Energy Conversion and Management 160 (2018) 495–508

Contents lists available at ScienceDirect

Energy Conversion and Management

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

Lifecycle cost and CO_2 emissions of residential heat and electricity prosumers in Finland and the Netherlands

Benjamin Manrique Delgado[a,*], Rajesh Kotireddy[b], Sunliang Cao[c], Ala Hasan[d], Pieter-Jan Hoes[b], Jan L.M. Hensen[b], Kai Sirén[a]

[a] HVAC Technology, Department of Mechanical Engineering, School of Engineering, Aalto University, PO Box 14400, FI-00076 Aalto, Finland
[b] Building Physics and Services, Eindhoven University of Technology, PO Box 513, 5600 MB Eindhoven, The Netherlands
[c] Department of Building Services Engineering, Faculty of Construction and Environment, The Hong Kong Polytechnic University, Kowloon, Hong Kong
[d] VTT Technical Research Centre of Finland, Espoo, PO Box 1000, FI-02044 VTT, Finland

ARTICLE INFO

Keywords:
CO_2emissions
LCC
Heat and electricity prosumers
Multiobjective optimization
Renewable energy systems

ABSTRACT

The complexity of finding solutions to reach energy sustainability in the built environment poses a significant challenge. Therefore, there is interest in adequate management of the generation, conversion, storage, use and exchange of heat and electricity. The novelty of this study exists in presenting and comparing multiobjective optimizations for operational CO_2 emissions and lifecycle costs (LCC) of heat and electricity prosumers in the Netherlands and Finland, with and without net-metering. The premise relies on using surplus electricity to drive heat pumps for heat export instead of exporting surplus electricity. In the Netherlands, the calculated cost optimal solutions consist of using surplus electricity to drive an air source heat pump and export heat, with CO_2 emissions and ΔLCC of −41.1 $kgCO_2eq/(m^2 a)$ and €−69.7/m^2 (22% lower), respectively. In Finland, the heat export strategy allows a ΔLCC of €−24.5/m^2 (8% lower), with CO_2 emissions reduced by −32.5 $kgCO_2eq/(m^2$ a). Without net-metering, the ΔLCC of the energy system rises to €−4/m^2 in the Netherlands; with net metering, the ΔLCC lowers to €−65.6/m^2 in Finland. The results indicate the potential for significant economic and emission reductions in heat and electricity prosumers.

1. Introduction

Through the Energy Performance of Building Directive (EPBD), all Member States of the European Union agreed to find and implement solutions to reach energy sustainability in the built environment [1]. This has sparked a vast amount of discussion and research in the countries involved, as each of them has its own socio-economical, cultural and environmental context, and thus each of them needs to find its own most suitable solution(s). This is seen in the varying building energy standards or references defined by each country, such as the Energy Saving Ordinance in Germany [2], the Nearly Energy Neutral Buildings (BENG) in the Netherlands [3], the French Thermal Regulation [4] and the National Building Code of Finland [5].

A topic that faces a high level of complexity is the interaction between the different forms of energy generated onsite and the energy demand of the building, which in turn influence the unidirectional and bidirectional exchanges between the building and the grid(s) [6]. Georges et al. [7] investigated the potential to improve the balance between onsite generation and demand. They found that load management and optimal sizing of photovoltaics (PV) systems enhanced load matching, cost savings and CO_2 emission reductions. Brange et al. [8] studied heat prosumers in Sweden and showed their potential to contribute significant amounts of heat to district heating grids, *heat prosumers* being buildings that generate a surplus of heat and export it beyond the system boundaries. Salom et al. [6] discuss indicators that aim to measure the interaction between generation, demand and grid, such as *load matching* or *grid interaction*. The authors highlight on the need to identify appropriate values for each of these indicators based on the type of building, the climate, and the energy type. Even though a net-zero energy building is commonly thought to be a building where the annual electricity consumption is equal to its annual electricity generation [9], buildings hardly rely on only one form of energy. Thus, Cao et al. [10,11] identified the need for differentiating between electricity, heating and cooling, and developed and tested separate indicators for each. Their study shows the complexity of evaluating the performance of a system that includes energy grid connections, generation and storage components for different forms of energy. Moreover, in the definition of the 4th Generation District

* Corresponding author.
E-mail address: benjamin.manriquedelgado@aalto.fi (B. Manrique Delgado).

https://doi.org/10.1016/j.enconman.2018.01.069
Received 21 September 2017; Received in revised form 24 January 2018; Accepted 26 January 2018

Nomenclature

Abbreviations

ASHP	air source heat pump
DH	district heating
DHW	domestic hot water
FH	floor heating
GSHP	ground source heat pump
HWST	hot water storage tank
LCC	lifecycle cost
NG	natural gas
NPV	net present value
NSGA-II	non-dominated sorting genetic algorithm II
NZEB	net-zero energy building
O&M	operation and maintenance
PE	primary energy
PV	photovoltaic
ST	solar thermal
VAT	value added tax
WT	wind turbine
WP	wood pellet

Symbols

A_{net}	net conditioned area
A_{salv}	salvage value
C	expense
$CO_{2,eq}$	equivalent CO_2 emissions
exp	export
E	energy
El	electricity
F_1, F_2	objective functions
F	fuel
f_{CO2}	specific emissions factor
I_{ini}	initial investment
imp	import
net	net
single	single
th	thermal
Q	heat
X	exergy
x	continuous design variable
y	discrete design variable

Heating, Lund et al. [12] contemplate smart interaction between the grid and the fluctuating energy sources, such as PV systems or wind power, and they warn that grid interaction with low-energy buildings is a major challenge since low-temperature sources and heat recycling might be required. Therefore, there is interest in adequate management of the generation, conversion, storage, use and exchange of various forms of energy in the built environment; failing to do so might leave the optimal solutions out of reach.

The complexity of this problem poses a significant challenge to the scientific community across Europe, since building topology, insulation levels, climate, energy supply and demand, prices, regulatory frameworks, and several other conditions must be addressed to evaluate the building performance. Single or multiobjective optimization can assist in this endeavor since it allows identifying optimal solutions when several variables are present. Multiobjective optimization enabled Mohamed et al. [13] to evaluate system configurations for small-scale multigeneration technologies in zero-energy buildings. The authors identified the optimal solutions in terms of cost and environmental benefits, as well as the effect of including PV panels in the system. The mixed integer linear programming approach by Harb et al. [14] showed that the optimal design and operation strategy of energy systems depends on the type of residential building. In their study, they found that boilers in combination with PV are preferable for single-family houses, while combined heat and power (CHP) and local heating networks are preferable for larger buildings and neighborhoods, respectively. Hamdy et al. [15] conducted a multi-stage optimization process to find the optimal combinations of building envelope and heat recovery options, and the corresponding optimal heating/cooling systems. Through this process, the authors found that fulfilling and surpassing the current energy standards in Finland can be achieved in a cost-optimal way, yet incentives are required get close to the net-zero energy level. While these are only a few examples of optimization studies on energy system design and/or management in the built environment, they illustrate the level of problem complexity that this method can handle and the quality of the information it can provide.

The reported literature gives an insight into the applicability of optimization in the study of the built environment, and into the challenge of optimal design and management of onsite energy systems. Thus, it is apparent that optimization can allow finding the energy solutions in buildings that deliver the best performance. Further, investigating heat and electricity, as opposed to simply *energy*, presents alternatives to how buildings can manage their onsite generation, and how they can exchange energy with its surroundings. As a result, multiobjective optimization of onsite heat and electricity systems in the buildings arises as an opportunity to come closer to sustainability in the built environment. This was investigated by Manrique Delgado et al. [16], where optimized energy systems for heat and electricity prosumers in Finland were presented. The study focuses on the environmental, economic and exergetic performance of a residential building with several energy configurations. Among them, an option to use a ground source heat pump (GSHP) to convert surplus electricity into heat for further export was presented and compared to other traditional heat supply options such as CHP and district heating. The results show that the heat export strategy can lead to optimal solutions concerning operational CO_2 emissions and lifecycle costs, yet the most cost-optimal solution is reached with a more conventional GSHP system without heat export capability. Overall, the results indicate potential and encourage further investigation of heat and electricity prosumers, particularly regarding their performances under various economical, climatic and energetic contexts.

The current study investigates the developed methodology [16] for its suitability in different conditions (the Netherlands) in order to evaluate the generic nature of the methodology. For this purpose, multiobjective optimizations for operational CO_2 emissions and lifecycle costs (LCC) of heat and electricity prosumers in the Netherlands and Finland. It relies on using surplus electricity to drive heat pumps with the purpose of exporting heat, instead of exporting the surplus electricity. While this aspect has been presented and investigated previously [16–18], the topic remains far from exhausted. The novelty of this article relies on four cornerstones. First, it presents the economic and emissions performance of heat and electricity prosumers in the Netherlands and describes the optimal energy system configurations. Second, the study presents the similarities, contrasts and transferable conclusions between prosumers in Netherlands and Finland. This provides an insight into the performance of the energy systems in two different contexts where climate, building typology, economic parameters, and energy practices are different. Third, the presence and capacity of the generation and storage components along the optimal fronts is studied in detail, and guidance on how to prioritize investments is given. Fourth, the article investigates the consequences for heat and electricity prosumers, and for regular prosumers, of a possible phase-out of net-metering in the Netherlands—which could lead to a