Energy System Simulator Development: Architecture and Interfaces

Masterarbeit

zur Erlangung des akademischen Grades „Master of Science (M.Sc)“ im Studiengang Wirtschaftswissenschaft der Wirtschaftswissenschaftlichen Fakultät der Leibniz Universität Hannover

vorgelegt von

Name: Hamann Vorname: Julian

[redacted] [redacted] [redacted] [redacted]

Prüfer: Prof. Dr. Michael H. Breitner

Ort, Datum: Hannover, den 30.09.2016

Contents

1 Introduction

1.1 Historical Background, Motivation and Research Question

Over the course of the past two centuries human society has experienced fundamental changes. Since the second half of the 18th century, the industrial revolution led to historically unmatched economic growth and altered the standard of living for people all over the planet. This economic growth was primarily possible, because of the abundant availability of fossil fuels, which were used as the main resources for supplying the necessary energy to produce goods and increase Gross World Product (GWP). Not only the production of goods, but also the subsequently rising standard of living influenced societal resource consumption. The newly experienced general abundance led to an enormous growth of the human population. In the period between 1821 and 2000 the worlds per capita income increased eightfold, human population fivefold and the average live-expectancy doubled (Maddison 2001, p. 18ff). As seen in figure 1 the combined effects of a higher standard of living and a growing population caused a 26-fold increase in natural resource consumption during the same period (Smil 2010).

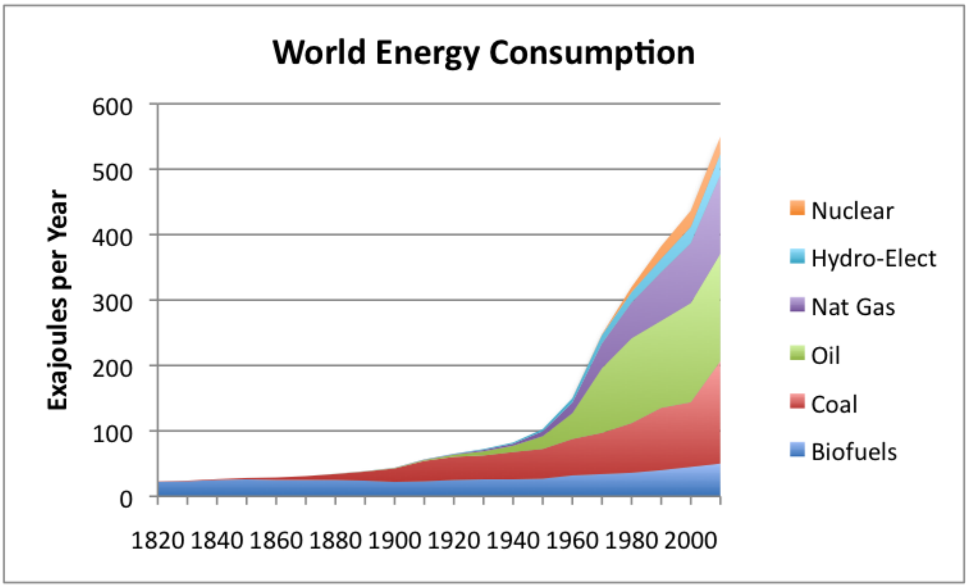

Figure 1: World Energy Consumption

Worldwide resource consumption is distributed very unevenly between different countries, with developed countries having a much larger resource consumption per capita than emerging and developing countries (Smil 2010). This uneven distribution is also reflected by the standard of living in a given country, measured by Gross Domestic Product (GDP), as there is a strong positive correlation between resource consumption per capita and GDP per capita (Smil 2010). The correlation between resource consumption and standard of living leads to serious problems if the gap between standards of living in different countries starts to close, as resource consumption in developing and emerging countries would rise

sharply.
To put these findings into perspective, it is necessary to acknowledge the dependency of most achievements defining modern society on the availability of a reliable source of energy, e.g. electricity. As seen in figure 1, almost the worlds entire energy consumption is supplied by converting fossil fuels into usable energy, with the most commonly used fuels being coal, oil and natural gas.
The dependency on fossil fuels as the primary supply for usable energy has led to a variety of political, economical and environmental problems. Due to the uneven distribution of natural resources on Earth, many developed countries are forced to import almost their entire consumption of natural resources. These import-dependencies have been the cause of multiple international political crises, when resource exporting countries used the dependency of resource importing countries as leverage in conflict situations.
The process of converting fossil fuels into usable energy releases Carbon Dioxide (CO2), a greenhouse gas, which is one of the main drivers of human-induced global warming and climate change (Cox et al. 2000). To address the global economical and political problems resulting from climate change, the United Nations Framework Convention on Climate Change (UNFCCC) was negotiated in 1992, came into effect in 1994 and was amended several times since then. The UNFCCC is an international treaty, in which targets for the reduction of greenhouse gas emissions were negotiated. Even though United Nations (UN) member states ratified these targets, they are not legally binding. Instead they serve as a guideline for realistic and necessary greenhouse gas reduction targets, which are implemented by the member states through national law. In contrast to this practice, the European Union (EU) has set legally binding greenhouse gas emission targets for its member states, which can only be amended by individual state legislation (The European Commission 2011). The EU targets define a percentage reduction of greenhouse gas emissions in reference to the emissions in 1990. These emission targets state, that individual member states have to reduce their greenhouse gas emissions by 20% until 2020 and by 60%-80% until 2050, where countries with high emissions in 1990 have to reduce their consumption by the larger proportion.
To adapt the specified by EU legislation, the Federal Government of Germany has passed several laws and guidelines, formulating short, medium and long term intermediate goals (BMWi 2012). The first goal was met in 2010, when greenhouse gas emissions should be reduced by 20% in reference to 1990. The future goals are a 40% reduction by 2020, a 55% reduction by 2030, a 70% reduction by 2040 and a 80% reduction by 2050. Additionally to these minimum goals, there is a guideline, that by 2050 greenhouse gas emissions should be reduced by 95% in reference to 1990.
In order to be able to meet the political greenhouse gas reduction goals, two different strategies are deployed (BMWi 2012) p. 6ff. The first strategy aims to increase the share of renewable energies in primary energy and electricity consumption. By 2050 renewable

energies are supposed to supply 60% of primary energy and 80% of electricity. The second strategy aims to reduce primary energy consumption by increasing resource conversion and energy-efficiency. Through increases in energy-efficiency, primary energy consumption is supposed to be reduced by 50% and electricity consumption by 25% in 2050 with 2008 as reference year (BMWi 2012 p. 6f).

Similar to most developed countries, Germany's current energy infrastructure is strongly on dependent fossil fuels and the import of natural resources. In 2015 renewable energies accounted for 12.5% of primary energy consumption and 69.7% of consumed resources had to be imported (AG Energiebilanzen e.V. 2015). The divergence between the current energy infrastructure and the 2050 strategy shows, that the energy system will have to undergo massive transformations in the near future, with a strong increase in the share of renewable energies.

Due to the inherent complexities of regional, national and international energy systems, many different transformation paths are possible and it is an important task to define and implement effective political measures to facilitate an efficient transformation process.

In order to assess the usefulness of a political measure it would be very valuable to know an efficient composition for a target energy system in 2050. To obtain knowledge of efficient energy system compositions, simulations can be a very useful tool to create and analyze different scenarios for the transformation process and the target system. These findings from different scenarios can then be compared to define a meaningful, efficient target system and transformation process and to further analyze strengths, weaknesses and risks of different transformation approaches.

This thesis describes the development of the LiFE 2050 Energy System Simulator (LESSI), an energy system simulation tool. The tool is implemented using an individually tailored combination of the web development framework Ruby on Rails (Rails) and the numerical calculation software MATrix LABoratory (MATLAB). These software tools were primarily chosen, because of the interdisciplinary team working on the LiFE 2050 research group. MATLAB is a very popular programming language and mathematical modeling tool in engineering sciences, which is why it was chosen as the back-end for the algorithmic implementation of the simulator.

However MATLAB is constrained by inefficient data management possibilities, especially if multiple complex datasets and scenarios are changed frequently and have to be distributed among multiple end-users. Therefore Rails is used as the front-end to efficiently manage data and scenarios and to provide a layer of abstraction from the actual code implementation in MATLAB, so that end-users can focus on testing scenarios. The use of a web server additionally allows using a computationally more powerful computer than a desktop computer to run the MATLAB simulation.

The purpose of the energy system simulator lies in the analysis of important topics regarding policy targets to shape future energy systems and the current system's transformation

towards these systems. These topics include environmental, social, political and economical questions. The central research question of this thesis is: How can the current energy system in the region of Hanover be transformed to reach the political goals for 2050 and which changes are necessary to facilitate this transformation?
The energy system simulator is constructed as a Design-Science-Research artifact and is supposed to provide and analyze possible answers to this question.

1.2 Structure the Thesis

The first chapter of this thesis introduces the problems resulting from a worldwide increase in natural resource consumption. The root of these problems is the simultaneously increasing human population and the rising standard of living. Due to the limited supply of natural resources and their unavoidable depletion, a transition of the world's energy system towards renewable energies is mandatory to maintain the current standard of living.
In the second chapter the research background and methods are described. In the first part of the chapter, relevant literature for the research area of energy system simulation is collected, analyzed and reviewed. The energy system literature is necessary to develop an accurate and reliable abstraction for an energy system of a given scale. Due to the importance of energy-related issues, these research areas are densely populated and a large amount of high quality research has already been done. This research serves as the basis for the development of the energy system simulation model. In the second part of the chapter, the research design is discussed. Appropriate research methods are selected and evaluated and the link to this thesis is established.
The third chapter introduces the simulation model underlying the software implementation of LESSI. First, the mathematical model of the energy system's energy flows is designed and explained. Second, an overview of the system architecture of LESSI is given and the architecture and its design are explained. Third, the code architecture and algorithmic implementation of the energy system model in MATLAB are described and explained.
The fourth chapter elaborates on the results of the third chapter. It describes the energy system simulator development as a combination of a MATLAB back-end and a Rails front-end. The front-end architecture and implementation is explained and important parts, like the database model and structure, are examined in detail. The fourth chapter also includes a full use case of the entire application.
The fifth chapter is a case study, where the current state of the energy system in the region of Hanover is simulated and possible transformations and future scenarios are simulated and analyzed. The scenarios focus on the electricity market, the policy goals regarding this market and the influence of electricity storage systems on energy systems with a high

7 Conclusion

In this thesis the development of an energy system simulator was described. First, important literature and previous research regarding energy system simulation was examined and evaluated. Based on this knowledge, the mathematical model for the simulator was developed as a team effort of nine people. This mathematical was then implemented using the MATLAB programming language and a user-friendly front-end was designed and implemented using the web-development framework Ruby on Rails. This simulator was then demonstrated and used to simulate multiple transformation paths and energy system states. The simulator was constructed as a Design Science Research artifact, which is used to address important social, ecological, economical and political questions.
To be able to address these questions, the applicability of the results of the simulations needs to be assessed. To apply simulation results to the real world, a simulation has to approximate the important aspects of the modeled real world problem as closely as possible. Due to the inherent complexity of energy systems, abstractions and assumptions are necessary to enable simulation. After the simulator prototype was successfully constructed, strong assumptions and abstractions need to be lifted in order to make the simulation results applicable to the real world energy system.
The simulators weaknesses can be divided into technical and conceptual problems. The conceptual problems regard missing aspects of the real world energy system, which should be included to provide a better model of the energy system. These problems are the missing traffic sector, which is already finished, but not implemented yet, the missing cost and investment calculations and the missing power grids and heating networks. Another important conceptual problem is the deterministic calculation of all time series. The only non-deterministic factors results from the randomness in the construction of the yearly weather time series. Further, the assumption, that the entire future electricity demand and supply is perfectly known to the storage optimization algorithm is highly unrealistic. Here a new algorithm should be implemented, which incorporates stochastic influences and uncertainty into the decision process. The hourly time resolution for the simulation is exclusively a result of the frequency of the supplied weather data. If weather data can be gathered in higher resolutions, the simulator's time resolution can immediately be updated to the higher resolution.
The technical problems regard internal calculations and procedures. The main technical problem lies in the optimization procedure, which is used to control electricity production. This procedure is not conform with the real electricity market procedure and has to be changed to conform to a real world market situation. This is a direct result of the missing cost calculations, because costs are the primary determining factor in electricity production decisions. Further, the optimization procedure suffers from the same problems of deterministic calculation and assumed perfect information as the optimization procedure

for storages.
Future work should be directed to address these problems and extend the energy system simulator.