Energy & Buildings 281 (2023) 112731

Contents lists available at ScienceDirect

Energy & Buildings

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

Exploring the link between the EU emissions trading system and net-zero emission neighbourhoods

Stian Backe [a,c,*], Dimitri Pinel [b,c], Magnus Askeland [b,c], Karen Byskov Lindberg [b,d], Magnus Korpås [b], Asgeir Tomasgard [a]

[a] Department of Industrial Economics and Technology Management, The Norwegian University of Science and Technology, Trondheim, Norway
[b] Department of Electric Power Engineering, The Norwegian University of Science and Technology, Trondheim, Norway
[c] Energy Systems, SINTEF Energy Research, Trondheim, Norway
[d] Architectural Engineering, SINTEF Community, Oslo, Norway

ARTICLE INFO

Article history:
Received 9 November 2021
Revised 14 December 2022
Accepted 17 December 2022
Available online 26 December 2022

Keywords:
Energy system modelling
Capacity expansion modelling
Linear programming
Climate and energy policy
Low-carbon buildings
Electricity emission factors
Soft-linking models
Sector coupling
Net-zero energy districts

ABSTRACT

Climate policy is transforming the energy system and the building sector. Since these sectors overlap, we need to understand how the short-term operational link between them impact their long-term development subject to overlapping climate policies. This paper investigates how the integrated development of the European heat and electricity system is influenced by net-zero emission neighbourhoods that compensate own carbon emissions with local renewable energy. The study is made in the context of EUs emission trading system. In our approach, we soft-link two mathematical programming models to couple energy transition policies at the European level with the neighbourhood scale. Results suggest that zero emission neighbourhoods make European decarbonisation more cost-efficient. When low carbon energy technologies in neighbourhoods become competitive, investments in large-scale technologies are reduced on the European level, including nuclear and fossil gas power and heating. Thus, early policy support to neighbourhood technologies could prevent stranded assets later in the transition. Further, results imply that more stringent emission caps earlier could help avoiding CO_2 allowance price spikes later.

1. Introduction

The European Union (EU) sets ambitious climate-neutrality targets that affect the development in the energy sector [1]. One of the policy tools employed is the EU emissions trading system (EU ETS) [2]: a cap-and-trade system covering around 40% of European greenhouse gas (GHG) emissions, including large-scale heat and electricity production. The EU ETS was established in 2005 as the world's first international ETS. The EU ETS regulates European-wide GHG emissions by politically defining how much GHG emissions can be emitted over one year by employing a cap that is reduced over time. Based on the total cap, emission allowances are allocated to installations that emit CO_2, and these quotas can be traded in a market.

Another policy tool to achieve climate neutrality in the EU is the energy performance of buildings directive (EPBD) [3], which requires that all new buildings are nearly zero energy buildings (NZEB) [4] from 2021. An amendment of the directive is currently being considered [5], and the new proposal strengthens the focus on buildings to become zero-emission. Buildings account for about 40% of final energy demand and 36% of energy related CO2 emissions [6]. Increased energy efficiency and the use of renewable energy for supplying the remaining energy needs of the buildings lead to a reduction of the GHG emission [7], which is the combination that have inspired the NZEB concept [8–11]. In an NZEB, electricity and heat usage is compensated by exporting energy from onsite renewable energy production [12]. The definition of NZEB varies across Europe because policy makers adapt the NZEB definition in policy initiatives, varying for example 'closeness to zero', system boundaries, metric type, and weighting factors, in consider-

Abbreviations: CHP, Combined Heat and Power; COP, Coefficient Of Performance; DHW, Domestic Hot Water; EPBD, Energy Performance of Buildings Directive; ETS, Emissions Trading System; EU, European Union; GHG, GreenHouse Gas; NZEB, Nearly Zero Energy Building; PV, Photovoltaic; SH, Space Heating; SOFC, Solid Oxide Fuel Cell; VRES, Variable Renewable Energy Sources; ZEN, Zero Emission Neighbourhood.

* Corresponding author at: Department of Industrial Economics and Technology Management, The Norwegian University of Science and Technology, Hogskoleringen 1, 7491 Trondheim, Norway.

E-mail address: stian.backe@ntnu.no (S. Backe).

https://doi.org/10.1016/j.enbuild.2022.112731
0378-7788/

Nomenclature

EMPIRE sets

$\mathcal{G}$ Set of possible generator types
$\mathcal{B}$ Set of possible storage types
$\mathcal{R}$ Set of possible converter types from electricity to heat
$\mathcal{I} = \{1, 2, \ldots, I\}$ Set of investment time periods
$\mathcal{H} = \{1, 2, \ldots, H\}$ Set of operational time periods
$\mathcal{S}$ Set of seasons
$\mathcal{N}$ Set of nodes
$\mathcal{A} \subset \mathcal{N} \times \mathcal{N}$ Set of unidirectional interconnectors
$\mathcal{L} \subset \mathcal{A}$ Set of bidirectional interconnectors
Ω Set of stochastic scenarios
$\mathcal{G}_{\mathrm{EL}} \subset \mathcal{G}$ Set of possible electricity generator types
$\mathcal{G}_{\mathrm{HT}} \subset \mathcal{G}$ Set of possible heat generator types
$\mathcal{G}_n \subseteq \mathcal{G}$ Set of available generator types in node $n \in \mathcal{N}$
$\mathcal{G}^{\mathrm{NoReg}} \subset \mathcal{G}$ Set of generator types not regulated by the emission cap
$\mathcal{G}^{\mathrm{Ramp}} \subset \mathcal{G}$ Set of generator types limited by up-ramping
$\mathcal{G}^{\mathrm{RegHyd}} \subset \mathcal{G}$ Set of regulated hydro generator types
$\mathcal{G}^{\mathrm{Hyd}} \subset \mathcal{G}$ Set of all hydro generator types
$\mathcal{B}_{\mathrm{EL}} \subset \mathcal{B}$ Set of possible electricity storage types
$\mathcal{B}_{\mathrm{HT}} \subset \mathcal{B}$ Set of possible heat storage types
$\mathcal{B}_n \subseteq \mathcal{B}$ Set of available storage types in node $n \in \mathcal{N}$
$\mathcal{B}^{\dagger} \subseteq \mathcal{B}$ Set of storage types with dependent ratio between energy and power
$\mathcal{R}_n \subseteq \mathcal{R}$ Set of available converters from electric to thermal load in node $n \in \mathcal{N}$
$\mathcal{H}_s \subset \mathcal{H}$ Set of operational time periods in season $s \in \mathcal{S}$ $(\mathcal{H}_s = \{h_s^1, h_s^2, \ldots, h_s^{H_s}\})$
$\mathcal{H}_s^- \subset \mathcal{H}_s$ Set of operational time periods except the first in season $s \in \mathcal{S}$ $(\mathcal{H}_s^- = \{h_s^2, h_s^3, \ldots, h_s^{H_s}\})$
$\mathcal{A}_n^{\mathrm{in}} \subset \mathcal{N} \times \mathcal{N}$ Set of arcs flowing into node $n \in \mathcal{N}$
$\mathcal{A}_n^{\mathrm{out}} \subset \mathcal{N} \times \mathcal{N}$ Set of arcs flowing out from node $n \in \mathcal{N}$
$\mathcal{Z}$ Set of Zero Emission Neighbourhood types
$\mathcal{Z}_n$ Set of Zero Emission Neighbourhood types available in node $n \in \mathcal{N}$

EMPIRE parameters

$c_{a,i}^{\mathrm{node}}$ Cost per unit of investing in asset $a \in \mathcal{G} \cup \mathcal{B} \cup \mathcal{R} \cup \mathcal{Z}$ in period $i \in \mathcal{I}$
$c_{b,i}^{\mathrm{storPW}}$ Cost per unit of investing in power of storage $b \in \mathcal{B}$ in period $i \in \mathcal{I}$
$c_{n_1,n_2,i}^{\mathrm{tran}}$ Cost per unit of investing in bidirectional interconnection $(n_1, n_2) \in \mathcal{L}$ in period $i \in \mathcal{I}$
$q_{g,i}^{\mathrm{gen}}$ Cost per unit of operating generator type $g \in \mathcal{G}$ in period $i \in \mathcal{I}$
$q_{g,i}^{\mathrm{CO2}}$ CO2 emission factor of generator type $g \in \mathcal{G}$ in period $i \in \mathcal{I}$
$q_{n,i}^{\mathrm{ll,EL}}$ Value (cost) of lost electric load in node $n \in \mathcal{N}$ in period $i \in \mathcal{I}$
$q_{n,i}^{\mathrm{ll,EL}}$ Value (cost) of lost thermal load in node $n \in \mathcal{N}$ in period $i \in \mathcal{I}$
i_a^{life} Lifetime of investment in asset $a \in \mathcal{G} \cup \mathcal{B} \cup \mathcal{L} \cup \mathcal{R} \cup \mathcal{Z}$
γ_g Ramping factor for generator type $g \in \mathcal{G}_{\mathrm{Ramp}}$
η_r^{E2H} Efficiency factor for converter $r \in \mathcal{R}$ from electric to thermal load
$\eta_{n_1,n_2}^{\mathrm{tran}}$ Efficiency factor for transmission losses along arc $(n_1, n_2) \in \mathcal{A}, \eta_{n_1,n_2}^{\mathrm{tran}} \in (0, 1)$
η_b^{chrg} Efficiency factor for charge losses with storage type $b \in \mathcal{B}, \eta_b^{\mathrm{chrg}} \in (0, 1)$
$\eta_b^{\mathrm{dischrg}}$ Efficiency factor for discharge losses with storage type $b \in \mathcal{B}, \eta_b^{\mathrm{dischrg}} \in (0, 1)$
η_b^{bleed} Efficiency factor for bleed losses with storage $b \in \mathcal{B}, \eta_b^{\mathrm{bleed}} \in (0, 1)$
ρ_b Capacity ratio between charge/discharge for storage type $b \in \mathcal{B}$
β_g^{CHP} Share of electric output per heat output from CHP generator $g \in \mathcal{G}_{\mathrm{EL}}, \forall g \notin \mathcal{G}_{\mathrm{EL}} \cap \mathcal{G}_{\mathrm{HT}} : \beta_g^{\mathrm{CHP}} = 1$
β_b^{stor} Ratio between power and energy capacity for storage type $b \in \mathcal{B}^{\dagger} \subseteq \mathcal{B}$
κ_b Share of installed energy capacity initially available in storage type $b \in \mathcal{B}$ in each representative time period.
ρ_b Capacity ratio between charge/discharge for storage type $b \in \mathcal{B}$
Q_i^{CO2} CO2 emission cap for all generators (except $g \in \mathcal{G}^{\mathrm{NoReg}}$) in period $i \in \mathcal{I}$
$\bar{x}_{a,n,i}^{\mathrm{node}}$ Initial capacity of nodal asset $a \in \mathcal{G}_n \cup \mathcal{B}_n \cup \mathcal{R}_n$ in node $n \in \mathcal{N}$ in period $i \in \mathcal{I}$
$\bar{x}_{b,n,i}^{\mathrm{storPW}}$ Initial capacity of power of storage $b \in \mathcal{B}_n$ in node $n \in \mathcal{N}$ and period $i \in \mathcal{I}$
$\bar{x}_{n_1,n_2,i}^{\mathrm{tran}}$ Initial capacity of bidirectional interconnection $(n_1, n_2) \in \mathcal{L}$ in period $i \in \mathcal{I}$
$\bar{X}_{a,n,i}^{\mathrm{node}}$ Max investments in nodal asset $a \in \mathcal{G}_n \cup \mathcal{B}_n \cup \mathcal{R}_n \cup \mathcal{Z}_n$ in node $n \in \mathcal{N}$ and period $i \in \mathcal{I}$
$\bar{X}_{b,n,i}^{\mathrm{storPW}}$ Max investments in power of storage $b \in \mathcal{B}_n$ in node $n \in \mathcal{N}$ and period $i \in \mathcal{I}$
$\overline{X}_{n_1,n_2,i}^{\mathrm{tran}}$ Max investments in bidirectional interconnection $(n_1, n_2) \in \mathcal{L}$ in period $i \in \mathcal{I}$
$\bar{V}_{a,n,i}^{\mathrm{node}}$ Max installed capacity of asset $a \in \mathcal{G}_n \cup \mathcal{B}_n \cup \mathcal{R}_n \cup \mathcal{Z}_n$ in node $n \in \mathcal{N}$ and period $i \in \mathcal{I}$
$\bar{V}_{b,n,i}^{\mathrm{storPW}}$ Max installed capacity of storage of power $b \in \mathcal{B}_n$ in node $n \in \mathcal{N}$ and period $i \in \mathcal{I}$
$\overline{V}_{n_1,n_2,i}^{\mathrm{tran}}$ Max installed capacity of bidirectional interconnection $(n_1, n_2) \in \mathcal{L}$ in period $i \in \mathcal{I}$
π_ω Probability of scenario $\omega \in \Omega$
$\xi_{g,n,h,i,\omega}^{\mathrm{gen}}$ Availability of generator type $g \in \mathcal{G}_n$ in node $n \in \mathcal{N}$ in period $h \in \mathcal{H}, i \in \mathcal{I}$ and scenario $\omega \in \Omega$
$\xi_{n,h,i,\omega}^{\mathrm{load}}$ Electric demand in node $n \in \mathcal{N}$ in period $h \in \mathcal{H}, i \in \mathcal{I}$ and scenario $\omega \in \Omega$
$\xi_{n,h,i,\omega}^{\mathrm{load,HT}}$ Heat demand in node $n \in \mathcal{N}$ in period $h \in \mathcal{H}, i \in \mathcal{I}$ and scenario $\omega \in \Omega$
$\xi_{n,s,i,\omega}^{\mathrm{RegHydLim}}$ Max output from regulated hydro in node $n \in \mathcal{N}$ in $s \in \mathcal{S}, i \in \mathcal{I}$ and $\omega \in \Omega$
ξ_n^{HydLim} Max expected annual output from total hydro in node $n \in \mathcal{N}$
$\xi_{z,n,h,i,\omega}^{\mathrm{ZEN,EL}}$ Availability of electricity supply from Zero Emission Neighbourhood type $z \in \mathcal{Z}_n$ in node $n \in \mathcal{N}$ in period $h \in \mathcal{H}, i \in \mathcal{I}$ and scenario $\omega \in \Omega$
$\xi_{z,n,h,i,\omega}^{\mathrm{ZEN,HT}}$ Availability of heat supply from Zero Emission Neighbourhood type $z \in \mathcal{Z}_n$ in node $n \in \mathcal{N}$ in period $h \in \mathcal{H}, i \in \mathcal{I}$ and scenario $\omega \in \Omega$

EMPIRE variables

$x_{a,n,i}^{\mathrm{node}}$ Capacity investments in nodal asset $a \in \mathcal{G}_n \cup \mathcal{B}_n \cup \mathcal{R}_n \cup \mathcal{Z}_n$ in node $n \in \mathcal{N}$ in period $i \in \mathcal{I}$
$x_{b,n,i}^{\mathrm{storPW}}$ Capacity investments in power of storage $b \in \mathcal{B}_n$ in node $n \in \mathcal{N}$ in period $i \in \mathcal{I}$
$x_{n_1,n_2,i}^{\mathrm{tran}}$ Capacity investments in bidirectional interconnection $(n_1, n_2) \in \mathcal{L}$ in period $i \in \mathcal{I}$
$v_{a,n,i}^{\mathrm{node}}$ Existing capacity of asset $a \in \mathcal{G}_n \cup \mathcal{B}_n \cup \mathcal{R}_n \cup \mathcal{Z}_n$ in node $n \in \mathcal{N}$ in period $i \in \mathcal{I}$
$v_{b,n,i}^{\mathrm{storPW}}$ Existing capacity of power of storage $b \in \mathcal{B}_n$ in node $n \in \mathcal{N}$ in period $i \in \mathcal{I}$
$v_{n_1,n_2,i}^{\mathrm{tran}}$ Existing capacity of bidirectional interconnection $(n_1, n_2) \in \mathcal{L}$ in period $i \in \mathcal{I}$

$y^{gen}_{g,n,h,i,\omega}$	Output from generator type $g \in \mathcal{G}_n$ in node $n \in \mathcal{N}$ in period $h \in \mathcal{H}, i \in \mathcal{I}$ and scenario $\omega \in \Omega$
$y^{ZEN,EL}_{z,n,h,i,\omega}$	Net electricity supply from neighbourhood type $z \in \mathcal{Z}_n$ in node $n \in \mathcal{N}$ in period $h \in \mathcal{H}, i \in \mathcal{I}$ and scenario $\omega \in \Omega$
$y^{ZEN,HT}_{z,n,h,i,\omega}$	Net heat supply from neighbourhood type $z \in \mathcal{Z}_n$ in node $n \in \mathcal{N}$ in period $h \in \mathcal{H}, i \in \mathcal{I}$ and scenario $\omega \in \Omega$
$y^{tran}_{n_1,n_2,h,i,\omega}$	Power flow from node $n_1 \in \mathcal{N}$ to $n_2 \in \mathcal{N}$ in period $h \in \mathcal{H}, i \in \mathcal{I}$ and scenario $\omega \in \Omega, (n_1, n_2) \in \mathcal{A}$
$y^{chrg}_{b,n,h,i,\omega}, y^{dischrg}_{b,n,h,i,\omega}$	Charging/discharging of storage type $b \in \mathcal{B}_n$ in node $n \in \mathcal{N}$ in period $h \in \mathcal{H}, i \in \mathcal{I}$ and scenario $\omega \in \Omega$
$w^{stor}_{b,n,h,i,\omega}$	Energy content of storage type $b \in \mathcal{B}_n$ in node $n \in \mathcal{N}$ in period $h \in \mathcal{H}, i \in \mathcal{I}$ and scenario $\omega \in \Omega$
$y^{E2H}_{r,n,h,i,\omega}$	Conversion of electric to heat by converter type $r \in \mathcal{R}_n$ in node $n \in \mathcal{N}$ in period $h \in \mathcal{H}, i \in \mathcal{I}$ and scenario $\omega \in \Omega$
$y^{ll,EL}_{n,h,i,\omega}$	Electric load shed in node $n \in \mathcal{N}$ in period $h \in \mathcal{H}, i \in \mathcal{I}$ and scenario $\omega \in \Omega$
$y^{ll,HT}_{n,h,i,\omega}$	Heat load shed in node $n \in \mathcal{N}$ in period $h \in \mathcal{H}, i \in \mathcal{I}$ and scenario $\omega \in \Omega$

ZENIT sets

$t(\mathcal{T})$	Timestep in hour within year, $\in [0, 8759]$
$\kappa(\mathcal{K})$	Cluster representative (centroid)
$t_\kappa(\mathcal{T}_\kappa)$	Timestep within cluster $\kappa, \in [0, 23]$
$b(\mathcal{B})$	Building or building type
$i(\mathcal{I})$	Energy technology, $\mathcal{I} = \mathcal{F} \cup \mathcal{E} \cup \mathcal{HST} \cup \mathcal{EST}; \mathcal{I} = \mathcal{Q} \cup \mathcal{G}$
$f(\mathcal{F})$	Technology consuming fuel (gas, biomass, etc.)
$e(\mathcal{E})$	Technology consuming electricity
$hst(\mathcal{HST})$	Heat storage technology
$est(\mathcal{EST})$	Electricity storage technology
$q(\mathcal{Q})$	Technologies producing heat
$g(\mathcal{G})$	Technologies producing electricity

ZENIT parameters

α_{CHP}	Heat-to-electricity ratio of the CHP
α_i	Part load limit as ratio of installed capacity
$\dot{Q}^{MaxPipe}_{b_1,b_2}$	Maximum heat flow in the heating grid pipe going from b_2 to b_1 [kWh]
$\dot{Q}^{max}_{st}$	Maximum charge/discharge rate of *est*/*hst* [kWh/h]
η_{est}, η_{hst}	Efficiency of charge and discharge
η_{inv}	Efficiency of the inverter
η_i	Efficiency of *i*
$\phi^{CO_2,f}$	CO_2 factor of fuel type *f* [g/kWh]
$\phi^{CO_2,e}_t$	CO_2 factor of electricity at *t* [g/kWh]
σ_κ	Number of occurrences of cluster κ in the year
$\varepsilon^{tot}_{r,D}$	Discount factor for the duration of the study *D* with discount rate *r*
B^{DHW}_q	Binary parameter stating whether *q* can produce DHW
C^{HG}	Cost of investing in the heating grid [€]
$C^{maint}_{i,b}$	Annual maintenance cost of *i* in *b* [€/kWh]
$C^{var,disc}_{i,b}, C^{fix,disc}_{i,b}$	Variable/Fixed investment cost of *i* in *b* discounted to the beginning of the study including potential re-investments and salvage value [€/kWh]/[€]
C_{sl}	Cost of external carbon offsetting [€/gCO_2]
$COP_{hp,b,t}$	Coefficient of performance of heat pump *hp*
$E_{b,t}$	Electric load of *b* at *t* [kWh]
G^{stc}	Irradiance in standard test conditions: $1000W/m^2$
GC	Size of the neighborhood grid connection [kW]
$H^{SH}_{b,t}, H^{DHW}_{b,t}$	Heat (Space Heating/Domestic Hot Water) load of *b* at *t* [kWh]
IRR^{tilt}_t	Total irradiance on a tilted plane [W/m^2]
M	"Big M", taking a large value
P^{grid}	Electricity grid tariff [€/kWh]
$P^{input,max}_{hp,b,t}$	Maximum Power consumption of *hp* at *t* based on manufacturer data and output temperature
P^{ret}	Retailer tariff on electricity [€/kWh]
P^{fuel}_f	Price of fuel of *g* [€/kWh]
P^{spot}_t	Spot price of electricity at *t* [€/kWh]
$Q^{HGloss}_{b_1,b_2}$	Heat loss in the heating grid in the pipe going from b_2 to b_1
T^{coef}	Temperature coefficient
T^{noct}	Normal operating cell temperature [°C]
T^{stc}	Ambient temperature in standard test conditions [°C]
T_t	Ambient temperature at *t* [°C]
X^{max}_i	Maximum investment in *i* [kW]
X^{min}_i	Minimum investment in *i* [kW]

ZENIT variables

$\overline{x_{i,b,t}}$	Maximum production from *i* [kWh]
b^{HG}	Binary for the investment in the Heating Grid
$b_{i,b}$	Binary for the investment in *i* in *b*
$d_{e,t,b}$	Electricity consumed by *e* in *b* at *t* [kWh]
e_{sl}	Emission compensated via external carbon offsetting [gCO_2]
$f_{f,t,b}$	Fuel consumed by *f* in *b* at *t* [kWh]
$g^{curt}_{t,b}$	Solar energy production curtailed [kWh]
$g^{dump}_{g,t,b}$	Electricity generated but dumped by *g* at *t* [kWh]
$g_{g,t,b}$	Electricity generated by *g* at *t* [kWh]
$g^{ch}_{t,g,b}$	Electricity generated by *g* used to charge the 'prod' batteries at *t* [kWh]
$g^{selfc}_{t,g,b}$	Electricity generated by *g* self consumed in the neighborhood at *t* [kWh]
$o_{i,t,b}$	Binary controlling if *i* in *b* is on or off at *t*
$q^{ch}_{t,st,b}, q^{dch}_{t,st,b}$	Energy charged/discharged from the neighborhood to the storage at *t* [kWh]
$q^{dump}_{t,b}$	Heat dumped at *t* in *b* [kWh]
$q^{HGtransfer}_{b_1,b_2,t}$	Heat transferred via the heating grid from b_1 to b_2 at *t* [kWh]
$q^{HGused}_{b,t}$	Heat taken from the heating grid by *b* at *t* [kWh]
$q_{q,t,b}$	Heat generated by *q* in *b* at *t* [kWh]
$v^{stor}_{t,st,b}$	Level of the storage *st* in building *b* at *t* [kWh]
$x_{i,b}$	Capacity of *i* in *b*
$y^{ch}_{t,est,b}$	Electricity charged from on-site production to *est* at *t* [kWh]
$y^{dch}_{t,est,b}$	Electricity discharged from *est* to the neighborhood at *t* [kWh]
$y^{exp}_{t,est,b}$	Electricity exported from the *est* to the grid at *t* [kWh]
$y^{imp}_{t,est,b}$	Electricity imported from the grid to *est* at *t* [kWh]
$y^{exp}_{t,g,b}$	Electricity exported by *g* to the grid at *t* [kWh]
y^{imp}_t, y^{exp}_t	Electricity imported from the grid to the neighborhood/-exported at *t* [kWh]

ation of climatic conditions and resource availability [9]. There are also ongoing initiatives to expand the system boundary to an area level (see e.g. [13]), but these are not currently part of EU legislation.

European large-scale electricity and heat production is subject to the EU ETS, while the European building sector is subject to an increasing adoption of NZEB concepts centred around GHG emissions [14]. Also, there is an ongoing debate to extend the reach of the EU ETS to the buildings and transport sectors [15]. Because buildings traditionally use electricity and heat from the national infrastructure, there is an overlap between the EU ETS and other policies. Hence, an efficient interaction of policies regulating different sectors is vital for an efficient transformation [16,17]. There is a need to better understand how international and local climate policies interact, and it is unclear how the coexistence of the EU ETS and NZEB developments impact investment decisions on the transition towards climate neutrality by 2050. As we show in the following section, literature lacks research exploring the interaction between climate ambitions at different scales, specifically the link between the European electricity and heat system and neighbourhood energy systems. In this paper, we study the interaction between the EU ETS and Zero Emission Neighbourhoods (ZEN) [18] (see Section 2.3), and we address the following research questions:

- How are investment decisions in ZEN impacted when the surrounding electricity and heat system develops in line with planned emission reductions?
- How are investment decisions in the large-scale electricity and heat system, subject to the planned development of the EU ETS, impacted by ZEN?

Because it is practically impossible for one model to consider everything with high detail, researchers often employ linking of models to capture complex interactions [19–21]. Since we are dealing with spatially different scales, one model is used for the long-term nationally aggregated European electricity and heat system subject to the EU ETS, which is soft-linked it to a neighbourhood energy system model representing the ZEN concept via investment decisions that compensates operational GHG emissions. This novel methodological framework is based on our report from 2021 [22] which expands our preliminary study from 2018 [23]. We contribute to the existing literature in two parts:

- First, we quantify how investments towards ZEN is affected when the EU ETS drives decarbonisation of the European electricity and heat sector.
- Second, we quantify how the development of ZENs across Europe affects investments in the European electricity and heat sector subject to the EU ETS.

The remaining parts of the paper is structured as follows: Section 2 presents related research on climate policy strategies at the European level and at the neighbourhood level, and further highlights the contribution of this paper. Section 3 presents the mathematical models used in our case study, while Section 4 presents results from our case study. Section 5 discusses our assumptions, results, and limitations, before Section 6 concludes the paper.

2. Background

2.1. European climate policy and the EU ETS

The question of how to best politically mitigate climate change has been studied for decades, e.g., by [24] on the balance between regulating prices (carbon tax) versus quantities (carbon cap). Although it is considered the cornerstone of EU climate policy, the EU ETS coexists with a mix of both quantity and price based climate policies, e.g., feed-in tariffs [25]. [26] argues that national policies limiting fossil fuel use subject to the EU ETS does not reduce GHG emissions; however, national climate policies are still effective if they improve the implementation of the EU ETS, correct for market failures, and/or serve other policy objectives than emission reduction. [27] make similar arguments for the coexistence of the EU ETS and support schemes for renewable energy, and [28] argue that renewable energy support schemes could facilitate political bargaining for a more stringent EU ETS cap. The EU ETS has recently been strengthened with the implementation of a market stability reserve which will increase the linear reduction factor of the EU ETS cap from 1.74% to 2.2% [29].

2.2. Capacity expansion modelling for policy analysis

Impacts of climate policy on the future energy mix are commonly explored using capacity expansion models, assuming climate targets are achieved for different future scenarios [30]. With high shares of variable renewable energy sources (VRES), energy system capacity expansion models need to represent short-term load variations [31,32]. [33] study the transition pathway for the European power system to meet its climate targets subject to an emission cap representing the EU ETS, and they assume perfect information and perfect foresight. Previous research shows that stochastic capacity expansion models are needed to avoid capacity inadequacy in future power systems, because perfect foresight will underestimate the capacity expansion of dispatchable generation [34] and VRES [35]. Further, capacity expansion models are increasingly considering power-to-heat flexibility [36,37]. In this paper, we use the EMPIRE model [38] because it is a stochastic capacity expansion model for the European electricity and heat system that allows the consideration of power-to-heat flexibility, which is a crucial feature to consider European building stocks and neighbourhoods.

There exists several models and studies exploring the design of energy systems in buildings [39] and microgrids [40] towards economical and/or environmental objectives and policy targets. [41] review modelling tools to analyse hybrid energy systems, and none of the tools reviewed focus on the explicit fulfilment of criteria related to the concept of NZEB. [42] develop a model for a multi-energy system in a neighbourhood including seasonal storage, and they use the model in a case study of a neighbourhood in Switzerland. Although they consider optimization of carbon emissions, [42] do not optimise the design of NZEB or ZEN. [43] study the cost optimal design of NZEBs, and they find that the results depend significantly on heating and cooling systems, and energy prices.

2.3. Zero Emission Neighbourhoods—definition and modelling

A Zero Emission Neighbourhood (ZEN) is defined by [18] as a group of interconnected buildings and distributed energy resources within a confined geographical area. The neighbourhood becomes ZEN by reducing and compensating direct and indirect GHG emissions over its life cycle, for example by producing surplus renewable electricity and heat. Note that the energy resources that compensate GHG emissions in ZEN needs to be physically located within the confined neighbourhood area. Also note that the ZEN concept only entails GHG emissions, and it does not explicitly consider other forms of emissions. [44] develop a life cycle assesment model for the GHG emissions related to a neighbourhood by categorising the neighbourhood into five physical elements: Buildings, mobility, open spaces, networks, and on-site energy infrastructure. Reducing direct and indirect GHG emissions towards zero in the ZEN requires on-site renewable energy production, but the ZEN also aims towards high energy efficiency and sustainable transport to reduce GHG emissions. The ZEN concept is also linked to energy communities [45] and net-zero energy districts [46].

[14] review 144 papers related to ZEN and similar concepts, and they find that there is a need for a clear and concise definition of a Zero Emission Neighbourhood. Although [18] provide a ZEN definition, the concept is still under development regarding system boundaries, stakeholders, and demarcations. In this study, we define ZEN as a neighbourhood where all produced or imported GHG emissions related to energy use are compensated by surplus renewable energy. The surplus renewable energy is assumed to

replace GHG emissions elsewhere, and hence the neighbourhood is, arguably, contributing to zero (energy-related) emissions.

In pursuit of the ZEN ambition as used in this study, information about the surrounding electricity system is key to quantify imported GHG emissions from electricity [47,48]. The cost-optimal ZEN solutions depend on the price and carbon intensity of surrounding electricity and heat systems [49]: the higher the CO_2 emissions in the surrounding energy system, the higher the value of renewable energy generated within neighbourhoods. In this paper, we use the ZENIT model [47,48] because it considers the cost optimal capacity expansion of a neighbourhood electricity and heat system subject to the achievement of the ZEN ambition.

2.4. Research gaps

Soft-linking of capacity expansion problems is applied to couple power system models and energy system models, e.g., by [19], [20], and [50]. However, integrating optimisation on the aggregate scale with optimisation on the local scale is to our knowledge less investigated and only done by [51], who build on the framework by [52]. [51] soft-link a power dispatch model with a household model to investigate how local investment decisions of photovoltaics (PVs) and batteries in households are affected by electricity market feedback. In this paper, we widen the scope of a single household to a whole neighbourhood.

Further, few studies consider how the NZEB concept impacts the development of the surrounding energy system. [53] explore how NZEBs impact the Scandinavian energy system. They find that the introduction of NZEBs substitute electricity production from wind, non-flexible hydropower, and combined heat and power (CHP). To the authors' knowledge, no prior research explores the bidirectional link between the EU ETS and the concept of zero emission targets at the local level. Therefore, the remainder of this paper contributes to cover this research gap by investigating the path towards European policy targets and the impact of including ZEN in the energy system decarbonization strategy.

3. Methods

3.1. The EMPIRE model

EMPIRE (European Model for Power system Investment with (high shares of) Renewable Energy) is a stochastic linear program minimising investment and operational costs for the European heat and electricity system. The EU ETS is represented in the model as a cap on emissions for each investment period. Investment decisions are modelled in 5-year periods from today until 2060. This section presents an overview of the model, and a more detailed description can be found in Appendix A. An open version of EMPIRE can be downloaded from [54], and its mathematical formulation as used in this paper is based on [38].

EMPIRE represents short-term operational constraints. The European system is represented as a network, where nodes represent country-wide energy markets and arcs represent international transmission. Operations are modelled in representative weeks with hourly resolution within each investment period. Several independent representative weeks are modelled in stochastic scenarios to represent uncertainty related to hourly electricity and heat load and hourly VRES availability.

Electricity and building heat markets are explicitly modelled in each node with four representative weeks and hourly operations for winter, spring, summer, and autumn. Each representative week has unique realisations in three stochastic scenarios. EMPIRE endogenously decides whether to supply building heat demand from the electricity market or directly through other energy carriers.

The input to EMPIRE consists of costs, existing capacities, and technological characteristics representing different technologies producing and storing electricity and building heat. Input also includes costs and existing capacities of international transmission. The output from EMPIRE describes the optimal long-term energy system expansion plan and quantifies the total system costs of supplying heat and electricity. Results include technology investments that satisfy hourly market clearings and EU-wide climate targets.

3.2. The ZENIT model

The ZENIT (Zero Emission Neighbourhood Investment Tool) is an optimisation model that minimises the energy system investment- and operational costs (with a socio-economic perspective) for a given neighbourhood allowing it to reach zero-emission status during its lifetime. This section describes the model's components, and a more detailed model description, including the mathematical formulations, can be found in Appendix B or [48].

The objective function considers investment in several technologies both at the building and at the neighbourhood level, in which case a heating grid is also necessary, and also considers the system's cost-optimal operation.

To be considered a ZEN, the neighbourhoods need to have net-zero emissions in their lifetime. In the framework used by the ZEN research center, several ambition levels exist. They correspond to the different phases of the lifetime of the neighborhood. It ranges from only considering direct emissions from the operation phase of the neighborhood to the entire lifecycle emissions. Moreover, only greenhouse gas emissions are considered in this study. As this paper focuses on the link between the local policy of the ZEN and the European policy of the EU ETS, we only consider the emissions from the operational phase to keep consistency between the scope of the policies we link. In addition, the framework used assumes that the electricity exports from renewable sources in the neighbourhood reduce the emissions in the bidding zone by replacing some of the more carbon-intensive power generation. Therefore, from the neighbourhood perspective, such local electricity export is counted as compensations (or negative emissions) in the net emission calculation. By this definition, one could model non-efficient buildings and invest sufficiently in local generation to obtain a zero emission neighborhood. However, in this study we assume new and energy efficient buildings.

We only consider technologies applicable inside the boundary of the neighborhood, and as such, technologies such as wind turbines and nuclear plants are not represented in ZENIT. We include technologies based on data availability, and Appendix C presents the technologies included and their corresponding data.

When it comes to the operation of the neighbourhood, we consider the same hourly time steps as in EMPIRE: three scenarios of one week per season and two peak days. Load balances for electricity, domestic hot water (DHW) and space heating (SH) are considered separately. The heat produced at the central heating plant is distributed to the buildings through a heating grid, considering temperature losses.

For most technologies, the amount of fuel used for generating heat or electricity is based on their conversion efficiency. A solar availability factor describes the solar technologies' available output (solar thermal collectors and PV panels). For heat pumps, an hourly coefficient of performance (COP) describes conversion from electricity to heat dependent on the outdoor temperature. Technologies at the neighbourhood level are placed in a central plant and use the heating grid to deliver heat to each building. Technology prices are different depending on the building type (apartment-

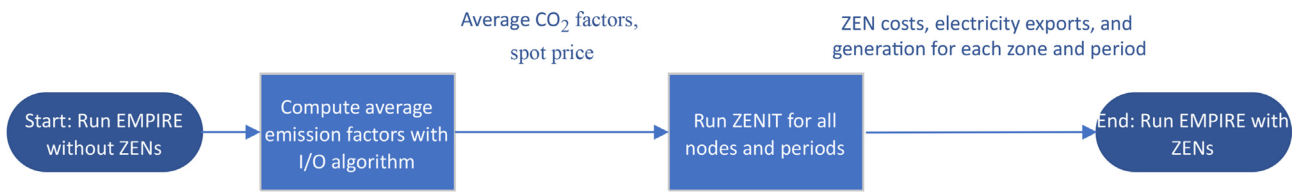


Fig. 1. Flow chart of the soft linkage and transferred data.

complex or single-family house). Heat and electric energy storage are modelled with their charge and discharge efficiencies and only consider the storage's daily operation.

3.3. Linking the models

Fig. 1 presents the way the study is conducted and the linking of the two models. First, we use the EMPIRE model [38] to find a transition pathway for the European heat and electricity system with least total costs while respecting the decreasing EU ETS cap towards 2060 in line with [55]. The results allow computation of future emission factors; the future spot price of electricity as the dual of the market clearing constraint; and the price of allowances as the dual of the European emission constraint. Then, the price (EUR MWh^{-1}) and emission factor (g CO_2e kWh^{-1}) for electricity from EMPIRE are used as input to the neighbourhood energy system model ZENIT [48]. Further, ZENIT finds the least cost heat and electricity system of representative neighbourhoods in different European countries at different future periods, ensuring that the annual operational emission balance of the neighbourhood is strictly zero. In this study, 24 nodes representing 20 European countries and three future periods (2030, 2040, and 2050) are considered.

The result from ZENIT (corresponding to different neighborhood's energy systems in the countries considered) is provided to EMPIRE as a 'ZEN investment option' with associated costs and operational patterns. Neighbourhoods in EMPIRE are equivalent to a package of electricity generation, building heat generation, and conversion of electricity to heat. Thus, the 'ZEN investment option' in EMPIRE consists of the neighbourhood's entire technology portfolio consisting of several ZEN assets. We further assume that the ZEN assets' hourly operations are preserved as a net supply of electricity and heat in EMPIRE, which means that we consider the investment cost of neighbourhoods in EMPIRE to include both capital costs and all operation and maintenance costs, including fuel costs. Lastly, EMPIRE is solved again with the option to develop ZEN as a part of the overall European decarbonisation strategy. Note that there are endogenous decisions in EMPIRE on how many ZENs to develop in each country, and the endogenous ZEN investments are scaled linearly in EMPIRE subject to the investment costs estimated by ZENIT. EMPIRE only considers the possibility to invest in ZENs in the three periods considered in ZENIT (2030, 2040, 2050).

3.4. Input data

An overview of the input data used in this study can be found in Appendix C and Appendix D. The costs, efficiencies and other technical data in ZENIT are obtained from the Danish Energy Agency and can partly be found in [48]. For EMPIRE, technical data are also from the Danish Energy Agency for building heating options and from the PRIMES model [56] for the electricity generation options. More details can be found in [38]. Note that data presented by [56] have been updated for the PRIMES model with the EU reference scenario 2020 [57]; however, technology costs are similar, and we follow [56] in this study.

Emission intensities for heat and electricity production for stationary combustion are estimated according to the 2006 IPCC guidelines for national greenhouse gas inventories [58]. The resulting CO_2 emissions are scaled endogenously in EMPIRE and ZENIT according to operations depending on fuel efficiencies.

The baseline scenario for the future European heat and electricity system is calculated by solving EMPIRE, assuming a growth in European electricity demand towards 2060 based on the EU reference scenario 2016 [59]. We do not update demand growth according to the EU reference scenario 2020 [57] as the gross electricity demand in Europe by 2050 is significantly reduced in the EU reference scenario 2020 compared to 2016, and we therefore consider the projections from the EU reference scenario 2016 to be more in line with recent electricity demand projections, e.g., the TYNDP 2022 by ENTSO-E [60]. We assume an unchanged net annual heat demand for the entire horizon as we assume increased energy efficiency and climate change causing lower heat demand is counteracted with growth in building mass and lacking renovations [61]. Note that the assumption of unchanged net annual heat demand towards 2050 does not consider efficiency gains from heat pumps as this is an endogenous decision in EMPIRE. Nevertheless, this assumption is conservative compared to the heat demand projected by other studies [57,59,62]; however, only 0.4–1.2% of the European building stock is currently renovated each year, and 85% of the renovations are considered minor [61]. We do not consider cooling in our study.

Load profiles in EMPIRE are provided with an hourly resolution for nationally aggregated heat and electricity demand within representative weeks. Electricity load profiles are scaled historical data for European countries from the ENTSO-E Transparency platform [63]. Building heat load profiles are gathered from two sources. The first source is the When2Heat project [64], where the aggregated total building heat load profiles are used for 16 European countries[1] from the year 2016. The second source is the load profile generation tool presented in [65], where the input is hourly temperatures and total square meters per building type, and the output is hourly building heat demand. For heat pumps, hourly COP values are calculated based on a polynomial fit of manufacturer's data and the difference between the supply and the source temperature. We have used temperatures from the year 2016 from Norsk Klimaservicesenter[2] for Norway and Open Power System Weather Data[3] for Finland, Sweden, and Denmark. Building area estimations are according to the EU building observatory[4] and the Norwegian Energy Regulator [66]. Due to a lack of data, EMPIRE does not consider building heat demand (and thereby no ZEN options) in Spain, Portugal, Italy, Bosnia-Herzegovina, Serbia, North Macedonia, or Greece; however, electricity demand is still represented in those countries.

[1] Austria, Belgium, Bulgaria, Switzerland, Germany, France, Great Britain, Croatia, Hungary, Ireland, Luxemburg, Netherlands, Poland, Romania, Slovenia, and Slovakia.
[2] https://klimaservicesenter.no/observations/
[3] https://doi.org/10.25832/weather_data/2019-04-09
[4] https://ec.europa.eu/energy/eu-buildings-database_en

We further assume that the European heat and electricity system respects a decreasing emission cap according to the European Commission's vision for the power sector [55]. Like the EU ETS, we only account for operational CO_2 emissions, and we do not assume CO_2 emissions from any renewable energy sources, including biomass. As the EU ETS only covers large-scale installations, emissions from small-scale non-electric heat boilers are not part of the EMPIRE emission cap, and we assume no exogenous CO_2 price. To focus on the impact of ZENs in the European electricity and heat system, we do not consider the option of carbon capture and storage or the production and use of hydrogen.

In ZENIT, the neighbourhood unit for an energy system covers $250,000\ m^2$ of ground floor area representing $100,000\ m^2$ of heated floor area. The floor area and share of each building type are based on the building mix of Oslo. The composition of the building mix and their ground area were obtained using GIS data from Oslo. In this case, we consider seven types of buildings: houses (split into two blocks), apartments (split into two blocks), offices, shops, kindergartens, schools, and nursing homes. The load time series of these buildings were obtained from [67,68] using ambient temperatures of the geographical location in question. We assume a lifetime of 60 years for the neighbourhood and a discount rate of 4%. The effect of climate change on temperatures and loads are not considered in this study.

All time series correspond to the climatic year 2016. The time series for ambient temperature were gathered from measuring stations for Norway and from the Open Power System Data (OPSD) Project for other countries. The solar irradiances also come from the OPSD project. The electricity spot prices and CO_2 allowance prices used in ZENIT are outputs from EMPIRE. The hourly average emission factors of electricity are computed based on the EMPIRE results, namely the generation per type of generator in each node and the transmission between nodes using the multi-regional input–output methodology of [69]. Those elements: temperature profiles (and in turn load profiles), irradiance, electricity prices and emissions factors, are what constitute the differentiation between the different countries and lead to differences in ZEN designs. All other assumptions, including technology costs, are identical between countries in ZENIT runs.

3.5. Computations

EMPIRE is implemented in Python and solved using the interior point method with the FICO Xpress Solver 64bit v8.8.3. EMPIRE is solved on a server with a 2x 3.5 GHz Intel Xeon Gold 6144 CPU - 8 core, with 384 Gb of RAM. The first EMPIRE run without ZENs solves in 12,262 s, and the latter EMPIRE run with ZENs solves in 14,980 s.

ZENIT is implemented in Python and solved using Gurobi. ZENIT is solved on a server with a 12 core, 24 threads intel Core i9-9920X at 3.5 GHz with 128 GB of RAM. One ZENIT run takes approximately 1,260 s, and it is solved for 25 European price zones and three future investment periods.

4. Results

4.1. Future net-zero emission neighbourhood development

Fig. 2 presents the evolution of the annual averages of the prospective hourly spot prices and emission factors for electricity from EMPIRE without ZENs. Due to investments in renewable sources and less generation by fossil sources, the carbon emission intensity of electricity decreases to reach values close to zero after 2040, driven by the cap reduction, and the average spot prices increase by about EUR 30 MWh^2 between 2020 and 2060.

Fig. 3 presents the optimal ZEN energy system designs. The designs vary in time and between regions due to changes in the technologies' cost and the evolution of external factors, such as the spot price, the carbon emission intensity of electricity, and temperatures that affect energy demand. In 2030 and 2040, the neighbourhoods' energy systems rely heavily on PV panels to reach net-zero emissions (Fig. 3), but the roof area limits the size of this investment in most cases. The contribution of PV panels in reaching the net-zero emissions varies considerably based on latitude, and other technologies are also needed. The heat is provided by a combination of several technologies, in particular, heat pumps, solar thermal, and biomass, at both building level and neighbourhood level (marked with * in Fig. 3). Investments in heat storage are also significant and enable neighbourhoods to take advantage of variations in the spot price and the carbon emission intensity of electricity. In 2050, bio-based solid oxide fuel cells (SOFC) and batteries become prominent, primarily because of their assumed cost reduction [70].

The main information needed to calculate the European-scale optimal deployment strategy of ZENs in EMPIRE is their discounted investment costs and the energy generation time series as summarised in Fig. 4. The costs of the neighbourhoods are generally lower at lower latitudes, which could be explained by the increased contribution of PV panels to the net-zero emission

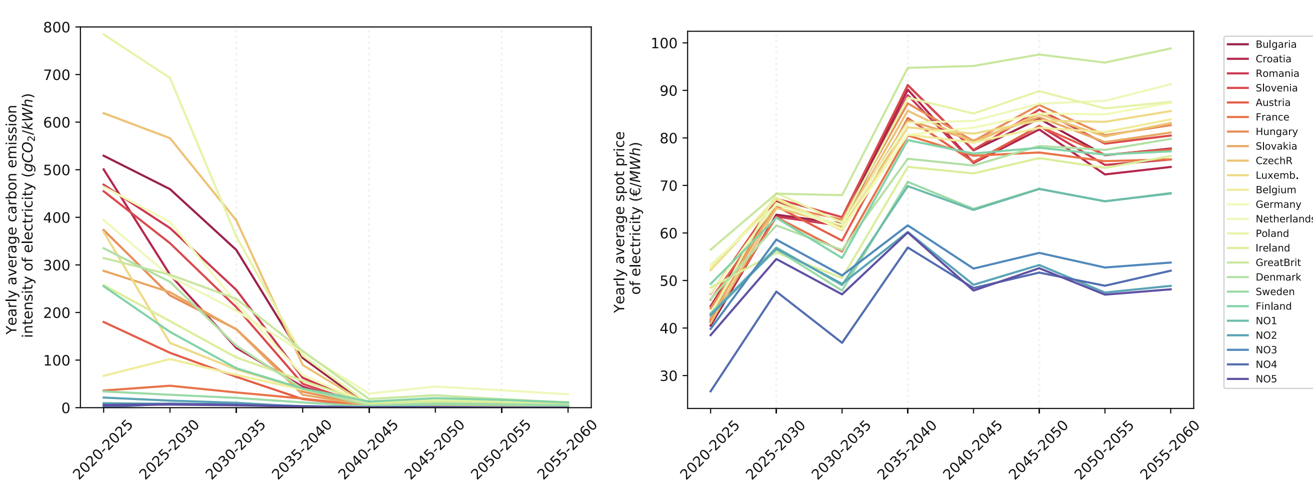


Fig. 2. Yearly average of the CO_2 factor of electricity (left) and of the spot price (right) in the countries considered in ZENIT from the results of EMPIRE. The countries are colour-coded based on their latitude.

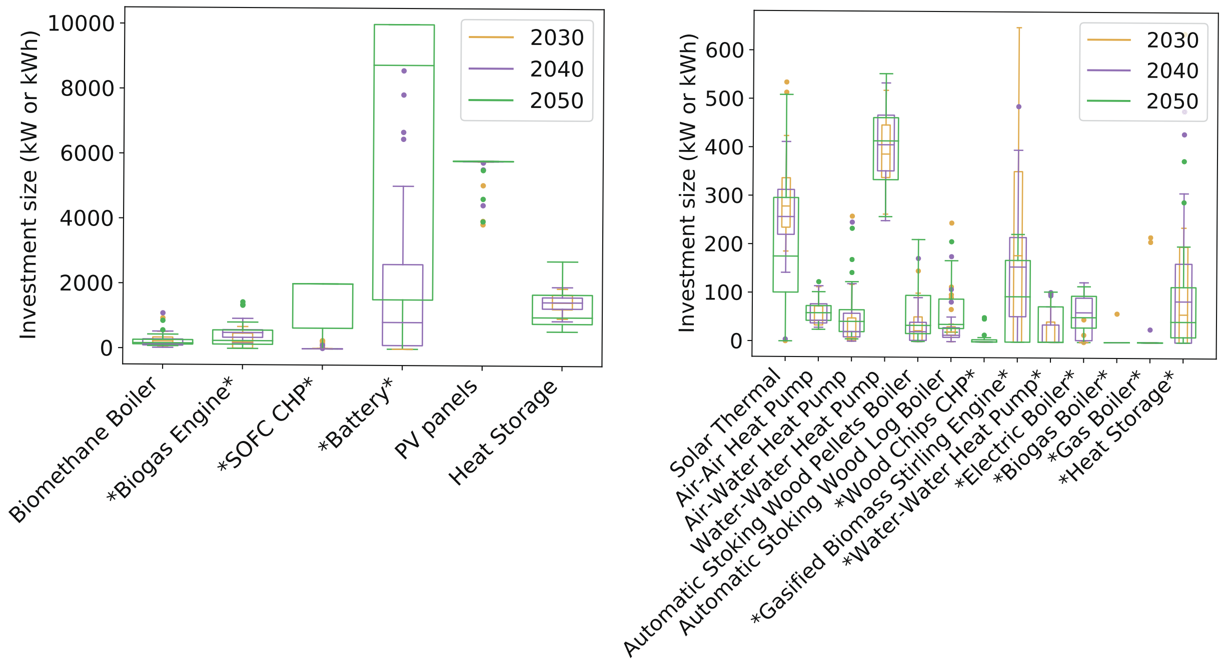


Fig. 3. Box plot of technology investments in the ZEN energy systems for all the considered countries in the three periods. Each box represents the variation in investment between the countries considered. The technologies at the neighbourhood level are marked as *...*. The other technologies are at the building level. In addition, the following technologies are not chosen: electric radiators, electric boilers, wood log stove, biogas CHP, biomethane boiler, gas boiler, *wood pellets CHP*, *wood pellets HOP*, *wood chips HOP*. The storage technologies unit is kWh and the production technologies unit is kW.

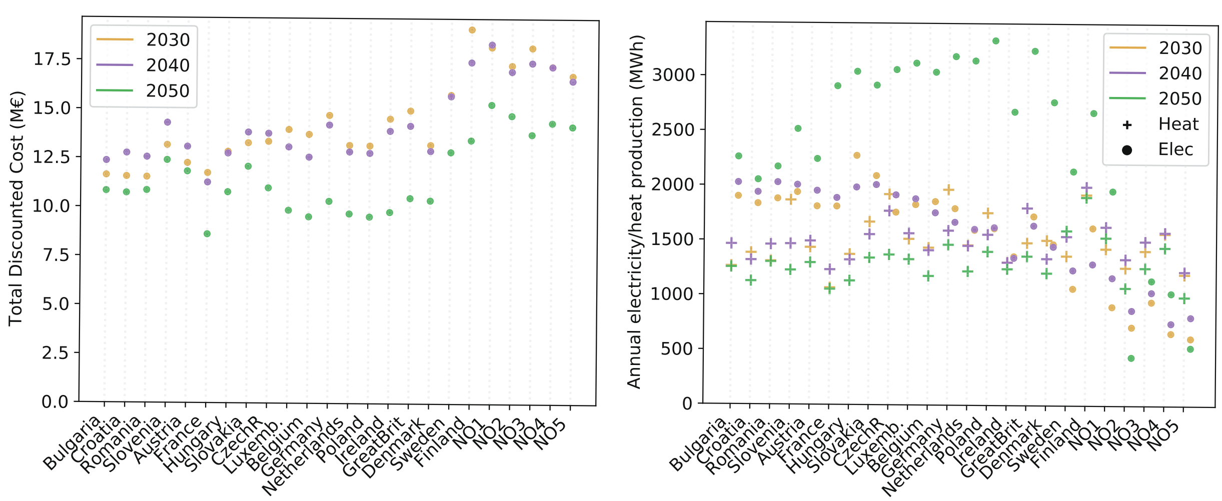


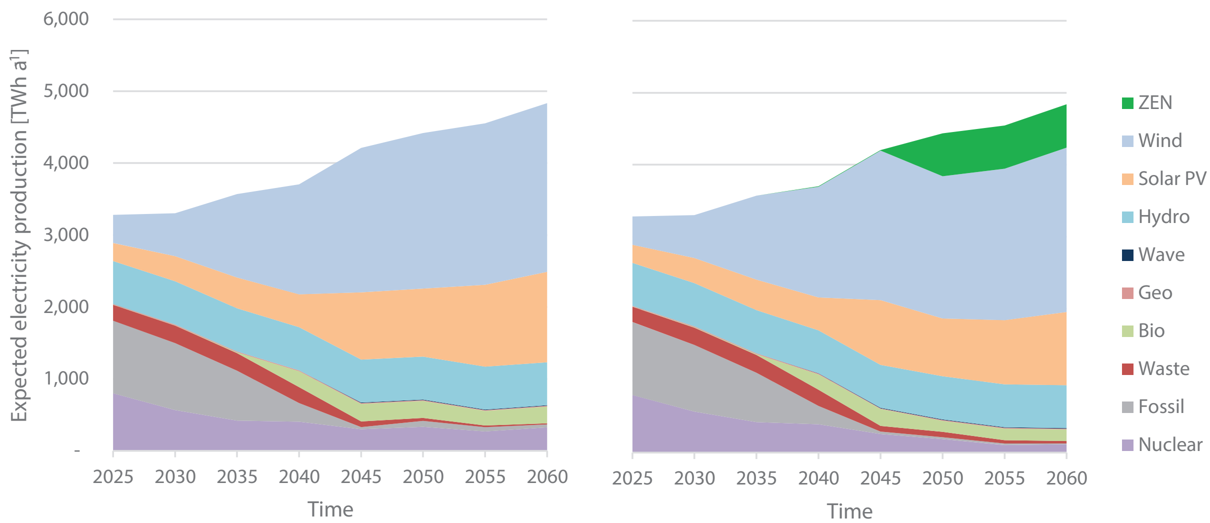
Fig. 4. Total discounted cost for each country in each period (left) and annual electricity and heat production from the ZEN (right) by country and period.

requirement in the south and lower heat demands. The costs of the neighbourhoods' energy systems are reduced by 20% on average between 2030 and 2050. The investment in SOFC leads to high electricity generation from neighbourhoods, particularly in the middle of Europe.

4.2. Energy system transformation with net-zero emission neighbourhoods

The second EMPIRE run is identical to the first, but also includes ZEN as a capacity expansion option designed for 2030, 2040, and 2050 in the 20 countries considered in ZENIT (Fig. 2 and 4). Although the ZEN option is available in all investment periods after 2030, most ZENs are developed with the 2050 design, which is not available before the sixth investment period in EMPIRE. The delay of ZEN deployment happens mainly because the ZEN options are less costly in 2050 (Fig. 4) and and because the European emission cap in EMPIRE increasingly limits high-carbon technology options towards 2060.

Fig. 5 illustrates electricity production for Europe as a whole with and without the ZEN option. In both cases, more than 50% of European electricity is generated via VRES after 2040. Onshore wind dominates electricity production towards 2060, followed by solar PV. This result is driven by wind and solar being the most cost-competitive options without regulated CO_2 emissions, despite their generation variability. In EMPIRE with ZENs (Fig. 5b), there is decreased generation by regular solar PV and bio-based heat and electricity compared to the run without ZENs (Fig. 5a); however,

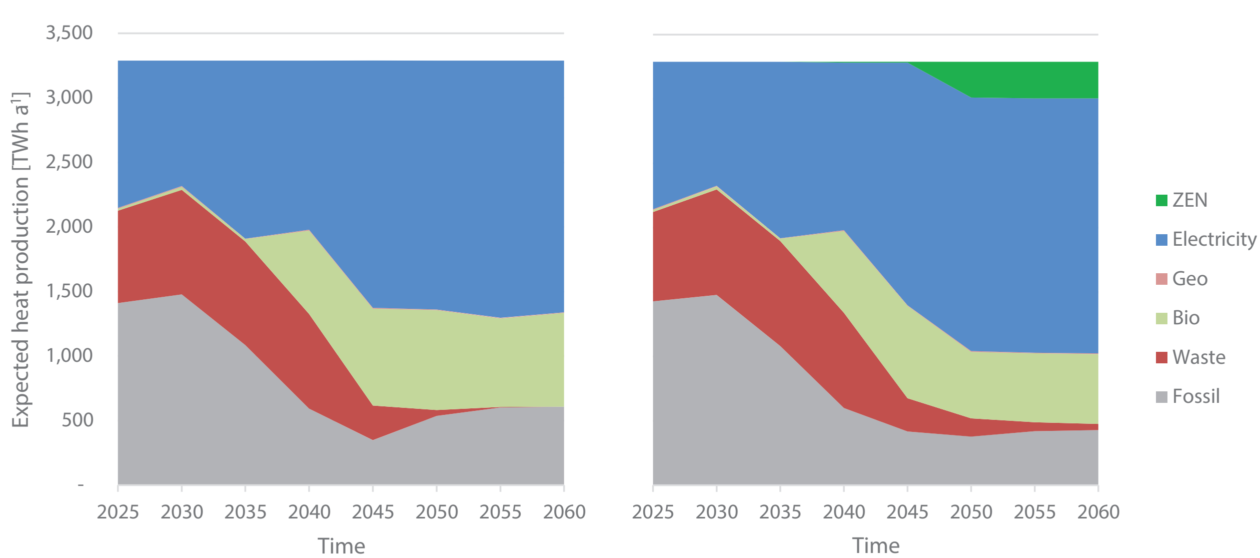


(a) Without ZENs (b) With ZENs

Fig. 5. Expected electricity production in EMPIRE by source for Europe in 5-year steps towards 2060.

there is a net increase in electricity generation from these sources because they are part of the ZENs (Fig. 3). Electricity from ZENs replaces electricity from nuclear (−17%) and wind (−2%) compared to the run without ZENs. Some electricity production by fossil gas is also replaced by ZENs (−4%), while waste-based CHP production is increased when ZENs are introduced (+7%). ZENs produce on average 12% of European electricity by 2060 in EMPIRE with ZENs.

Fig. 6 illustrates building heating sources for Europe with and without ZENs. For both cases, building heat is increasingly electric towards 2060. The introduction of ZENs causes a net increase in electric heating (Fig. 6), but because of the use of additional efficient heat pumps in ZENs (water-water heat pumps, see Fig. 3), total electricity production in EMPIRE remains the same as in the run without ZENs. The reason why ZENs have more efficient heat pumps is because the technology overlap between ZENIT and EMPIRE is not complete. Heat pumps in ZENIT can be partly or completely powered by local electricity within ZENs. Note that heat pumps in EMPIRE are still considered to be an aggregate representation of many smaller heat pumps within each country, but always powered by the national electricity mix. For both cases, the dominating building heat technology in EMPIRE becomes air-sourced heat pumps powered by electricity, accompanied by bio-based heating. Although ZENs contain bio-based heating, there is a net decrease in bio-based heating in EMPIRE with ZENs. Fossil sourced heating remains cost-competitive towards 2060, and because we assume its CO_2 emissions are not regulated or taxed, 18% of heating is provided by small-scale fossil gas boilers in 2060 in the run without ZENs (Fig. 6a). The ZENs replace some fossil heating, resulting in 13% fossil gas heating in 2060 (Fig. 6b). The ZENs allow more waste-sourced heating (+6%) within the same emission constraints as the run without ZENs (Fig. 6). ZENs pro-



(a) Without ZENs (b) With ZENs

Fig. 6. Expected heat production by source for Europe as a whole in 5-year steps towards 2060.

duce on average 9% of European building heating by 2060 in EMPIRE with ZENs.

Transmission expansion between European countries in EMPIRE is not affected by ZENs in our case study, likely because nearly all transmission expansion happens before ZENs are developed. Note that ZENs not affecting transmission expansion is a result rather than an assumption in our study. Part of the lithium-ion batteries are moved inside the ZENs, reducing the amount of grid-scale batteries in EMPIRE by 21%, but the total amount of lithium-ion batteries in the system remain similar. Interestingly, the largest decrease in capacity expansion of lithium-ion batteries caused by ZENs is in Italy, which is one of the countries without ZEN options. Italy does not have ZEN options because we do not consider building heat demand in Italy due to lacking data. When ZENs are developed in neighbouring countries, Italy reduces its investments in solar PV (−11%) and lithium-ion batteries (−16%) because it imports surplus electricity from neighbouring countries with ZENs instead.

The impact of ZENs on expected European CO_2 emissions is illustrated in Fig. 7, along with the endogenous cost in EMPIRE of respecting the emission cap, i.e., the shadow value of the emission constraint in EMPIRE. Note that this is the cost of staying below the emission cap in EMPIRE, which is not covering all sectors regulated by the EU ETS. Therefore, the shadow value of the emission constraint in EMPIRE is only partly representing the EU ETS price. Total CO_2 emissions in EMPIRE exceed the emission cap in all periods because the regulated quota [55] is filled, and emissions from small-scale building heating are not included in the emission quota. Until 2035, decreasing technology costs counteract the effect of quota reductions and stabilises the average shadow value of the emission constraint at 10–20 EUR ton^{-1}. From 2035 to 2045, the rapid decrease in the emission cap causes a rapid increase in the shadow value, and the run without ZENs surprisingly yields a lower shadow value than with ZENs. Lower carbon price without ZENs occurs because EMPIRE anticipates an improved ZEN design after 2045 and therefore develops a more expensive system from a short-term point of view in 2040–2045, such that the system is more cost-efficient in the long run. More explicitly, EMPIRE substitutes investments in solar PV and bio-based heating with more investments in wind and fossil-based heating in 2040–2045 when anticipating the improved ZEN design. After 2045, the shadow value of the emission constraint drops when the new ZEN designs are developed, which means that European emission targets can be met more cost-effectively.

Fig. 7 shows that ZENs cause a decrease in expected allowance price from 2045, which means that ZENs reduce the cost of achieving European climate targets. Because we assume the same emission cap as in the run without ZENs, the ZEN development does not cause reductions in regulated emissions. However, the expected unregulated emissions are decreased by ZENs through the substitution of small-scale fossil gas heating in buildings, and ZENs lead to a total expected CO_2 emission reduction of 2% for the whole horizon compared to the run without ZENs.

5. Discussion

It is important to discuss the underlying reasons behind the attractiveness of ZENs in EMPIRE, and the value of ZENs in the European electricity system. In EMPIRE, the selection of ZENs from 2050 is a result of combined attributes, namely competitive costs, low emissions, and attractive supply profile for heat and electricity. Further, the stronger cap on emissions in EMPIRE excludes fossil alternatives, which makes ZENs more attractive. In addition, the technological advances and their cost reductions reshape the energy system design of ZENs into more useful and less expensive investment options. Indeed, the large reliance on PV to reach net-zero emissions in ZENs is decreased by the introduction of bio-based SOFC, whose electricity production is both decarbonised, flexible, and weather independent. There are also more batteries in ZENs in 2050 which are further reshaping the ZEN supply profile. Also note that the technologies available in ZENIT and EMPIRE do not perfectly overlap, and SOFC is only available in EMPIRE through ZEN. This can also contribute partially to the selection of ZENs in 2050.

An important assumption in our study is the unchanged heat demand in buildings in Europe towards 2050. This assumption represents a failure of European renovation policy, but it is in line with current renovation activity: 75% of the EU building stock is considered energy inefficient according to current building standards, and it will take more than 100 years to renovate the EU building stock at current rates [61]. Optimistic assumptions for the evolution of the building stock are more common in similar studies [57,59,62]. In our study, assuming a decreasing heat demand in European buildings (before considering heat pumps) towards 2050 will impact the first run of EMPIRE, which again will impact the ZEN design resulting from ZENIT and the uptake of ZEN across Europe in the second run of EMPIRE. Further work is needed to understand how our results change when modifying assumptions regarding heat demand development.

Our study shows that ZENs can partly avoid unregulated CO_2 emissions, and further CO_2 emission avoidance by ZEN is dependent on the policy design on the European level. In EMPIRE, we

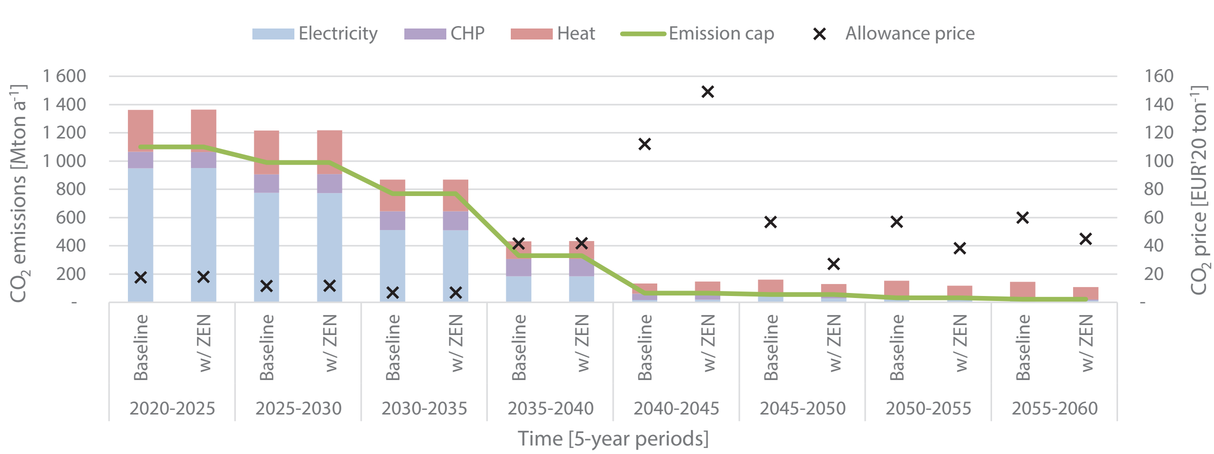


Fig. 7. Expected CO_2 emissions (left) and expected CO_2 allowance price (right) for the European heat and electricity system towards 2060 in EMPIRE with and without ZENs.

assume the only emission policy on the European level is a simplified cap-and-trade system, where the emission cap is exogenous input and the allowance price is endogenous output. Therefore, by design, the introduction of any cost-competitive low carbon option like ZEN will not affect the exogenous cap, but rather decrease the demand for allowances, effectively making it less costly to reach the same CO_2 emission cap. In practice, there will not just be feedback effects between ZENs and the energy system, but also between the energy system and climate policy design. [71] claims that new EU ETS rules are 'temporarily puncturing the waterbed', i.e., that the total allowed emissions are decreased by market behaviour, not only political decisions.

One limitation of our study is that the two models are computed without a feedback loop. The cost of ZENs depends on the electricity prices and emissions factor from EMPIRE, which will change when ZENs are developed in the second EMPIRE computation. Results from the last run of EMPIRE could produce updated input to ZENIT. Hence, the process of back and forth between EMPIRE and ZENIT can possibly be repeated multiple times until convergence. However, in the study, we run the models sequentially, but not iteratively, because of the high number of nodes, periods, and cases would result in unacceptable computation times. The convergence procedure may be of interest for further work since it is better suited for studies where the scope is limited to a few countries or bidding zones. Despite this limitation, it is possible to investigate the differences between key indicators in the first and second run of EMPIRE. The root mean square deviation of the spot price and emission factor are EUR 60 MWh^{-1} and 13 gCO_2 kWh^{-1}, respectively, while the average deviations are EUR -2.3 MWh^{-1} and 0.04 gCO_2 kWh^{-1}. These observations indicate deviations between the two runs, but these are mostly compensated in other time steps. An analysis of the same indicators for each period shows that the deviations in emission factor in each country compensate for one another, while the spot price increases in 2040–2045 before decreasing in the next period. An iteration-based approach would likely affect the design of the neighbourhoods' energy system and may shift some investment in ZENs to other countries, but the implications on a European scale should remain largely unaffected.

Another limitation of our study lies in the ZEN framework setup. Indeed, despite the name, the focus is entirely on GHG emissions and the climate change potential and disregards other important emissions, such as NOx and particles, which also have consequent health impacts. A future work could focus on improving our models to include such emissions and their impact.

6. Conclusion

This paper explores the link between decarbonising the European heat and electricity system and zero emission concepts on the neighbourhood level. The ZEN concept [18] relies on avoiding emissions via on-site renewable energy, and our results indicate that neighbourhoods generate more electricity to become ZEN as the surrounding energy system decarbonises in line with the EU ETS. This is in line with previous findings by [49] where the PV capacity of NZEBs increases with decreasing CO_2 factors, as the exported renewable electricity from NZEBs compensate less CO_2 emissions per kWh. Once ZENs become cost-competitive, results indicate that they are developed widely across Europe, mainly reducing investments in other low carbon energy sources. The ZEN development in EMPIRE is driven by decreasing technology costs in ZENIT and the EU ETS cap reduction. Due to the assumption of an exogenously given emission pathway for the European electricity and heat system, ZENs do not directly reduce the total European-level emissions. Consequently, ZENs indirectly affect the feasibility of decarbonized electricity and heat systems by being part of the overall transition pathway.

Our study has the following policy implications. Firstly, if the emission caps would be more ambitious in the next couple of decades than currently planned [55], a sudden increase in the allowance price in the EU ETS around 2040 might be reduced. A spiked allowance price would strongly signal the transition from fossil to renewable energy. However, the transition may be more politically robust if carbon price spikes can be avoided. Secondly, suppose policy can support low carbon energy technologies in neighbourhoods to become cost-competitive sooner than assumed in our study. In that case, neighbourhood energy systems could potentially outcompete more alternative investments than our results suggest. Specifically, if neighbourhood energy systems could outcompete more fossil investments, it could help reducing future CO_2 prices and avoiding stranded assets.

CRediT authorship contribution statement

Stian Backe: Conceptualization, Methodology, Software, Formal analysis, Writing - original draft, Writing - review & editing, Visualization. **Dimitri Pinel:** Conceptualization, Methodology, Software, Formal analysis, Writing - original draft, Writing - review & editing, Visualization. **Magnus Askeland:** Conceptualization, Methodology, Formal analysis, Writing - original draft, Writing - review & editing. **Karen Byskov Lindberg:** Conceptualization, Writing - review & editing, Supervision. **Magnus Korpås:** Conceptualization, Writing - review & editing, Supervision. **Asgeir Tomasgard:** Conceptualization, Funding acquisition, Writing - review & editing, Supervision.

Data availability

Data will be made available on request.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

This paper has been written within the Research Centre on Zero Emission Neighbourhoods in Smart Cities (FME ZEN). The authors gratefully acknowledge the support from the ZEN partners and the Research Council of Norway.

Appendix A. EMPIRE model description

This appendix presents the optimisation formulation of EMPIRE.

A.1. Objective function

$$\begin{aligned}\min z = & \sum_{i\in\mathcal{I}}(1+r)^{-5(i-1)} \\ & \times \Bigg[\sum_{n\in\mathcal{N}}\sum_{a\in\mathcal{G}_n\cup\mathcal{B}_n\cup\mathcal{R}_n\cup\mathcal{Z}_n} c^{\text{node}}_{a,i}x^{\text{node}}_{a,n,i} + \sum_{n\in\mathcal{N}}\sum_{b\in\mathcal{B}_n} c^{\text{storPW}}_{b,i}x^{\text{storPW}}_{b,n,i} \\ & + \sum_{(n_1,n_2)\in\mathcal{L}} c^{\text{tran}}_{n_1,n_2,i}x^{\text{tran}}_{n_1,n_2,i} + \vartheta\sum_{\omega\in\Omega}\pi_\omega\sum_{s\in\mathcal{S}}\alpha_s\sum_{h\in\mathcal{H}_s}\sum_{n\in\mathcal{N}} \\ & \times\left(\sum_{g\in\mathcal{G}_n} q^{\text{gen}}_{g,i}y^{\text{gen}}_{g,n,h,i,\omega} + q^{\text{ll,EL}}_{n,i}y^{\text{ll,EL}}_{n,h,i,\omega} + q^{\text{ll,HT}}_{n,i}y^{\text{ll,HT}}_{n,h,i,\omega}\right)\Bigg] \end{aligned} \quad (1)$$

The objective function (1) discounts all costs at an annual rate of r, and the investment periods are given as five year blocks. The factor $\vartheta = \sum_{j=0}^{4}(1+r)^{-j}$ scales annual operational costs to the five year investment periods.

The first two terms of (1) relates to investment costs in additional capacity of generation, transmission and storage. The last three terms relate to operational costs of generation and costs of load shedding. The terms for operational costs are scaled with the scenario probability π_ω and the seasonal scaling factor α_s, where α_s make sure the seasonal costs are scaled up to the length of each season.

A.2. Operational constraints

Total supply from electric power generators and storage units, as well as imports and electric load shedding, must be balanced with electric load, exports and charging:

$$\begin{aligned}&\sum_{g\in\mathcal{G}_{\mathrm{EL}}\cap\mathcal{G}_n}\beta_g^{\mathrm{CHP}}y_{g,n,h,i,\omega}^{\mathrm{gen}}+\sum_{b\in\mathcal{B}_{\mathrm{EL}}\cap\mathcal{B}_n}\eta_b^{\mathrm{dischrg}}y_{b,n,h,i,\omega}^{\mathrm{dischrg}}\\&+\sum_{(n_1,n_2)\in\mathcal{A}_n^{\mathrm{in}}}\eta_{n_1,n_2}^{\mathrm{tran}}y_{n_1,n_2,h,i,\omega}^{\mathrm{tran}}+\sum_{z\in\mathcal{Z}\cap\mathcal{Z}_n}y_{z,n,h,i,\omega}^{\mathrm{ZEN,EL}}+y_{n,h,i,\omega}^{\mathrm{ll,EL}}=\xi_{n,h,i,\omega}^{\mathrm{load,EL}}\\&+\sum_{b\in\mathcal{B}_{\mathrm{EL}}\cap\mathcal{B}_n}y_{b,n,h,i,\omega}^{\mathrm{chrg}}+\sum_{(n_1,n_2)\in\mathcal{A}_n^{\mathrm{out}}}y_{n_1,n_2,h,i,\omega}^{\mathrm{tran}}\\&+\sum_{r\in\mathcal{R}_n}y_{r,n,h,i,\omega}^{\mathrm{E2H}},\qquad n\in\mathcal{N},h\in\mathcal{H},\qquad i\in\mathcal{I},\omega\in\Omega.\end{aligned}\tag{2}$$

Note that $\beta_g^{\mathrm{CHP}}=1$ for all $g\notin\mathcal{G}_{\mathrm{EL}}\cap\mathcal{G}_{\mathrm{HT}}$, that is all non-CHP electric generators. For CHP generators ($g\in\mathcal{G}_{\mathrm{EL}}\cap\mathcal{G}_{\mathrm{HT}}$), β_g^{CHP} represents how much electricity is being produced per unit of heat output.

Similarly, total supply from thermal generators and storage units, as well as electric conversions to thermal load and thermal load shedding, must be balanced with thermal load and charging:

$$\begin{aligned}&\sum_{g\in\mathcal{G}_{\mathrm{HT}}\cap\mathcal{G}_n}y_{g,n,h,i,\omega}^{\mathrm{gen}}+\sum_{b\in\mathcal{B}_{\mathrm{HT}}\cap\mathcal{B}_n}\eta_b^{\mathrm{dischrg}}y_{b,n,h,i,\omega}^{\mathrm{dischrg}}+\sum_{r\in\mathcal{R}_n}\eta_r^{\mathrm{E2H}}y_{r,n,h,i,\omega}^{\mathrm{E2H}}\\&+\sum_{z\in\mathcal{Z}\cap\mathcal{Z}_n}y_{z,n,h,i,\omega}^{\mathrm{ZEN,HT}}+y_{n,h,i,\omega}^{\mathrm{ll,HT}}\\&=\xi_{n,h,i,\omega}^{\mathrm{load,HT}}+\sum_{b\in\mathcal{B}_{\mathrm{HT}}\cap\mathcal{B}_n}y_{b,n,h,i,\omega}^{\mathrm{chrg}},n\in\mathcal{N},h\in\mathcal{H},i\in\mathcal{I},\omega\in\Omega.\end{aligned}\tag{3}$$

Conversion of electricity to heat is limited by the available installed capacity:

$$y_{r,n,h,i,\omega}^{\mathrm{E2H}}\leqslant v_{r,n,i}^{\mathrm{node}},\qquad r\in\mathcal{R}_n,n\in\mathcal{N},h\in\mathcal{H},\ i\in\mathcal{I},\omega\in\Omega.\tag{4}$$

Production from generators and Zero Emission Neighbourhoods are limited by the available installed capacity:

$$y_{g,n,h,i,\omega}^{\mathrm{gen}}\leqslant\xi_{g,n,h,i,\omega}^{\mathrm{gen}}v_{g,n,i}^{\mathrm{node}},\quad g\in\mathcal{G}_n,n\in\mathcal{N},\quad h\in\mathcal{H},i\in\mathcal{I},\omega\in\Omega,\tag{5}$$

$$y_{z,n,h,i,\omega}^{\mathrm{ZEN,EL}}=\xi_{z,n,h,i,\omega}^{\mathrm{ZEN,EL}}v_{z,n,i}^{\mathrm{node}},\quad z\in\mathcal{Z}_n,n\in\mathcal{N},\quad h\in\mathcal{H},i\in\mathcal{I},\omega\in\Omega,\tag{6}$$

$$y_{z,n,h,i,\omega}^{\mathrm{ZEN,HT}}=\xi_{z,n,h,i,\omega}^{\mathrm{ZEN,HT}}v_{z,n,i}^{\mathrm{node}},\qquad z\in\mathcal{Z}_n,n\in\mathcal{N},\quad h\in\mathcal{H},i\in\mathcal{I},\omega\in\Omega.\tag{7}$$

For generators subject to ramping constraints, ramping up load in between hours is limited:

$$y_{g,n,h,i,\omega}^{\mathrm{gen}}-y_{g,n,h-1,i,\omega}^{\mathrm{gen}}\leqslant\gamma_g^{\mathrm{gen}}v_{g,n,i}^{\mathrm{node}},\quad g\in\mathcal{G}_{\mathrm{Ramp}}\cap\mathcal{G}_n,n\in\mathcal{N},s\in\mathcal{S},\ h\in\mathcal{H}_s^{-},i\in\mathcal{I},\omega\in\Omega.\tag{8}$$

Total annual emissions are limited by an emission cap:

$$\sum_{s\in\mathcal{S}}\alpha_s\sum_{h\in\mathcal{H}_s}\sum_{n\in\mathcal{N}}\sum_{g\in\mathcal{G}_n\setminus\mathcal{G}^{\mathrm{NoReg}}}q_{g,i}^{\mathrm{CO2}}y_{n,g,h,i,\omega}^{\mathrm{gen}}\leqslant Q_i^{\mathrm{CO2}},i\in\mathcal{I},\omega\in\Omega.\tag{9}$$

All storages start with an initial energy level available as a percentage of installed capacity and runs a full cycle over each representative time period in each season:

$$\kappa_b v_{n,b,i}^{\mathrm{node}}+\eta_b^{\mathrm{chrg}}y_{n,b,h_s^1,i,\omega}^{\mathrm{chrg}}-y_{n,b,h_s^1,i,\omega}^{\mathrm{discrg}}=w_{n,b,h_s^1,i,\omega}^{\mathrm{stor}},\quad b\in\mathcal{B}_n,n\in\mathcal{N},s\in\mathcal{S},\ i\in\mathcal{I},\omega\in\Omega.\tag{10}$$

$$\kappa_b v_{n,b,i}^{\mathrm{node}}=w_{n,b,h_s^{H_s},i,\omega}^{\mathrm{stor}},\qquad b\in\mathcal{B}_n,n\in\mathcal{N},s\in\mathcal{S}\ \ i\in\mathcal{I},\omega\in\Omega.\tag{11}$$

The balance of storage is ensured between operational time steps:

$$w_{b,n,h-1,i,\omega}^{\mathrm{stor}}+\eta_b^{\mathrm{chrg}}y_{b,n,h,i,\omega}^{\mathrm{chrg}}-y_{b,n,h,i,\omega}^{\mathrm{discrg}}=\eta_b^{\mathrm{bleed}}w_{b,n,h,i,\omega}^{\mathrm{stor}},\quad b\in\mathcal{B}_n,n\in\mathcal{N},\ s\in\mathcal{S},h\in\mathcal{H}_s^{-},\ i\in\mathcal{I},\omega\in\Omega.\tag{12}$$

The energy content of storage is limited by capacity:

$$w_{b,n,h,i,\omega}^{\mathrm{stor}}\leqslant v_{b,n,i}^{\mathrm{node}},\quad b\in\mathcal{B}_n,n\in\mathcal{N},h\in\mathcal{H},i\in\mathcal{I},\omega\in\Omega.\tag{13}$$

The amount of charging and discharging per hour is also limited by capacity:

$$y_{b,n,h,i,\omega}^{\mathrm{chrg}}\leqslant v_{b,n,i}^{\mathrm{storPW}},\quad b\in\mathcal{B}_n,n\in\mathcal{N},h\in\mathcal{H},i\in\mathcal{I},\omega\in\Omega,\tag{14}$$

$$y_{b,n,h,i,\omega}^{\mathrm{dischrg}}\leqslant\rho_b v_{b,n,i}^{\mathrm{storPW}},\quad b\in\mathcal{B}_n,n\in\mathcal{N},h\in\mathcal{H},i\in\mathcal{I},\omega\in\Omega.\tag{15}$$

For hydroelectric generators, energy available is restricted by season and node:

$$\sum_{h\in\mathcal{H}_s}y_{\text{'RegHyd'},n,h,i,\omega}^{\mathrm{gen}}\leqslant\xi_{n,i,s,\omega}^{\mathrm{RegHydLim}},\quad n\in\mathcal{N},s\in\mathcal{S},\ i\in\mathcal{I},\omega\in\Omega,\tag{16}$$

$$\sum_{\omega\in\Omega}\pi_\omega\sum_{s\in\mathcal{S}}\alpha_s\sum_{h\in\mathcal{H}_s}\sum_{g\in\mathcal{G}^{\mathrm{Hyd}}\cap\mathcal{G}_n}y_{n,g,h,i,\omega}^{\mathrm{gen}}\leqslant\xi_n^{\mathrm{HydLim}},n\in\mathcal{N},i\in\mathcal{I}.\tag{17}$$

Transmission operation is in a net transfer capacity (NTC) representation:

$$y_{n_1,n_2,h,i,\omega}^{\mathrm{tran}}\leqslant v_{n_1,n_2,i}^{\mathrm{tran}},\quad (n_1,n_2)\in\mathcal{L},h\in\mathcal{H},i\in\mathcal{I},\omega\in\Omega,\tag{18}$$

$$y_{n_2,n_1,h,i,\omega}^{\mathrm{tran}}\leqslant v_{n_1,n_2,i}^{\mathrm{tran}},\quad (n_1,n_2)\in\mathcal{L},h\in\mathcal{H},i\in\mathcal{I},\omega\in\Omega.\tag{19}$$

$$v_{a,i}^{\mathrm{node}}=\bar{x}_{a,n,i}^{\mathrm{node}}+\sum_{j=i'}^{i}x_{a,n,j}^{\mathrm{node}},\qquad a\in\mathcal{G}_n\cup\mathcal{B}_n\cup\mathcal{R}_n\cup\mathcal{Z}_n,n\in\mathcal{N},i\in\mathcal{I},\ i'=\max\left\{1,i-i_a^{\mathrm{life}}\right\},\tag{20}$$

$$v_{b,n,i}^{\mathrm{storPW}}=\bar{x}_{b,n,i}^{\mathrm{storPW}}+\sum_{j=i'}^{i}x_{b,n,j}^{\mathrm{storPW}},\qquad b\in\mathcal{B}_n,n\in\mathcal{N},i\in\mathcal{I},\ i'=\max\left\{1,i-i_b^{\mathrm{life}}\right\},\tag{21}$$

$$v_{n_1,n_2,i}^{\mathrm{tran}}=\bar{x}_{n_1,n_2,i}^{\mathrm{tran}}+\sum_{j=i'}^{i}x_{n_1,n_2,j}^{\mathrm{tran}},\qquad (n_1,n_2)\in\mathcal{L},i\in\mathcal{I},\ i'=\max\left\{1,i-i_{n_1,n_2}^{\mathrm{life}}\right\}.\tag{22}$$

A.3. Investment constraints

Every generator, transmission line, and storage unit have existing capacity available in each period:

There are restrictions on investments and available capacity the technologies in each node:

$$x_{a,n,i}^{\text{node}} \leqslant \bar{X}_{a,n,i}^{\text{node}}, \quad a \in \mathcal{G}_n \cup \mathcal{B}_n \cup \mathcal{R}_n \cup \mathcal{Z}_n, n \in \mathcal{N}, i \in \mathcal{I}, \tag{23}$$

$$x_{b,n,i}^{\text{storPW}} \leqslant \bar{X}_{b,n,i}^{\text{storPW}}, \quad b \in \mathcal{B}_n, n \in \mathcal{N}, i \in \mathcal{I}, \tag{24}$$

$$x_{n_1,n_2,i}^{\text{tran}} \leqslant \bar{X}_{n_1,n_2,i}^{\text{tran}}, \quad (n_1, n_2) \in \mathcal{L}, i \in \mathcal{I}, \tag{25}$$

$$v_{a,n,i}^{\text{node}} \leqslant \bar{V}_{a,n,i}^{\text{node}}, \quad a \in \mathcal{G}_n \cup \mathcal{B}_n \cup \mathcal{R}_n, n \in \mathcal{N} \cup \mathcal{Z}_n, i \in \mathcal{I}, \tag{26}$$

$$v_{b,n,i}^{\text{storPW}} \leqslant \bar{V}_{b,n,i}^{\text{storPW}}, \quad b \in \mathcal{B}_n, n \in \mathcal{N}, i \in \mathcal{I}, \tag{27}$$

$$v_{n_1,n_2,i}^{\text{tran}} \leqslant \bar{V}_{n_1,n_2,i}^{\text{tran}}, \quad (n_1, n_2) \in \mathcal{L}, i \in \mathcal{I}. \tag{28}$$

Some storage technologies $b \in \mathcal{B}^{\dagger} \subseteq \mathcal{B}$, including lithium-ion batteries, have dependencies between power and energy capacity:

$$v_{b,n,i}^{\text{storPW}} = \beta_b^{\text{stor}} v_{b,n,i}^{\text{node}}, \quad b \in \mathcal{B}^{\dagger} \cap \mathcal{B}_n, n \in \mathcal{N}, i \in \mathcal{I}. \tag{29}$$

Appendix B. ZENIT model description

This appendix presents the optimization formulation inside of ZENIT in the most general form.

B.1. Objective function

The objective function minimizes the total cost of investing in the energy system and operating it. It includes investment in the heating grid, the energy technologies in the central plant and in the building, the cost of refurbishment and of a hydronic system (when refurbishment is considered). It also includes operational costs such as the operation and maintenance (O&M) costs, fuel costs, cost of electricity imports and revenues of electricity exports. It uses an hourly resolution.

The objective function of the optimization is: *Minimize*:

$$\begin{aligned} & b^{HG} \cdot C^{HG} + \sum_b \sum_i \left(\left(C_{i,b}^{var,disc} + \frac{C_{i,b}^{maint}}{\varepsilon_{r,D}^{tot}} \right) \cdot x_{i,b} + C_{i,b}^{fix,disc} \cdot b_{i,b} \right) \\ & + \frac{1}{\varepsilon_{r,D}^{tot}} \left(\sum_{t_\kappa} \sigma_\kappa \left(\sum_b \sum_f f_{f,t,b} \cdot P_f^{fuel} + \left(P_t^{spot} + P^{grid} + P^{ret} \right) \cdot \left(y_t^{imp} + \sum_b \sum_{est} y_{t,est,b}^{gb\_imp} \right) - P_t^{spot} \cdot y_t^{exp} \right) \right) \end{aligned} \tag{30}$$

The investment costs in the objective function are discounted using linear depreciation and taking into account reinvestments and salvage value: $\forall i$

$$C_i^{disc} = \left(\sum_{n=0}^{N_i - 1} C_i^{inv} \cdot (1+r)^{(-n \cdot L_i)} \right) - \frac{N_i \cdot L_i - D}{L_i} \cdot C_i^{inv} \cdot (1+r)^{-D} \tag{31}$$

with:

$$N_i = \lceil \frac{D}{L_i} \rceil \tag{32}$$

and the discount factor:

$$\varepsilon_{r,D}^{tot} = \frac{r}{1-(1+r)^{-D}} \tag{33}$$

B.2. Zero Emission constraint

In order to qualify as a ZEN, a neighborhood needs to have net zero emission of GHG in its lifetime. Here, we use the same representative periods as in the EMPIRE model.

$$\begin{aligned} & \alpha_{ZEN} \cdot \sum_{t_\kappa} \sigma_\kappa \left(\phi_t^{CO_2,el} \cdot \left(y_t^{imp} + \sum_b \sum_{est} y_{t,est,b}^{gb\_imp} \right) + \sum_b \sum_f \phi^{CO_2,f} \cdot f_{f,t,b} \right) \\ & \leqslant \sum_{t_\kappa} \phi_t^{CO_2,el} \\ & \cdot \sigma_\kappa \left(\sum_b \sum_{est} \eta_{est} \cdot \left(\alpha_{ZEN} \cdot y_{t,est,b}^{gb\_exp} + y_{t,est,b}^{pb\_exp} + (1-\alpha_{ZEN}) \cdot y_{t,est,b}^{selfc} \right) + \sum_b \sum_g \left(y_{t,g,b}^{exp} + (1-\alpha_{ZEN}) \cdot g_{t,g,b}^{selfc} \right) \right) \end{aligned} \tag{34}$$

The emission constraint contains the emissions from imports of electricity and from burning fuel and the compensations from exports of electricity. The term α_{ZEN} can be used to reduce the zero emission requirement. In this paper, it is set to one. An additional term could be added to represent the indirect emissions from the technologies or from the other phases of the lifecycle of the neighborhood but we only consider the operational phase in this paper.

B.3. Energy balances

The electricity balance of the electricity in the neighborhood is described by Eq. 35, 38 and 39.

Eq. 35 is the main part of the electricity balance and describes the way the electric load of the neighborhood is met:$\forall t$

$$\begin{aligned} & y_t^{imp} + \sum_b \left(\sum_{est} \left(y_{t,est,b}^{gb\_dch} + y_{t,est,b}^{pb\_selfc} \right) \cdot \eta_{est} + \sum_g g_{g,t,b}^{selfc} \right) \\ & = \sum_b \left(E_{b,t} + \sum_e d_{e,t,b} \right) \end{aligned} \tag{35}$$

The exports of electricity in Eq. 30 are defined as:$\forall t$

$$y_t^{exp} = \sum_b \sum_g y_{t,g,b}^{exp} + \sum_b \sum_{est} \left(y_{t,est,b}^{gb\_exp} + y_{t,est,b}^{pb\_exp} \right) \cdot \eta_{est} \tag{36}$$

The imports and exports of electricity are limited by the size of the connection to the grid:$\forall t$

$$\left(y_t^{imp} + y_t^{exp} + \sum_b \sum_{est} y_{t,est,b}^{gb\_imp} \right) \leqslant GC \tag{37}$$

Eq. 38 describes the flow of electricity of the on-site production of technologies and Eq. 39 describes the interface between the on-site production and the production side batteries. $\forall t, g, b$

$$g_{g,t,b} = y_{t,g,b}^{exp} + g_{g,t,b}^{selfc} + g_{t,g,b}^{ch} + g_{t,g,b}^{dump} \tag{38}$$

$\forall t, b$

$$\sum_g g_{t,g,b}^{ch} = \sum_{est} y_{t,est,b}^{prod\_ch} \tag{39}$$

The electricity in the neighborhood is handled in an aggregated way, or as a copper plate. The heat is, on the other hand, not aggregated and considers heat loss in the heating grid. The heat in buildings is also separated between space heating (SH) and domestic hot water (DHW), giving two heat balances:$\forall t, b$

$$\begin{aligned} & \sum_q q_{q,t,b}^{DHW} + \sum_{hst} \left(\eta_{hst} \cdot q_{t,hst,b}^{DHWdch} - q_{t,hst,b}^{DHWch} \right) + q_{t,b}^{HGusedDHW} \\ & = H_{b,t}^{DHW} \cdot A_b + q_{t,b}^{dump} \end{aligned} \tag{40}$$

$$\sum_q q_{q,t,b}^{SH} + \sum_{hst} \left(\eta_{hst} \cdot q_{t,hst,b}^{SHdch} - q_{t,hst,b}^{SHch} \right) + q_{t,b}^{HGusedSH} = H_{b,t}^{SH} \cdot A_b \tag{41}$$

At the Production Plant (PP) the balance considers the heat flowing out instead of a load: $\forall t$

$$\begin{aligned} & \sum_q q_{q,t,\text{'PP'}} + \sum_{hst} \left(\eta_{hst} \cdot q_{t,hst,\text{'PP'}}^{dch} - q_{t,hst,\text{'P'}}^{ch} \right) \\ & = \sum_{b \setminus \text{'PP'}} q_{t,\text{'PP'},b}^{HGtransfer} + q_{t,\text{'PP'}}^{dump} \end{aligned} \tag{42}$$

B.4. Constraints on the technology options

B.4.1. General Constraints

The investment in each technology is limited. The minimum corresponds to either the capacity already installed in the neighborhood or the minimum possible investment size and the maximum is chosen to limit the search space:$\forall i \cup est \cup hst, b$

$$X^{pre\_cap}_{i,b} \leqslant x_{i,b} \leqslant X^{max}_{i} \tag{43}$$

$$x_i \leqslant X^{max}_i \cdot b_{i,b} \tag{44}$$

$$x_i \geqslant X^{min}_i \cdot b_{i,b} \tag{45}$$

At the production plant, where larger-scale technologies than those available inside the buildings are available, the size of technologies is also limited and requires an investment in the heating grid: $\forall i$

$$x_{i,\text{'ProductionPlant'}} \leqslant X^{max}_i \cdot b^{HG} \tag{46}$$

Most of the technologies considered in the optimization are modeled using their efficiency, linking either their heat or electric production and their fuel consumption: $\forall \gamma \in \mathcal{F} \cap \mathcal{Q}, t, b$

$$f_{\gamma,t,b} = \frac{q_{\gamma,t,b}}{\eta_\gamma} \tag{47}$$

$\forall \gamma \in \mathcal{E} \cap \mathcal{Q}, t, b$

$$d_{\gamma,t,b} = \frac{q_{\gamma,t,b}}{\eta_\gamma} \tag{48}$$

The heat and electricity production is limited by the installed capacity:

$\forall q \setminus HP, t, b$

$\forall g, t, b$

$$q_{q,t,b} \leqslant x_{q,b} \tag{49}$$

$$g_{g,t,b} \leqslant x_{g,b} \tag{50}$$

Some technologies can only be operated in a certain range of their nominal capacity. This requires adding additional constraints with binary variables:

$$\overline{x_{i,t}} \leqslant X^{max}_i \cdot o_t \tag{51}$$

$$\overline{x_{i,t}} \leqslant x_i \tag{52}$$

$$\overline{x_{i,t}} \geqslant x_i - X^{max}_i \cdot (1 - o_t) \tag{53}$$

$$q_{i,t} \leqslant \overline{x_{i,t}} \tag{54}$$

$$q_{i,t} \geqslant \alpha \cdot \overline{x_{i,t}} \tag{55}$$

The type of heat that technologies can provide is enforced with: $\forall q, t, b$

$$q_{q,t,b} = q^{DHW}_{q,t,b} + q^{SH}_{q,t,b} \tag{56}$$

$$q^{DHW}_{q,t,b} <= M \cdot B^{DHW}_q \tag{57}$$

$$q^{SH}_{q,t,b} <= M \cdot B^{SH}_q \tag{58}$$

B.4.2. CHP constraints

For Combined Heat and Power (CHP) plants, the amount of heat produced is obtained using the efficiency, while the amount of electricity produced is derived from the heat-to-power ratio: $\forall t, \text{'CHP'}, b$

$$g_{CHP,t,b} = \frac{q_{CHP,t,b}}{\alpha_{CHP}} \tag{59}$$

B.4.3. Heat Pump constraints

Heat pumps are modelled using their Coefficient of Performance (COP) instead of an efficiency. This COP depends on the temperature to supply and the temperature of the source used by the heat pump as well as the characteristics of the unit used. The temperature to supply being different for SH and DHW leads to having different COPs. The coefficients in Eq. (60)–(62) are obtained from the datasheets of manufacturers and are used to calculate the COPs and the maximum electricity consumption (linked to the maximum heat production). Eq. 61 is used for air-air heat pumps while Eq. 62 is used for air–water and water-water heat pumps. The source temperature is the outside ambient temperature or the ground temperature depending on the type of heat pump. For heat pumps in the production plant and for DHW, the temperature to supply is 65°C. For SH, the supply temperature is a function of the outside temperature and of the type of building (in particular its building standard).

$\forall t, b, hp$

$$COP_{t,b,hp} = \sum_j k_{j,hp} \cdot \left(T^{supply}_{t,b} - T^{source}_t\right)^j \tag{60}$$

$$P^{input,max}_{aa,b,t} = \sum_j k'_{j,aa} \cdot \left(T^{supply}_{t,b} - T^{source}_t\right)^j \tag{61}$$

$$P^{input,max}_{aw-ww,b,t} = \sum_j k'_{j,aw-ww} \cdot \left(T^{supply}_{t,b}\right)^j \tag{62}$$

The heat pumps at the production plant are then modeled as: $\forall hp, t$

$$d_{hp,\text{'ProductionPlant'},t} = \frac{q_{hp,\text{'ProductionPlant'},t}}{COP_{hp,\text{'ProductionPlant'},t}} \tag{63}$$

$$d_{hp,\text{'ProductionPlant'},t} \leqslant x_{hp,\text{'ProductionPlant'}} \cdot P^{input,max}_{hp,\text{'ProductionPlant'},t} \tag{64}$$

In other buildings they are modelled differently to account for the production of both SH and DHW. In addition, if the building is refurbished, the supply temperature and thus the COPs and maximum power input will change. $\forall hp, t, b \setminus \text{'ProductionPlant'}$

$$d^{SH}_{hp,b,t} = \frac{q^{SH}_{hp,b,t}}{COP^{SH,P}_{hp,b,t}} \tag{65}$$

$$d^{DHW}_{hp,b,t} = \frac{q^{DHW}_{hp,b,t}}{COP^{DHW}_{hp,b,t}} \tag{66}$$

$$\frac{d^{DHW}_{hp,b,t}}{P^{input,max,DHW}_{hp,b,t}} + \frac{d^{SH}_{hp,b,t}}{P^{input,max,SH,P}_{hp,b,t}} \leqslant x_{hp,b} \tag{67}$$

B.4.4. Solar Technology constraints

The solar technologies are also modeled differently. Indeed, they require information about the solar irradiance: $\forall t$

$$g^{PV}_t + g^{curt}_t = \eta^{PV}_t \cdot x_{PV} \cdot IRR_t \tag{68}$$

$$q^{ST}_t = \eta_{ST} \cdot x_{ST} \cdot IRR_t \tag{69}$$

The efficiency of the PV panel is defined as in [72]:

$$\eta^{PV}_t = \frac{\eta^{inv}}{G_{stc}} \cdot \left(1 - T_{coef} \cdot \left(\left(T_t + (T_{noct} - 20) \cdot \frac{IRR_t}{800}\right) - T_{stc}\right)\right) \tag{70}$$

The formula for calculating the irradiance on a tilted surface is shown below.

$$IRR_t^{Tilt} = DHI_t \frac{1+cos(\phi_1)}{2} + \alpha \cdot (DNI_t + DHI_t)\frac{1-cos(\phi_1)}{2} + DNI_t\left(\frac{cos(\varphi_t)\cdot sin(\phi_1)\cdot cos(\phi_2-\psi_t)}{sin(\varphi_t)} + \frac{sin(\varphi_t)\cdot cos(\phi_1)}{sin(\varphi_t)}\right) \quad (71)$$

We assume that for some sun positions (sun elevations (φ) below 1 degree and sun azimuths (ψ) between −90 and 90 degrees), no direct beam reaches the panels. This means that the last term of Eq. 71 is removed at such times. We use a constant albedo factor (α) of 0.3 for the whole year. The tilt angle of the solar panel is ϕ_1; the orientation of the solar panel regarding the azimuth is ϕ_2. We do not consider snow or dust covering the solar panel.

B.5. Heating grid constraints

The heating grid is modelled in a radial way, meaning that the buildings cannot feed heat into it and no loop is allowed. The flows are limited by the size of the pipes. If there is no hydronic system in the building, then the heat cannot be used. The heating grid is used to supply the buildings with heat coming from the central production plant, where larger-scale technologies are available. $\forall b, t$

$$\sum_{b'} q_{t,b,b'}^{HGtrans} \leqslant \sum_{b''}\left(q_{t,b'',b}^{HGtrans} - Q_{b'',b}^{HGloss}\right) \quad (72)$$

$\forall b, b', t$

$$q_{t,b',b}^{HGtrans} \leqslant \dot{Q}_{b',b}^{MaxPipe} \quad (73)$$

$\forall b, t$

$$q_{t,b}^{HGused} = \sum_{b''}\left(q_{t,b'',b}^{HGtrans} - Q_{b'',b}^{HGloss}\right) - \sum_{b'} q_{t,b,b'}^{HGtrans} \quad (74)$$

$$q_{t,b}^{HGused} = q_{t,b}^{HGusedSH} + q_{t,b}^{HGusedDHW} \quad (75)$$

B.6. Energy storage constraints

The storages are modelled with their charge and discharge efficiencies. The storage levels in the different timesteps inside a cluster are linked with: $\forall t \in \mathcal{T}^*, est, b$

$$v_{t,est,b}^{pb} = v_{t-1,est,b}^{pb} + \eta^{est}\cdot y_{t,est,b}^{pb\_ch} - y_{t,est,b}^{pb\_exp} - y_{t,est,b}^{pb\_selfc} \quad (76)$$

$$v_{t,est,b}^{gb} = v_{t-1,est,b}^{gb} + \eta^{est}\cdot y_{t,est,b}^{gb\_imp} - y_{t,est,b}^{gb\_exp} - y_{t,est,b}^{gb\_dch} \quad (77)$$

$\forall t \in \mathcal{T}^*, hst, b$

$$v_{t,hst}^{heatstor} = v_{t-1,hst}^{heatstor} + \eta_{hst}^{heatstor}\cdot q_{t,hst}^{ch} - q_{t,hst}^{dch} \quad (78)$$

The charge and discharge of the storage are limited by its specifications. $\forall hst, t, b$

$$q_{t,hst,b}^{ch} = q_{t,hst,b}^{DHWch} + q_{t,hst,b}^{SHch} \quad (79)$$

$$q_{t,hst,b}^{dch} = q_{t,hst,b}^{DHWdch} + q_{t,hst,b}^{SHdch} \quad (80)$$

$\forall t, b$

$$\sum_{hst} q_{t,hst,b}^{SHch} \leqslant \sum_{q} q_{q,t,b}^{SH}\cdot b_q^{H2Onics} + q_{t,b}^{HGusedSH} \quad (81)$$

$\forall t, est, b$

$$v_{t,est,b}^{prod\_bat} + v_{t,est,b}^{grid\_bat} = v_{t,est,b}^{bat} \quad (82)$$

$$v_{t,est,b}^{bat} \leqslant x_{est,b} \quad (83)$$

$$y_{t,est,b}^{prod\_ch} + y_{t,est,b}^{gb\_imp} \leqslant \dot{Y}_{max,est}^{bat} \quad (84)$$

$$y_{t,est,b}^{grid\_dch} + y_{t,est,b}^{gb\_exp} \leqslant \dot{Y}_{max,est}^{bat} \quad (85)$$

$\forall t, hst, b$

$$v_{t,hst,b}^{heatstor} \leqslant x_{hst,b} \quad (86)$$

$$q_{t,hst}^{ch} \leqslant \dot{Q}_{max}^{hst} \quad (87)$$

$$q_{t,hst}^{dch} \leqslant \dot{Q}_{max}^{hst} \quad (88)$$

The storage values at the end and at the beginning of the period are set to be equal:

$\forall p, est, b, \kappa$

$\forall p, hst, b, \kappa$

$$v_{\kappa_{start},est,b}^{bat} = v_{\kappa_{end},est,b}^{bat} \quad (89)$$

$$v_{\kappa_{start},hst,b}^{heatstor} = v_{\kappa_{end},hst,b}^{heatstor} \quad (90)$$

Appendix C. ZENIT Data

C.1. Technology data

Generator technology data is listed in Table 1, cost data is listed in Table 2, and storage technology and cost data is listed in Table 4. The data for those technologies come from the Danish Energy Agency and Energinet[5]. Some technologies have variations or are limited to small (e.g. single family houses, SFH) or large buildings (e.g. apartment complex, AppC). The cost of the technologies are roughly in line with the technology assumptions from the EU reference scenarios 2020 [6] although there are variations in both directions for specific technologies. The technologies coverage is also not a complete overlap.

The investment costs used in the model are different for small and large buildings and are presented as a weighted average of the neighborhood composition in Table 2.

The data for prices of fuels come from different sources and are listed in Table 3. For the wood pellets and wood chips, they come from the Norwegian Bioenergy Association[7]. The data for the biogas and biomethane come from the European Biogas Association[8]. The price for gas is estimated based on the statistics of natural gas price in Europe for non-household consumers[9] (neighborhood level) and households consumers[10] (building level).

The data for CO_2 factor of fuels in Table 3 come from a report from Cundall[11].

[5] https://ens.dk/en/our-services/projections-and-models/technology-data

[6] https://energy.ec.europa.eu/data-and-analysis/energy-modelling/eu-reference-scenario-2020_en

[7] http://nobio.no/wp-content/uploads/2018/01/Veien-til-biovarme.pdf

[8] https://www.europeanbiogas.eu/wp-content/uploads/2019/07/Biomethane-in-transport.pdf

[9] https://ec.europa.eu/eurostat/statistics-explained/index.php?title = File:Natural_gas_prices_for_non-household_consumers,_second_half_2019_(EUR_per_kWh).png

[10] https://ec.europa.eu/eurostat/statistics-explained/index.php?title = File:Natural_gas_prices_for_household_consumers,_second_half_2019_(EUR_per_kWh).png

[11] https://cundall.com/Cundall/fckeditor/editor/images/UserFilesUpload/file/WCIYB/IP-4%20-%20CO2e%20emissions%20from%20biomass%20and%20biofuels.pdf

Table 1
Data Of Technologies Producing Heat (domestic hot water (DHW) and/or space heating (SH)) and/or Electricity.

Index	Tech.	Type	η_{th} (%)	α_i (% X)	X^{min} (kW)	Lifetime (year)	Fuel	α_{CHP}	El.	DHW	SH
At building level											
1	PV[1]	SFH		0	0	25			1	0	0
2	PV[1]	AppC		0	50	25			1	0	0
3	ST[2]	SFH	70	0	4.2	30			0	1	1
4	ST[2]	SFH	70	0	100	30			0	1	1
5	ASHP[10]	SFH	f(T_t)	0	0	12	Elec.		0	0	1
6	ASHP[3]	SFH	f(T_t)	0	0	18	Elec.		0	1	1
7	ASHP[3]	AppC	f(T_t)	0	100	20	Elec.		0	1	1
8	GSHP[4]	SFH	f(T_t)	0	0	20	Elec.		0	1	1
9	GSHP[4]	AppC	f(T_t)	0	100	20	Elec.		0	1	1
10	Boiler[5]	SFH	80	30	0	20	Wood Pellets		0	1	1
11	Boiler[5]	AppC	90	30	100	20	Wood Pellets		0	1	1
12	Boiler[11]	SFH	86	30	20	20	Wood Logs		0	1	1
13	Boiler[11]	SFH	75	0	0	20	Wood Logs		0	0	1
14	Heater	SFH	100	0	0	30	Elec.		0	1	0
15	Heater	AppC	100	0	100	30	Elec.		0	1	0
16	Heater	SFH	100	0	0	30	Elec.		0	0	1
17	Heater	AppC	100	0	100	30	Elec.		0	0	1
18	Boiler	SFH	96	20	0	20	Biomethane		0	1	1
19	Boiler	AppC	102	20	35	25	Biomethane		0	1	1
20	Boiler	SFH	96	20	0	20	Gas		0	1	1
21	Boiler	AppC	102	20	35	25	Gas		0	1	1
22	CHP	SFH	46	70	35	20	Gas	0.92	1	1	1
23	CHP	SFH	60	70	35	20	Biomethane	1.73	1	1	1
At neighborhood level											
24	CHP[6]		47	50	200	25	Biogas	1.09	1	1	1
25	CHP		98	20	1000	25	Wood Chips	7.27	1	1	1
26	CHP		83	20	1000	25	Wood Pellets	5.76	1	1	1
27	Boiler[7]		114	20	1000	25	Wood Chips		0	1	1
28	Boiler[7]		100	40	1000	25	Wood Pellets		0	1	1
29	CHP[8]		66	10	10	15	Wood Chips	3	1	1	1
30	Boiler[9]		58	70	50	20	Biogas		1	0	0
31	GSHP[4]		f(T_t)	10	1000	25	Elec.		0	1	1
32	Boiler		99	5	60	20	Elec.		0	1	1
33	Boiler		43	15	500	25	Biogas		0	1	1
34	Boiler		43	15	500	25	Gas		0	1	1

[1] Area Coefficient: 5.3 m^2/kW
[2] Area Coefficient: 1.43 m^2/kW
[3] Air Source Heat Pump (air - liquid)
[4] Ground Source Heat Pump
[5] Automatic stoking of pellets
[6] Gas Engine
[7] HOP
[8] Gasified Biomass Stirling Engine Plant
[9] Solid Oxyde Fuel Cell (SOFC)
[10] Air Source Heat Pump (air - air)
[11] Manual stoking of wood logs

Table 2
Cost Data of Technologies in (€/kW) for fixed and variable investment cost and as percentage of variable cost for O&M costs

Index	2030			2040			2050		
	C^{fix}	C^{var}	$C^{maint}_{i,b}$	C^{fix}	C^{var}	$C^{maint}_{i,b}$	C^{fix}	C^{var}	$C^{maint}_{i,b}$
1	0	830	1.24	0	830	1.24	0	560	1.6
2	0	570	1.47	0	570	1.47	0	450	1.6
3	735	325	5	735	325	5	664	294	5.1
4	23280	311	1	23280	311	1	21000	279	1
5	539	360	11.6	539	360	11.6	511	340	11.1
6	3000	750	8.5	3000	750	8.5	2500	625	9.6
7	25120	236	4.9	25120	236	4.9	22720	214	7.0
8	4500	1375	4.6	4500	1375	4.6	4048	1237	4.8
9	40000	250	4.7	40000	250	4.7	36000	225	2.9
10	1296	650	9.3	1296	650	9.3	1176	590	9.3
11	9920	250	2.8	9920	250	2.8	8960	225	2.9
12	1300	208	8.5	1300	208	8.5	1175	189	4.9
13	0	875	5.7	0	875	5.7	0	775	6.1
14	840	653	1.2	840	653	1.2	750	583	1.2
15	29440	429	0.07	29440	429	0.07	26720	389	0.07
16	840	653	1.2	840	653	1.2	750	583	1.2

Table 2 (*continued*)

Index	2030			2040			2050		
	C^{fix}	C^{var}	$C^{maint}_{i,b}$	C^{fix}	C^{var}	$C^{maint}_{i,b}$	C^{fix}	C^{var}	$C^{maint}_{i,b}$
17	29440	429	0.07	29440	429	0.07	26720	389	0.07
18	1110	189	10.5	1110	189	10.5	1000	170	10.6
19	3360	83	3.2	3360	83	3.2	3040	75	3.4
20	1110	189	10.5	1110	189	10.5	1000	170	10.6
21	3360	83	3.2	3360	83	3.2	3040	75	3.4
22	4160	5485	13	4160	5485	13	3000	4286	13.3
23	3150	4835	9	3150	4835	9	2800	3471	10.7
24	0	505	1.7	0	505	1.7	0	505	1.55
25	0	564	7.4	0	564	7.4	0	551	7.3
26	0	706	6.9	0	706	6.9	0	673	6.8
27	0	377	8.3	0	377	8.3	0	342	8.6
28	0	416	7.4	0	416	7.4	0	376	7.4
29	0	1267	0.8	0	1267	0.8	0	1267	0.8
30	0	2000	5	0	2000	5	0	800	5
31	0	255	0.8	0	255	0.8	0	230	0.87
32	0	110	0.9	0	110	0.9	0	100	0.9
33	0	50	3.8	0	50	3.8	0	50	3.4
34	0	50	3.8	0	50	3.8	0	50	3.4

Table 3
Data of Fuels.

Tech.	Fuel Cost (EUR/kWh)	CO_2 factor (gCO_2/kWh)
Electricity	$f(t)$	$f(t)$
Wood Pellets	0.03664	40
Wood Chips	0.02592	20
Biogas	0.07	0
Biomethane	0.07	100
Gas (neighborhood level)	0.041	277
Gas (building level)	0.121	277

Table 4
Data of Storage.

Index	One way eff. (%)	Inv. Cost (€/kWh)	O&M Cost (% of Inv. Cost)	Lifetime (year)	Min. Cap. (kWh)	Charge/ Discharge rate (% of Cap)
Battery						
1[1]	95	577	0	10	13.5	37
2[2]	938	500	0	15	210	23
3[3]	95	432	0	20	1000	50
Heat Storage						
1[4]	95	75	0	20	0	20
2[3]	98	3	0.29	40	45 000	1.7

[1] Based on Tesla Powerwall
[2] Based on Tesla Powerpack
[3] Based on Danish energy agency data
[4] Same data are used for the heat storage at the building or neighborhood level and for both SH and DHW

C.2. Neighborhood data

We consider a neighborhood of new energy efficient buildings. The composition of the neighborhood is based on building composition in Oslo and is described in Table 5.

The aggregated loads for the neighborhoods for each country is given in Table 6.

Table 5
Composition of the neighborhood considered in ZENIT.

Building type	Heated floor area (m^2)	Roof Area (m^2)
House	27 800	13 900
Apartments	44 010	9780
Offices	18 948	3158
Shops	1230	1230
Kindergarten	490	490
School	5032	1677
Nursing home	1062	531

Table 6
Total annual load of the neighborhood in the different countries modelled in GWh

	AU	BE	BA	BG	HR	CZ	DK	EE	FI	FR	DE	UK
El. specific	5.750	5.748	5.723	5.723	5.723	5.723	5.723	5.723	5.723	5.723	5.723	5.723
Heat	4.530	3.916	4.141	4.150	3.910	4.557	4.132	3.298	5.829	3.671	4.231	3.732
	GR	HU	IE	IT	LV	LT	LU	MK	NL	NO1	NO2	NO3
El. specific	5.723	5.723	5.723	5.723	5.723	5.723	5.723	5.723	5.723	5.723	5.723	5.723
Heat	3.334	3.910	3.632	3.421	5.107	5.085	4.222	4.183	3.837	4.774	4.408	4.667
	NO4	NO5	PL	PT	RO	RS	SK	SI	ES	SV	CH	
El. specific	5.723	5.723	5.723	5.723	5.723	5.723	5.723	5.723	5.723	5.723	5.723	
Heat	5.270	4.056	3.837	3.250	4.371	4.120	4.631	4.233	3.298	4.906	4.450	

Table 7
Technology options in EMPIRE from 2020–2040 with their respective investment cost (IC) in EUR/kW and operational costs (OC) in EUR/MWh.

Technology	2020–2025		2025–2030		2030–2035		2035–2040	
	IC	OC	IC	OC	IC	OC	IC	OC
Bio (CHP)	1,426.2	36.4	1,426.2	40.0	1,354.0	43.9	1,354.0	48.2
Bio (electricity only)	2,855.8	88.2	2,725.2	96.7	2,259.8	95.5	2,071.9	104.7
Bio (existing)	-	88.2	-	96.7	-	95.5	-	104.7
Bio (HOP)	1,339.0	33.0	1,339.0	36.0	1,281.3	39.2	1,281.3	42.8
Coal (electricity)	2,061.2	57.8	1,967.0	66.3	1,846.6	49.5	1,693.0	107.9
Coal (electricity, existing)	-	57.8	-	66.3	-	49.5	-	107.9
Coal (10% co-firing bio)	2,183.8	49.1	2,083.9	55.7	1,956.4	47.0	1,793.7	94.7
Electric heat (ASHP)	1,146.2	-	1,146.2	-	968.9	-	968.9	-
Electric heat (direct)	1,095.8	-	1,095.8	-	1,057.1	-	969.2	-
Electric heat (GSHP)	3,659.4	-	3,659.4	-	3,334.2	-	3,334.2	-
Gas (closed cycle)	962.1	65.6	962.1	71.3	932.1	68.4	854.6	95.8
Gas (electricity, existing)	-	77.5	-	82.7	-	79.3	-	109.5
Gas (electricity, open cycle)	714.8	92.5	714.8	99.9	714.8	97.0	655.3	135.2
Gas (heat, building boiler)	578.2	37.2	578.2	40.5	560.4	39.1	560.4	55.3
Gas (heat, district heat)	88.9	37.1	88.9	40.3	78.1	39.3	78.1	55.2
Geo (electricity)	6,503.4	0.3	6,503.4	0.3	6,119.4	0.3	5,610.5	0.3
Geo (heat, district heat)	2,230.6	8.4	2,230.6	8.4	2,041.8	8.4	2,041.8	8.4
Hydro (regulated)	3,178.9	0.3	3,033.5	0.3	2,847.9	0.3	2,611.0	0.3
Hydro (run-of-river)	2,463.2	-	2,350.5	-	2,153.3	-	1,974.2	-
Lignite (electricity)	2,385.6	51.2	2,276.4	55.5	2,137.2	37.4	1,959.4	101.7
Nuclear	7,600.9	17.4	7,253.3	17.6	6,728.8	17.8	6,169.2	18.0
Oil (electricity, existing)	-	148.5	-	168.1	-	167.7	-	224.3
Oil (heat, building boiler)	606.2	59.6	606.2	67.6	579.2	66.7	579.2	89.6
Solar PV	896.5	-	896.5	-	822.8	-	822.8	-
Waste (CHP)	2,479.7	11.8	2,479.7	12.6	2,400.1	9.5	2,400.1	20.8
Waste (electricity only)	2,714.4	15.0	2,714.4	16.8	2,595.3	9.1	2,595.3	35.4
Waste (HOP)	3,057.9	13.1	3,057.9	13.7	2,889.5	11.2	2,889.5	20.2
Wave	6,054.8	0.1	5,777.8	0.1	2,969.3	0.1	2,722.3	0.1
Wind (offshore)	3,399.5	0.4	3,399.5	0.4	2,506.8	0.4	2,506.8	0.4
Wind (onshore)	1,502.2	0.2	1,502.2	0.2	1,368.2	0.2	1,368.2	0.2

Table 8
Technology options in EMPIRE from 2040–2060 with their respective investment cost (IC) in EUR/kW and operational costs (OC) in EUR/MWh.

Technology	2040–2045		2045–2050		2050–2055		2055–2060	
	IC	OC	IC	OC	IC	OC	IC	OC
Bio (CHP)	1,197.2	52.9	921.6	57.7	685.6	63.3	384.4	63.3
Bio (electricity only)	1,747.6	112.0	1,455.6	122.8	1,076.4	134.7	603.5	134.7
Bio (existing)	-	112.0	-	122.8	-	134.7	-	134.7
Bio (HOP)	1,132.9	46.8	868.1	51.1	645.8	55.9	362.1	55.9
Coal (electricity)	1,497.0	272.7	1,246.9	189.7	927.6	247.5	520.1	309.8
Coal (electricity, existing)	-	272.7	-	189.7	-	247.5	-	309.8
Coal (10% co-firing bio)	1,586.0	232.3	1,321.0	163.1	982.7	209.1	551.0	256.7
Electric heat (ASHP)	968.9	-	896.7	-	667.1	-	374.0	-
Electric heat (direct)	857.0	-	639.0	-	475.3	-	266.5	-
Electric heat (GSHP)	3,334.2	-	2,525.2	-	1,878.6	-	1,053.3	-
Gas (closed cycle)	731.3	165.4	609.1	131.7	443.1	156.3	248.4	182.3
Gas (electricity, existing)	-	189.1	-	147.9	-	172.8	-	198.6
Gas (electricity, open cycle)	579.4	236.9	482.6	187.1	359.0	221.3	201.3	256.3

Table 8 (*continued*)

Technology	2040–2045		2045–2050		2050–2055		2055–2060	
	IC	OC	IC	OC	IC	OC	IC	OC
Gas (heat, building boiler)	560.4	98.2	422.1	77.1	314.0	91.8	176.1	107.2
Gas (heat, district heat)	69.1	97.2	55.4	77.3	41.2	91.9	23.1	107.2
Geo (electricity)	4,243.1	0.3	3,534.0	0.3	2,406.6	0.3	1,349.3	0.3
Geo (heat, district heat)	1,805.5	8.4	1,481.9	8.4	1,102.5	8.4	618.1	8.4
Hydro (regulated)	2,308.7	0.3	1,922.9	0.3	1,430.5	0.3	802.1	0.3
Hydro (run-of-river)	1,711.5	-	1,425.5	-	1,038.5	-	582.3	-
Lignite (electricity)	1,732.6	302.6	1,443.0	202.1	1,073.5	270.1	601.9	344.5
Nuclear	5,363.4	18.2	4,467.1	18.4	3,298.9	18.6	1,849.6	18.6
Oil (electricity, existing)	-	383.3	-	311.4	-	366.5	-	422.6
Oil (heat, building boiler)	579.2	153.9	433.1	122.1	322.2	144.0	180.7	166.2
Solar PV	589.8	-	491.2	-	323.3	-	181.3	-
Waste (CHP)	2,122.2	55.0	1,589.0	37.8	1,182.1	49.6	662.8	62.5
Waste (electricity only)	2,552.0	114.4	2,125.5	74.4	1,555.2	101.5	872.0	131.1
Waste (HOP)	2,555.0	47.0	1,957.6	33.4	1,456.3	42.6	816.5	52.7
Wave	1,654.2	0.1	1,377.7	0.1	968.8	0.1	543.2	0.1
Wind (offshore)	2,085.1	0.4	1,736.7	0.4	1,263.1	0.4	708.2	0.4
Wind (onshore)	1,063.2	0.2	885.5	0.2	613.9	0.2	344.2	0.2

Table 9
Fuel costs in EMPIRE in EUR/kWh.

Fuel	2020–2025	2025–2030	2030–2035	2035–2040	2040–2045	2045–2050	2050–2060
Coal	0.0086	0.0103	0.0123	0.0130	0.0136	0.0141	0.0145
Coal (10% bio)	0.0107	0.0125	0.0147	0.0157	0.0166	0.0174	0.0183
Lignite	0.0050	0.0050	0.0054	0.0054	0.0054	0.0054	0.0054
Bio	0.0296	0.0326	0.0358	0.0394	0.0434	0.0477	0.0525
Fossil gas	0.0290	0.0313	0.0341	0.0364	0.0376	0.0384	0.0390
Nuclear	0.0037	0.0038	0.0039	0.0040	0.0041	0.0041	0.0042
Oil	0.0450	0.0511	0.0562	0.0587	0.0623	0.0637	0.0652

Appendix D. EMPIRE Data

Technology cost data is presented in Tables 7 and 8. Costs for electricity generation technologies come from PRIMES 2018[12], while the data for heating come from the Danish Energy Agency and Energinet[13]. Note that investment costs include annualised capital costs with a discount rate of 5% plus fixed annual operation and maintenance costs. Fuel cost data is presented in Table 9, and the data come from the EU reference scenario 2016 for fossil fuels and derived from the VGB report from Eurelectric[14] for biomass and uranium.

[12] https://ec.europa.eu/energy/sites/ener/files/documents/2018_06_27_technology_pathways_-_finalreportmain2.pdf

[13] https://ens.dk/en/our-services/projections-and-models/technology-data

[14] VGB. Survey 2011: Investment and operation cost figures – Generation portfolio, November 2011.

References

[1] Pantelis Capros, Georgios Zazias, Stavroula Evangelopoulou, Maria Kannavou, Theofano Fotiou, Pelopidas Siskos, Alessia De Vita, Konstantinos Sakellaris, Energy-system modelling of the EU strategy towards climate-neutrality, Energy Policy 134 (2019).

[2] EU Emissions Trading System (EU ETS). https://climate.ec.europa.eu/eu-action/eu-emissions-trading-system-eu-ets_en. Accessed: Sep 2022.

[3] European Commission. Directive (EU) 2018/844. Official Journal of the European Union, 2018a.

[4] Eleonora Annunziata, Marco Frey, Francesco Rizzi, Towards nearly zero-energy buildings: The state-of-art of national regulations in Europe, Energy 57 (2013) 125–133.

[5] European Commission. Proposal for Directive (EU) 2021/802. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52021PC0802, 2021a.

[6] Factsheet - Energy Performance of Buildings. https://ec.europa.eu/commission/presscorner/detail/en/fs_21_6691. Accessed: Sep 2022.

[7] Oytun Babacan, Sven De Causmaecker, Ajay Gambhir, A. Mathilde Fajardy, William Rutherford, Andrea Fantuzzi, Jenny Nelson, Assessing the feasibility of carbon dioxide mitigation options in terms of energy usage, Nature Energy 5 (9) (2020) 720–728.

[8] Søren O. Aggerholm Thomas Boermans, Andreas Hermelink, Sven Schimschar, Jan Grözinger, Markus Offermann, Kirsten Engelund Thomsen, Jørgen Rose. Principles for Nearly Zero-energy Buildings. Paving the way for effective implementation of policy requirements. Technical report, Buildings Performance Institute Europe (BPIE), 2011.

[9] Anna Joanna Marszal, Per Heiselberg, Julien S Bourrelle, Eike Musall, Karsten Voss, Igor Sartori, Assunta Napolitano, Zero Energy Building–A review of definitions and calculation methodologies, Energy and buildings 43 (4) (2011) 971–979.

[10] Igor Sartori, Assunta Napolitano, Karsten Voss, Net zero energy buildings: A consistent definition framework, Energy and buildings 48 (2012) 220–232.

[11] Xiaodong Cao, Xilei Dai, Junjie Liu, Building energy-consumption status worldwide and the state-of-the-art technologies for zero-energy buildings during the past decade, Energy and buildings 128 (2016) 198–213.

[12] Daniel Satola, T. Maria Balouktsi, A Houlihan Lützkendorf, Wiberg, and Arild Gustavsen. How to define (net) zero greenhouse gas emissions buildings: The results of an international survey as part of iea ebc annex 72, Building and Environment 192 (2021).

[13] Silvia Bossi, Christoph Gollner, Sarah Theierling, Towards 100 Positive Energy Districts in Europe: Preliminary Data Analysis of 61 European Cases, Energies 13 (22) (2020) 6083.

[14] Johannes Brozovsky, Arild Gustavsen, Niki Gaitani, Zero Emission Neighbourhoods and Positive Energy Districts–A State-of-the-Art Review, Sustainable Cities and Society (2021) 103013.

[15] European Commission. Proposal amending Regulation (EU) 2018/842 on binding annual greenhouse gas emission reductions by Member States from 2021 to 2030 contributing to climate action to meet commitments under the Paris Agreement. https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=COM:2021:555:FIN, 2021b.

[16] Delivering the European Green Deal. https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal/delivering-european-green-deal_en. Accessed: Sep 2022.

[17] Policy scenarios for delivering the European Green Deal. https://energy.ec.europa.eu/data-and-analysis/energy-modelling/policy-scenarios-delivering-european-green-deal_en#scenario-results. Accessed: Sep 2022.

[18] Marianne Rose Kjendseth Wiik, Kristin Fjellheim, Camille Margaux L. Vandervaeren, Synne Krekling Lien, Solveig Meland, Tobias Nordström, Daniela Baer, Caroline Y Cheng, Shannon Truloff, Helge Brattebø, and Arild Gustavsen. Zero Emission Neighbourhoods in Smart Cities. Definition, key

performance indicators and assessment criteria: Version 3.0. https://hdl.handle.net/11250/2997415, 2022. Accessed: day.
[19] Anne Sjoerd Brouwer, Machteld van den Broek, Ad. Seebregts, André Faaij, Operational flexibility and economics of power plants in future low-carbon power systems, Applied Energy 156 (2015) 107–128.
[20] Matija Pavičević, Andrea Mangipinto, Wouter Nijs, Francesco Lombardi, Konstantinos Kavvadias, Juan Pablo Jiménez Navarro, Emanuela Colombo, and Sylvain Quoilin. The potential of sector coupling in future european energy systems: Soft linking between the dispa-set and jrc-eu-times models. Applied Energy, 267: 115100, 2020. ISSN 0306–2619. doi: 10.1016/j.apenergy.2020.115100. https://www.sciencedirect.com/science/article/pii/S0306261920306127.
[21] Miguel Chang, Jakob Zink Thellufsen, Behnam Zakeri, Bryn Pickering, Stefan Pfenninger, Henrik Lund, Poul Alberg Østergaard, Trends in tools and approaches for modelling the energy transition, Applied Energy 290 (2021).
[22] Stian Backe, Dimitri Pinel, Magnus Askeland, Karen Byskov Lindberg, Magnus Korpås, and Asgeir Tomasgard. Zero Emission Neighbourhoods in the European Energy System. ZEN Report no 30, 2021a. https://hdl.handle.net/11250/2725182.
[23] Stian Backe, Pedro Crespo, Asgeir del Granado, Dimitri Pinel Tomasgard, Magnus Korpås, Karen Byskov Lindberg, Towards Zero Emission Neighbourhoods: Implications for the Power System, in: 2018 15th International Conference on the European Energy Market (EEM), IEEE, 2018, pp. 1–6.
[24] Martin L Weitzman, Prices vs. quantities, The review of economic studies 41 (4) (1974) 477–491.
[25] Andri Pyrgou, Angeliki Kylili, Paris A. Fokaides, The future of the Feed-in Tariff (FiT) scheme in Europe: The case of photovoltaics, Energy Policy 95 (2016) 94–102.
[26] Jos Sijm, The interaction between the EU emissions trading scheme and national energy policies, Climate Policy 5 (1) (2005) 79–96.
[27] Paul Lehmann, Erik Gawel, Why should support schemes for renewable electricity complement the eu emissions trading scheme?, Energy Policy 52 (2013) 597–607
[28] Erik Gawel, Sebastian Strunz, Paul Lehmann, A public choice view on the climate and energy policy mix in the EU–How do the emissions trading scheme and support for renewable energies interact?, Energy Policy 64 (2014) 175–182
[29] Kenneth Bruninx, Marten Ovaere, Erik Delarue, The long-term impact of the market stability reserve on the EU emission trading system, Energy Economics 89 (2020).
[30] Hans Auer, Pedro Crespo del Granado, Pao-Yu Oei, Karlo Hainsch, Konstantin Löffler, Thorsten Burandt, Daniel Huppmann, and Ingeborg Grabaak. Development and modelling of different decarbonization scenarios of the European energy system until 2050 as a contribution to achieving the ambitious 1.5) C climate target–establishment of open source/data modelling in the European H2020 project openENTRANCE. e & i Elektrotechnik und Informationstechnik, pages 1–13, 2020.
[31] Seán Collins, John Paul Deane, Kris Poncelet, Evangelos Panos, Robert C Pietzcker, Erik Delarue, Ó. Brian Pádraig, Gallachóir: Integrating short term variations of the power system into integrated energy system models: A methodological review, Renewable and Sustainable Energy Reviews 76 (2017) 839–856.
[32] Hans-Kristian Ringkjøb, Peter M Haugan, Ida Marie Solbrekke, A review of modelling tools for energy and electricity systems with large shares of variable renewables, Renewable and Sustainable Energy Reviews 96 (2018) 440–459.
[33] Guido Plessmann, Philipp Blechinger, How to meet EU GHG emission reduction targets? A model based decarbonization pathway for Europe's electricity supply system until 2050, Energy Strategy Reviews 15 (2017) 19–32.
[34] Hans-Kristian Ringkjøb, Peter M Haugan, Pernille Seljom, Arne Lind, Fabian Wagner, Sennai Mesfun, Short-term solar and wind variability in long-term energy system models-A European case study, Energy 209 (2020).
[35] Stian Backe, Mohammadreza Ahang, Asgeir Tomasgard, Stable stochastic capacity expansion with variable renewables: Comparing moment matching and stratified scenario generation sampling, Applied Energy 302 (2021).
[36] Hans-Martin Henning, Andreas Palzer, A comprehensive model for the German electricity and heat sector in a future energy system with a dominant contribution from renewable energy technologies–Part I: Methodology, Renewable and Sustainable Energy Reviews 30 (2014) 1003–1018.
[37] Andreas Bloess, Wolf-Peter Schill, Alexander Zerrahn, Power-to-heat for renewable energy integration: A review of technologies, modeling approaches, and flexibility potentials, Applied Energy 212 (2018) 1611–1626.
[38] Stian Backe, Magnus Korpås, and Asgeir Tomasgard. Heat and electric vehicle flexibility in the European power system: A case study of Norwegian energy communities. International Journal of Electrical Power & Energy Systems, 125: 106479, 2021c. ISSN 0142–0615. doi: 10.1016/j.ijepes.2020.106479. http://www.sciencedirect.com/science/article/pii/S0142061520322079.
[39] Monica Carvalho, Miguel A Lozano, Luis M Serra, Multicriteria synthesis of trigeneration systems considering economic and environmental aspects, Applied Energy 91 (1) (2012) 245–254.
[40] A.D. Hawkes, M.A. Leach, Modelling high level system design and unit commitment for a microgrid, Applied energy 86 (7–8) (2009) 1253–1265.
[41] Sunanda Sinha, S.S. Chandel, Review of software tools for hybrid renewable energy systems, Renewable and Sustainable Energy Reviews 32 (2014) 192–205.
[42] Paolo Gabrielli, Matteo Gazzani, Emanuele Martelli, Marco Mazzotti, Optimal design of multi-energy systems with seasonal storage, Applied Energy 219 (2018) 408–424.
[43] Mohamed Hamdy, Ala Hasan, Kai Siren, A multi-stage optimization method for cost-optimal and nearly-zero-energy building solutions in line with the EPBD-recast 2010, Energy and Buildings 56 (2013) 189–203.
[44] Carine Lausselet, Vilde Borgnes, Helge Brattebø, Lca modelling for zero emission neighbourhoods in early stage planning, Building and Environment 149 (2019) 379–389.
[45] Andreas Fleischhacker, Georg Lettner, Daniel Schwabeneder, Hans Auer, Portfolio optimization of energy communities to meet reductions in costs and emissions, Energy 173 (2019) 1092–1105.
[46] Yamina Saheb, Sophie Shnapp, and Daniele Paci. From nearly-zero energy buildings to net-zero energy districts. Technical report, JRC Technical Reports, 2019.
[47] Dimitri Pinel, Magnus Korpås, Karen Byskov Lindberg, Cost optimal design of zero emission neighborhoods'(zens) energy system model presentation and case study on evenstad, in: Advances in Energy System Optimization Proceeding of the 2nd International Symposium on Energy System Optimization, Springer Verlag, 2019.
[48] Dimitri Pinel, Magnus Korpås, and Karen B. Lindberg. Impact of the co2 factor of electricity and the external co2 compensation price on zero emission neighborhoods' energy system design. Building and Environment, 187: 107418, 2021. ISSN 0360–1323. doi: 10.1016/j.buildenv.2020.107418. https://www.sciencedirect.com/science/article/pii/S036013232030785X.
[49] Karen Byskov Lindberg, David Fischer, Gerard L. Doorman, Magnus Korpås, Igor Sartori, Cost-optimal energy system design in Zero Energy Buildings with resulting grid impact: A case study of a German multi-family house, Energy and Buildings 127 (2016) 830–845, https://doi.org/10.1016/j.enbuild.2016.05.063.
[50] J.P. Deane, Alessandro Chiodi, Maurizio Gargiulo, and Brian P. Ó Gallachóir. Soft-linking of a power systems model to an energy systems model. Energy, 42 (1): 303–312, 2012. ISSN 0360–5442. 2010, doi: 10.1016/j.energy.2012.03.052. https://www.sciencedirect.com/science/article/pii/S0360544212002551. 8th World Energy System Conference, WESC.
[51] Joel Goop, Emil Nyholm, Mikael Odenberger, and Filip Johnsson. Impact of electricity market feedback on investments in solar photovoltaic and battery systems in Swedish single-family dwellings. Renewable Energy, 163: 1078–1091, 2021. ISSN 0960–1481. doi: 10.1016/j.renene.2020.06.153. https://www.sciencedirect.com/science/article/pii/S0960148120310752.
[52] Verena Heinisch, Mikael Odenberger, Lisa Göransson, Filip Johnsson, Prosumers in the Electricity System-Household vs. System Optimization of the Operation of Residential Photovoltaic Battery Systems, Frontiers in Energy Research 6 (2019) 145.
[53] Pernille Seljom, Karen Byskov Lindberg, Asgeir Tomasgard, Gerard Doorman, Igor Sartori, The impact of Zero Energy Buildings on the Scandinavian energy system, Energy 118 (2017) 284–296.
[54] Stian Backe, Christian Skar, Pedro Crespo, Ozgu del Granado, Turgut, and Asgeir Tomasgard: Empire: An open-source model based on multi-horizon programming for energy transition analyses, SoftwareX 17 (2022).
[55] European Commission. A Clean Planet for all - A European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52018DC0773, November 2018b. Accessed: day.
[56] Alessia De Vita, Izabela Kielichowska, Pavla Mandatowa, P Capros, E Dimopoulou, S Evangelopoulou, T Fotiou, M Kannavou, P Siskos, G Zazias, et al. Technology pathways in decarbonisation scenarios. https://ec.europa.eu/energy/sites/ener/files/documents/2018_06_27_technology_pathways_-_finalreportmain2.pdf, 2018. Accessed: day.
[57] European Commission, Directorate-General for Climate Action, Directorate-General for Energy, Directorate-General for Mobility, Transport, A De Vita, P Capros, L Paroussos, K Fragkiadakis, P Karkatsoulis, L Höglund-Isaksson, W Winiwarter, P Purohit, A Gómez-Sanabria, P Rafaj, L Warnecke, A Deppermann, M Gusti, S Frank, P Lauri, F Fulvio, A Florou, M Kannavou, N Forsell, T Fotiou, P Siskos, P Havlík, I Tsiropoulos, S Evangelopoulou, P Witzke, M Kesting, N Katoufa, I Mitsios, G Asimakopoulou, and T Kalokyris. EU reference scenario 2020: energy, transport and GHG emissions: trends to 2050. Publications Office, 2021. doi/10.2833/35750.
[58] S. Eggleston, L. Buendia, K. Miwa, T. Ngara, K. Tanabe. 2006 IPCC guidelines for national greenhouse gas inventories. Volume 2 Energy. Chapter 2 Stationary combustion. Institute for Global Environmental Strategies Hayama, Japan, 2006.
[59] Pantelis Capros, Maria Kannavou, Stavroula Evangelopoulou, Apostolos Petropoulos, Pelopidas Siskos, Nikolaos Tasios, Georgios Zazias, Alessia DeVita, Outlook of the EU energy system up to 2050: The case of scenarios prepared for European Commission's 'clean energy for all Europeans' package using the PRIMES model, Energy strategy reviews 22 (2018) 255–263.
[60] ENTSO-E. TYNDP 2022 Scenario Report – Version April 2022. https://2022.entsos-tyndp-scenarios.eu/, 2022. Accessed: day.
[61] Faidra Filippidou and Juan Pablo Jimenez Navarro. Achieving the cost-effective energy transformation of Europe's buildings. Publications Office of the European Union, EUR 29906 EN, JRC117739, 2019. DOI: 10.2760/278207.
[62] Lukas Kranzl, Michael Hartner, Andreas Müller, Gustav Resch, Sara Fritz, Tobias Fleiter, Andrea Herbst, Matthias Rehfeldt, Pia Manz, and A Zubaryeva. Heating & Cooling Outlook Until 2050, EU-28. https://www.hotmaps-project.

eu/wp-content/uploads/2018/05/Hotmaps_D5-2_v16_2019-03-01.pdf, 2018. Accessed: day.
[63] ENTSO-E Transparency Platform. https://transparency.entsoe.eu/. Accessed: Sep 2022.
[64] Oliver Ruhnau, Lion Hirth, Aaron Praktiknjo, Time series of heat demand and heat pump efficiency for energy system modeling, Scientific data 6 (1) (2019) 1–10.
[65] Karen Byskov Lindberg et al. Modelling electric and heat load profiles of non-residential buildings for use in long-term aggregate load forecasts. Utilities Policy, 58: 63–88, 2019a.
[66] Synne Krekling Lien, Benedicte Langseth, Dag Spilde, Karen Byskov Lindberg, Leap-norge 2016, in: The Norwegian water and energy directorate (NVE), Oslo, 2018.
[67] Karen Byskov Lindberg, Steffen J. Bakker, and Igor Sartori. Modelling electric and heat load profiles of non-residential buildings for use in long-term aggregate load forecasts. Utilities Policy, 58: 63–88, 2019b. ISSN 0957–1787. DOI: 10.1016/j.jup.2019.03.004.
[68] K.H. Andersen, S.K. Lien, H.T. Walnum, K.B. Lindberg, and I. Sartori. Further development and validation of the PROFet energy demand load profiles estimator. In (submitted to) Building Simulation 2021 Conference, 1–3 Sep., Bruges, Belgium (BuildSim), 2021.
[69] John Clauß, Sebastian Stinner, Christian Solli, Karen Byskov Lindberg, Henrik Madsen, Laurent Georges, Evaluation method for the hourly average co2eq. intensity of the electricity mix and its application to the demand response of residential heating, Energies 12 (7) (2019).
[70] Danish Energy Agency and Energinet. Technology Data. https://ens.dk/en/our-services/projections-and-models/technology-data, 2020. Accessed: day.
[71] Grischa Perino, New EU ETS Phase 4 rules temporarily puncture waterbed, Nature Climate Change 8 (4) (2018) 262–264.
[72] H.P. Hellman, M. Koivisto, and M. Lehtonen. Photovoltaic power generation hourly modelling. In Proceedings of the 2014 15th International Scientific Conference on Electric Power Engineering (EPE), pages 269–272, 5 2014.