A SPATIAL RESOLUTION IN FOUR LEVELS FOR A TECHNO-ECONOMIC MUNICIPAL ENERGY SYSTEM MODEL

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ABSTRACT
The energetic optimisation of a municipality or region requires energy system models which, besides offering a high temporal resolution, go beyond single buildings or building blocks to embrace the complexity of the system as a whole. Since the optimisation can be significantly affected by spatial effects, a spatial resolution is an important feature of such a model. This article presents a techno-economic energy system model with a spatial resolution in four hierarchic levels. The approach is applied to a real use case, comparing the system with and without spatial resolution.

The results show that the taken approach is valid, being able to incorporate spatial effects. They also validate qualitatively the expected deviations between the spatially resolved and the model without spatial differentiation.

INTRODUCTION
The transition of our energy systems towards minimal GHG emissions requires measures on all spatial scales: internationally, nationally, regionally, and locally. One of the measures to be taken is to increase the proportion of energy from renewable sources, another the extension of district heating networks in combination with higher shares of CHP, thus leading to higher efficiencies. On the demand side, energetic refurbishment of buildings can significantly reduce the energy demand for space heating. It is important to realise that many of the measures interact with each other, meaning that there are interdependencies which should be taken into account to make sound decisions. This is why a systemic approach is needed, exceeding the optimisation of solely a single dwelling or building block. While many different aspects are of importance, at least a technical and economical view should be combined, when setting up a model.

Against this background and focusing on the local and regional level, the municipal energy system model KomMod has been developed. It serves as a tool to support municipal stakeholders, namely local authorities, utilities, local companies, and politicians, in their strategic decisions with scientific expertise. The techno-economic model is characterised by a high technical, temporal and spatial resolution, covering the demand sectors heat and electricity. The latter embraces also transport based on electricity. By taking many of the occurring interdependencies into account, the model calculates overall optimal solutions for a given objective function. The model is set up completely linear, using AMPL as a modelling environment and CPLEX as mathematical solver (AMPL Optimization Inc (2015): International Business Machines Corp. IBM (2015)). The general features of the model have already been discussed in detail in (Eggers and Stryi-Hipp (2013)). Complementary, this article elaborates on the approach of a four level spatial resolution, which has been developed for and implemented in the model. A spatial resolution allows to incorporate the spatial character of many of the aspects and framework conditions of an energy system and thus often leads to more reliable results. This becomes obvious, looking at district heating and gas networks, electric grids, the differences in local renewable energy potentials, or the different building types which form a city. After giving an insight into the approach, a comparison is presented, where an energy system is calculated with and without spatial resolution. This use case is based on real data.

SPATIAL APPROACH
Requirements on a spatial approach
A suitable spatial resolution has to be able to incorporate at least the major effects which are influencing the solutions to a given problem. With respect to the examples mentioned in the introduction, this includes the differentiation of locations of demand and supply, some kind of representation of energy networks and the integration of spatial interdependencies, i.e. local potentials of renewable energy sources. Additionally, the level of detail and the effort to run the model, regarding modelling, data collection and calculation time, have to be balanced.

Existing approaches
There are two main existing approaches to integrate a spatial resolution into an energy system model. The first one implements a graph based resolution, aligning locations of demand and supply along networks for district heating, electricity or gas ((Bruckner (1997); Bakken et al. (2007); Scholz (2012)). In general, this approach allows for the integration of detailed properties and restrictions of the network. The penalty of the precision is the effort in modelling the network structure, in data requirements and in calculation time. The second approach is more generic. Locations of de-
mand and supply are displayed by areas, which might be interconnected via exchange processes. The real structure of energy networks is neglected. The model described in (Loulou et al. (2005)) is an example for this. The existence of exchange processes facilitates the representation of many different research questions beyond the focus on energy flows. For the representation of municipal energy systems though it would be helpful to have a hierarchical spatial structure.

As a consequence of the pros and cons of the two approaches, a spatial resolution on four hierarchical levels has been developed. The aim is to provide enough flexibility and precision to be able to incorporate all relevant detail from a system perspective while keeping the effort for data processing and calculation as low as possible.

Specification of the spatial approach taken

The approach for a spatial resolution used in the model structures the energy system into four hierarchical levels. The top level incorporates the whole energy system and is referred to as system level (Figure 1). It distinguishes between the affiliation to the area of investigation and the surroundings. The lower levels in descending order are zones, sub-zones and building types. They are organised in a tree structure as can be seen in the example shown in Figure 2. The complexity of the combination of the three lower levels is restricted only by computational power.

Zones allow for the differentiation of the system by a first criterion. Criterion here can also be a group of properties, not only a single aspect. The criteria for choosing zones can vary from one zone to another as long as they aren’t contradictory. So for example, in a first step, all areas, where a district heating network is available, are transferred into zones. The criterion of differentiation here is the existence and extent of such a network. The remaining area without any heating network could then be structured into additional zones by another criterion, i.e. ownership of the buildings. Within a zone, sub-zones allow for further differentiation. Thus, a zone defining an area with a heating network could be structured into a part where the network is already in place and a second part where the extension of the network should be analysed. The use of zones and sub-zones in a model is optional.

The hierarchical level of building types defines locations of energy demand. Building types can be placed on every other hierarchical level. They can represent a single, specific building as well as a class of buildings accordingly to the specification in (Loga et al. (2012)). When used as a class, i.e. single-family houses, hundreds of real buildings in one area can be gathered in one type. A mixture of both applications in the same model is possible as well. This could be used to analyse several buildings in detail while grouping the rest into classes, thus lowering the calculation effort.

A specific location is addressed by a triple of numbers giving the zone $z$, sub-zone $s$ and building type $b$ (q.v. Figure 1 and 2). The value null is used for two purposes. It addresses all parallel instances of one level together or indicates that the level is missing, respectively. An example for the first case is the triple (0,0,0) which refers to the system level. The second case occurs with the combination (1,0,2), which stands for building type 2 in zone 1. Because the value for $s$ is zero, the building type located directly in zone 1 is addressed and not building type 2 in one of zone 1’s sub-zones.

Energetic structure and interaction

Every instance of a hierarchical level forms a nodal point where a thermal ($x = \text{th.}$) and electrical ($x = \text{el.}$) energy balance are calculated for every time step $t$ (Equation 1). When using this equation, energy flows entering a nodal point or being produced within the
nodal point are required to have a positive value. Energy flows leaving the node and energy demand within the node get negative values.

\[
0 = P_{x,dem}(z, s, b, t) + \sum_{i, j} P_{x,supply}(i, j, z, s, b, t) + P_{x,imp}(z, s, b, t) + P_{x,exp}(z, s, b, t),
\forall x, i, j, z, s, b, t \text{ and } x \in \{\text{el., th.}\} \text{ and } i, j \in \{\text{components}\}
\]

The energy demand \(P_{x,dem}\) is defined exogenously and integrated as a time series into the model. There has to be one time series for every instance of a building type.

The supply side of the energy system can consist of multiple kinds of power plants, heating facilities and energy storages, grouped into so-called components. Energy processes or technologies are gathered in one component if, with respect to the given depth of modelling, their behaviour can be characterised by an identical set of physical equations. Thus a coal fired power plant with a steam cycle and a gas turbine belong to the same component despite their thermodynamic processes being totally different. The required distinction, i.e. in power output, efficiency, load acceptance rates or costs, is made by different parameter sets, deviding the component into sub-components. Equations and data, i.e. parameters sets, are strictly separated. This enables the user to add, delete or modify sub-components of existing components by solely dealing with parameter sets and without any notice or changes of the physical equations. As components are kept modular, the same is true for them, regarding changes to the rest of the model. Components and their sub-components can be placed on every hierarchical level from a building type to the system level. The supply side, including the option of energy import and export, is optimised in structure (design) and operation simultaneously according to the aims of the objective function. Energy exchange via import \(P_{x,imp}\) and export \(P_{x,exp}\) is possible along the tree structure (Figure 2). It can be restricted in power, the amount of energy, and costs. Exchange along the tree structure means that energy is exported to the superior level and also imported from there. There is no direct exchange between two parallel building types for example. For every nodal point, import and export can be combined to an exchange term \(P_{x,exch}\).

\[
P_{x,exch}(z, s, b, t) = P_{x,imp}(z, s, b, t) + P_{x,exp}(z, s, b, t),
\forall x, z, s, b, t.
\]

In case the needs of import and export of the next lower level do not even out, they result in a surplus or residual demand on the current level. For a sub-zone this can be formulated as

\[
P_{x,dem}(z, s, 0, t) = \sum_{b} P_{x,exch}(z, s, b, t),
\forall x, z, s, b, t; \ b \geq 1.
\]

On a zone level, a term for the sub-zones has to be added to the equation

\[
P_{x,dem}(z, 0, 0, t) = \sum_{b} P_{x,exch}(z, 0, b, t), \ b \geq 1
+ \sum_{u} P_{x,exch}(z, s, 0, t), \ s \geq 1,
\forall x, z, s, b, t.
\]

The resulting energy demand on the system level comprises of directly subordinated building types and zones

\[
P_{x,dem}(0, 0, 0, t) = \sum_{b} P_{x,exch}(0, 0, b, t), \ b \geq 1
+ \sum_{z} P_{x,exch}(0, 0, z, 0, t), \ z \geq 1,
\forall x, z, b, t.
\]

While the energy demand in building types always has negative values, on higher levels also positive values can occur, indicating the need of net export.

Economic structure and interaction

In parallel to the energetic relations of the different hierarchical levels, there are economic dependencies as well. For the objective of minimising the overall costs, they are concentrated in the objective function

\[
0 = P_{x,dem}(z, s, b, t) + \sum_{i, j} P_{x,supply}(i, j, z, s, b, t) + P_{x,imp}(z, s, b, t) + P_{x,exp}(z, s, b, t),
\forall x, i, j, z, s, b, t \text{ and } x \in \{\text{el., th.}\} \text{ and } i, j \in \{\text{components}\}
\]
The first two lines describe the costs due to import \( C_{\text{lev,sys}} \) and export \( C_{\text{lev,exp}} \). Via the third line the costs generated by the components \( C_{\text{lev,comp}} \) are integrated. Usually, at least investment costs, costs for operation and maintenance, and fuel costs are included here. Analogue to the concept of components and subcomponents, additional cost items can be amended without any changes in the equations by adding a new cost category and the corresponding values. All costs are calculated on a levelised annual basis as indicated by the index lev. While the objective is cost minimisation, the term costs is also used for revenues as they could occur due to exports, for instance.

**Components and data structure**

Beyond the integration into the framework of the model the spatial approach has an effect on the component models. Thus the data set of every subcomponent is divided into two parts. The first part contains properties which are location independent. This can be seen as a data sheet of a facility including specifications like power output, efficiency at full load or investment costs. The second part is specific to the location and contains for example the upper and lower bounds of the installed capacity, of the provided amount of energy and of the full load hours of each sub-component.

The optimisation of energy networks is beyond the scope of the model. Accordingly, the structure of the networks is neglected as well as temperature or pressure profiles. Instead, networks are reduced to their systemic properties and modelled as a component analogue to a facility. At present, their parameter set consists mainly of their specific length in an area and their costs. Improvements, regarding temperature losses are under progress but not fully implemented yet.

**SIMULATION**

**Set up and pre-processing**

As a use case, the spatial concept is applied to an inner-city quarter of a city located in southern Germany. It is based on a real project where recommendations for the future energy supply of the quarter have been developed, regarding two future points in time, 2030 and 2050, each over a temporal horizon of 20 years. The original spatial resolution comprises 58 nodal points. The corresponding results are compared to an identical system, aggregated to a single node, to evaluate if the approach is fit for purpose.

In the originating study, a special focus is put on the viability of extending existing district heating networks in combination with small motor based CHP plants. The system is evaluated in comparison to an option where the heating network and its facilities are kept in status quo and most of the heat demand has to be covered by decentral facilities. These two options can be regarded as variants in spatial structure. Here, only the option analysing the extension of the network is discussed.

The area of investigation has been divided into 15 zones on the basis of different criteria which have been applied simultaneously (Figure 3). The main criterion has been the existence of a district heating network. Further criteria were owner ship and the structure of the area regarding building types. Classical aspects for the planning of district heating systems, i.e. heat density, heat flux and the length of the additional piping, were taken into account as well.

The zones with grey background colour in Figure 3 indicate three areas were a heating network either exists or could be installed. Currently, CHP plants and heating networks are in place in zones 5, 7, 12, 13 and 14. In zones 12 and 13 only small changes in the network structure are considered but the networks in zone 5, 7 and 14 could be extended according to the neighbouring areas of same colour. For scenarios where the heating network is extended, the zones, were the extension takes place, are shifted into sub-zones. Thus, zones 2, 3 and 4 become sub-zones of zone 7. Zone 6 is converted into a sub-zone of zone 5 and zones 8, 9, 10 are transferred to sub-zones of zone 14. This structural change is necessary due to the fact that the facilities are considered to stay in zones 5, 7 and 14 and import and export always take place via the next higher hierarchical level.

As facilities, motor based combined heat and power plants (CHP), photovoltaics (PV), solar thermal applications (ST), electric heat pumps (HP), oil, gas and wood boilers and thermal storages (TS) are available. CHP plants are available in two options, one with a nominal power output of 300 kWel and another one with 600 kWel, depending on the local restrictions. Gas boilers also come in two variants, one with 1 MWth capacity for district heating stations and a second one with 20 kWth for distributed applications. The larger boilers have notably lower fuel costs. Import and export of electricity and fuels from the surroundings are granted but thermal exchange is not. The installation of the components is bounded according to local restrictions, regarding for example roof top areas for solar applications.

In a first stage, the building stock of the whole area is aggregated to eight building types with respect to...
the type of dwelling, its age and its state of energetic refurbishment. The resulting categories are single-family/two family houses, medium sized multi-storey dwellings, large sized multi-storey buildings, high-rise buildings and other buildings. Additionally the first three categories are split into two stages of age. Purely industrial dwellings are not in the scope of the study.

For each of the building types a SHM model is set up to calculate a time series of heating demand ((ISO (2008))). The time series for domestic hot water and electricity are calculated as well, using additional models and tools ((Jordan and Vajen (2003); Fraunhofer ISE (2014))).

To lower the size of the model, in a second stage, the eight building types and their time series have been aggregated to four building types: Single-family houses/ two family houses, medium sized multi-storey dwellings, large sized multi-storey buildings, high-rise buildings and other buildings. Subsequently, the building types are assigned to the zones and sub-zones according to their existing distribution. Combined with the restrictions on import, export and installed capacities as well as technical and cost data, the spatially resolved model is set up for the optimisation runs. The single node system is generated by aggregating the energy demand profiles to a single times series for electricity and heat and by cumulating the upper and lower limits for every component.

Results comparing the spatially resolved with the single node system

The presentation of results consists of two parts. The first part compares the spatially resolved system to the single node system on a system level. The second part goes into detail with the 58 node system, looking at the results of the nodal points.

The single node system shows 3.5% lower levelised total costs of 13.1 compared to 13.6 millions of euros per year for the spatially resolved system (Tables 1 and 2). Of the two CHP options available, only the 600 kW_{el} engine is used in the single node system, producing electricity at 81 euros/MWh. The system with spatial resolution has electricity costs for CHP of 82 euros/MWh (600 kW_{el}) and 91 euros/MWh (300 kW_{el}). PV produces for the same cost of 163 euros/MWh in both systems. Costs of electricity import are at an average of 106 euros/MWh for the single node system compared to 117 euros/MWh.

Heating costs in the single node system vary from 47 euros/MWh for heat pumps over 66 euros/MWh for CHP, 92 euros/MWh for central gas boilers with 1 MW_{th} nominal power output to 167 euros/MWh for solar thermal applications. The system with spatial resolution has slightly higher costs for every component, but the order of the facilities stays the same. Distributed gas boilers (20 kW_{th}) are the most expensive supply option (191 euros/MWh).

Both systems have a thermal demand of 76.9 GWh/a including heat losses. The electricity demand of the single node system is lower due to a minor use of
heat pumps (37.8 GWh/a vs. 41.0 GWh/a) while the amount of electricity production is very similar in both systems. For the single node system this results in a higher share of internal electricity production of 91.3% compared to 83.3% and less electricity import. Electricity export of the single node system is higher, though, in both cases, small compared to the overall internal production.

The overall installed capacity of the CHP plants, approximately 7 MW$_{el}$ and 8 MW$_{th}$, is very similar in both cases. In the single node system though, solely the larger CHP engine with an installed nominal power of 600 kW$_{el}$ is used, while in the system with 58 nodes also the smaller engine with 300 kW$_{el}$ has to be installed due to local restrictions. As its share is less than 10% of the total capacity, the resulting overall effect remains small.

In both system variants, PV and solar thermal applications are only installed to the extent of the given lower limits. The peak load of electricity import for the single node is slightly lower than for the spatially resolved system while it is the other way round for export of electricity. Thus in both cases import determines the maximal grid load.

Gas boilers are clearly dominant over heat pumps in both systems regarding capacity. Analogue to the CHP plants, solely large boilers (1 MW$_{th}$) are installed in the single node system while the 58 node system installs distributed gas boilers (20 kW$_{th}$) as well due to spatial restrictions. Distributed boilers based on other fuels, namely oil and wood pellets are available in the model but not competitive under the given assumptions.

The amount of storage capacity is 26% lower in the single node system, consisting of 41.0 MWh compared to 55.5 MWh in the spatially resolved system. Also the number of charging cycles is lower in the single node system, reaching 182 full cycles, while the system with 58 nodes ends up with 230 full cycles a year. Regarding the provided amount of energy, PV, solar thermal applications and CHP plants are in close proximity in both systems. CHP provides the main part of the electric and thermal demand. The most significant differences between both cases show in the amount of heat supplied by boilers and heat pumps.

In the spatially resolved system heat pumps contribute 28.8 GWh/a, thus delivering the second most amount of thermal energy following CHP. Boilers contribute 14.8 GWh/a. In the single node system boilers come in second with an amount of 27.3 GWh/a and heat pumps cover 16.3 GWh/a of the heat demand.

**Results for the different hierarchical levels of the spatially resolved system**

The comparison between the spatially resolved and the single node system examined the system level. Complementary, the results for the nodal points show the distribution and operation of the different facilities at each specific location. As the presentation of all 58 nodes is too bulky, only some comprehensive conclusions are discussed in brief.

Regarding the heat supply, the results for the nodal points can be distinguished in three cases. The first case are nodal points where a district heating station is located. The second case are nodes which are connected to a district heating network but don’t contain a district heating station. Nodal points which are supplied by distributed facilities form the third group. The groups differ in the combination of supply technolo-
Table 2: Key data for the system without spatial resolution (1 node)

<table>
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<td>max. 5.9 (el.)</td>
<td>4.0 (el.)</td>
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<tr>
<td>Export</td>
<td>-41</td>
<td>avg. 61 (el.)</td>
<td>max. 5.6 (el.)</td>
<td>0.7 (el.)</td>
<td>-</td>
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<td>-</td>
<td>-</td>
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<td>CHP 600 kW_{el}</td>
<td>4582</td>
<td>81 (el.)</td>
<td>7.4 (el.)</td>
<td>29.7 (el.)</td>
<td>3990</td>
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Lev. = Levellised, tot. = total, prod. = product, inst. = installed, prov. = provided, avg. = average, max. = maximum. All cost data levellised and given in €2030.

DISCUSSION AND RESULT ANALYSIS

The differences in the results between the spatially resolved and the single node system are relatively small, especially regarding the objective function subject and the installed capacities of the different facilities. The most significant differences occur in the amount of installed storage capacity and the operation of the facilities. Nevertheless, the expected deviations are clearly visible. They are mainly based on the fact that interdependencies, which are embraced in the spatially resolved system, are neglected in the single node system. So in the single node system, for instance, thermal demand which originates from zone 15 can be covered by CHP plants, despite the fact, that zone 15 doesn’t have a district heating network in real life. This leads to a lower requirement of import and storage capacity, less load cycles for the storages and less installed supply capacity. If import and export costs are time dependent, as it is the case in the example, it also trends to result in lower import costs and higher export revenues due to a higher internal flexibility. Additionally, local restrictions in the choice of facilities cannot be integrated. Thus, the fact that in some of the zones only the smaller CHP engine makes sense, is neglected. The same applies for the two boiler options, leading to underestimated costs. Differences on the electric supply side are small because the exchange of electricity between the different nodal points has not been restricted in the spatially resolved system. Furthermore, spatial differences in the distribution of the facilities and their operation become visible only in the spatially resolved system. The results thus are considered to be more realistic as additional details or restrictions can be respected.

CONCLUSION

The presented approach for a spatial resolution on four hierarchical levels enables the user to incorporate spatial differences into the energy system model. The decision to not include a graph based network structure but to go for a more generic approach seems to be valid, offering enough flexibility and precision for sound results from a system’s perspective. This could be proven by the application to a first real use case which shows promising results combined with acceptable calculation times of several hours. As next steps, the spatial approach has to be tested in more detail and...
on a wider range of use cases, starting with a higher resolved version of the system described above.

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NOMENCLATURE

\[ C_{lev,x,imp} = \text{Levellised cost of energy import} \]
\[ C_{lev,x,exp} = \text{Levellised cost of energy export} \]
\[ C_{lev,comp} = \text{Levellised total cost of a component} \]
\[ P_{x,dem} = \text{Energy demand} \]
\[ P_{x,comp} = \text{Energy supply by a component} \]
\[ P_{x,imp} = \text{Imported energy} \]
\[ P_{x,exp} = \text{Exported energy} \]
\[ P_{x,exch} = \text{Energy exchange} \]
\[ lev. = \text{Index for levellised costs} \]
\[ x = \text{Index for the demand sector (el., th.)} \]
\[ i = \text{Index for the component} \]
\[ j = \text{Index for the sub-component} \]
\[ z = \text{Index for zone} \]
\[ s = \text{Index for sub-zone} \]
\[ b = \text{Index for building types} \]
\[ el. = \text{Electric} \]
\[ th. = \text{Thermal} \]
\[ t = \text{time step} \]

* = Power or heat flux

References


Fraunhofer ISE 2014. Synthetische Lastprofile – synPRO (Synthetical load profiles, in German).


