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A Model-based Approach to Decarbonize an Island's Energy System

Case Study on the Island of Föhr, Germany

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Abstract. To achieve climate goals and contain further global warming, it is inevitable to reduce CO_2 emissions especially in energy consumption. A way to do so is by integrating renewable energy sources (RES) into an energy system's power generation. However, there is no standard procedure to decarbonise a locally restricted system. Therefore, the various local conditions have to be analysed and taken into consideration.

The authors propose a model-based approach to decarbonise the energy system of the island Föhr, Germany. This includes various collected data sets on local conditions such as climate data and heat and power demand. The data is used to represent the island's energy system and design a model-based solution in a simulation software.

The authors identify potentials by comparing costs and revenues by addressing the deployment of different RES technologies. One finding is that heat generation causes 91 % of CO_2 emissions making it the major producer. However, with the designed solution, emissions could be reduced to a third.

Keywords: decarbonisation, renewable energies, island

Introduction

The climate change becoming more and more perceptible, decarbonisation of energy systems is a topic of interdisciplinary interest. This paper approaches the complex problem as a case study by looking at the island Föhr, located in northern Germany in the North Sea.

Characterised by a strongly fluctuating population and therefore varying energy demand throughout the year, the island has lots of potential for efficiently harmonising power generation and consumption.

The island's municipal administration aims for a nearly CO_2-neutral energy cycle. Thus the extension of renewable energy sources and a more distributed generation are required. Föhr's municipal administration reached out to TH Wildau to conduct a holistic study on the topic of decarbonisation, especially focusing on reducing CO_2 emissions caused by electricity and heat sector. Previously, both sectors only have been considered individually. Results of this project are being presented and taken into account in this paper. Decentralizing an energy system accounts for major difficulties regarding system reliability and security due to fluctuations of the availability of renewable energy sources [1]. A solution for the decentralization and distributed generation of energy is the application of smart grids [2]. Hwang et al. [3] proposed a renewable-energy-based smart grid system on Gapa island, South Korea. However, with a maximum demand of 224 kWh and 281 residents, the island is 28-times smaller than Föhr, so results are not entirely transferable. For the utilization of the renewable energy sources and the implementation of a smart grid system, local conditions have to be taken into account. Within the framework of the case-study, this paper presents a model-based decarbonized system for the island Föhr.

Related Works

For a model-based approach of decarbonizing an energy budget, islands or isolated regions are particular suited due to their clearly defined boundaries. Hence, they can often be found as case studies [4].

However, due to a wide variety in local conditions such as climate, energy demand or local policies, a standardized solution is not feasible. Tarasov [5] presents a methodological approach for decarbonizing isolated energy systems. These are characterized by extreme climate conditions which exclude the installation of wind and solar energy.

In contrast, Pascasio et al. [6] present a hybrid energy system for Philippine off-grid islands. Utilizing wind and solar energy, alongside with diesel generators and battery packs. The authors consider installation sites, costs and profits and show a reduction in emissions of 61.38%.

With the progress or further expansion of renewable energies, decentralized energy generation structures are emerging. However, there are some challenges such as uncertainty of generation output and unbalanced system conditions. A solution to that is implementing smart grids [7].

Case Study

Overview

With a surface area of about 82 km^2 and a longitudinal expansion of 12.5 km, the island Föhr is located in the far north of Germany close to the Danish-German border. It is surrounded by the Wadden Sea, part of the North Sea and UNESCO World Heritage. This results in roughly 200,000 tourists per year that visit the island. Figure 1 shows an aerial image of the island.

Figure 1. Aerial image of Föhr

The large number of tourists contrast strongly to Föhr's population of 8,248 inhabitants (2018) [7]. Thus, the amount of people residing on the island varies strongly throughout the year. The peak of the population is reached during the summer in July and August with an additional percentage of inhabitants from 100 to 120 %.

Electrical energy is provided by the local distribution system operator, using a submarine cable as a connection to the mainland. In addition, a cable connection to the neighbouring island Amrum exists.

The initial data for that is the island’s resident population plus the number of overnight visitors, both in 2018. The numbers remained constant compared to the previous year’s record result [8]. Due to seasonal fluctuations, the number of tourists varies throughout the year with a peak in the summer months. Since tourists are having a significant impact on the island’s economy, they can be considered as additional inhabitants. These so called population equivalents are calculated from the tourist figures. However, only overnight stays were considered. It is assumed that one overnight stay is equivalent to one resident per day.

From 1.86 million overnight stays are resulting 5,095 population equivalents by tourists per year. These annual population equivalents are only of limited use, since the number of tourists fluctuates over the year. The overnight stays were distributed over the months of the year. As basis for the calculation the overnight stays in the whole of Schleswig-Holstein were used and thus a percentage share was obtained for each month. This was then applied to the total overnight stays on the island Föhr and from this the tourist population equivalents are calculated.

Data Acquisition

Electric Energy Demand

Since the island’s specific power consumption was unclear, numbers had to be calculated using national averages for electricity consumption in Germany in 2018. The main sectors are industry (43.9 %), residential (i.e. private households, 24.9 %), commercial (29 %) and transportation (2.2 %).

For private households, there is a per capita consumption of 1,550 kWh [9] which makes for Föhr’s 8,248 inhabitants a total residential/household demand of 12.78 GWh. For calculating the total demand, the national average from the gross electricity consumption per person was used, which is 7,274 kWh for all sectors. In figure 2, an overview of the calculated average electricity demand per month in kWh, with a maximum of 3,680 MWh in July, is given.

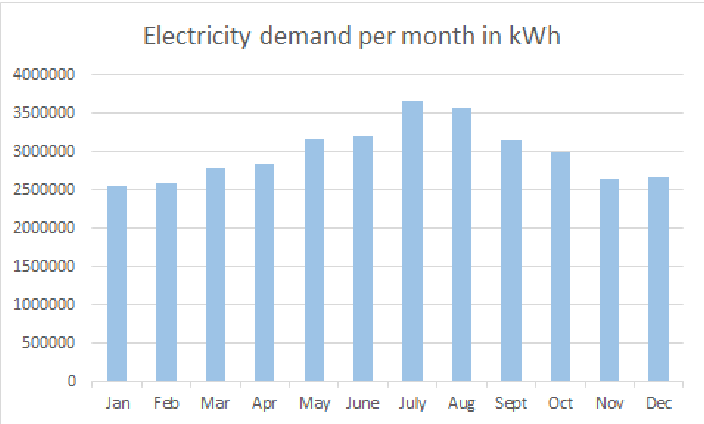

Figure 2. Total electricity demand per month

Heat demand

The term heat demand refers to the need for space heating and hot water. In 2018, the heat demand of an average household in Germany for hot water was 2608.38 kWh. Multiplied by the 3,916 households on Föhr this results in a demand of 10.21 GWh for hot water per year for the household sector. More differentiated statistics are available for the energy demand for space heating [10]. The number of different households on Föhr is derived from the absolute numbers of households on Föhr-Amrum, and was extrapolated down to the island of Föhr under the assumption that the distribution is the same. With the help of these figures, a space heating demand of 52.06 GWh per year for the household sector on Föhr could be determined.

The heat demand for the commercial sector could only be estimated by using the statistics from the Federal Environment Agency from the year 2017 [11]. Thereby, the total consumption figures of the sectors were put into relation as a percentage. This results in the commercial sector having about 41.47% of the space heating demand and 18.01% of the domestic hot water demand. Thus, the annual demand for the tertiary sector was calculated to be 21.59 GWh for space heating and 1.84 GWh for hot water.

To include tourists into the calculation, initially the heating degree days were analysed from the nearest weather station on the island of Sylt. The heating limit was set at 15 degrees Celsius, meaning when the outside temperature is lower, the day is considered a heating day.

In the heat sum, the respective difference between the outdoor temperature and the heating limit were added for each day [12]. In relation to the total heat sum, a percentage of the heating demand per month can be determined in relation to the year. These percentages are multiplied by the space heating demand of the households to obtain the monthly space heating demand. The number of inhabitants on Föhr was used to downscale this demand to one person. This was a step to determine the demand for tourists with the help of the population equivalents for the tourist’s sector.

To calculate the tourist’s energy demand for hot water, the demand for households was divided by the number of inhabitants, resulting in a demand per person per year. This value was multiplied by the monthly population equivalents of the tourists to establish their energy demand for hot water.

Figure 3 shows the calculated heat demand per month. There is a basic demand for hot water throughout the year which is increasing in summer due to the tourists. Additionally to the basic demand, the demand for space heating is added up, mostly in winter. The island’s total heat demand was calculated to be 109.67 GWh per year with the tourism sector making about a quarter of it.

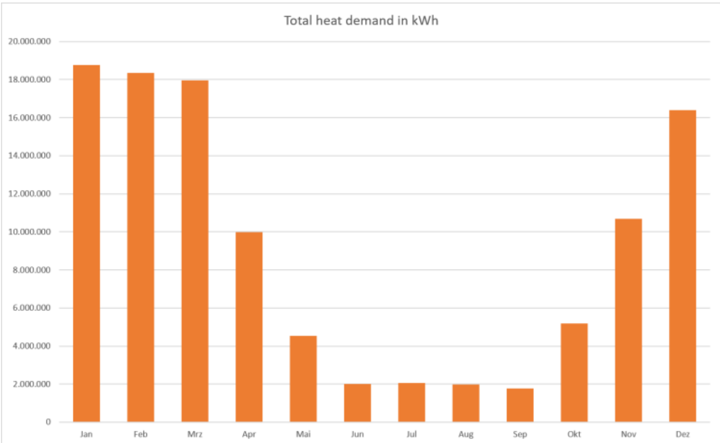

Figure 3. Total heat demand per month in kWh

Analysis of RES potential

On site available (renewable) energy sources are wind and biogas, and potentially solar and geothermal energy as a source for heat production. In a first analysis, potentials were examined and presented.

Concerning biogas, the town council of Wyk on Föhr did not favour the extension of existing biogas plants as corn cultivation would be needed. This would lead to high water consumption for the cultivation and negative impacts on landscape which was considered to be not beneficial for attracting tourists [13]. Hence, enlarging a potential biogas plant with corn silage as a substrate is not possible. In addition, the utilization of biowaste to biogas was assessed as unsuitable and therefore not considered any further.

Regarding Föhr’s local climate conditions, the installation of photovoltaic plants and solar collectors holds potential. One restricting point is that modules can only be placed in the free field due to the inappropriate building structures of the majority of houses on the island.

For geothermal energy, a potential for geothermal probes was discovered. Two design options were available, either with a large heat pump for district heating or decentralized heat pumps for local heating. Due to the undesired addition of further wind power stations, a simple expansion with more wind turbines is not possible. Nevertheless, a simulation of the existing power plants was made to estimate a possible optimization through the addition of power storage modules.

Data preparation and processing

For the simulation, usable time series from the collected data were created and additional data for further time series used. First of all, the actual state of the islands energy systems was modelled using a software called TopEnergy by GFaI. From the previously determined electricity demand, time series were created using standard load profiles [14]. Two different profiles were used for the calculation of the demand for households and tourists and for the commercial sector. All load profiles have a resolution of 15 minutes. Figure 4 shows the time series for the total electricity demand per sector.

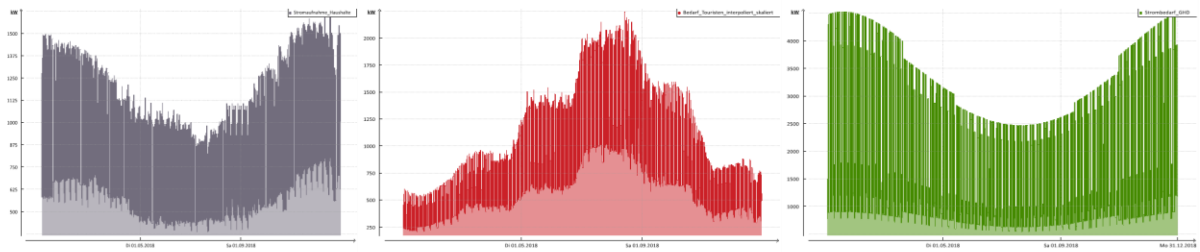

Figure 4. Time series for power demand per sector in TopEnergy software. Left: Private sector; middle: tourist’s sector; right: commercial sector

The input of weather data was indispensable for calculating the heat demand, but also the potential of renewable energies. The used parameters are the ambient temperature, global solar radiation and wind speed. Figure 5 shows the resulting time series for heat demand per sector.

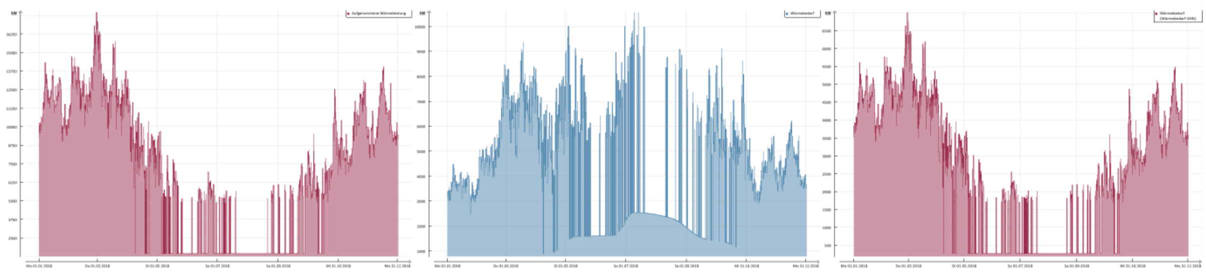

Figure 5. Time series for power demand per sector in TopEnergy software. Left: Private sector; middle: tourist’s sector; right: commercial sector

Simulation

Actual state

A model of the actual state represents the island’s current state of the energy supply in the form of electricity and heat in a simplified way. In the power grid, a distinction is made between the three sectors households, tourists and commercial. The demand is described by the already mentioned time series. The power grid is supplied by an electricity supplier that bills the electricity via a local electricity tariff. Average local figures for CO_2 emissions in electricity generation were used and included in the simulation.

The simulation of the heat supply is based on the assumption of a district heating network that supplies all consumers, which is not exactly the case in reality. The consumers and their demands are connected to this heat network. Here, too, there is a breakdown into the household, tourist and commercial sectors based on the prepared time series. Figure 6 shows the model created in TopEnergy.

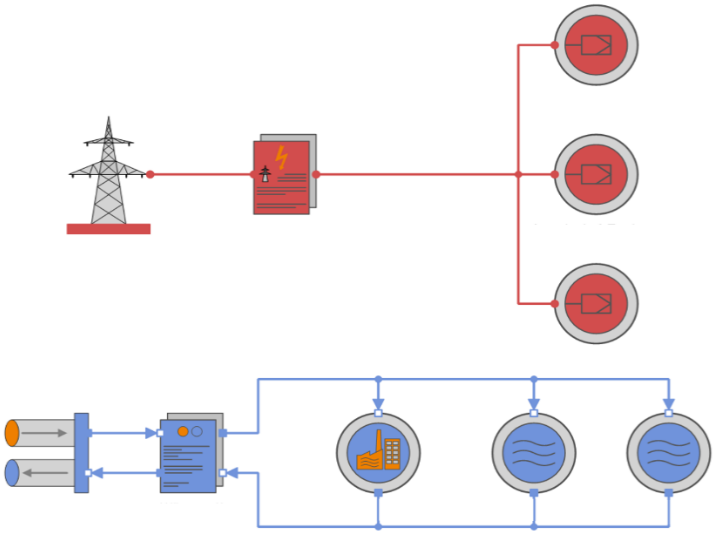

Figure 6. Model of the islands energy system’s actual state

Results

To obtain results for the energy system’s target state, the actual state was modified and supplemented. Figure 7 shows the much more complex model for the hypothetical target state.

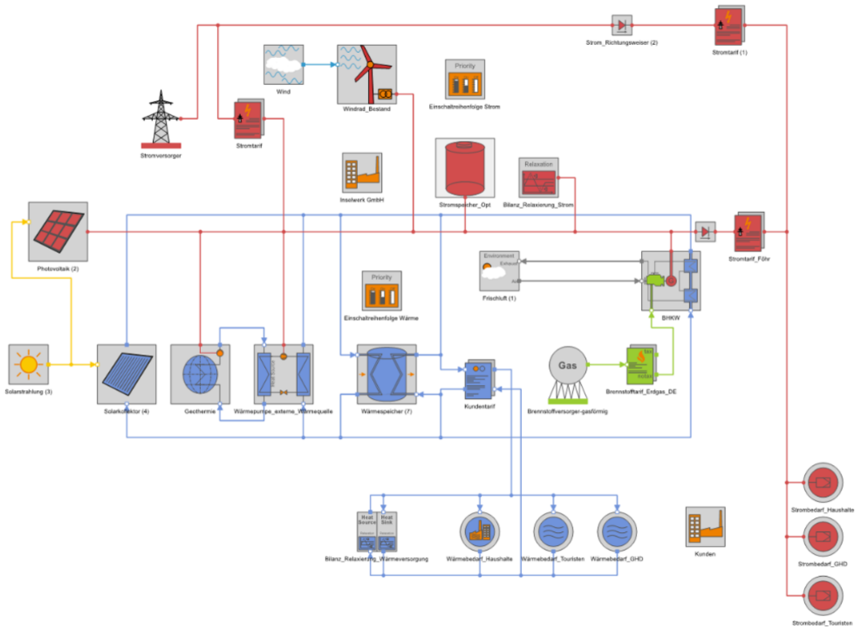

Figure 7. Model of the islands energy system’s target state involving RES technologies

In this combined model, components of wind power, solar energy, both solar collectors and photovoltaics and geothermal energy were implemented. In addition a cogeneration unit was operated, which emerged from the evaluation of the neighbourhood as well as island solution. For the control of the power flow, power direction indicators were used and switchon sequences for the cogeneration unit. A heat storage was used to mainly store surpluses from the solar collectors, thus reducing the load on the geothermal probes and reducing their size. The electricity storage was mostly used to store electricity from wind power and photovoltaics. The model contained eight time series with 35,040 time points each. To reduce optimization errors, relaxation modules were built in. Their function is to absorb surpluses and close shortages and show exact numbers of when and how much electricity or heat was spare or missing.

The simulation showed that the total electricity demand remained about constant throughout the year. In contrast, the demand for heat varies strongly throughout the year. Only the base load is constant and increases in summer due to the higher number of tourists. Especially in spring there is a high heat demand. This decreases in summer, when cold days, which cause a significant heat demand, are rare. In fall, the heat demand then increases again.

The CO_2 emissions of the actual state amount to a total of 31.4 kt/a. Of these, 9% are caused by electricity supply and 91% by heat. With its 28.5 kt/a of CO_2 emissions, the heat supply represents a very large factor in the total emissions. Accordingly, the highest savings potential was expected there.

As a result after comparing costs and revenues, the use of solar collectors for generating heat could not be recommended. Other mentioned technologies could be used to employ more electricity and heat produced by renewable energies. Figure 8 shows the comparison of costs and revenues.

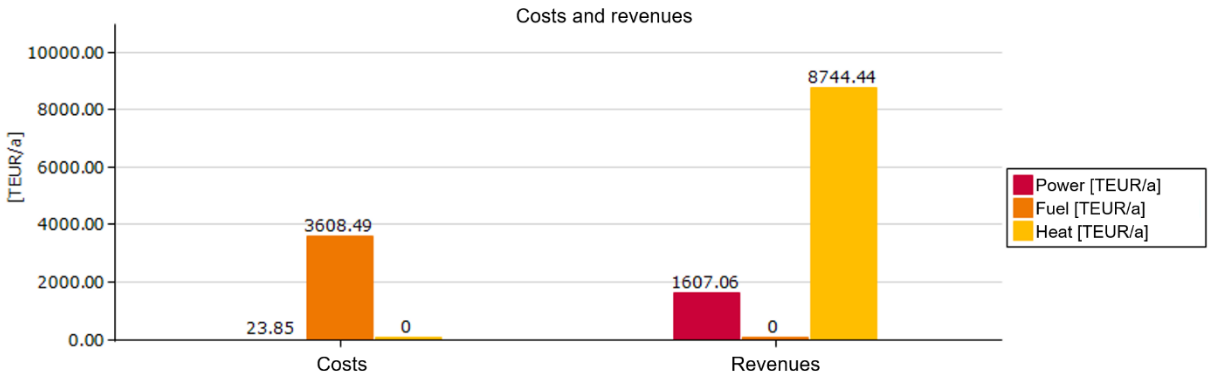

Figure 8. Comparison of costs and revenues per technology

In terms of reducing CO_2 emissions, applying a combination of the presented technologies would lead to a reduction of about a third compared to the actual state. Figure 9 shows the comparison regarding CO_2 emissions of the energy system’s actual state and the target state (in two variants).

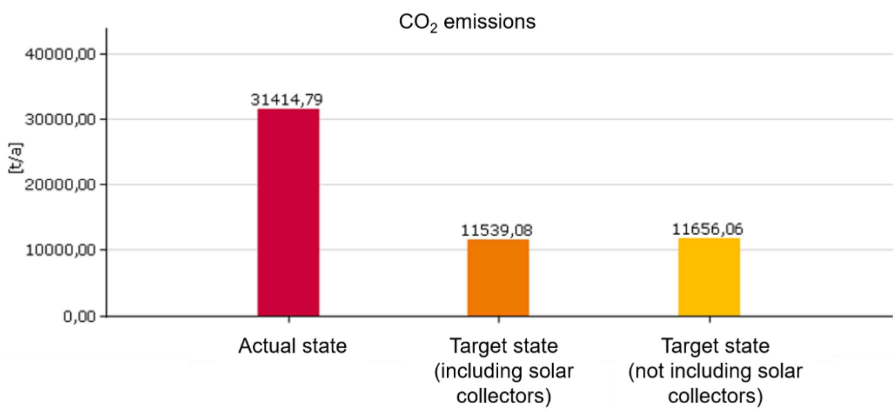

Figure 9. Comparison of CO_2 emissions

Conclusion

In this paper, a model-based approach for decarbonizing an island’s energy system is presented. First, the process of data acquisition for calculating a custom electricity and heat demand is presented. Further, the authors analyse the potential of on-site available renewable energy resources. Local climate data and calculated demands are processed into time series. A software model describing the island’s as-is state is explained and employed in the simulation to determine a baseline. Then the baseline model is expanded to integrate wind, solar and geothermal energy and a combined heat and power plant as well as storage technologies. As a result, solar collectors are not profitable within the local conditions. Nevertheless, the authors can show a significant decrease in CO_2 emissions by 63.27 %. A discussion of the applicability of a Smart Grid for the described energy system will be addressed by the authors in future work.

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