Analysis of Prospective Energy Scenarios using a Multiple-Level Approach

Mevina Feuerstein, Student Member, IEEE, and Franziska Adamek, Student Member, IEEE

Abstract—The aim of the presented research is to analyze prospective power supply scenarios for an exemplary Swiss region using a multiple-level model. The considered region is subdivided into its settlement units to form the levels. Each level comprises distinct conversion technologies to supply the load. The power supply is composed of various energy carriers, like electricity, gas and heat, in order to exploit synergy effects. Renewable and conventional power plants produce the demanded heat and electricity. The optimal power supply policy for the region is determined applying a bottom-up optimization approach. Optimality is defined by either minimum costs, or minimum emissions that are necessary for the proposed supply strategy. Two prospective scenarios are examined and compared with respect to their costs, the use of different energy carriers, and their environmental impacts. Depending on the implemented scenario, primary grid-energy demand decreases more significantly than final energy demand because of synergy effects.


I. NOMENCLATURE

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>BaU</td>
<td>Business as Usual</td>
</tr>
<tr>
<td>CHP</td>
<td>Combined Heat and Power</td>
</tr>
<tr>
<td>HP</td>
<td>Heat Pump</td>
</tr>
<tr>
<td>PV</td>
<td>Photovoltaics</td>
</tr>
<tr>
<td>SFOE</td>
<td>Swiss Federal Office of Energy</td>
</tr>
<tr>
<td>VSE</td>
<td>Verein Schweizer Energieunternehmer, Association of Swiss Electricity Companies</td>
</tr>
<tr>
<td>VoFEN</td>
<td>Vision of Future Energy Networks</td>
</tr>
</tbody>
</table>

II. INTRODUCTION

Increasing difficulties extracting oil, highly volatile energy prices and increasing energy demand influence our energy consumption behavior and the energy infrastructure. The effects of climate change on human living standard is another important topic of current public discussion. To keep human impacts on climate change as low as possible, energy demand and the emissions of carbon dioxide or other greenhouse gases have to be minimized. Additionally, energy supply costs have to be kept as low as possible in order to fulfill customers’ desires. One step to enforce a greener energy production is the use of renewable energy sources, such as wind, solar or biomass, that have significantly lower greenhouse gas emissions than fossil fuels. These technologies most probably characterize the future energy infrastructure and cause a shift from centralized to decentralized power supply.

The work presented in this paper combines renewable energy production with synergy exploitation of different energy sources, and analyzes their effects on prospective future power supply. Therefore, an exemplary Swiss community is examined with regard to costs and emissions of different power supply scenarios. The two scenarios “Business as usual” and “Renewable 2050” differ in the amount of energy produced from renewable technologies and the quantity of energy demand. The considered community consists of districts and an industrial area. One district is divided into two residential areas. All parts of the community together form a multiple-level model that allows the determination of the cost or emission optimal power supply of the region. The objective of the presented work is to analyze future energy supply scenarios using a multiple-level model.

Multiple-level models exist in various research and application areas. In Control Systems a multiple-level feedback loop controls three-dimensional motion [1]. The Petroleum Industry is modeled as a multiple-level model in [2]. The case study in ref. [3] uses a multi criteria procedure for decision making in economics. In energy supply, the use of multiple-level models is not very common, although approaches exist [4].

Various studies exploring the prospective Swiss energy situation exist. All of them propose different scenarios. The Swiss Federal Office of Energy (SFOE) examines the future of Swiss energy supply and consumption in detail in [5]. Four different scenarios cover the range of the expected situations. The Association of Swiss Electricity Companies (Verein Schweizer Energieunternehmer, VSE) [6] and the Building Management of the Canton Zurich [7] propose similar scenarios. The scenarios used in this work base on these reports.

The remainder of the paper is organized as follows: Sec. III. defines the energy scenarios. Sec. IV. introduces the exemplary Swiss region being optimized and Sec. V. explains the multiple-level model. Sec. VI. presents the results obtained from the optimization and Sec. VI. concludes. The paper finishes with the outlook and future work (Sec. VIII.).
III. SCENARIOS

Long-term predictions of prospective energy supply infrastructures are nearly impossible. Therefore, different scenarios model the development and general conditions of technologies, power demand and infrastructure. In this work, two different scenarios for the year 2050 are compared in terms of costs and emissions. They are called “Business as Usual” and “Renewable 2050”. The scenario “Business as Usual” (BaU) assumes a constant growth in the use of renewable energy sources and a significant rise in electricity consumption (Table 1). The scenario “Renewable 2050” is similar to the concept of the 2000 W society [7]. Many of the buildings have very good insulation and the equipment used is energy efficient. This leads to a decrease in final energy consumption while the consumption of electric energy remains at today’s level. New renewable energies such as solar heat and electricity, wind and biomass electricity or geothermal heat are used increasingly on all different levels of the community that will be introduced below.

<table>
<thead>
<tr>
<th>TABLE 1 ENERGY DEMAND AND USE OF RENEWABLES COMPARED TO THE PRESENT.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Business as Usual</td>
</tr>
<tr>
<td>Total Energy Consumption</td>
</tr>
<tr>
<td>Electricity Consumption</td>
</tr>
<tr>
<td>Heating Energy Demand</td>
</tr>
<tr>
<td>Use of Renewable Energy</td>
</tr>
</tbody>
</table>

IV. EXAMPLE

The two scenarios presented above are applied to the exemplary Swiss community seen in Fig. 1. The community consists of three districts and an industrial area. One of the districts is further subdivided into two residential areas. About 7500 inhabitants reside in the community, distributed over all three districts.

Several conventional energy carriers (oil, gas, district heat and electricity) supply the community with energy. Various renewable energy sources (photovoltaic panels, wind power, heat from wood furnaces or heat pumps and biomass power) are available within the community. The investment and fuel costs of renewable energy technologies are assumed to be equal to zero for reasons of simplicity. Further work to improve the correctness of the results is presented in Sec. VIII.

V. MULTIPLE-LEVEL MODEL

The multiple-level model structures the community hierarchically using different levels. The levels are determined by the settlement structure (here: community, living districts, residential and industrial areas). The industrial and residential areas form the lowest level (Fig. 2).

Specific conversion technologies for each level cover part of the energy demand. The residential areas obtain missing energy from the superimposed level, district 1. The industrial area is directly connected to the highest level, the community.

The energy conversion technologies of each level are aggregated in an energy hub. The concept of the energy hub was developed within the Vision of Future Energy Networks Project (VoFEN) at the ETH Zurich [8]. The energy hub is a device that allows conversion, conditioning and storage of various energy carriers such as oil and electricity.

Energy hubs have different loads $L$ which are to be covered using the inputs $P$ from the grid such as electricity and gas (Fig. 3). Renewable inputs $R$ such as solar heat and electricity also help to cover the load. In addition, excess electricity is fed back into the grid via $T$. Storage elements can be included in the energy hub model. However, they are not considered in the present work, and consequently not reviewed here.
The energy hub is modeled mathematically using the conversion matrix $C$ \cite{9}. The renewable energy sources are modeled to decrease the total energy load while the excess energy vector $T$ decreases the required energy input.

$$L = C \cdot P \text{ resp. } L - R = C \cdot (P - T)$$ \hspace{1cm} (1)

Eq. (1) has to be balanced at all time instants. The aim of the energy hub model is to supply the load $L$ using the renewables $R$ and the conventional energy $P$ while minimizing costs and emissions of the supply:

$$P^* = \arg\min F(P,T) \text{ s. t. } (1)$$ \hspace{1cm} (2)

The optimization of the multiple-level model is analogue to the energy hub optimization. The objective is either to minimize costs or emissions of the community. The optimization follows a bottom-up approach. The hubs of the lowest level are optimized first. Their required inputs $P$ determine the load of the superimposed level (district 1). Then, the hubs of the next level are optimized. The procedure continues until the highest level is reached (community).

VI. RESULTS

The multiple-level model was optimized for the present and both scenarios “Business as Usual” and “Renewable 2050”. The amount of electricity and heat demand from the grid, the composition of the energy carriers covering the heat load, energy costs, emissions and excess electricity resulted from the optimization are shown here. Instead of presenting the results of all optimized hubs in both scenarios, the results of the residential area 1 are presented here. The trend is the same for all hubs.

A. Electricity and heat demand

As mentioned before, the renewable energy input is modeled to decrease the load. In the case of electricity, the total electricity load is covered using renewable energy sources and electricity from the grid. The results show only the electricity used from the grid and the heat demand from conventional energy sources, without the amount covered by renewable energy sources.

The electricity demand grows by about 10 % for the scenario “Business as Usual”, as can be seen in Fig. 4. It does not grow by 30 % as assumed in the definition of the scenarios (Sec. III. ) due to the use of renewable energies that reduce the demand. For the scenario “Renewable 2050”, the grid electricity demand decreases by about 35 % instead of remaining constant compared to the present. A substantial part of the total electricity demand can thus be covered with renewable energy sources.

Fig. 4 shows that much more heating energy is used during winter than during summer. Overall heating demand decreases for the scenarios “Business as Usual” and “Renewable 2050”, again due to the use of renewable energy sources that reduce the demand for conventional energy carriers.

B. Heating energy composition for residential area 1, summer vs. winter

The present heat energy required during summer is only covered by district heat, if emissions are minimized (see Fig. 5). Also the heat energy needed in summer in scenario “Business as Usual” is covered using district heat only. If costs are minimized, the heat demand is covered using gas and ambient heat for heat pumps. Fig. 4 shows that no heating energy is needed in summer for the scenario “Renewable 2050”. All heating energy needed to heat water is taken from renewable energy technologies. That heat demand is not shown in the results since renewable energy technologies are assumed to reduce the load.
Fig. 5 Composition of heating energy demand for residential area 1, Summer.

Fig. 6 shows that the composition of the heating energy carriers for the winter is different. The composition of heating energy carriers for the presence and the scenario “Business as Usual” is the same for both minimal costs and minimal emissions. All available energy carriers are needed to cover the load during winter.

Half of the heating energy demand of the presence is covered using oil. However, the share of gas used to cover the heating energy demand grows in the scenario “Business as Usual” and grows even more in the scenario “Renewable 2050”. More gas is used in the renewable scenario when optimizing costs compared to optimizing emissions, but less district heat and ambient heat.

D. Excess Electricity

In the scenario “Renewable 2050”, excess electricity is generated with renewable energy technologies. However, excess electricity cannot be generated at every time instant. The renewable energy technologies have intermittent character and cannot cover the loads all the time. During periods with less electricity generation from renewable energy technologies, electricity from the grid is needed. If excess electricity is generated, it can be fed back into the grid to feed regions with less electricity generation.

VII. CONCLUSIONS

The results gained from this work show that a clear reduction of energy use is possible if the scenario “Renewable 2050” is realized. Efficient devices, good insulation and a growing use of renewable technologies lower the energy demand from conventional sources. No heating energy is needed during the summer for that scenario. Heating energy is needed only for warm water, not for heating rooms. The energy needed for heating water comes from renewable energy sources during the summer. The heating energy demand during winter is covered using district heat, gas and ambient heat. Less gas and more district heat cover the load if minimum emissions are the target. Better efficiencies of the conversion technologies and lower demand reduce both costs and emissions clearly. The goal of the Swiss government to reduce the country’s greenhouse gas emissions by 50 % by the year 2050 can be achieved for this scenario (without transportation). Electricity can be generated with just renewable energy technologies for the modeled region. Excess energy can be fed into the grid and sold to regions with worse premises for renewable energy technologies. However, backup generation plants need to be ready to cover the electricity demand in times of low production from renewable energy technologies.
Population growth and increasing use of energy dependent devices cause the electricity consumption of the scenario “Business as Usual” to rise although the efficiencies of the conversion technologies and household appliances increase. Heating energy demand during the winter is covered using mostly gas and oil, but also some district and ambient heat. Ambient heat and gas could cover the heating energy demand during the summer with minimal costs, district heat could be used for minimal emissions. Energy costs can be reduced only marginally due to high energy demand and low renewable energy input. However, better conversion equipment causes emissions to decrease by about 40%. Electricity will still be drawn from the grid and not from renewable energy technologies. No excess electricity is available to feed back into the grid. That implies that conventional, centralized power plants will still be necessary, if the scenario “Business as Usual” is implemented.

VIII. OUTLOOK AND FUTURE WORK

Investment and fuel costs for renewable energy sources have to be included in the model in a first step, to obtain conclusions that are more realistic. Energy demand and costs will be higher than in the results presented here, but also more accurate.

Storage devices such as batteries additionally have to be included in the model to improve the analysis. In addition, the level where renewable energies should be inserted optimally can be found using the multiple-level model. A sensitivity analysis for energy prices shows different outcomes for the optimization. Different price scenarios can be covered with the analysis.

IX. ACKNOWLEDGMENT

The authors would like to thank the members of the Vision of Future Energy Networks project team at ETH Zurich, and Prof. Klaus Fröhlich and Prof. Andersson, for inspiring discussions. Special thanks goes to Peter Aicin for providing the programming for the hub optimization.

X. REFERENCES


XI. BIOGRAPHIES

Mevina Feuerstein (M’2009) received her Bachelor’s degree in Mechanical Engineering in 2007 and her Master’s Degree in Energy Science and Technology in 2009 from the Swiss Federal Institute of Technology ETH Zurich. She is currently working as project leader for the Energy Services division of ewz, the Zurich Municipal Electric Utility company.

Franziska Adamek (M’2004) received her Bachelor’s degree in 2005 and her Diploma in 2008 from the Technical University of Munich. As a scholarship holder she studied at Nottingham University, Great Britain, and at the Papal Catholic University of Chile in Santiago de Chile. Since 2008, she is a PhD student at the High Voltage Laboratory of the ETH Zurich, Switzerland. She is a member of the Cigré Working Group on Storage Technologies.