Energy 118 (2017) 284–296

Contents lists available at ScienceDirect

Energy

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

The impact of Zero Energy Buildings on the Scandinavian energy system

Pernille Seljom [a, b, *], Karen Byskov Lindberg [c, d], Asgeir Tomasgard [a], Gerard Doorman [c], Igor Sartori [e]

[a] Department of Industrial Economics and Technology Management, Norwegian University of Science and Technology (NTNU), 7491 Trondheim, Norway
[b] Department of Energy Systems, Institute for Energy Technology (IFE), Post Box 40, 2027 Kjeller, Norway
[c] Department of Electric Power Engineering, Norwegian University of Science and Technology (NTNU), 7491 Trondheim, Norway
[d] The Norwegian Water Resources and Energy Directorate (NVE), Post Box 5091 Majorstuen, 0301 Oslo, Norway
[e] SINTEF Building and Infrastructure, Post Box 124 Blindern, 0314 Oslo, Norway

ARTICLE INFO

Article history:
Received 1 April 2016
Received in revised form
16 November 2016
Accepted 3 December 2016

Keywords:
Zero Energy Building
TIMES model
Stochastic programming
Photovoltaic power
Energy system model

ABSTRACT

This paper investigates how an extensive implementation of net Zero Energy Buildings (ZEBs) affects cost-optimal investments in the Scandinavian energy system towards 2050. Analyses are done by a stochastic TIMES model with an explicit representation of the short-term uncertainty related to electricity supply and heat demand in buildings. We define a nearly ZEB to be a highly efficient building with on-site PV production. To evaluate the flexibility requirement of the surrounding energy system, we consider no use of energy storage within the ZEBs. The results show that ZEBs reduce the investments in non-flexible hydropower, wind power and Combined Heat and Power, and increase the use of direct electric heating and electric boilers. With building integrated PV production of 53 TWh in 2050, ZEBs increase the Scandinavian electricity generation by 16 TWh and increase the net electricity export by 19 TWh. Although the increased production reduces the electricity prices, the low heat demand in ZEBs gives a drop in the electricity consumption by 4 TWh in 2050. Finally, the results demonstrate that the Scandinavian energy system is capable of integrating a large amount of ZEBs with intermittent PV production due to the flexible hydropower in Norway and Sweden.

1. Introduction

A net Zero Energy Building (ZEB) is a building with low energy demand that produces, on an annual basis, as much renewable energy as its energy consumption [1,2]. This paper presents the cost-optimal adaption of an extensive introduction of ZEBs in the Scandinavian energy system towards 2050. To study this, we have developed a stochastic TIMES (The Integrated MARKAL-EFOM System) model [3–7], with an explicit modelling of the short term-uncertainty related to electricity generation and heat demand in buildings.

1.1. Research motivation

Implementation of ZEBs is identified as one of the remedies to meet the Energy Strategy of the European Union, and according to the Energy Performance of Buildings Directive (EPBD), all new buildings shall be 'nearly' ZEBs from 2020 [8]. The initial experiences with ZEBs show that Photovoltaic electricity (PV), integrated in the façade and roof of the building, has been a propitious solution to produce energy in ZEBs [9,10]. This leads to challenges for the surrounding energy system since ZEBs may export electricity in periods of high PV production and import electricity when the solar radiation is low. In Scandinavia the electricity consumption in buildings is highest in winter when the solar conditions are poor. Hence, the electricity sector will serve as a seasonal storage for the ZEBs, where excess electricity from a ZEB is supplied to the electricity grid in summer, and electricity is provided from the grid to the ZEBs in winter.

The energy system needs to consider the reduced heat demand and the on-site electricity generation with an integration of ZEBs.

* Corresponding author. Department of Energy Systems, Institute for Energy Technology (IFE), Post Box 40, 2027 Kjeller, Norway.
E-mail addresses: Pernille.Seljom@ife.no (P. Seljom), karen.lindberg@ntnu.no (K.B. Lindberg), asgeir.tomasgard@iot.ntnu.no (A. Tomasgard), gerard.doorman@ntnu.no (G. Doorman), igor.sartori@sintef.no (I. Sartori).

http://dx.doi.org/10.1016/j.energy.2016.12.008
0360-5442/

Abbreviations

CHP	Combined Heat and Power
DH	District Heat
EPBD	Energy Performance of Buildings Directive
HP	Heat Pump
PV	Photovoltaic electricity (solar power)
PE	Primary Energy
TIMES	The Integrated MARKAL-EFOM System
ZEB	net Zero Energy Building

This implies that the existing energy system needs to adapt with respect to both operation and future investments. Although the net energy demand of the ZEBs is low, the existing electricity capacity might need to be maintained, as the ZEBs do not necessarily lower the peak electricity demand. However, if heated by electricity, the low heat demand in ZEBs, caused by energy efficiency measures, can reduce the peak electricity demand.

The electricity mix in Scandinavia is unique. Denmark is the EU nation with the largest share of electricity generation from Combined Heat and Power (CHP) and wind power at 65% and 35% respectively in 2013 [11]. The electricity generation in Norway and Sweden is also distinctive, as the two countries have the largest hydro production among the EU countries, with 129 TWh and 61 TWh in 2013 [11], and have about 70% of the European hydro storage capacity with 82 TWh and 34 TWh respectively [12]. Due to flexible CHP plants, hydro reservoirs and an integrated electricity grid, the Scandinavian countries are well suited to integrate a larger share of intermittent PV production caused by ZEBs. Hence, it is interesting to study how, and to what extent, hydro production and other renewable energy technologies adapts to an extensive introduction of ZEBs. With a low energy demand and on-site energy production, ZEBs might impact the cost-optimal investments in the overall energy system and change the operation pattern of the flexible production technologies. In order to quantify these changes, an extensive analysis on the aggregated system level is needed. It is assumed that a large share of ZEBs influences the electricity price, and thereby affects both investments in the electricity sector and in heating technologies within buildings, including ZEBs. Consequently, it is important to evaluate the cost-optimal heating design in buildings together with its interaction with the remaining energy system.

1.2. Recent studies and scope of study

This section presents literature that is related to the scope of this paper. The first part focus on the energy system with ZEBs and the second part motivates for the applied stochastic methodology.

1.2.1. Energy systems with ZEBs

The literature concerning ZEBs is mostly related to a single building, investigating e.g. the architecture and building envelope, and/or the energy technologies within the building. Congedo [13] and Evola [14] investigate cost-effective building design alternatives for nearly ZEBs, considering different materials and thickness for the respective building elements, but has no integrated optimisation approach. Milan [15] and Lindberg [16,17] treat the building envelope as given, and investigate the energy system design of the ZEB using linear optimisation. Hamdy [18], Lu [19] and Zhang [20] have developed different kinds of multi-objective or multi-stage optimisation approaches, first finding the cost-efficient building envelope and secondly the energy system design within the ZEB.

Literature that investigates ZEBs in the national or regional energy system is scarce. The presented literature above do not consider that the energy related decisions in a ZEB can have an impact on the surrounding energy system, as for example changing the electricity price. This can be a reasonable assumption with a limited share of ZEBs in the building sector, but is less valid with an extensive implementation of ZEBs. To capture such feed-back effects, this paper uses a methodology that optimises the interaction between the building sector and the surrounding energy system including endogenous investment decisions in the building, electricity and district heat sector. There are however related studies, such as Henning [21] and Palzer [22], that evaluate the cost-optimal evolvement of the energy system with significant renewable electricity generation and increased energy efficiency measures in the building sector, reaching a target of 50% reduction of a country's primary energy consumption.

1.2.2. Stochastic modelling approach

The existing literature using long-term energy system models of Scandinavia, including [23–29], apply a deterministic modelling of short-term uncertainty. Unlike our stochastic approach, a simplified deterministic model includes only one operational situation and provides investment decisions that do not directly take into account a range of operational situations which can occur. It is therefore unclear whether the results from deterministic models are valid with the presence of short-term uncertainty. This is supported by Seljom [30] that concludes that the method used to represent the unpredictable characteristics of wind power in investment models can significantly affect the model results. A stochastic approach to incorporate short-term uncertainty in TIMES was first introduced in Loulou [31] and is used to represent intermittent wind capacity in Seljom [30]. This approach provides cost-optimal investment decisions, which are valid for a range of representative operational situations. For a realistic representation of the grid interaction of a ZEB and the surrounding energy system, we apply a stochastic representation of short-term uncertainty of electricity supply and heat demand in buildings.

There are studies, focusing only on the electricity sector, that have incorporated a stochastic modelling of the short-term uncertainty of intermittent renewables in investment models. For example, Nagl [32] apply stochastic modelling of wind power and PV in a combined investment and dispatch optimisation model of the European electricity market. Their results demonstrate that intermittent renewables are significantly overvalued, flexible energy technologies are underestimated and that the total system cost is significantly underestimated in deterministic electricity models. Other work includes [33–37]. As this literature does not include investments in the building sector, they do not include a stochastic representation of heat demand in buildings. It is however appropriate to consider the uncertainty of heat demand, when analysing the interaction of ZEBs with the surrounding energy system, as the heat demand is highly dependent on the outdoor temperature.

1.3. Outline

The remainder of this paper is structured as follows; Section 2 gives an overview of the methodology and Section 3 is devoted to the model cases that are used in the analyses. Finally, the results are presented in Section 4 and the conclusions are given in Section 5.