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Smart energy system design for large clean power schemes in urban areas

Peter D. Lund*, Jani Mikkola, J. Ypyä

Aalto University, School of Science, P.O. Box 14100, FI-00076 AALTO, Espoo-Otaniemi, Finland

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ABSTRACT

Urban areas play a key role in climate change mitigation. We investigate here energy systems design to increase the use of renewable electricity (RE) such as photovoltaics and wind power in cities. We analyzed the hourly temporal and spatiotemporal energy demand and supply patterns in Delhi, Shanghai and Helsinki to understand how energy systems respond to high RE shares, and to determine realizable levels of RE power. The results indicate that if limiting the RE output to the instantaneous power demand, a 20% yearly share of electricity could be reached. Increasing the RE beyond this limit without a smart design adds only limited benefit. Adding short-term electrical storage could increase the RE share of power in Shanghai to 50–70%, in Delhi to 40–60%, and in Helsinki to 25–35%. An electricity-to-thermal conversion strategy in which surplus RE power is utilized for heating, enables to increase the wind power use in Helsinki up to 64% of the yearly electricity demand, but in addition, to cover 30% of the yearly heat demand. Such a scheme would add ca 10% to the overall wind power investment. A high RE share affects the existing power mix and the plant capacity factors, which need to be re-optimized. In the above cases, RE replaces fossil fuel and coal power plants and therefore the CO_2 emission reductions from smart design are proportional to the RE shares shown. Smart energy system design could help mainstreaming renewable electricity as part of the cities' carbon reduction strategies.

1. Introduction

Urban areas will become increasingly important for climate change mitigation due to the rapid urbanization. During the next 20–25 years, the cities' share of the energy demand and carbon emissions will approach the 80%-mark (IEA, 2008). Urban lifestyles heavily rely on electricity and mobility, often provided through fossil fuels such as coal and oil which combined stand for 80% of all energy-related carbon emissions (IEA, 2013). Countries with many mega-cities such as China and India play a key role in this context as close to 80% of their domestic power generation is based on coal (IEA, 2013). But also in highly industrialized countries that prioritize sustainable energy, fossil fuels may play a major role in cities. For example, in some Nordic cities the share of fossil fuels in energy production may be considerable, though they often employ co-generation and district heating characterized by a high fuel efficiency. For example in Copenhagen (Denmark) the share of fossil fuels in district heating is 46% (2010) and in Helsinki (Finland) the share in energy production is >80% (Helsinki Energia, 2013). Still both cities target to be carbon-free by 2050.

Designing clean and sustainable energy solutions for cities is therefore of high priority (Suzuki et al., 2010). The rapid market penetration of new energy technologies such as solar and wind power (IEA, 2013), or distributed clean power technologies in general, could well fit into city-scale and provide the basis for a low-carbon society and could be complementary to other renewable energy forms such as bioenergy or bio-waste. However, a major challenge with such distributed clean power schemes, when applied in large scale, is their integration into the energy system and to manage the variable renewable electricity supply (IEA, 2009). Smart grids could provide the necessary interconnections and control, but their capability to cope with a high share of variable renewable energy depends on the mismatch between the power demand and supply. We recognize that in theory energy storage may be an ideal solution to systemic issues such as variability and power flexibility, but the magnitude and spread of the

Abbreviations: Avg, average; c, curtailment level; CHP, combined heat and power; COP, coefficient of performance; ETT, electricity-to-thermal energy conversion; P, energy production; PV, photovoltaics; Q, energy demand; RE, renewable energy or electricity; s.f., solar fraction; SG, smart grid; STO, storage; t, time; x, space coordinate; y, space coordinate; σ, standard deviation.

* Corresponding author. Tel.: +358 40 5150144.
E-mail addresses: peter.lund@aalto.fi, peter.lund@tkk.fi (P.D. Lund).

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mismatch may determine whether a storage option is practical or not. One of the aims of this paper is to investigate up to what point of urban renewable electricity utilization could an electrical storage still be feasible, but we also look for more advanced system approaches such as conversion of surplus renewable electricity into thermal energy to overcome issues with high shares of new renewable energy technologies.

We notice the ample literature available on smart grids (SG) as a solution for renewable energy (RE) integration (Cardenas et al., 2014), advanced strategies such as electric vehicle-to-grid strategies to reduce losses with RE and SG (Görde et al., 2012), the use of co-generation or optimal sizing algorithms for better power management (Andersen and Lund, 2007), re-optimization of the existing power mix with RE power (Lund et al., 2012), grid stability (Lund, 2005), the importance of better metering to accomplish sustainability (O'Driscoll et al., 2013), different approaches to increase the capacity factor of RE (Mohammad Rozali et al., 2013; Xydis, 2013), multi-energy carriers (Geidl and Andersson, 2007), converting surplus RE power to gas (Niemi et al., 2012), and even large super-grids providing spatial compensation of RE (Battaglini et al., 2009; Purvins et al., 2011). Our approach differs from these in that we look on the integration issue more from the side of the energy end-use than just from the production side. Considering a whole urban energy system instead of a single or a few buildings, provides several systemic benefits, e.g. smoothing effects (IEA, 2009; Lund, 2012). We employ in the analyses a mid-size North European city, Helsinki (Finland) and two Asian mega-cities, Shanghai (China) and Delhi (India), to cover the two ends of both urban size and climatic conditions. Integration of high shares of renewable energy on a country level has earlier been studied e.g. in Denmark (Lund, 2010a; 2010b).

Excluding the transport sector, electricity typically stands for 20–35% of the final energy in the built environment, whereas 50–80% of the end-use is in the form of thermal energy (heating, hot water, cooling) (WBCSD, 2009). Therefore, running the electric and thermal energy system in parallel could offer an alternative buffer for varying clean power production, e.g. by converting the RE that exceeds the self-use limit of electricity into thermal energy (ETT strategy) (Lund and Mikkola, 2013). It is also well known that thermal energy is much easier and cheaper to store than electricity. In this way the nominal size of the clean power system could be oversized, helping also to reach a notable RE share during modest solar or wind conditions.

Employing electricity-to-thermal conversion for RE schemes have been previously studied more from a top-down perspective on a national (Kiviluoma and Meibom, 2010) and regional energy planning (Mathiesen and Lund, 2009) level employing macro-level energy system modeling tools. We take a bottom-up approach in which the cities' energy systems are modeled in detail both spatially and temporally enabling to identify systemic bottlenecks or finding systemic solutions for large-scale RE integration, and to better understand how much RE could be utilized in an urban district. We employ Helsinki (Finland) that has a large heat demand and a well-established district heating network as the primary case for the ETT analysis. Both thermal and electric energy flows are considered.

In summary, we aim here at finding solutions to increase the share of renewable electricity use in urban areas beyond the traditional self-use limit of power by introducing advanced strategies for managing the RE power output. The focus of the analysis is on electric storage and electricity-to-thermal energy conversion of surplus RE. The effects of these options on the existing urban energy production systems will also be analyzed. The paper starts by describing the characteristics of urban energy and the analysis method used in this study followed by the results and conclusions.

2. Urban energy characteristics

An urban energy system is a complex networked system consisting of individual load and energy production units spatially distributed, which may be connected to each other through networks. Traditional power production is typically centrally located, whereas renewable electricity could be both distributed (e.g. PV or small-scale wind power) and centrally located (e.g. large off-shore wind power farms).

The energy demand of an urban area depends on several factors such as weather, economic activities, city typology, infrastructure, etc. but typically the peak demand occurs in the city center declining towards the outskirts (Larivière and Lafrance, 1999; McDonald, 1989). Also, cultural differences may explain city typologies, e.g. Asian and European cities tend to be more concentrated than the North-American ones. Sometimes there may be several localized peaks in the demand pattern, e.g. through industrial zones, suburbs or concentration of shopping areas (O'Sullivan, 2009). Thus both the thermal and electric power density may vary considerably within a city and between cities, both in time and space.

We employ here an in-house simulation tool (Niemi et al., 2012; Mikkola and Lund, 2014) to generate the necessary load Q(x,y.t) and the energy production profiles P(x,y,t) for each hour of the year. For temporal resolution in the energy modeling, an 1 h time step is mostly adequate, even though in some transient analysis a shorter step may be necessary. For spatial resolution, varying $dx \times dy$ dimensions are often necessary due to the strong heterogeneities in a city, but depending on the city size the steps could be between 100 m and 5000 m. The spatial distribution of the RE schemes can be arbitrarily chosen, but it is also necessary to consider the carrying capacity of the distribution networks, e.g. the electric grid, which may require a more sophisticated RE layout than just even distribution over the city. A good starting point may be to locate the RE power close to the high-demand sites, or strong networks (Niemi and Lund, 2010).

The method used here is a top-down model which is able to generate micro-level urban energy profiles from macro-level input data. The method is documented in (Mikkola and Lund, 2014) and the placement strategies of the RE schemes are described in Lund et al. (2012).

Fig. 1 illustrates the spatio–temporal profiles from an hour-by-hour simulation for Helsinki, which we will use later in the urban energy analysis. The peak heat demand in the winter is 160 MW/km^2 and the peak electric power is 80 MW/km^2, both found in the city center. Minimum hourly load values occur in the summer time and during the nights.

3. Approach

In an energy system with smart grids, demand side management (DSM), and smart control, both the energy supply and load can be controlled up to a certain point to improve their matching. Here we keep the load Q(x,y,t) unchanged as given by the simulation, e.g. as in Fig. 1, but the supply P(x,y,t) can be varied. P can furthermore be split into the traditional and renewable energy parts. All renewable energy is here in the form of electricity.

At the self-use limit of electricity $P = Q$ if allowing for spatial transfer of power throughout the city. If $P > Q$ then surplus of RE is produced. The surplus $P–Q$ could be transferred outside the city through the transmission network, but it could also be stored locally as electricity (e.g. battery) or converted through the ETT strategy into thermal energy if e.g. trying to avoid any large-range effects from large RE schemes. If the surplus exceeds the thermal energy demand, a part of it could be stored (e.g. in a water heat