Abstract

The world has never been more urbanised, and urbanisation rates are still growing. Climate change on the one hand and air pollution, on the other hand, are resulting in adverse effects on the society. Nowadays, the majority of energy consumption occurs in cities, which are central parts of the overall economic activity. Constant changes in urban form, rising urbanisation rates, need for cleaner energy sources, variability in energy generation and rising economic output all contribute to the complexity of the urban energy transition. The solution for the future urban energy supply is further complicated by the interdisciplinarity of the urban transition. Energy engineers, mechanical engineers, civil engineers, architects and social scientists and others all have specific, and often different, objectives and approaches when focusing on the urban energy transition.

This thesis is focused on the technical aspects of the urban energy transition, the role of different technologies in the future urban energy supply, flexibility sources in urban energy systems, the role of district heating and district cooling in an urban context, the role of different storage types, the role of biomass in an urban context, energy transition of the mobility sector and optimal set-ups of future energy systems. It is a result of collaboration with many different researchers, industry and institute representatives. In order to deal with the energy transition in different contexts and case studies, three different models were used in this PhD thesis, both simulation and optimisation ones. One linear optimisation model was developed as a part of this thesis, to allow for specific modelling of different storage types, flexibility technologies, demand-response techniques and relations between different energy sources and technologies.

Results of several different case studies, from three different continents, showed that the urban energy transition is possible in different locations, albeit with different optimal mixes of different technologies. An important aspect that connects all the solutions is the need for integrated and holistic energy planning, as the sectoral integration of urban energy systems provides the flexibility needed for integrating large shares of variable renewable energy sources. Variable renewable energy sources can be integrated into the energy sources via different flexibility techniques: different storage types, import/export of electricity over the system boundary, demand-response technologies and power-to-heat and power-to-gas technologies. All four flexibility options were addressed in this PhD thesis and quantitatively evaluated. Optimal shares of thermal energy storage were usually higher than the capacity of other storage types. Urban energy systems integrated with the surroundings of a city, contrary to the notion of a self-sustainable city, yielded significant savings in socio-economic terms. Different demand-response technologies were tested in this thesis, and they all had a role in an optimal urban energy system of future: flexible demand for electricity in industry and buildings, as well as flexible district heating demand. The latter was achieved in this thesis by utilising thermal building mass for storage, with and without preheating, depending on different scenarios. It was further shown that district cooling could play a significant integrating role of variable renewable energy sources, in a similar manner to district heating. Nevertheless, it was also shown what the optimal levels of energy efficiency measures in terms of socio-economic costs in the urban context are, and what the optimal shares of individual and district energy supply in an urban context are.

The energy transition of the transport sector proved to be challenging. It was shown that everything that can be electrified should undergo electrification. However, parts of the transport sector that cannot be directly electrified will impose significant energy demand on the system. Several alternatives were investigated, and both biofuels and synthetic fuels produced via electrolysers and synthesis proved to be challenging regarding sustainably utilising available resources.

The role of biomass in future urban energy systems was one of the core aspects of this thesis. Although disputed by different scientific articles, as discussed in this PhD thesis, the burning of biomass is often counted as a carbon-neutral source, if the total amount of living biomass compared to the previous year is not decreasing (e.g. the European Commission and the US Environmental Protection Agency follow this approach). Biomass can be further utilized for dispatchable biomass power plants. It can also be used for cogeneration plants and heat-only boilers, as well as for biofuel production. Papers that focused on the large-scale case studies in this PhD thesis showed that biomass demand will be significant in the future and it will be essential to constrain its excessive use that would make biomass unsustainable regarding climate change. Worryingly, biomass can be performing poorly regarding air pollution (SOx, NOx and particulate matter emissions), resulting in negative externalities imposed on the society, which was discussed in this PhD thesis. When seeking for the climate-friendly solution in terms of CO_2 emissions, it is important not to neglect the aspects of the air pollution.

Furthermore, it was shown that power-to-heat and power-to-gas-to-power technologies could play an important integrating role between different energy sectors in the future urban energy systems. A significant contribution from this PhD thesis was to quantify the potential of electrolysers and fuel cells from the system point of view.

This PhD thesis provided several solutions for urban energy transition from the technical point of view, detected important interactions between different energy sectors, pointed to the usually less emphasised problems and opened several questions for future research, among others the energy transition of the heavy transportation modes and the assumption of carbon neutrality of biomass. This thesis will hopefully contribute to the discussion on urban energy transition, the role of different storage types, air pollution in cities and the modelling approach(es) of urban energy transition.