TIME AND SPATIAL RESOLVED SIMULATION AS KEY INSTRUMENT TO DEVELOP SUSTAINABLE URBAN ENERGY SYSTEMS BASED ON RENEWABLE ENERGIES

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ABSTRACT

A growing number of cities worldwide become aware that they are key actors to tackle global challenges like climate change and energy scarcity. To support cities to become sustainable the German Fraunhofer Society on applied research formed a research network under the brand name »Morgenstadt – City of the future«. Urban energy systems are a relevant research topic since energy is very important for cities to become sustainable.

The transformation of an urban energy system to a sustainable energy system based on Renewable Energy Sources (RES) needs several years at least for large cities. New technologies, equipment and infrastructure must be developed and installed for generation, conversion, storage, distribution and consumption of electricity, heat and cold, and energy sources for transport.

At the beginning of the transformation, an ENERGY MASTER PLAN must be developed including the ENERGY TARGET SYSTEM and the ENERGY ROADMAP, which describes the path to achieve the ENERGY TARGET SYSTEM. A procedure to develop the ENERGY MASTER PLAN step-by-step is described. An extensive involvement of main stakeholders and strong governance structures are important to implement such a process successfully.

To identify the optimal ENERGY TARGET SYSTEM the ENERGY TARGET must be set precisely. Especially the origin of the RES and the balancing period must be well defined. Based on that ENERGY SYSTEM SCENARIOS can be simulated and the TARGET ENERGY SYSTEM identified.

Since the fluctuating solar energy and wind energy are usually the main RES used, temporally resolved simulations of ENERGY SYSTEM SCENARIOS are necessary. Therefore Fraunhofer ISE is developing the model »KomMod«, which allows to simulate detailed TARGET ENERGY SCENARIOS as a sound basis for decisions on the ENERGY ROADMAP.

To cover the interdependencies of the components of the energy system »KomMod« includes all four demand sectors and takes a macro-economic perspective. System design and operation are optimised simultaneously and the model is provided with perfect foresight. All components are implemented with the modelling environment AMPL, following a homogenous modelling approach and building one simultaneously solved equation system.

Keywords: urban energy system, energy system model, energy master plan, energy roadmap

INTRODUCTION

In the 21st century, mankind has to tackle serious challenges like the scarcity of conventional energy sources, scarcity of raw materials, climate change, an ageing society and growing population. A growing number of cities worldwide become aware that they are key actors to develop appropriate solutions since there is a strong tendency of urbanization worldwide. To support cities to become sustainable the German Fraunhofer Society on applied research formed a network under the brand name »Morgenstadt – City of the future« to do research in the sectors energy, buildings, mobility, water, production and logistics, security, information and communication technologies (ICT) and governance. Urban energy systems are a relevant research topic in the network since energy plays a key role for cities to become sustainable.

Smart urban energy systems based on renewable energy sources (RES) are main pillars of sustainable cities, since they avoid CO_2-emissions, mitigate climate change, generate local added value and create jobs. Due to their decentralized structure, RES enable cities to generate energy on their own area and the surrounding region and become self-sufficient.

In Germany and several other countries a growing number of cites are setting ambitious goals regarding their future energy supply. For example, the city of Copenhagen with 650,000 inhabitants set the goal to become the first carbon-neutral capital by 2025, the city of Munich with 1.4 Mio inhabitants aims to supply the whole city with electricity from RES by 2025, and in the German city of Freiburg with 220,000 inhabitants a study was conducted which explains how Freiburg can become carbon-neutral by 2050.

Several decades are necessary to transform the energy system of a larger city to a sustainable energy system based on RES. New technologies, equipment and infrastructure must be developed and installed in generation, conversion, storage, distribution and consumption of electricity, heat and cold, and energy sources for transport. To run this transformation successfully a strategic long-term approach based on a well-defined target, a transparent governance structure, a strong political commitment, and the involvement and acceptance of the important stakeholder in the city are needed.

At the beginning of the transformation an ENERGY MASTER PLAN should be developed including the TARGET ENERGY SYSTEM and the ENERGY ROADMAP, which describes the path to achieve the TARGET ENERGY SYSTEM. To support these activities a standardized procedure of developing an ENERGY MASTER PLAN step-by-step is proposed. In this process the temporally and spatially resolved model for urban energy systems called »KomMod« can be a supportive tool, which allows to simulate detailed ENERGY SYSTEM SCENARIOS as a sound basis for decisions on the ENERGY ROADMAP.

PROCEDURE TO DEVELOP AN ENERGY MASTER PLAN

The challenge for cities to develop a sustainable urban energy system is twofold.

Firstly, most of the cities and their decision-making representatives and bodies are not experienced in designing the city's energy system. Most of them delegate the right to supply their citizens with energy to a utility company. But even if a city is owner of the local utility company the energy system is usually designed by experts of the utility company and only some framework conditions are set by the politicians.

Secondly, there is a lack of experiences on how a medium-sized or large city can mainly be supplied by RES. The vision of an urban energy system mainly based on RES has been a dream already for several decades, but the conviction that this is a realistic technological option which can be achieved within a few decades even in medium-sized and larger cities in industrialized countries is only some years old based on the strong growth of RES in countries like Denmark and Germany in the last decade. Nevertheless there are various issues unresolved yet: how a sustainable urban energy system will look like in detail, which technologies will be available at which costs, how stability and security of energy supply can be assured and how the energy market must be designed.

A systematic procedure for the development of an ENERGY MASTER PLAN is recommended as shown in Figure 1. In the first phase (step 1-5) a precise long-term ENERGY TARGET SYSTEM must identified by setting a precise ENERGY TARGET and calculating the ENERGY SYSTEM

1. ENERGY TARGET setting Political decision based on stakeholder consultation	• Which energy sources, level of autonomy, CO_2-emissions • Autonomy on an annual balance or at any hour of the year • Origin of RES, how much import / export is allowed
2. Data gathering Demand: profiles Supply: potential current and forecasts	• Data from all sectors: electricity, heating/cooling, transport • Demand profiles: households, industry, institutions, … • Forecasts for development of efficiency, demography, population, economic growth, …
3. Simulation of ENERGY SYSTEM SCENARIOS Which energy system will meet the demand	• Identifying the solution space: Temporally and spatially resolved simulation of the energy system to identify possible energy systems for different sets of framework conditions • Sensitivity analysis on changes in framework conditions
4. Assessment of the ENERGY SYSTEM SCENARIOS Advantages and drawbacks	• Economic, social, technological and environmental advantages and drawbacks of the energy system scenarios • Robustness (flexibility to react on changes of conditions)
5. Decision on a TARGET ENERGY SYSTEM Based on extensive stakeholder consultations	• Stakeholder forums to explain the options for the energy system, their advantages and drawbacks • Identify the most practical scenario with the highest acceptance of the citizens and stakeholder groups
6. Development of the ENERGY ROADMAP Implementation plan for the Target Energy System	• Defining subprojects, evaluation of costs, time, resources, know-how and requisites to implement them • Business models, communication, lighthouse projects,… • Governance of the transition process, responsibilities
7. Monitoring concept Periodical review of the process and the targets	• Definition of key indicators and data sets collected • Frequency, structure and transparency of reporting • Resources needed for reporting
8. Final decision on the ENERGY MASTER PLAN Based on extensive stakeholder consultations	• Structuring the subprojects to a comprehensive Master Plan, defining involved actors and necessary budgets • Improving the Master Plan by stakeholder consultation • Aiming for a decision based on a high acceptance of the citizens and stakeholder groups
9. IMPLEMENTATION	

Figure 1: Procedure of the development of an ENERGY MASTER PLAN

SCENARIOS, with which the target can be achieved. This task is challenging, since the results are dependent on the predictions on the framework conditions e.g. the influence on the energy demand by improving efficiency, ageing society and growing or shrinking population. In the second phase (step 6-8) the ENERGY ROADMAP must be developed describing the steps to implement the TARGET ENERGY SYSTEM. In the third phase the ENERGY ROADMAP will be implemented.

Several aspects must be considered by implementing such a process. It must be accepted that it is not possible to identify the optimal TARGET ENERGY SYSTEM since a lot of conditions are unknown for the target year or not precisely predictable, regarding the development of the socio-economic data as well as of the available technologies. Therefore robust development paths must be identified and the implementation plan and its underlying assumptions must be regularly revised based on the progress achieved. This underlines the high importance of implementing a monitoring system (step 7) for energy consumption and CO_2-emissions to be able to measure the progress. Such a fundamental transition needs a strong backing by the majority of the citizens. Therefore, the ENERGY MASTER PLAN must be developed in an extensive stakeholder process to take into account the views of all stakeholder groups to get a high acceptance and a strong support for the implementation.

HOW TO IDENTIFY A TARGET ENERGY SYSTEM

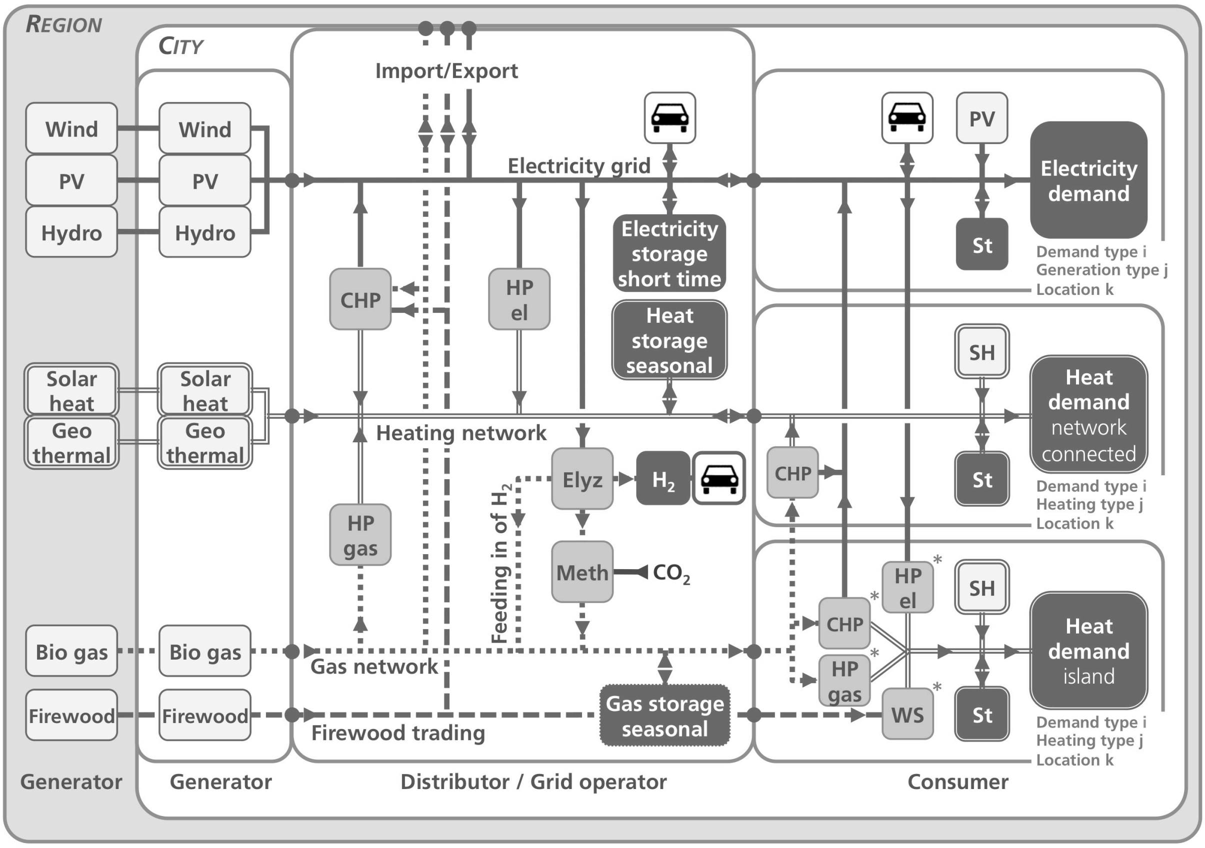
Already the first step of the ENERGY MASTER PLAN development, the ENERGY TARGET setting is challenging. Typically a target like »Carbon-neutrality by 2025« or »100% RES by 2050« is set by a city. Since the corresponding TARGET ENERGY SYSTEM which fulfils this target is very much dependent on the set of boundary conditions like the definition and acceptance of carbon-neutral energy sources (nuclear power, waste incineration, fossil fuel with CCS or RES), the origin of the RES and the balancing period, these conditions must be defined precisely. Some consequences of different definitions are shown in Table 1.

Balancing period→ **Origin of the RES↓**	**Energy supply and demand balanced over the year**	**Energy supply and demand balanced every hour**
RES only from the city area and its surrounding region	CALCULATED LOCAL AUTONOMY Feasibility dependent on local RES (e.g. availability of wind power); large storage capacity or complementary energy generation needed in other regions to compensate seasonal imbalance;	TRUE LOCAL AUTONOMY Very difficult to achieve at least for larger cities; large on-site seasonal storage capacity needed; not optimal from the macroeconomic standpoint;
RES partly imported from other regions of the country	CALCULATED LOCAL AUTONOMY WITH NATIONAL RES IMPORT The use of RES from other regions of the country reduces seasonal imbalance and the need of storage capacity; beneficiary from the macroeconomic standpoint;	Not reasonable
RES partly imported from other countries	CALCULATED LOCAL AUTONOMY WITH INTERNATIONAL RES IMPORT Attractive RES sources in other countries can be used (e.g. solar power in southern Europe); transmission lines are needed; import dependency is increasing;	Not reasonable

Table 1: Types of ENERGY TARGETS *for an urban energy system*

To define the optimal TARGET ENERGY SYSTEM first the solution space must be identified by modelling ENERGY SYSTEM SCENARIOS, which correspond with the ENERGY TARGET. Based on well-defined criteria (e.g. costs or acceptance) the optimal TARGET ENERGY SYSTEM must be selected. How such a TARGET ENERGY SYSTEM principally looks like is shown in Figure 2. This graph shows that in energy systems with a high share of RES the energy sectors electricity, heating and cooling and gas are highly integrated and interacting strongly.

Since potential analysis shows that usually the fluctuating solar energy and wind energy are the main RES used, temporally resolved simulation of ENERGY SYSTEM SCENARIOS is necessary to identify the share of the different RES, the storage capacities and import/export of energy sources needed. Heating and cooling networks will play an important role in such systems since they allow the use of larger combined heat and power units, the transport of heat generated by RES to city areas without space of solar thermal collectors and the integration of large seasonal thermal storage. Therefore also spatially resolved simulations of ENERGY SYSTEM SCENARIOS are necessary as well.



HP el/gas = Heat pump electric / gas, CHP = Combined heat & power, WS = Wood stove, St = storage, SH = Solar heat,
Elyz = Elektrolyzer, Meth = Methanation - Heat generators with * are alternativ (one generator per building)

Figure 2: Structure of an urban energy system based on 100% RES

THE URBAN ENERGY SYSTEM MODEL »KOMMOD«

For the identification of optimal TARGET ENERGY SYSTEMS, Fraunhofer ISE is developing the urban energy system model »KomMod«, which allows to simulate temporally and spatially resolved ENERGY SYSTEM SCENARIOS [1]. »KomMod« is meant as a strategic tool, supporting cities with the structural analysis of their energy system and resulting strategic decisions. A major aspect within this task is the consideration of multiple interdependencies. Cross-sectoral interdependencies occur between all four demand sectors (electricity, heat/cold, natural gas, and (local) transport), intra-sectoral interdependencies between different technologies, and furthermore interdependencies between structure (design) and operation of the components of an energy system as well as dependencies between technical and economical aspects have to be taken into account.

To cover these interdependencies »KomMod« includes all four demand sectors and takes a macro-economic perspective instead of calculating solutions optimal only for single stakeholders. System design and operation are optimised simultaneously and the model is provided with perfect foresight. This means that the model is able to adjust both, the capacities of the technologies used as well as their operation, under the premises of knowing the energy demand for every future time step, until it finds a well-balanced optimum. This process is dynamic in the way that the requirements of future time steps are already taken into account for current decisions. In contrast to short term operation planning, for strategic decisions it is sufficient to model every time step as a point of steady-state operation thus meaning that the dynamic behaviour of the components is only partly integrated.

All components are implemented with the modelling environment AMPL, following a homogenous modelling approach and building one simultaneously solved equation system. Technically, the component models include part-load efficiencies, load acceptance rates, minimal charging levels (reducing the net capacity of a storage) and self-discharge of storages for example. Grouping technologies into components of similar physical behaviour allows for their description with identical equations while differences between the elements of a technology are expressed by a change in the parameter sets.

To be able to model the requirements of high shares of RES properly, the temporal resolution is set to an averaging period of one hour, intended to be reduced to 15 minutes. This also enables »KomMod« to provide answers to questions with respect to the amount and operation of short-term storage. The spatial division into zones, sub-zones, and building types provides a finely graded basis to adjust the model to the specific needs of the respective municipality.

As a result »KomMod« enables the user to analyse and optimise urban energy systems and identify the optimal TARGET ENERGY SYSTEM. Different scenarios of possible technical, economical and/or socio-economic developments and their assessment as well as recommendations for the capacity and number of facilities to be installed, the relevant time series for their operation, and cost data can be included in the calculations.

CONCLUSION

The transformation of their energy system is a key element for cities to become sustainable. As a solution, a concept of an urban energy system based on renewable energy sources (RES) is presented. A standardized step-by-step approach is proposed to develop an ENERGY MASTER PLAN, including the TARGET ENERGY SYSTEM, which defines the target and the ENERGY ROADMAP, which describes a robust path to implement the concept. To identify the optimal TARGET ENERGY SYSTEM, temporally and spatially resolved simulations of ENERGY SYSTEM SCENARIOS are necessary. With the urban energy system model »KomMod«, Fraunhofer ISE provides a tool for cities to plan the transformation of their energy system on a sound basis.

REFERENCES

[1] J. B. Eggers, G. Stryi-Hipp: KomMod as a tool to support municipalities on their way to becoming Smart Energy Cities, Proc. of the Sustainable Building Conf. 2013, Graz, 2013.