Energy Hubs for Decentral Energy Supply –

Development of a Decision Support System

Masterarbeit

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1. Introduction

1.1. Motivation and Relevance

In times of increasing awareness of climate change and the need to bring about a change in behavior worldwide, the energy sector plays a key role. With a share of 85% of total greenhouse gas (GHG) emissions in 2015, energy-related emissions account for the largest share (Umweltbundesamt, 2017). This fact also finds its way into national, European and global politics, so that with the Paris Agreement in 2015, a globally unified and long-term climate agreement was concluded. The target of this agreement of keeping the rise in the global average temperature below 2°C above the pre-industrial level was adopted to define both medium-term and long-term German climate targets. The latter include not only an increase in regenerative electricity generation up to 30% in 2020 and 100% in 2050 but also the use of regenerative energies in the heat and mobility sector in order to reduce the total GHG emissions by 80 to 95% compared to the value of 1990. Since the major part of regenerative energy is converted into electricity, the increased use of these sources inevitably leads to an improvement in the GHG balance in the electricity sector. However, it is not clear from this context, what effect this has on emissions in the heating sector. Consequently, an increase in the use of power-to-heat technologies and, thus, the advancement of sector coupling represents a further political key objective. This change in energy supply involves many challenges and questions:

- Is the potential of regenerative sources sufficient to cover the entire energy demand?
- How can such plants be integrated into the existing grid?
- What does the total supply from regenerative sources look like and how can it be realized?

It becomes apparent that plants for the use of regenerative energies, such as wind energy and solar energy, have smaller plant sizes compared to fossil power plants and are also dependent on local weather conditions. The resulting distribution over a high number of locally dispersed plants shows that an increasing decentralization in supply is characteristic. Besides the challenges resulting from this structural change, e.g. the extension of the distribution grid, decentralized supply holds several chances, especially for the development of rural areas. Here it is necessary to investigate how increasing decentralization affects social, economic, technical and environmental aspects, so that potential concepts for restructuring can be developed. The energy hub concept, which was developed at ETH Zurich as part of the project "Vision of Future Energy Networks", is such a concept. The goal of an energy hub is to optimize the energy supply for a given situation. Due to its abstract characteristics, the energy hub concept can be applied to many situations and cases, ranging from island energy systems over large buildings to rural and urban districts (Bayod-Rújula, et al., 2018, p. 2 and Geidl, et al., 2007a, p. 3). This shows that in order to apply the energy hub concept to a particular use case, and, thus, to realize a decentral energy supply (DES), a more detailed approach for the actual implementation is needed. Taking into account economic, social and political aspects, a combined target function of cost and emission minimization is an effective instrument for achieving climate goals. This raises the question of how the energy hub concept can be specified to be applied in practice. For this purpose, this thesis centers around the development of a decision support system (DSS).

1.2. Objective of the Thesis

With the development of the DSS, which is based on the energy hub concept, the overall objective of this thesis, namely the optimization of DES, is stated. Due to the complexity of this key objective, it makes sense to define sub-objectives. One of these sub-objectives focuses on the question, whether the potential of regenerative sources is sufficient to achieve the ambitious climate goals. The emerging decentralization in energy generation shows that the turnaround in energy generation is not limited to the sources used, but also includes structural changes in view of the production characteristics. This raises the question of which infrastructural requirements must be met and what effects this change will have. Taking up this complex of themes, the underlying research question of this thesis can be formulated:

In times of a changing energy sector, how can decentral energy supply on a regional level be realized and optimized?

When developing a DSS which targets to provide an answer to this question, the energy hub concept serves as a theoretical framework and also represents the current state of the art. This thesis, therefore, aims at transforming the theoretical concept into a practically applicable system and at proving its applicability.

1.3. Structure of the Thesis

The aim of this thesis is to develop a DSS which helps the user to find an optimal DES according to their regional conditions. In order to obtain this goal, a number of previous steps and aspects need to be considered, which are described in the following foundational chapters. The structure of the thesis is shown in Figure 1.

The second chapter focuses on the current situation of energy supply in Germany. Within this chapter, German climate protection policies are introduced, which contain various measures to drive forward change in the energy sector. The subsequent review of different energy sources provides an overview of fossil and regenerative sources. The focus here is not only on the kind of use, but also on the significance of these sources in energy supply. The examination of current energy supply is completed by an observation of the situation in Germany including specified energy consumption and the potential of regenerative sources.

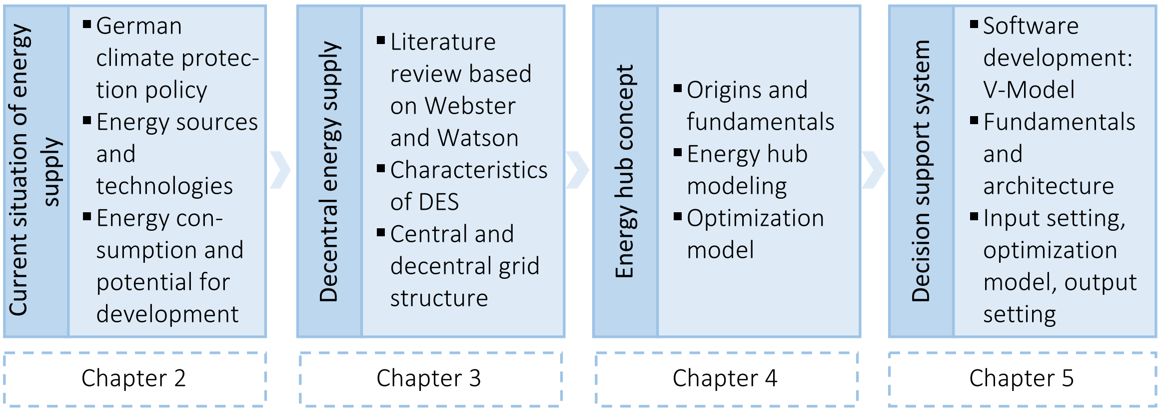

Figure 1: Structure of the thesis
Source: Own illustration

Furthermore, based on the change in the supply structure resulting from an increased use of regenerative sources, DES is introduced in chapter three. After presenting the applied methodology for the literature review according to Webster and Watson, DES is further examined in order to evaluate its characteristics. Besides the consideration of social, political, economic, technical and ecological aspects, the major change when implementing a DES, namely the network structure, is investigated. The energy hub concept is presented in chapter four. This specific concept focuses on the optimization of DES, where a high flexibility is given due to its universally valid optimization model. Taking into account political and economic aspects, the energy hub optimization described in section 4.3. can realize not only cost minimization, which represents a purely economic objective, but also GHG emission minimization. Before explaining the development of the adaptable DSS, the underlying methodology for such a development is focused upon in the beginning of chapter five. Within the scope of the DSS, its infrastructure, mathematical fundament and adjustment possibilities to different use cases are explained. In the following chapter, the developed DSS is applied to the example of a region in the northern part of Germany including three different use cases. Subsequently, the corresponding results of the computational study including limitations of both the DSS and the entire thesis are discussed. This is followed by a conclusion, which also offers an outlook for future research.

9. Conclusion and Outlook

The energy sector in transition: Starting from an energy supply largely based on fossil fuels such as coal and oil, the advancing climate change and the finiteness of fossil fuels are calling for a rethink. To reach the German target of reducing GHG emissions by 80 to 95% compared to 1990 until 2050, several political measures and sub goals are defined. A universally valid goal is the increased use of regenerative sources not only for electricity generation but also for covering heat consumption and consumption in the transport sector. In this context, sector coupling through the use of power-to-X technologies, like heat pumps, as well as an increased use of CHP generation are methods to enhance the share of regenerative energies in all sectors.

The change in the energy supply requires a reorientation in the generation of useful energy. While centralized generation with a small number of large power plants is currently predominant, regenerative plants are characterized by smaller plant sizes and decentralization. Besides the challenges resulting from a transformation to a more decentralized energy system, it also holds chances for social, economic and ecologic development. Due to the generally higher number of supply plants being located mostly in rural areas, the employment increases particularly in such regions. In addition to the individual economic benefit due to additional employments, the regional energy supply increases the added value within the region. Clearly, the reason for a change towards a more DES, namely the increased use of regenerative plants, represents the major ecological benefit as well. These aspects show that the change to DES has brought regionalism to the fore.

This fact is also taken up by the energy hub concept which pursues the optimization of the energy supply with regard to various criteria, e.g. minimization of costs or GHG emissions, at regional level. By using a greenfield approach currently existing structures are neglected to determine not only an optimum based on the present situation, which is characterized by a highly central supply, but to enable a restructuring towards decentralization. Furthermore, the energy hub concept is characterized by the simultaneous consideration of different energy carriers, converters and storage systems and through this sector coupling is, therefore, in line with political key objectives.

Based on this theoretical framework a DSS was developed to realize a DES. In this DSS, the generally valid optimization model of the energy hub concept was further specified with the target to minimize the total costs and GHG emissions. Taking into account the requirements of a user-friendly interface, high efficiency and high automation, the architecture of the DSS is divided into three parts: the input template, the programming and the result.

Within the context of a computational study, the DSS is applied to different use cases for the municipality List, which is characterized by high wind speeds due to its location at the sea.

Various findings can be derived from the results of this study, both with regard to the DSS and the selected use cases. In summary, they indicate that the DSS determines an optimal solution that is plausible and practically feasible with regard to the use of DES, on the one hand. On the other hand, the DSS is also able to identify a sole centralized supply as optimal solution, if the given parameters and circumstances indicate so. From this, a superiority of the system compared to the current, central supply can be derived.

Furthermore, the results of the study include extensive use of regenerative energies as well as power-to-X technologies and CHP converters. As this is also in line with political key objectives for future energy supply, the applicability of the DSS for future goals becomes apparent.

Due to the fact that the DSS considers only a limited period of time, certain untypical weather conditions and settings may influence the result more than they would if a longer time period was considered. For example, a severe weather may occur within the course of a year without much influence on the final result, whereas the same severe weather has a huge impact on the result if only one single week is considered. Consequently, in order to obtain a long-term optimum, a representative time period must be chosen.

In terms of a change in energy supply from centralized to increasingly decentralized supply, various concepts for the realization must be developed. In order to place the energy hub concept in this context, further investigations should evaluate the performance of the energy hub in a comparative study. An elaboration of existing concepts, possible evaluation methodologies and performance assessment criteria complement the underlying study and are needed for further examination and processing of the results.

Additional future research may focus on the further development of the presented DSS. As this system addresses the issues of which energy sources and which equipment should be used and how they should be operated, further development can specify the connections within the hub, including the number of devices used and the location of each device. For this purpose, it is necessary to examine the regarded region in which the energy hub is supposed to be applied. By doing so, the demand within in the hub can be geographically subdivided and, thus, be optimized. For instance, it can make sense to locate most of the different technologies close to where the majority of demand comes from.

Furthermore, the optimization of multiple interconnected hubs can be an extension of the DSS. As partially described in chapter 4, this is already part of the presented energy hub modelling from which a further practical application could be developed. In times of increasing use of smart technologies, they can also be applied in the energy sector for an adaptive and flexible optimization of energy supply, which is supported by information exchange between hubs.

As presented in section 2.3.2, residential energy consumptions account only for a part of the total energy consumption and, thus, an optimization based on the entire consumption, which includes industry, transport and public services as well, could be performed to obtain a holistic solution. Due to different load profiles in the different sectors, a different optimum compared to the presented study can be assumed. Additional reliability of the study results could be achieved, if, in addition to using data from long-term measurements, the living conditions and infrastructure were updated based on the new 2021 census.

With regard to the initial research question "*In times of a changing energy sector, how can decentral energy supply on a regional level be realized and optimized?*", the DSS can be considered a proper tool to find an optimal solution for a DES. It is the practical realization of the energy hub concept and, thus, a way of optimizing future energy supply under the aspect of an increasing decentralization. The need for an increased use of regenerative energies is considered as well as the increasing use of more efficient technologies and the expansion of regenerative sources to all sectors. In order to achieve a far-reaching, cross-sectoral optimization of the supply, it is necessary to extend the system and enable a simultaneous and adaptive optimization of several hubs.