OPTIMIZATION MODEL FOR THE ENERGY SUPPLY IN CITY QUARTERS

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ABSTRACT

The demand for energy and cost efficient supply with electricity and heat is rising. This work follows an approach with a holistic examination of city quarters in order to create a basis for investment decisions for the energy supply for residential housing based on optimized distributed energy conversion. Using mixed-linear-integer programming an optimal setup of energy conversion units like heat pumps, photovoltaic systems or conventional heatings is determined considering the investment as well as their operation costs over a period of 20 years. In addition a local district heating network can be designed using graph theory in order to take advantage of load balancing effects and the economies of scale. The functionality of the model is shown by analysing a small city quarter in Germany.

INTRODUCTION

Enhancing energy efficiency is one major conclusion when being faced with rising energy prices, the limitation of fossil fuels and the need for climate protection. A second driver for this work are rising penetration rates of photovoltaic systems and combined heat and power (CHP) units for residential buildings as they can generate electricity at lower prices than typical utilities' tariffs due to subsidies as well as avoided grid fees and taxes. This work shall contribute to increase energy efficiency in city quarters dominated by residential housing based on optimized distributed energy conversion.

When installing state-of-the-art conversion technologies such as co-generation, heat pumps and photovoltaic systems beside conventional heating different energy carriers become interdependent. Therefore the energy supply of neighbourhoods has to be examined in a holistic approach regarding energy infrastructure and conversion units at the same time.

In this context, holistic shall be understood as the simultaneous consideration of electricity, heat and natural gas. When combined with an energy management system the connection between electricity and heat can be one key for the network integration of renewable energy sources. The thermal storage of heat pumps and CHP units can be used for generating flexibilities which may be able to balance their fluctuating generation [1].

The aim of the presented model is to calculate optimal solutions for the energy supply by means of considering city quarters instead of single households which can generate synergies between different energy carriers and technologies. These benefits can result from the aggregation of several heat sinks via district heating systems and subsequently the employing of larger and more efficient units. The result describes a basis for investment decisions regarding type and size of conversion units as well as a layout for a district heating system.

MODELLING APPROACH

Based on input parameters like the effective heat and electricity demand or the availability of natural gas to the households, the tool will calculate an optimal set of conversion units using mixed-linear-integer programming (MILP). Currently different conversion technologies such as CHP units, heat pumps, heating systems based on natural gas, wood pellets and wood chips as well as photovoltaic systems are considered. To compare the advantage of district heating against individual heating systems a (partial) district heating network is generated by applying graph theory. Heat losses are considered as well as benefits from the load balancing effects of the aggregated objects. Beside conversion technologies one important aspect is the load side with the comprehension of customer behaviour and energetic improvements.

Input data

In order to represent individual households as detailed as possible and to ensure a high level of flexibility at the same time a set of input parameters has been chosen in order to reproduce a variety of buildings and neighbourhood configurations.

In addition to household-specific variables, such as the expected annual electricity and heat demand or the required flow temperature of the heating system, e.g. the availability of natural gas to the households is taken into account. Furthermore, the roof's down-grade and orientation for evaluating the profitability of photovoltaic systems are considered as well. Climate data for the analysed region is taken from DWD test reference years (TRY) [2].

Optimization model

Based on the given input data, firstly electric and thermal load profiles as well as generation profiles for photovoltaic systems are generated. In order to represent the individual behaviour of each single household – which is necessary when considering internal consumption instead of feed-in – probabilistic load profiles are used for electricity demand instead of standard load profiles [3].

Using the TRY data thermal load profiles are derived from [4] and PV generation profiles from a physical model under consideration of roof properties and radiation time series.

After the pre-processing of the input data the actual optimization is started. As investment decisions and technical constraints require both integer and bool variables a mixed-linear integer programing using MATLAB with CPLEX as solver has been chosen.
The objective function (1) contains the technology-specific investment costs as wells as the individual operating costs for fuel and maintenance in order to minimize the total costs of the thermal and electric energy supply. The detailed description of the operating costs is given in (2). External impact factors like subsidies resulting from several laws like Germany's renewable energy law are considered as potential revenues as well. Considering the period feed-in-tariffs for PV are warranted, the investigation ranges over a period of 20 years.

$$\min \sum_{h=1}^{H}\left[C_h^{el} + C_h^{th} - R_h + \sum_{k=1}^{K} C_{h,k}^{invest}\right] + C_{nw}^{invest} \qquad (1)$$

with

$$C_h^{el} + C_h^{th} - R_h = \qquad (2)$$
$$\sum_{t=1}^{T}\left[\left(\sum_{k=1}^{K} c_{h,k,t}^{th}\cdot P_{h,k,t}^{th} - rs_{h,k,t}^{el}\cdot p_{rs,k}^{el} - ev_{h,k,t}^{el}\cdot p_{ev,k}^{el}\right) + c^{el}\cdot fb_{h,t}^{el}\right]$$

with

h, H	Index of houses	$\in \mathbb{N}$
k, K	Index of technology types	$\in \mathbb{N}$
$\mathbf{C^{invest}}$	Investment costs	$\in \mathbb{R}$
$\mathbf{C^{el}}$	Electricity generation costs	$\in \mathbb{R}$
$\mathbf{C^{th}}$	Heat generation cost	$\in \mathbb{R}$
R	Revenues	$\in \mathbb{R}$
$\mathbf{C^{invest}_{nw}}$	Investment costs for optional district heating network	$\in \mathbb{R}$
$\mathbf{c^{th}}$	Variable costs heat generation (fuel, maintenance, etc.) [€/kWh$_{th}$]	$\in \mathbb{R}$
$\mathbf{P^{th}}$	Thermal power [kW$_{th}$]	$\in \mathbb{R}$
$\mathbf{rs^{el}}$	Grid feed-in [kW$_{el}$]	$\in \mathbb{R}$
$\mathbf{p^{el}_{rs}}$	Payment for feed-in [€/kWh$_{el}$]	$\in \mathbb{R}$
$\mathbf{ev^{el}}$	Internal electricity consumption [kW$_{el}$]	$\in \mathbb{R}$
$\mathbf{p^{el}_{ev}}$	Payment for internal energy consumption [€/kWh$_{el}$]	$\in \mathbb{R}$
$\mathbf{fb^{el}}$	Electricity from the grid [kW$_{el}$]	$\in \mathbb{R}$
$\mathbf{c^{el}}$	Electricity price [€/kWh$_{el}$]	$\in \mathbb{R}$

This approach enables the simultaneous selection and dimensioning of a cost-optimal set of conversion units for the electrical and thermal energy supply as well as the calculation of the particular operation schedule.
The constraints include - amongst others - secured thermal and electric energy supplies at any time or individual efficiency factors and minimum loads depending on the specific technology.

Optional district heating network

To compare the advantage of district heating against individual heating systems a (partial) district heating network can optionally be analysed. The heating network is not only characterized by its geographical structure but also by the necessary nominal diameter of the pipes and the heat losses that come along with it. To determine the network's geographic structure it is considered as graph with the edges representing paths of potential heating network pipes and the nodes the buildings' locations.
In order to meet the demands on the computing power for the optimization, a recursive algorithm is implemented to gradually develop heating network structures. In a pre-processing step uneconomic paths are removed from the pool of potential edges in order to reduce the maximal number of iterations. Criteria for removing are the expected energy transport per year and meter and local conditions that would preclude the installation of the heating network. The recursive function is called with the remaining paths and the costs of the individually optimized energy supply infrastructure as initial solution.
Within the function, paths are iteratively added to the heating network. For each network, the minimal spanning tree is determined applying Kruskal's algorithm [5]. Thus, a district heating network without cycles is designed with its smallest possible length in order to minimize investment costs and losses.

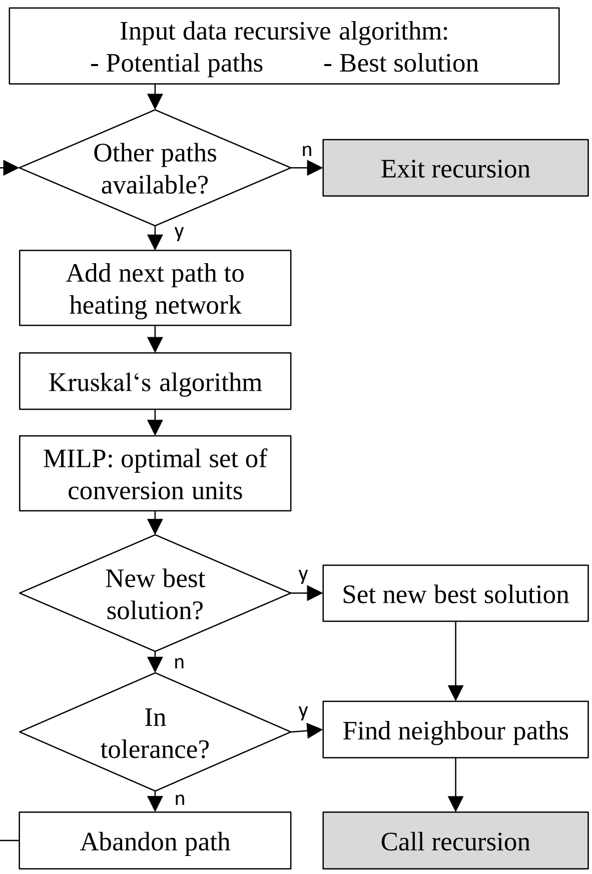

Figure 1 Calculation of district heating network with integrated optimization

Afterwards, the required set of conversion units is optimized for the network structure currently under investigation by solving the MILP. The resulting total costs of the thermal and electrical energy supply are compared to the currently best solution. Assuming that a new best solution is found, the observed path is preserved and incorporated into the currently optimal heating network structure. However, to prevent paths that result in heating network structures with costs only slightly above the current best solution from being rejected directly, a tolerance limit has been added to the model. If during further investigation of a path which initially provided a solution within the tolerance limit a new best solution is found, the local heating network structure is set as a new instantaneous optimum. Otherwise, the specific path is rejected. The different steps using Kruskal's algorithm is demonstrated in Figure 2.

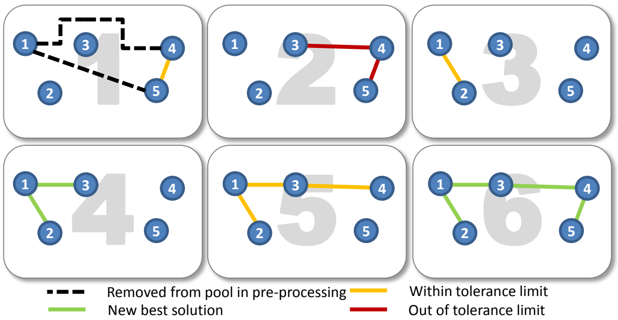

Figure 2 Development of district heating structure

Within the implemented recursive algorithm the origin function is always recalled when a new best solution or a solution within the tolerance limit is found. In contrast to the first call, only the paths that connect directly to the currently investigated heating network serve as input parameters. Thus, firstly individual district heating network sections are designed which may be linked in later recursion calls.

Important feature of a recursive algorithm is the termination condition to cause an exit of the respective function call. In the developed algorithm, this is the pool of the potential paths that must be investigated. Once there are no more paths available, the corresponding function will be cancelled in order to return to a previous level.

CASE STUDY

The developed model is able to determine optimal solutions for the thermal and electrical energy supply of city quarters. Based on an individual optimal solution for every single building the effects of a district heating network can be investigated and its optimal structure determined in case it generates economic advantages compared to the individual heating supply. So far, the model is able to handle city quarters of up to 100 households. This limitation is caused by the approach of determined optimization without using decomposition approaches.

Description of neighbourhood

To present exemplary results a particular city quarter was chosen due to its amount of available data. It consists of 15 buildings in Lampertheim, Hesse, Germany and is shown in Figure 3. The neighbourhood is characterized by open, regular construction of one- and two-family houses which were built in the 1960s. In total, 23 households are considered. Typically, the heat demand ranges from 15 to 25 MWh per annum and household, whereas the electricity demand reaches from 3 to 5 MWh per annum. Input data which were not available were replaced by reasonable assumptions. This includes the way of generating domestic hot water and the flow temperature required by the installed heating system.

The exogenous cost parameters were chosen based on the current local market prices. For the capital costs of energy and local heating infrastructure regressions were performed based on available market data and studies. For the demonstration of the model's functionality including the development of district heating network structures, no existing facilities are considered in the optimization. This is equal to the assumption that houses of this age use old heating systems whose replacement is economical feasible in most cases.

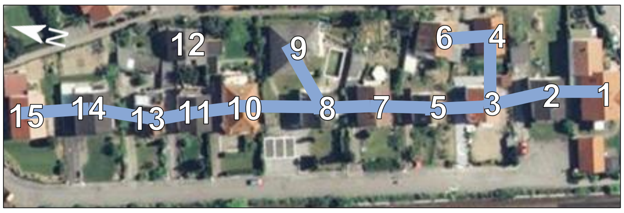

Figure 3 Neighbourhood with district heating network

Results

For the city quarter under investigation and the given input data the optimization results in the recommendation to equip all available roof area with west, south or east exposure with photovoltaic systems. Due to the warranted feed-in-tariff photovoltaic systems can operate profitably even if most parts of the converted energy are fed into the grid. However, self-use of electricity has economic advantages over the feed-in. In the current case, no CHP plants were economically feasible and therefore no further recommendations could be made despite covering the electricity demand via the grid.

Compared to a reference case with low temperature gas boilers the initial solution with gas condensing boilers and heat pumps would save approx. 10% of the total costs. This includes the exchange of old but still functioning systems. Additional investment costs are overcompensated by the higher fuel efficiency.

Derived from the initial solution for this specific neighbourhood the implementation of a district heating network has been proven advantageous over an individual heating supply as it reduces the heating costs of twenty years by approximately 9% compared to the initial solution (Figure 4). This value does not consider any price increases. In the optimal setup all buildings except building 12 are connected to the heating network as shown in Figure 3.This particular building should be fed by a heat pump as it is capable of low temperature heating. Therefore a connection to the heating network is not profitable. However, all other buildings take economical advantage from a central heating structure. For this purpose a wood chip heating unit would be installed in building 8 to distribute the heat efficiently. The result bases on the assumption that the building is capable of sufficient space for the implementation of the unit and wood chips storage.

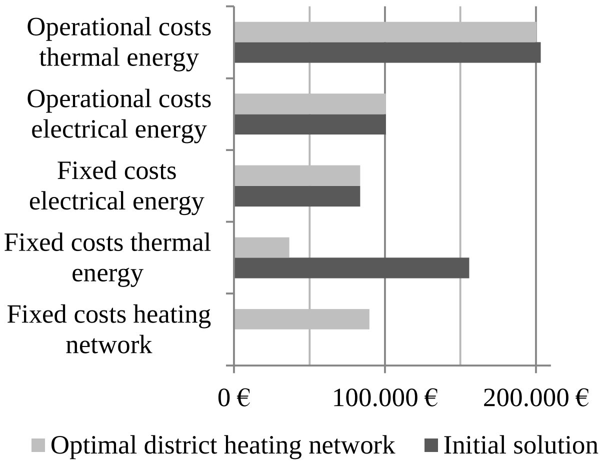

Figure 4 Comparison of costs

Despite the additional costs of the heating network, the total fixed costs for the central heating structure are lower than in case of an individual supply with regards to the economies of scale as well as lower required nominal power due to load balancing effects. Furthermore, a woodchip heating facility as technology using renewable energy sources with low operating costs can be used comprehensively. These plants are characterised by comparably high investment costs and are not operated efficiently in small individual households as they require high thermal loads.

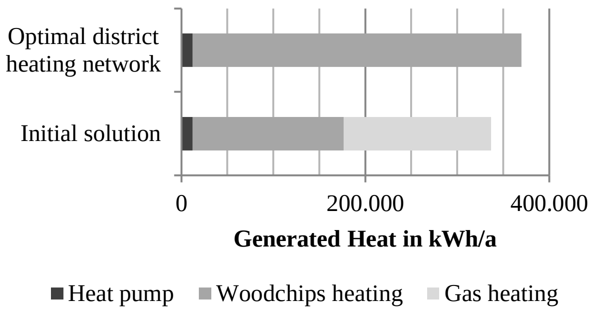

Figure 5 Impact of district heating on heat demand

However, the implementation of a district heating network does not only implicate advantages since it causes thermal losses as well. These losses amount for approximately 10% of the annually generated heat and are modelled as additional heat demand (see figure 5). As a consequence, the operational costs of thermal energy do not significantly differ from the individual heat supply solution although wood chips offer fuel cost advantages over natural gas.

CONCLUSION AND OUTLOOK

The current modelling approach allows executing calculations to determine the optimal setup of distributed energy resources and an optional district heating network. Currently the objective function aims to find the lowest total costs over a period of 20 years.

One next step will be the extension to a multi-criteria optimization where environmental factors or political goals like a guaranteed share of renewable energies in the energy supply are considered as well. In this context the endogenous consideration of the load side e.g. by integrating upgrades of the thermal insulation into the optimization model is another important step.

Finally the electrical distribution grid is assumed as capable to deal with the additional generation as well as new loads like heat pumps. In further investigations the results of models have to be examined with the approach of probabilistic load flow analysis.

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