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Methodology for optimal energy system design of Zero Energy Buildings using mixed-integer linear programming

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ABSTRACT

According to EU's Energy Performance of Buildings Directive (EPBD), all new buildings shall be nearly Zero Energy Buildings (ZEB) from 2018/2020. How the ZEB requirement is defined has large implications for the choice of energy technology when considering both cost and environmental issues. This paper presents a methodology for determining ZEB buildings' cost optimal energy system design seen from the building owner's perspective. The added value of this work is the inclusion of peak load tariffs and feed-in-tariffs, the facilitation of load shifting by use of a thermal storage, along with the integrated optimisation of the investment and operation of the energy technologies. The model allows for detailed understanding of the hourly operation of the building, and how the ZEB interacts with the electricity grid through the characteristics of its net electric load profile. The modelling framework can be adapted to fit individual countries' ZEB definitions. The findings are important for policy makers as they identify how subsidies and EPBD's regulations influence the preferred energy technology choice, which subsequently determines its grid interaction. A case study of a Norwegian school building shows that the heat technology is altered from HP to bio boiler when the ZEB requirement is applied.

1. Introduction

The recast of the EU Directive on Energy Performance of Buildings (EPBD) states that all new buildings are to be nearly Zero Energy Buildings[1] (ZEB) from 2018/2020 [1]. The definition of nearly ZEBs in the EPBD states that "*a nearly zero-energy building means a building that has a very high energy performance. The nearly zero or very low amount of energy required should be covered to a very significant extent by energy from renewable sources, including energy from renewable sources produced on-site or nearby*" [2]. Generally speaking a nearly ZEB is an energy efficient building with low energy demand that to a high extent is covered by on-site generated renewable energy [3–5]. Because ZEBs need on-site energy generation in order to compensate for their energy use, they will inevitably become an active and integrated part of the energy system.

Even though the EPBD sets a definition framework, each of the EU member states shall define their own boundary conditions, weighting factors and ambition level when calculating the zero energy balance, due to differences in climate, culture & building tradition, policy and legal frameworks. As of April 2015, about half of the member states of the EU have accomplished this, and about 5 of the 28 states have chosen to use carbon emissions as weighting factors, thus aiming at Zero *Emission* Buildings,[2] rather than Zero Energy Buildings [6]. Accordingly, a Zero Emission Building is essentially the same as a Zero Energy Building, the only difference is that the balance is calculated by using carbon emissions instead of energy units (see more in Section 1.1). Whenever using ZEB in the

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[1] The notation net ZEB, or nZEB, is also used to highlight that even though the ZEB target is on an annual or lifetime level, the balance is calculated on an hourly or monthly level. In the following of this paper, whenever using ZEB this means net ZEB.

[2] Zero Emission Buildings are also denoted as Zero Carbon Buildings.

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Nomenclature

Sets

I^{heat} Heat technologies, subset of I, I^{heat} = {ST, ASHP, GSHP, EB, BB, DH, GB, CHP}
I^{el} Power technologies, subset of I, I^{el} = {PV, CHP}
I All energy technologies $I = I^{el} \bigcup I^{heat}$
F Energy carriers, F = {el import, el export, bio pellets, natural gas, district heat}

Indexes

p Period
τ Year within period, $\tau = 1, \ldots, N$
t Time step within year, $t = 1, \ldots, T$
i Energy technology
f Energy carrier
m Month within year, $m = 1, \ldots, 12$
k Reinvestment number

Parameters

$C_i^{totspec}$ Discounted specific investment costs, including reinvestments, for technology i [EUR/kW]
$C_i^{totfixed}$ Discounted fixed investment costs, including reinvestments, for technology i [EUR]
C_i^{am} Annual maintenance costs for energy technology i [EUR/kW per year],
Φ_i Expected lifetime of energy technology i [years]
$D_{t,p}^{el}$ Electricity demand of building, at hour t within an average year in period p [kWh/h]
$D_{t,p}^{heat}$ Heat demand of building, at hour t, in period p [kWh/h]
$P_{t,p}^{buy,D}$ Price of electricity bought from the grid at hour t, in period p [EUR/kWh]
$P_{t,p}^{buy,HP}$ Price of electricity bought from the grid at hour t, in period p [EUR/kWh]
$P_{t,p}^{sell,PV}$ Feed-in-tariff of PV electricity exported to the grid at hour t, in period p [EUR/kWh];
$P_{t,p}^{sell,CHP}$ Feed-in-tariff of CHP electricity exported to the grid at hour t, in period p [EUR/kWh];
P_p^{bio} Price of bio pellets in period p [EUR/kWh];
P_p^{gas} Price of natural gas in period p [EUR/kWh];
r Discount rate [-]
η_i Efficiency of technology i [-]
$\eta_{i,t,p}$ Efficiency of technology i, at hour t, in period p [-]
$COP_{i,t,p}$ Coefficient of performance of technology i, at hour t, in period p [-]
$Y_{PV,t,p}$ Specific PV electricity generation, at hour t, in period p [kW/kWp]
$Q_{ST,t,p}$ Specific solar heat generation, at hour t, in period p [kW/m^2]
$G_{f,p}$ Carbon emissions for energy carrier f, in period p [$g_{CO2\text{-}eq}$/kWh]
$PE_{f,p}$ Primary energy factor for energy carrier f, in period p [kWh_{PE}/kWh]
$PE^{embodied}$, $G^{embodied}$ Weighted embodied energy (PE or carbon) [kWh_{PE} or $g_{CO2\text{-}eq}$]
PE^{ref}, G^{ref} Weighted energy imports (PE or carbon) without ZEB restriction [kWh_{PE} or $g_{CO2\text{-}eq}$]
GRCH Annual grid charge [EUR]
$PPCH_m$ Peak power charge, for each month m [EUR/kW]
H_m^{acc} Hour number of the last hour, for each month m [-]
$T_{t,p}^{SH}$ Temperature of water for space heating demand, at hour t, in period p [°C]
$T_{t,p}^{DHW}$ Temperature required for DHW, at hour t, in period p [°C]
$T_{t,p}^{source}$ Temperature of the heat source for HPs (ambient air temperature for ASHP, and ground temperature for GSHP) [°C]
$T_{t,p}^{collector}$ Temperature within the ST collector (assumed equal to storage temperature) [°C]

Ambient air temperature [°C]

$IRR_{t,p}^{tilt}$ Global irradiation on a tilted plane at hour t, in period p [W/m^2]
γ Factor for ZEB level [-]

Variables

x_i Installed capacity of technology i [kW]
c_p^{run} Annual operational cost, for a typical year in period p [EUR/yr]
$q_{i,t,p}$ Heat generated by technology i, at hour t, for a typical year in period p [kWh/hr]
$d_{i,t,p}$ Electricity consumed by technology i, at hour t, for a typical year in period p [kWh/hr]
$b_{t,p}$ Bio pellets consumed in BB at hour t, for a typical year in period p [kWh/hr]
$g_{t,p}^{CHP}$ Natural gas consumed in CHP at hour t, for a typical year in period p [kWh/hr]
$g_{t,p}^{GB}$ Natural gas consumed in GB at hour t, for a typical year in period p [kWh/hr]
$s_{t,p}$ Heat stored in accumulator tank (S) at end of hour t, in period p [kWh/hr]
$y_{i,t,p}$ Electricity generated by technology i, at hour t, for a typical year in period p [kWh/hr]
$y_{i,t,p}^{exp}$ Electricity exported to the grid, from technology i, at hour t, in period p [kWh/hr]
$y_{i,t,p}^{selfcD}$ Electricity consumed in the building, from technology i, at hour t, in period p [kWh/hr]
$y_{i,t,p}^{selfcHP}$ Electricity consumed in HPs, from technology i, at hour t, in period p [kWh/hr]
$y_{t,p}^{impD}$ Electricity imported from the grid, at hour t, for a typical year in period p [kWh/hr]
$y_{t,p}^{impHP}$ Electricity imported from the grid to HP, at hour t, for a typical year in period p [kWh/hr]
$\delta_{t,p}^{exp}$ Binary variable, 1 if electricity is exported from the building, 0 if import
$\delta_{t,p}^{imp}$ Binary variable, 0 if electricity is exported from the building, 1 if import
$y_{m,p}^{maximp}$ Monthly maximum electricity import value, for each month m, in period p [kWh/hr]

Definitions and terms used

FiT Feed-in tariff
Electric specific demand Demand of electricity services (lighting, fans&pumps, appliances, etc.)
Heat demand Demand of heat services (space heating and domestic hot water demand)
Electricity consumption Consumption of electricity, including electricity for heating purposes (if any)

following it embraces both Zero Energy and Zero Emission Buildings.

The balance of a ZEB is calculated as energy consumed minus energy generated over a year or over the total lifetime of the building. However, the building still exchanges electricity with the grid