EFFECTS OF RETROFITTING ON THE OPERATION AND DEPLOYMENT OF TECHNOLOGIES WITHIN A DECENTRALIZED SYSTEM

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Abstract— The effects of retrofitting of buildings on the energy system configuration have up to date not been examined thoroughly. Currently, most studies analyze the direct effect on the energy saving potential or the economic benefits for home owners, rather than the system effects.

In this analysis, an evaluation of the effects of the different KFW standards of building retrofitting on a decentralized system is carried out. The main focus of the analysis is to evaluate the effect on the technology mix (heating systems, retrofitting measures, storages, heating and electricity grid) in terms of operation and deployment. This has been done with a model based analysis. However, this paper focuses on the methodology of addressing the retrofitting issue in Germany and qualitatively evaluates the effects on a system level.

Keywords—Energy System, decentralized system, retrofit, system flexibilities

INTRODUCTION

The German energy transition has been gaining more importance and attention in the past years. Starting from the phasing out of nuclear energy generation, to the rapid increase of renewable energy generation, the power sector has experienced a rapid and big change in the past years. However, the heating and cooling sector in Germany has not been given that much attention yet. Nevertheless the heating of buildings and hot water supply, as well as process heat account for 56% of the German energy consumption [1]. The building sector alone accounts for around 28% of the total energy consumption [2]. These numbers show very high potential of energy saving by either increasing the amount of renewable energy generation in the heating sector or reducing the energy demand. Many studies show that the biggest energy saving potential exists within the building sector. Studies show that there is reduction potential up to 60% that can be achieved by the year 2050 [1].

This paper captures these thoughts and presents an analysis of the retrofitting effects of the building sector within a decentral system. Not only will retrofitting have a great effect on the system cost, but also on the required technology mix and hence flexibility technologies to cope with the new system configuration. The analysis shows these effects on a small scale energy system.

METHODOLOGY

The main objective of this paper is to present a method of evaluating the effects of retrofitting and the deployment of technologies within a decentralized system. One of the main challenges is integrating this into an optimization model. The following sub-questions will be answered within this paper.

A. Research questions:

- How can part load be integrated adequately in the model
- What is an adequate methodology to integrate building retrofit in the optimization model
- How can efficiency measures within industry process be integrated in a model
- What are qualitative findings can be drawn from modelling an exemplary system in terms of system costs, technology portfolio, and operation of technologies?

B. Description of the Basic Model

The energy system model is an optimization model with the objective function to minimize the total costs of the system. The model is written in General Algebraic Modeling System (GAMS). The main characteristics and strong points of the model is that it covers the heat and electricity sector and its coupling technologies within a decentralized system [3]. It covers the deployment and the operation of the heat and electricity generating technologies, storages as well as the heating and electricity grid. The solver can deploy any technology at any given time. Each technology has a certain life time and is then decommissioned according to boundary conditions in the model.

1) Technologies: The following technologies are integrated in the model setup: In order to be able to present the status quo of the building sector and their heat generating technologies the current technologies like oil boilers, gas boilers, wood pellet boilers and district heating are modelled. The renewable heat and power generation are represented by solar thermal collectors and renewable energies like photovoltaic and wind. Since the focus is on the sector coupling technologies and heating sector for the retrofitting analysis, technologies like CHP plants on different scales, heat pumps and thermal storage systems are included.

2) The System: As previously mentioned the modelled region is a decentralized system in order to be able to analyze the effects on the operation and deployment of technologies in more detail. The system is defined by the building stock (residential buildings and industry) as well as central generating or storing technologies, like large CHP plants or hot water storages, ground mounted PV plants or wind farms. Additionally the district heating, as well as the electrical grid are represented within the model. Another aspect assigned for is the electricity market (EEX). This enables the possibility of trading electricity of the utilized technologies at any point of time [4].

The building stock and the specifications of the buildings were developed in a previous project at the Fraunhofer ISE, E Hub. Other Input parameters like the status quo of the heating systems were distributed according to the German technology mix [4].

3) Heat and Electricity Demand- Buildings The heat demand is calculated per building whereas the electrical demand is modelled on household level. The demand profiles for the residential buildings were generated by a bottom up Model named SynPro *[5]* based on data collected from the buildings *[6]*. The post retrofitting demand is also simulated with the

SynPro Model to get the hourly demand curve, and not only a percentage reduction of the previous heat demand.

4) Heat and Electricity Demand- Industry: The demand curves of these industries were generated by the Wuppertal Institute in Germany. Each industry has around 4-6 different processes with differentiated demands and efficiency potential. This is generated for the electrical and heat consumption. This allows the model later to deploy energy efficiency measures specific for the processes and reduces the demand accordingly.

MODEL EXTENSION

The above described setup of the basic model is extended in terms of part load of the heat and power generation plants. Additionally it is extended by the option of retrofitting the building stock and energy efficiency measures within the industry. The equations that enable the integration of the above mentioned will be described in great detail.

A. Part Load

All the technologies using combustion have the option of running on part load, which has been modelled according to a three step method.

The partial load ranges are illustratively regarded or called blocks. The three blocks are each assigned to a specific operation mode. The overall performance of a combustion technology is split into three partial load ranges A, B and C with different efficiencies. Block A is assigned to a load varying between zero and 50%, block B from 50% to 75% and block C from 75% till 100%. For the decision if one block is turned on or running 3 binaries are utilized, which determine in which the partial load range is, are defined. In the case of CHP the partial load refers to power generation whereas heat generating technologies on the internal heat generation. If a system is in operation, the load is at least as large as determined by load level low (block A). The load can also vary between the load steps, however, the efficiency varies only when the next load stage is reached. To avoid a non linear problem in the model, the primary energy demand ($P_{primary}$) is calculated as follows:

$$P_{primary} = (\frac{P_{Total}}{\eta_{Total}}) = \frac{P_{start1}}{\eta_{start1}} + \frac{P_{start2}}{\eta_{start2}} + \frac{Pstart_2}{\eta_{start3}} \qquad \textbf{4.1}$$

The output of each block is divided by the respective efficiency. The efficiencies of block B and C (η2, η3) have to be taken into consideration. Both of which are greater than 1 in order to represent the correct overall total efficiency (η_Total). To calculate the efficiencies of the two higher blocks (η2, η3), the real efficiencies (η1real_tec, η2real_tec, η3real_tec) as well as the respective load in percent is needed. The efficiencies are dependent on the technology (tec). These are calculated in pre-calculations in the GAMS model. For example:

$$\eta 2real_{tec} = \frac{P2_{tec} - P_{tec}}{\frac{P2_{tec}}{\eta 2_{tec}} - \frac{P1_{tec}}{\eta 1_{tec}}} \qquad \textbf{4.2}$$

To assure that block B is only active if block A is fully used a binary for each Block is integrated (∇) in the following equation is used. The binary variables are implemented for each time step (t), each building (h) and each technology (tec). To be able to use Block B for example, Block A has to be turned on, i.e the binary variable (∇(A)) has to be one.

$$\nabla(A)_{t,h,pec} \geq \nabla(B)_{t,h,tec} \qquad \textbf{4.3}$$

To assure that block C is only active if block B is fully used, the following equation is applied:

$$\nabla(B)_{t,h,tec} \geq \nabla(C)_{t,h,tec} \quad \textbf{4.4}$$

Again in this assures that the binary variable (∇(C)) can only take on a 1 if the binaries (∇(A)) and (∇(B)) are also one.

In addition to these conditions, two other equations had to be applies to ensure that the power output (PB, PC) of an inactive block equals to zero. This is required for the cases of block B and C. Since the constraints are all (≤) with non-negative right-hand sides, the bigM method is applied [7].

$$PB_{t,h,tec} \leq \nabla(B)_{t,h,tec} * bigM \quad \textbf{4.5}$$

$$PC_{t,h,tec} \leq \nabla(C)_{t,h,tec} * bigM \quad \textbf{4.6}$$

In the three following equations the respective performance for each block is calculated in dependence of the installed power and the partial load percentage. It is important that the performance of block B and C representing additional power since the power is only calculated for the identified block and not the complete part load.

$$PB_{t,h,tec} \leq cap_{t,h,ptec} * (P2start_{tec} - P1start_{tec}) \quad \textbf{4.7}$$

$$PC_{t,h,tec} \leq cap_{t,h,tec} * (P3start_{tec} - P2start_{tec}) \quad \textbf{4.8}$$

$$PA_{t,h,tec} = cap_{t,h,tec} * P1start_{tec} \quad \textbf{4.9}$$

With the conditions for block B and C, since the power is lower or equals to the installed capacity (cap) times the power percentage (P1, P2, P3) calculated previously, it is possible for the blocks to be off. However, for block A there is only an equal sign. This is for the fact that one can start by reading in a parameter from the database and start with a set or specific part load. For this reason other conditions have to be added to make it possible for block A to be off as well [8].

$$PA_{r_{t,h,tec}} \geq PA_{t,h,tec} - \left(1 - \nabla(A)_{t,h,tec}\right) * bigM \quad \textbf{4.10}$$

$$PA\_r_{t,h,tec} \leq PA_{t,h,tec} + (1 - \nabla(A)_{t,h,ptec}) * bigM \quad \textbf{4.11}$$

$$PA\_r_{t,h,tec} \geq - PA_{t,h,tec} * bigM \quad \textbf{4.12}$$

$$PA\_r_{t,h,tec} \leq PA_{t,h,tec} * bigM \quad \textbf{4.13}$$

With the previous equations it is possible to calculate the power for each block. Since it is necessary to calculate the total power output of the plant, the following sum is calculated: **A.1**

$$\sum_{t,h,ptec} gen_{t,h,tec} = PA\_r_{t,h,tec} + PB_{t,h,tec} + PC_{t,h,tec} \quad \textbf{4.14}$$

As a final step an equation for the specification of the primary energy demand is added. This equation is for the partload technologies different than the other technologies and hence the following equation:

$$PE_{t,h,ptec,fuel} = \frac{PAr_{t,h,tec}}{\eta start1_{tec}} + \frac{PB_{t,h,tec}}{\eta start2_{tec}} + \frac{PC_{t,h,tec}}{\eta start3_{tec}}$$

B. *Retroffiting of the Building Stock*

The second model extension is the retrofiting of the building stock. The used methodology and the corresponding equations within the GAMS model are as follows:

Within the model one retroffiting measure for a building can be chosen according to a certain KfW standard. For each building three different standards or the option of no retrofiting are implemented. Within the optimization time horizion (typically 10 years) only once a new standard can be deployed, since it is very unlikely for a building to undergo more than one complete retrofitting within that time frame.

Deploy only one standard:

$$\sum_{rt} bin\ retrofit_{t,h,rt} \leq 1 \qquad \textbf{4.16}$$

The model cannot retrofit at T=1:

$$\sum_{rt} bin\ retrofit_{t=0,h,rt} = 0 \qquad \textbf{4.17}$$

According to a precalculation in the model the differences between the demand before and after retrofitting is calculated for each standard and each building. This parameter is then used to calculate the new demand after deploying one standard according to the model.

$$retrofit\ gen_{t,h} = \sum_{rt} generation\ retrofit_{t,h,rt} * bin\ retrofit_{t,h,rt} \qquad \textbf{4.17}$$

This is possible since retrofit is modelled as a technology, and can hence 'generate' heat. Based on this concept, the generated heat or saved heat can be added in the heat balance equation, where the heat generation plus the imports minus the exports within one building needs to meet the demand. Since the decision to retrofit is done using a binary variable, which is turned on and stays on to calculate the difference in demand correctly, the following method for calculating the investment cost had to be chosen. Because the investment cost for retrofitting occurs more or less at the time where the decision is made, a difference of the binary variable at each T is calculated.

$$diff\ bin\ retrofit_{t,h,rt} = bin\ retrifit_{t,h,rt} - bin\ retrofit_{t-1,h,rt} \qquad \textbf{4.18}$$

If this difference is one, then an investment is made. This prevents the model to assign investment cost at each T.

QUALITATIVE FINDINGS

For this paper a small system (based on a real building stock) [4] is selected to analyze different effects of retrofitting on the deployment and operation the technologies. Figure 1 shows the sum of the annual heat duration curve required for the different KfW standards in the selected system. The difference is not exceedingly high since the buildings are mostly multi story buildings and since the district has already undergone some partial retrofitting in the past.

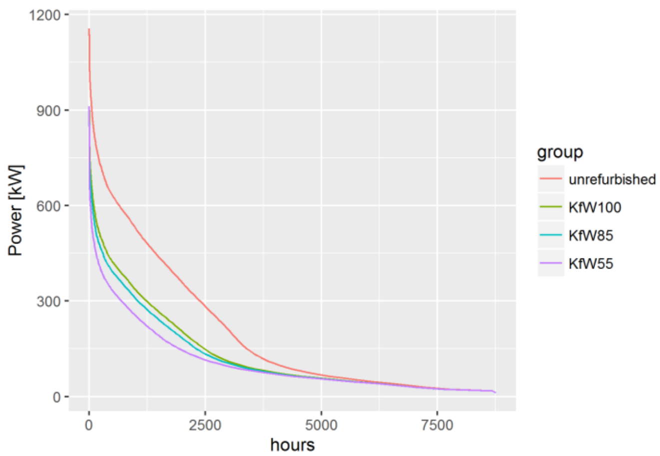

FIGURE 1 ANNUAL LOAD DURATION CURVE

It can be observed from the analysis that the optimization model does not chose to retrofit versus a technology deployment. Therefore, it can be concluded that: The main factor for the feasibility of retrofitting is the specific cost vs the saved energy per m2. And since the system has a lot of high story buildings in a rather high building standard, it is not likely that the retrofitting decision takes place. For this case, the energy demand per person per m2 is much lower than in a case with more single households.

Additionally it can be concluded that with retrofitting and combining different temperature levels in the system, technologies are deployed and operated differently. Heat pumps for example are used more effectively in retrofitted buildings. The electricity supply for heat pumps either comes from roof top PVs or from CHP plants [4].

As a preliminary result it can be stated that based on the current prices and regulations, retrofitting buildings needs some incentives to take place. The main and easiest incentive in this case is a support in the investment cost. Some programs already exist and prove to be successful. However, little studies have shown the different effects of the extent of retrofitting and the effects on different operation and deployment strategies of generation technologies.

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