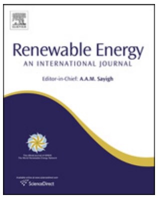
Renewable Energy 48 (2012) 524–536

Contents lists available at SciVerse ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene



# Urban energy systems with smart multi-carrier energy networks and renewable energy generation

R. Niemi, J. Mikkola, P.D. Lund*

*Aalto University, School of Science, P.O. Box 14100, FI-00076 Aalto (Espoo), Finland*

ARTICLE INFO

*Article history:*
Received 30 December 2011
Accepted 30 May 2012
Available online 5 July 2012

*Keywords:*
Energy networks
Renewable energy
Distributed energy generation
Smart city
Smart grid
Multi-energy

ABSTRACT

Employing different energy carrier networks in connection with distributed renewable energy generation is an attractive way to improve energy sustainability in urban areas. An effective option to increase local renewable energy production is to convert surplus electricity into e.g. thermal energy. Here a methodology to study such multi-carrier urban energy systems is presented which enables to analyze spatial energy demand and supply, and spatial energy flows. The results indicate that in a northern midsized city wind power coupled both to an electric grid and a district heating network could raise the allowable wind capacity over the non-heat case by 40–200%. In an Asian megacity dominated by cooling demand, employing dispatched local photovoltaics and tri-generation could cover even beyond 30% of all energy demand and lead to major carbon emission reductions.

## 1. Introduction

Climate change and energy security are among the central factors that will shape the energy systems world-wide. The built environment stands for close to half of all energy use and emissions, and hence this sector will be of central importance for finding solutions to the grand challenges ahead [1]. In industrialized countries 80% and globally 50–60% of the carbon emissions need to be cut by 2050 [2]. Much of the necessary changes to meet these goals in urban context will come through new and renewable energy technologies combined with energy efficiency. For example, the European Union foresees that all new houses from year 2020 onwards could be almost emission free and incorporating on-site renewable energy production [3]. In China, eco-cites with 70% less energy demand than usual and almost carbon-free in operation have been planned [4]. Many other such examples can be found world-wide [5,6].

Finding sustainable energy solutions for urban regions is also important due to the rapid urbanization of the developing world. Half of the world's population is now living in cities, but this may increase up to 70% by 2050 [7]; in the industrialized countries this share may then exceed 85%. This shift will put high pressure on energy demand and how to satisfy it in an environmentally benign way.

There are a range of well-known sustainable energy technology options for urban regions ranging from local renewable energy utilization to more efficient fuel use such as co-generation [6]. Solar energy, both as a thermal and an electric option, is well suitable for the built environment. In particular building integrated solar photovoltaics (BIPV) is a highly promising urban energy option requiring hardly any new infrastructures and offering synergies with building components. Considering the fast growing PV market and declining prices could lead to a major energy impact [8,9]. Contrary to fuel based energy production, renewable electricity, in particular intermittent sources, may require more advanced balancing options, consideration of the inherently lower power density, and management of highly dispersed production capacity. Such requirements could be met with smart grids or networks [10]. From a resource point of view, the adequacy of local renewable sources may be a less critical factor: for example in Manila with one of the highest population densities ($\sim 25$ $m^2$/cap), highly integrated future BIPV systems ($\eta = 20\%$) could produce electricity up to 10 MWh/cap which exceeds by more than an order of magnitude the average electricity demand (0.6 MWh/yr) [1].

The objective of this study is to find more optimal sustainable energy solutions for urban areas as a whole based on (renewable) distributed energy production and employing intelligent energy networks striving for high on-site generated energy share. Another target is to employ cost-minimizing system planning baselines for given boundary conditions. We consider here different final energy forms (heat, cooling, electricity, fuel/gas) simultaneously as well as their spatial transport through multi-carrier energy networks to

---

* Corresponding author. Tel.: +358 40 5150144; fax: +358 9 4513195.
*E-mail addresses:* peter.lund@tkk.fi, peter.lund@aalto.fi (P.D. Lund).

0960-1481/$ – see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.renene.2012.05.017

**Nomenclature**

| | |
|---|---|
| $c_P$ | Heat capacity (J/kg K) |
| $C.C'$ | Power exchange terms (W) |
| $d$ | Pipe diameter (m) |
| $\Delta D$ | Distance of a node from the energy interconnector (m) |
| $E$ | Energy production (W) |
| $h$ | Heat loss factor (W/m$^2$K) |
| $H$ | Enthalpy (J/kg) |
| $I$ | Current (A) |
| $L$ | Length of distribution line (km) |
| $\dot{m}$ | Mass flow (kg/s) |
| $p$ | Pressure (Pa) |
| $P$ | Maximal power density (W) |
| $q$ | Power allocated for exchange (W) |
| $Q$ | Energy demand (W) |
| $r$ | Distance from city center (km) |
| $R$ | Resistance (Ω) |
| $S$ | Stored energy (J) |
| $t$ | Time (s) |
| $T$ | Temperature (°C) |
| $U$ | Voltage (V) |
| $v$ | Flow velocity (m/s) |
| $Z$ | Heat transmission limit after which the temperature begins to rise in the pipe (W) |
| $\alpha$ | Width parameter |
| $\beta$ | Time specific variable |
| $\eta$ | Efficiency |
| $\varphi$ | Power factor |
| $\rho$ | Density (kg/m$^3$) |
| $\xi$ | Drag coefficient |
| $\phi$ | Transmission of power (W) |

*Abbreviations*

| | |
|---|---|
| BIPV | Building integrated photovoltaics |
| CHP | Combined heat and power |
| $CO_2$ | Carbon dioxide |
| DEGS | Distributed energy generation system |
| DH | District heating |
| EIN | Energy interconnector node |
| E-to-H | Electricity to heat conversion |
| ICT | Information and communication |
| PV | Photovoltaics |
| SOFC | Solid oxide fuel-cell |

*Subscripts*

| | |
|---|---|
| $a$ | Ambient |
| env | Environment |
| $i, j$ | Node ($x$ and $y$ coordinate) |
| $m$ | Load component |
| in | Input |
| out | Output |
| th | Thermal |
| tot | Total |
| I | First-law efficiency of thermodynamics |
| II | Second-law efficiency of thermodynamics |

*Superscripts*

| | |
|---|---|
| $k, l$ | Final energy forms |
| boiler | Boiler or furnace |
| cool | Cooling |
| elec | Electricity |
| fuel | Fuel |
| heat | Heating |
| heat pump | Heat pump |
| loss | Losses |

cover the different energy demands in the built environment, but we exclude the transport sector here. Conversion between different energy carriers enables to address the energy efficiency aspect (e.g. co-generation or tri-generation) as well.

We employ here a modeling approach in which the urban area is covered by both energy consumption and production nodes connected together by energy networks which enable spatial energy flows. Active injection and extraction of energy into the networks takes place locally, though being backed-up with a centralized production scheme if necessary. In this way, a city turns into a highly dynamic energy system in which local demand and supply imbalances are getting better matched than in traditional more static top-down energy systems enabling at the same time a high share of local energy production. In addition, we incorporate intelligence (smart networks) and advanced components to the system such as energy storage and electricity-to-thermal conversion technologies.

The concept and modeling of urban or distributed energy and energy networks is by no means new [11]. The literature on this subject is ample and just some high-lights relevant to this study are given here. In particular on the electricity side, much work on distributed electricity production systems and their issues has been done [12,13]. Electrical network analysis can be considered quite standard and several methods to analyze flows are available, e.g. Gauss–Seidel or Newton–Raphson approaches to name a few [14]. On multiple energy carriers, Geidl and Andersson [15] analyzed their interaction in adjacent networks of a few units; Dincer et al analyzed multiple energy flows in a national energy system [16]. Studies on hydrogen often link gas to the multi-energy context [17–19]. Smart grids linked with information and communication technologies (ICT) are also well-known for stabilizing intermittent production [10]. Modeling of thermal or gaseous energy flows is typically handled by text-books [20].

Compared to the existing literature, our approach differs in some important points: firstly, we use a whole energy system approach in which both the macro and micro levels are considered simultaneously enabling a more realistic picture on the spatial interactions. Secondly, control functions and network intelligence are incorporated, and thirdly contrary to the previous abstract conceptual formalisms, this study is conducted through a rigorous approach, starting from energy flows and conversion, and ending up to an overall description of the energy system. The goal of this study is to fully utilize the possibilities of networks to absorb power from different intermittent renewable energy sources and to ease the shift towards a new energy economy. When striving to view the urban energy systems as a whole and as realistically as possible, some simplifications in the modeling approach were necessary. For example, the electric network analysis is limited to real power flows in radial networks to avoid large sets of non-linear equations and thus use a single matrix operation for each intersection of the networks [13,14,21,22].

## 2. Energy systems with multi-carrier energy networks

### 2.1. General description of methodology

The energy system consists of different energy conversion and distribution processes as illustrated in a principle scheme Fig. 1.