Towards 100% renewable energy supply for urban areas and the role of smart control

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Abstract

In the Netherlands, 60% of the consumed energy is for the thermal demand of buildings and industrial processes. More than half of this is for heating purposes of the built environment, predominantly by natural gas boilers. At present, only 4.5% of the primary energy input is from renewable energy sources. Recently, integration of renewable energy in the built environment and increasing energy efficiency of buildings are receiving much attention. Policies of the Dutch government are aimed at phasing out the use of natural gas for heating buildings entirely within a time period of 40 years. This will lead to a larger amount of district heating projects and heat pump installations the coming years, using renewable sources as bio-based fuels, solar PV, wind turbines, waste heat streams and underground thermal sources.

Besides a shift from fossil towards renewable energy supply, often in the form of electrical energy generation (solar PV and wind turbines), part of the demand is also being electrified, e.g. heat pumps for the thermal demand and electric vehicles for transportation. As a consequence, the existing electricity grid experiences increasing demand and supply peaks due to fluctuating generation and fluctuating demand patterns. To overcome this, energy storage and smart control of devices can offer flexibility which may avoid problematic supply and demand peak loads.

As renewable energy is generated on decentral levels in the vicinity of the real demand, regional and local energy generation, storage technology and smart control receive increasing attention. For these decentral energy systems, renewable energy supply and expected demand patterns determine which generation and storage capacity and which control scheme is as optimal as possible. This thesis is dedicated to the development of tools for these aspects and demonstrates how smart control leads to near optimal capacities and operation of renewable energy system assets.

The thesis is centered around a smart grid demonstration project called "Meppelenergie". The purpose of this project is to demonstrate a completely renewable energy system for a new built district in which a biogas cogenerator supplies thermal energy for a district heating system and electrical energy for a group of heat pumps. The goal is to determine optimal capacities and control of generation and storage assets. Models for household space heating and cooling demand are developed, also for household hot water and electricity demand and for the state of charge of a thermal storage and electrical batteries. Of particular interest is the possibility to store thermal energy within concrete floor heating systems for which a model is developed and effects on thermal comfort and costs for residents are investigated. Within the thesis, the models are either used to generate demand patterns or for model predictive control as part of smart control methods.

To determine optimal capacities of assets for two urban energy cases, a case specific model and a generalized system model are developed. The generalized model includes prioritization of energy generation and storage and can be applied to analyze specific urban energy cases. For one case, the hourly energy exchanges with the power grid are investigated and the possible improvements when smarter control methods are used. For this case, three possible system layouts are investigated with the goal to reach 100% renewable energy supply. The costs and environmental performance of these layouts are compared. This analysis also considers newly built districts from 2020 when Near Zero Energy Building standards are mandatory. Of special interest is the question whether to invest in district heating or in individual heating systems in such cases.

The urban energy case analysis shows that smart control, e.g. of storage devices and generators, is beneficial to keep grid exchanges within permitted boundaries or to eliminate them totally. To study this in more detail, a model predictive control method is developed for a specific case: controlling a central co-generation unit and a large group of heat pumps for the "Meppel-energie" project. The control method is verified on computational effort and performance in terms of reaching the control objectives, thermal comfort and on/off switching behavior of the devices. Next to the Meppel case, a small neighborhood of 16 houses with a central co-generation unit, solar PV, electric batteries and some flexible appliances is investigated. Of particular interest is the possibility for near off-grid operation with this energy system through smart control.

In relation to the control problem of renewable energy powered, urban energy systems, the thesis shows that smart control is effective if: (a) the control is able to forecast demand and generation of renewable sources, at least a couple of hours ahead, and (b) the control objective is aimed at making use of renewable energy sources as much as possible while maintaining acceptable comfort for residents. Also, it is demonstrated that smart control could lead to higher costs for residents than conventional control methods which should be avoided by dynamic energy tariffs. For predictions of household energy consumption, the thesis shows that there are methods available which avoid gathering privacy sensitive information from households on aggregated levels.

The urban energy case analysis demonstrates a method to determine optimal capacities of generators and storage facilities and shows which smart energy control functionality should be implemented to avoid peak grid loads. In theory this should lead to less grid related investments and prolonged service life-time of energy system related assets. Besides that, the smart heat pump control case shows that thermal comfort for residents can be improved while reducing their energy costs.