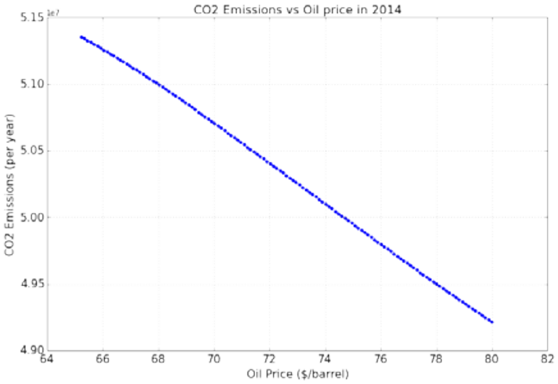

Figure 4.1 CO2 emissions vs Oil price in 2014

Since Figure 4.2 and 4.3 are based on historical data, the certainty factor of the correlation results is relatively high. The only error in the results could have occurred since the model is fully correct with the real world situation. However, since the validation showed the usefulness of the model the correlation results provide a fruitful approximation.

Simulation Results of 2015 – 2030

The results in Figure 4.2 and 4.3 provide interesting results to assess designed policies in the Dutch electricity system. However, for designing new and robust policies, insights in the future behavior of correlations can be helpful. Therefore the same analysis as in the previous section is done, only in this section Monte Carlo simulations have been executed as uncertainty on scenario development have to be taken into account.

Besides, the cumulative CO_2 emissions over the period 2016 to 2030 have been calculated and used in the correlation analysis. This to eliminate the time factor and to provide an overview of the effect of the oil price on the relative CO_2 emissions (instead of insights in the effect of the oil price on the absolute CO_2 emissions).

Figure 4.4 shows the expected correlation between oil price and the cumulative CO_2 emissions towards 2030. From the figure could be concluded that the higher the oil price, the lower the CO_2 emissions become.

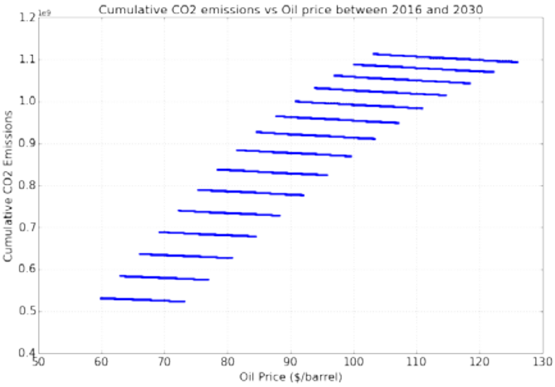

Figure 4.4 Cumulative CO_2 emissions vs Oil price between 2016 and 2030

The blue line in the left corner is the correlation line of 2016 and the blue line in the top right line is the correlation line in 2030.

Figure 4.5 shows the expected correlation between the oil price and the cumulative CO_2 emissions in 2016 – based on the scenario and modeling assumption of the SD-model designed by Groot (2015).

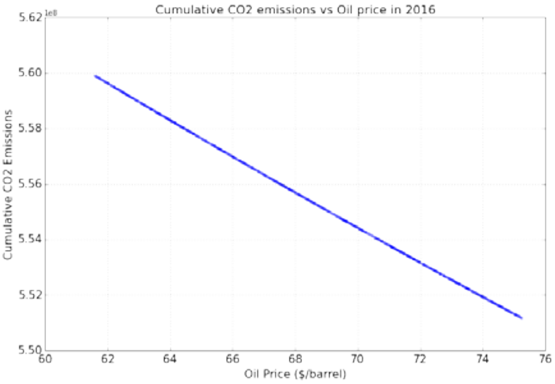

Figure 4.5 Cumulative CO_2 emissions vs Oil price in 2016

Calculations show that when the oil price increases with 1% in 2016, that the yearly CO_2 emissions will decrease with 0.068%.

Figure 4.6 provides the expected correlation between the oil price and the cumulative CO_2 emissions in 2030 – based on the same scenario and modeling assumptions as in Figure 4.5.

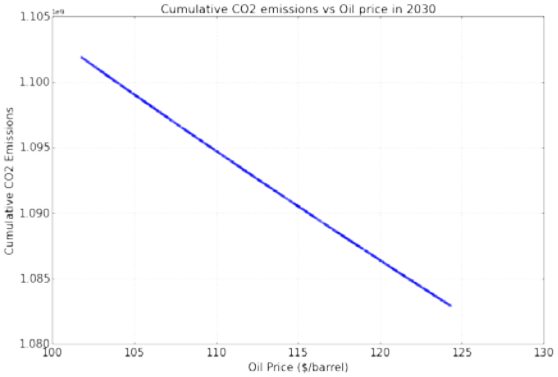

Figure 4.6 Cumulative CO_2 emissions vs Oil price in 2030

Calculations show that when the oil price increases with 1% in 2030, the yearly CO_2 emissions will decrease with 0.075%.

The difference in correlation between 2016 and 2030 can be clarified by the differences in the values of external force scenarios. In 2030, the CO_2-price is expected to be higher than in 2016. Next to that, it is expected that subsidies for renewable energy capacity development will become higher towards 2030. To verify these explanations, more research should be done on the effects that different external forces have on the CO_2 emissions and which external forces strengthen or weaken each other.

5. Conclusion and Discussion

To quantify the correlation between oil prices and CO_2 emissions of the Dutch electricity system, a System Dynamics model on this electricity system designed by Groot (2015) is used. To illustrate the process of quantifying the specific correlation,

To build a simulation model of the Dutch electricity system, a Policy Approach Framework was used. This framework contains a system domain (core of the simulation system), External Forces and Megatrends,

Policies and as main outcome of interest the electricity prices towards 2030.
Based on the design of the Dutch electricity system, six system components were identified. Two policies – the Emission Trading Scheme and the SDE+ Subsidy – were identified as important external influences of the simulation model.
Studies have shown that an important external factor influencing the demand is the price of energy. When the price of energy goes up, the energy demand will go down.

Monte Carlo simulation results of the System Dynamics model on the Dutch electricity system show that the effect of the oil price on the CO_2 emissions increases. A one percent increase of the oil price leads to a decline of the yearly CO_2 emissions of 0.068%, whereas in 2030 the decrease will be approximately 0.075%. The difference could be clarified by the different assumed values of the scenarios of external forces. The CO_2 price and subsidies for renewable energy capacity development is higher in 2030 than in 2016. However, further research should be done to clarify this explanation.

Discussion
As Jon Sterman has stated that all models are wrong since it is a simplification of reality (Sterman, 2000), there are limitations to this research. Some process in the System Dynamics model of Groot could be improved – as some processes. Another important limitations of the research is the lack of literature supporting some scenarios of the model and therefore being compulsory to assume uncertainty factors of 10%. An example is the scenario of the expected development of the CO_2 price towards 2030, as only one research was found which could therefore not be verified. Therefore, assumptions for expected development of scenarios needed to be made, which should be checked in future research.
Besides, further research should be executed to better understand the effects of other external forces on the CO_2 emissions and to determine which external forces strengthen and weaken each other.

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