Research Centre on
ZERO EMISSION
NEIGHBOURHOODS
IN SMART CITIES

ZERO EMISSION NEIGHBOURHOODS IN THE EUROPEAN ENERGY SYSTEM

Implications of linking local and international emission targets

ZEN REPORT No. 30 – 2021

Stian Backe, Dimitri Pinel, Magnus Askeland, Karen Byskov Lindberg, Magnus Korpås,
Asgeir Tomasgard | NTNU / SINTEF

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Zero Emission Neighbourhoods in the European Energy System

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Preface

Acknowledgements

This report has been written within the Research Centre on Zero Emission Neighbourhoods in Smart Cities (FME ZEN). The author gratefully acknowledge the support from the Research Council of Norway, the Norwegian University of Science and Technology (NTNU), SINTEF, the municipalities of Oslo, Bergen, Trondheim, Bodø, Bærum, Elverum and Steinkjer, Trøndelag county, Norwegian Directorate for Public Construction and Property Management, Norwegian Water Resources and Energy Directorate, Norwegian Building Authority, ByBo, Elverum Tomteselskap, TOBB, Snøhetta, Asplan Viak, Multiconsult, Sweco, Civitas, FutureBuilt, Hunton, Moelven, Norcem, Skanska, GK, Nord-Trøndelag Elektrisitetsverk - Energi, Smart Grid Services Cluster, Statkraft Varme, Energy Norway, Norsk Fjernvarme and AFRY.

The Research Centre on Zero Emission Neighbourhoods (ZEN) in Smart Cities

The ZEN Research Centre develops solutions for future buildings and neighbourhoods with no greenhouse gas emissions and thereby contributes to a low carbon society.

Researchers, municipalities, industry and governmental organizations work together in the ZEN Research Centre in order to plan, develop and run neighbourhoods with zero greenhouse gas emissions. The ZEN Centre has nine pilot projects spread over all of Norway that encompass an area of more than 1 million m^2 and more than 30 000 inhabitants in total.

In order to achieve its high ambitions, the Centre will, together with its partners:

- Develop neighbourhood design and planning instruments while integrating science-based knowledge on greenhouse gas emissions;
- Create new business models, roles, and services that address the lack of flexibility towards markets and catalyze the development of innovations for a broader public use; This includes studies of political instruments and market design;
- Create cost effective and resource and energy efficient buildings by developing low carbon technologies and construction systems based on lifecycle design strategies;
- Develop technologies and solutions for the design and operation of energy flexible neighbourhoods;
- Develop a decision-support tool for optimizing local energy systems and their interaction with the larger system;
- Create and manage a series of neighbourhood-scale living labs, which will act as innovation hubs and a testing ground for the solutions developed in the ZEN Research Centre. The pilot projects are Furuset in Oslo, Fornebu in Bærum, Sluppen and Campus NTNU in Trondheim, an NRK-site in Steinkjer, Ydalir in Elverum, Campus Evenstad, NyBy Bodø, and Zero Village Bergen.

The ZEN Research Centre will last eight years (2017-2024), and the budget is approximately NOK 380 million, funded by the Research Council of Norway, the research partners NTNU and SINTEF, and the user partners from the private and public sector. The Norwegian University of Science and Technology (NTNU) is the host and leads the Centre together with SINTEF.

https://fmezen.no
@ZENcentre
FME ZEN (page)

Norwegian Summary

Implikasjoner ved å koble sammen lokale og internasjonale utslippsmål

Utviklingen av energisystemet drives av politiske ambisjoner for å dempe klimaendringene. Disse ambisjonene impliserer at energirelaterte klimagassutslipp må reduseres dramatisk i løpet av de neste tiårene. I tillegg til at kraftsystemet gjennomgår en stor forandring for å redusere klimagassutslipp, skjer det tilsvarende endringer også i andre sektorer som overlapper med kraftsystemet. I bygningssektoren blir energieffektiviteten stadig bedre, og pilotprosjekter verden rundt demonstrerer bygninger som produserer mer energi enn det som blir brukt over bygningens livssyklus. I FME ZEN er visjonen å utvikle nullutslippsnabolag (ZEN): en samling av bygninger med netto null utslipp av klimagasser over sin livssyklus. I denne studien setter vi utvikling av nullutslippsnabolag i sammenheng med dekarbonisering av kraftsystemet. Analysene som presenteres er plassert i en Europeisk kontekst og relatert til de politiske utslippsmålene, og vi ser på ulike scenarioer for utviklingen av kraftsystemet.

ZEN fører ikke direkte til klimakutt i det Europeiske kraftsystemet, men har en indirekte effekt som gjør det mulig å oppnå klimamålsetningene på en mer kostnadseffektiv måte

Resultatene viser lite markedsbasert utvikling av nullutslippsnabolag i kraftsystemet før 2050. I 2050 gir en kombinasjon av reduserte kostnader knyttet til utvikling av nullutslippsnabolag og strenge utslippsrestriksjoner betydelig utbygging av nullutslippsnabolag i Europa og dette bidrar til at systemkostnaden reduseres med 4%. Påvirkningen av dette på systemet er i hovedsak mindre kraftproduksjon fra kjernekraft og vindkraftverk.

Ett viktig poeng er at overskudd av fornybar kraft fra nabolag ikke reduserer klimagassutslipp i kraftsystemet når vi legger til grunn utslippstakene i Europeisk kraftproduksjon. Dette er fordi energi produsert av nabolaget ikke erstatter energiproduksjon med utslipp, men heller energi produsert fra lavkarbon produksjonsteknologier andre steder i systemet siden vi har et gitt utslippstak i tråd med et Europeisk karbonbudsjett. Likevel så observerer vi at når ZEN utvikles så gir dette en betydelig lavere karbonpris. ZEN fører altså ikke direkte til klimakutt i det Europeiske kraftsystemet, men har en indirekte effekt som gjør det mulig å oppnå klimamålsetningene på en mer kostnadseffektiv måte

Rollen til utslippskompensering som et verktøy for å redusere netto klimagassutslipp er en omdiskutert antagelse. Siden vi addresserer dette direkte er resultatene fra denne studien viktige for å kvantifisere nytten av ZEN som en del av det Europeiske kraftsystemet. Videre kan resultatene fra denne studien brukes i relaterte forskningsfelt som for eksempel livssyklusanalyser for nabolag.

Summary

Implications of linking local and international emission targets

Political ambitions to mitigate climate change are driving the transformation of energy systems. These ambitions imply that greenhouse gas (GHG) emissions from the energy sector must reduce dramatically within the next decades. While electricity systems undergo a major transformation to reduce GHG emissions, other economic sectors that overlap with the electricity sector are also changing to reach the goals of a low carbon society. The building sector improves its energy performance standards, and pilot projects worldwide are continuously demonstrating buildings producing more renewable energy than their total energy demand over the building's lifetime. Within FME ZEN, the vision is to develop Zero Emission Neighbourhoods (ZEN): a collection of buildings that contribute to net-zero GHG emissions over their lifetime. In this study, we aim to link the development of ZEN with the decarbonization of the power system on the European level. The case study is set in the context of Europe and European climate policy targets, and we analyse the development of the power system for different future scenarios.

ZENs do not directly reduce emissions in the European power system, but has an indirect effect that reduces the cost of reaching the GHG emission targets

Results show limited ZEN development from the central power system perspective before 2050. After 2050, the combination of reduced technology costs for ZEN and a European system subject to strict emission regulation causes a significant development of ZEN across Europe, contributing to a decrease in total system costs by 4%. The feedback of the central power system is mainly less electricity production by nuclear and wind power plants.

One important point is that surplus renewable energy produced within a neighbourhood does not reduce GHG emissions in the system directly. This is because the energy produced by the neighborhood does not replace energy produced with emissions but rather energy produced by other low carbon sources elsewhere in the system. However, we do observe that when ZENs are developed, the resulting emission allowance prices and total system costs are decreased. Hence, ZENs do not directly reduce emissions in the European power system, but has an indirect effect that reduces the cost of reaching the GHG emission targets.

The role of emission compensation as a tool to reduce neighborhoods' net GHG emissions is a disputed assumption. Therefore, since we tackle this issue directly, the results from this study are important to quantify the overall benefit of ZEN in the European power system. Furthermore, the results can be applied in related fields of research, such as life cycle analyses of neighbourhoods.

Contents

1. List of abbreviations

Abbreviation	**Full description**
ALL	'All capped' scenario
ASHP	Air-source heat pump
BAU	'Business as usual' scenario
CGE	Computational General Equilibrium
CHP	Combined Heat and Power
COP	Coefficient of Performance
DHW	Domestic Hot Water
EC	European Commission
EMPS	EFI's Multi-area Power-market Simulator
ENTSO-E	European Network of Transmission System Operators for Electricity
ETS	Emission Trading System
GHG	Greenhouse Gas
GIS	Geographic Information System
GSHP	Ground-Source Heat Pump
HOP	Heat Only Plant
KPI	Key Performance Indicator
LP	Linear Program
MCP	Mixed Complementarity Problem
MILP	Mixed-Integer Linear Program
OPSD	Open Power System Data
PV	Photovoltaic
RMSD	Root Mean Square Deviation
SH	Space Heating
SOFC	Solid Oxide Fuel Cell
ST	Solar Thermal collectors
VRES	Variable Renewable Energy Source
ZEB	Zero Emission Building
ZEN	Zero Emission Neighbourhood

2. Introduction

2.1 Background

Political ambitions to mitigate climate change are driving the transformation of energy systems. These ambitions imply that greenhouse gas (GHG) emissions from all economic sectors, including the energy sector, must reduce dramatically within the next decades. Key steps to achieve this decarbonization means a great expansion of renewable electricity supply in parallel with a net increase of electricity demand due to electrification of several economic sectors. Therefore, an interconnected electricity system is a cornerstone of a decarbonized energy future.

While electricity systems undergo a major transformation to reduce GHG emissions, other economic sectors that overlap with the electricity sector are also changing to reach the goals of a low carbon society. The building sector improves its energy performance standards, and pilot projects worldwide are continuously demonstrating buildings producing more renewable energy than their total energy demand over the building's lifetime.

In FME ZEN, the concept of Zero Emission Neighbourhoods (ZEN) is introduced.[1] The definition of ZEN is a collection of buildings that contributes to net-zero GHG emissions. The ZEN classification has different ambition levels related to the scope of the neighbourhood's lifetime stages, and it is achieved through two key measures: (1) minimize GHG emissions related to the neighbourhood within the scope of the ambition, and (2) compensate for the remaining GHG emissions through renewable energy generation in the neighbourhood.

The challenge of mitigating climate change is faced by society as a whole, and measures vary across sectors in scope and scale. All sectors ought to contribute with their own measures; however, the overlap between different sectors must be remembered as a low carbon society's political ambition is shared. There is a strong link between electricity producers and the many sectors using electricity in the electricity system because electricity needs to be generated and consumed simultaneously.

This report's starting point is the recognition that decarbonization measures in the electricity system will impact how a neighbourhood achieves the ZEN classification. Vice versa, the development of ZEN will affect how the electricity system develops to achieve its GHG emission reductions. Therefore, we study the bidirectional link between the development of the large-scale electricity system and medium-scale neighbourhood systems through a modeling linking exercise.

Two optimization models supporting capacity expansion of heat and electricity systems are linked in this study. One model focuses on the capacity expansion in Europe on a country level, while the other model focus on capacity expansion in a neighbourhood achieving the ZEN classification. The following research questions are raised:

- How does the European electricity system achieve decarbonization towards 2050 with and without the development of ZEN?
- How does the neighbourhood achieve the ZEN classification with a changing European electricity system?

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[1] https://fmezen.no/

2.2 Model linking for energy system analyses

Model linking approaches are increasingly being employed to assess the techno-economic implication of power system transitions. The primary motivation for linking models is to combine models with different temporal, spatial, and technological characteristics to gain insights that cannot be achieved with an individual model due to computational limitations. A review of methods for integrating short term variations in energy system models can be found in [1].

One group of literature can be defined based on the characteristic that one model is used to generate input data for a second model. In [2], the authors use data from optimization on a building level and load profile research to change the aggregate power system load profile by assuming a 50% deployment of zero emission buildings (ZEBs). The load profiles serve as inputs to the EFI's Multi-area Power-market Simulator (EMPS) to study the effect on the hydropower system and power prices. The main finding is that the Nordic power system can handle the introduction of ZEBs by adapting the hydropower dispatch. Furthermore, in [3] the authors assume 50% ZEBs in the Scandinavian building stock by 2050, and this assumption gives different load profiles. The ZEB introduction forms an input to the TIMES model to study the effect on investments and operation in the overall power system. Compared to this report, none of these papers considers a feedback effect on the ZEB design from the resulting adaptation of the power system. Furthermore, the amount of ZEBs is specified exogenously rather than being a modeling result.

A second group of literature uses sequential interaction of models according to some predefined specifications. Within this category, the authors in [4] uses a soft-linking of MARKAL-NL-UU and REPOWERS to combine long-term optimization with hourly simulation. The MARKAL model calculates power plant portfolios and CO_2 prices before these system designs are simulated with REPOWERS. In the end, a post-analysis is carried out to ensure the results are consistent across the models. In this paper, the authors found that existing flexibility is sufficient to accommodate renewables, but the efficiency of power plants will be reduced because of the variability. Also, it is shown that increasing levels of renewables will lead to a missing money problem as existing generators are unable to recover their costs. Also, in [5], which we build upon in this work, uses a neighbourhood specific model (ZENIT) and a Europe-level model (EMPIRE) to internalize ZEN deployment in a long-term assessment of the power system. A reference case is generated in EMPIRE to feed ZENIT. After that, EMPIRE is rerun based on ZENIT results. The results indicate that distributed generation can be beneficial under certain assumptions. The study is based on only electric energy, and the introduction of heat in the models is one of the extensions provided in this work.

A third category of model linking approaches is similar to the second one, but instead of running a predefined set of model interactions, the models are run iteratively until a convergence criterion is reached. Using this approach, the authors in [6] provides a general module-based framework for model linking. It suggests it will be increasingly important to combine models for a holistic assessment of energy system transition pathways. The paper presents a prototype where bottom-up models provide the energy supply data before prices and costs are calculated by a computable general equilibrium (CGE) model. The models are then solved iteratively until convergence is reached. Furthermore, in [7], the authors employ an iteration-based approach to formulate a bi-level energy system expansion planning model considering emission constraints.

An alternative to iteratively running models until convergence is reached is to either extend one model to include another one directly or to use a complementarity formulation to hard-link the models. In [8] the authors compare different approaches to link a top-down model with a bottom-up model. Various methods are studied: (1) Iterating between the models, (2) Mixed complementarity problem (MCP) formulation of both models and solving simultaneously as an integrated model, (3) the bottom-up model is extended by including the optimality conditions of the top-down model as constraints. It is found that the obtained solution can change depending on the linking approach.

2.3 Scope

In our work, we aim to combine two models where emission regulations and spatial characteristics differ. On the one hand, the ZENIT model seeks to optimize energy-related measures on a neighbourhood level to reach a long-term zero-emission goal. Conversely, the EMPIRE model aims to optimize transition strategies to achieve emission goals on a European scale. By combining these models, we contribute to the literature by investigating the implications of developing ZEN in the European energy system and compare with the base-case without ZEN. Although other studies address related problems, the scope and extent of the analyses in this work are novel compared to the existing literature.

2.4 ZEN as a part of the European energy transition

In this study, we aim to link the development of ZEN with the development of the central power system. The European context inspires our case study, and we analyze future scenarios fulfilling European climate policy targets.

We acknowledge that the "zero-emission" calculation defining a ZEN is highly dependent on assumptions related to the use of electricity generated outside the neighborhood boundary. Therefore, we aim to analyze how the design and operation of a neighbourhood energy system can meet the ZEN requirements with minimized costs given the changing future European power system. We compare ZEN designs for medium and long-term developments of the European power system and different ways of calculating emissions from the neighborhood perspective.

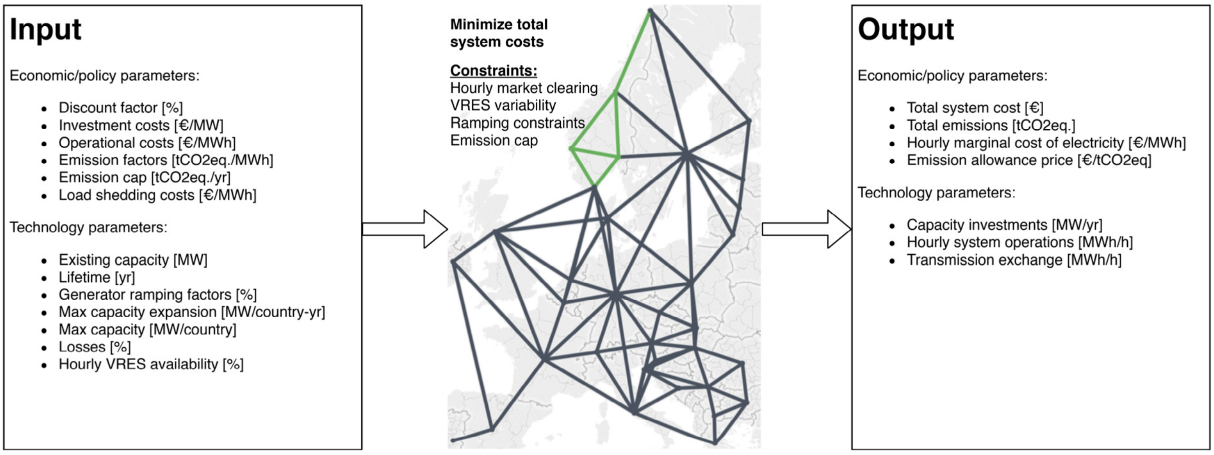
Vice versa, we also acknowledge that the central power system will be affected by a broad development of ZEN. It is still unclear what the impact of ZEN developments will be beyond its neighborhood boundary. Thus, we also aim to analyze which ZEN design is preferred in a European context and how the development of ZENs affects European future power prices and emission prices, the European generation mix, European transmission, and the European decarbonization pathway.

3. Models and methods

This section describes the two models used in this study conceptually along with the linking approach. For further details on the details of the models, the reader is referred to the appendices.

3.1 EMPIRE

The EMPIRE (European Model for Planning Investments in high shares of Renewable Energy) is a stochastic linear capacity expansion model focusing on the long-term development of the European power market while considering short-term variability and uncertainty related to demand and renewable availability. The model was developed as part of C. Skar's doctoral thesis [9] and has since been developed and further used in several projects (see e.g., [5], [10], [11], [12], [13], [14] [15]). An open version of EMPIRE can be downloaded from [16]. The EMPIRE version used in this study is a development of the version presented in [15]. The input and output of EMPIRE is illustrated in Figure 1. EMPIRE takes input on future costs, existing technology portfolios, technology-specific characteristics and emissions, and chronologic hourly demand in representative periods. The output represents the cost-optimal technology investments in multiple future investment periods and their operations in different future scenarios.



Input

Economic/policy parameters:

- Discount factor [%]
- Investment costs [€/MW]
- Operational costs [€/MWh]
- Emission factors [tCO2eq./MWh]
- Emission cap [tCO2eq./yr]
- Load shedding costs [€/MWh]

Technology parameters:

- Existing capacity [MW]
- Lifetime [yr]
- Generator ramping factors [%]
- Max capacity expansion [MW/country-yr]
- Max capacity [MW/country]
- Losses [%]
- Hourly VRES availability [%]

Minimize total system costs

Constraints:
Hourly market clearing
VRES variability
Ramping constraints
Emission cap

Output

Economic/policy parameters:

- Total system cost [€]
- Total emissions [tCO2eq.]
- Hourly marginal cost of electricity [€/MWh]
- Emission allowance price [€/tCO2eq]

Technology parameters:

- Capacity investments [MW/yr]
- Hourly system operations [MWh/h]
- Transmission exchange [MWh/h]

Figure 1 Overview of the input and output from EMPIRE.

EMPIRE represents the energy system through a nodal network. The nodes represent market regions, e.g., countries, while the arcs represent transmission between these markets. Investments in energy generation, storage, and conversion occur at each node, while investments in transmission occur at the arcs.

The objective function of EMPIRE quantifies total system costs related to asset investments and asset operations, and it is minimized when the model is run. The main output is an investment plan and corresponding system operation that satisfy the constraints at minimized total system costs.

The constraints of EMPIRE ensure that demand and supply of electricity and heat are balanced with an hourly resolution in each node. Energy demand is an input to the model, while investments and operations related to energy supply are outputs. Investments are restricted in each node and investment period, while a resource limit restricts the total installed capacity for each technology in the nodes. Energy supply by different technologies is limited by invested capacity and technology-specific characteristics, e.g., efficiency. Variable renewable electricity generation, such as solar and wind power, is limited by an hourly availability as a share of installed capacity. Thermal power generators are limited by up-ramping constraints, i.e., the increase in energy production from one hour to the next cannot exceed a technology-specific share of installed capacity. Total production by all hydropower plants, including regulated plants with reservoirs and run-of-river plants, is limited by a maximum annual generation. Regulated hydropower plants are further limited by a maximum seasonal generation, while run-of-river plants are limited by an hourly availability as a share of installed capacity. EMPIRE also considers storages that are restricted by charge/discharge and storage capacity, as well as the need to balance its state-of-charge.

The model applies a multi-horizon stochastic programming structure and considers multiple investment periods simultaneously in one optimization. This structure means it is a two-stage stochastic program while considering more than two future investment periods (see Figure 2). The first stage decisions represent asset investments in all future periods. The second stage decisions represent asset operations in different seasons and different realizations of uncertainty within these seasons. One stochastic scenario is always linked to precisely one investment period. The difference between the operational scenarios, i.e., the uncertainty, is related to the following input:

- Hourly demand of electricity and heating in buildings.
- Hourly availability of renewables (solar, wind, and run-of-river hydropower generators).
- Seasonal availability of regulated hydropower plants

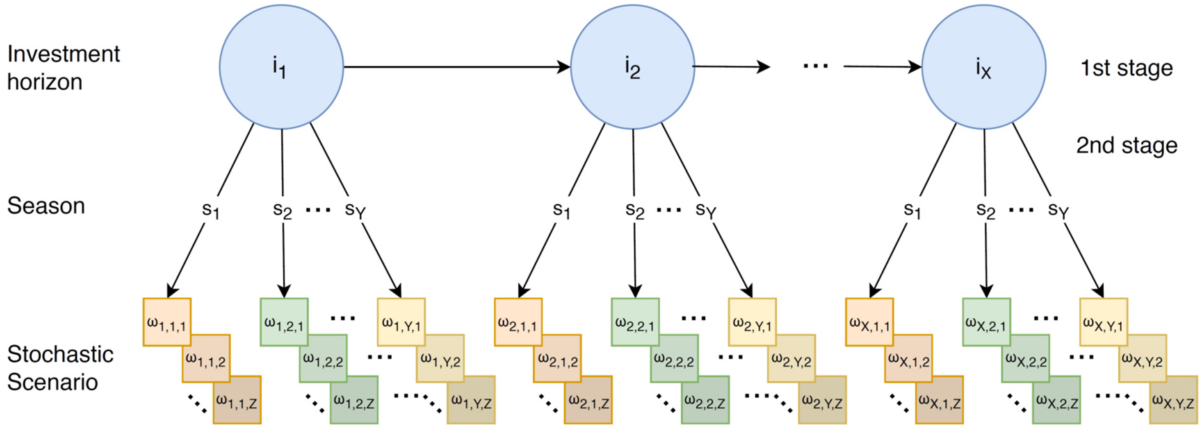


Figure 2 Illustration of the multi-horizon stochastic programming structure of EMPIRE [15]

3.2 ZENIT

The ZENIT (Zero Emission Neighborhood Investment Tool) minimizes the energy system investment and operation cost for a given neighborhood that allows it to reach zero-emission status during its lifetime. This section describes the model's components, and Complete ZENIT Model Description contains a more detailed model description, including the mathematical formulations. Figure 3 presents the data flows, including inputs and outputs, of the ZENIT model.

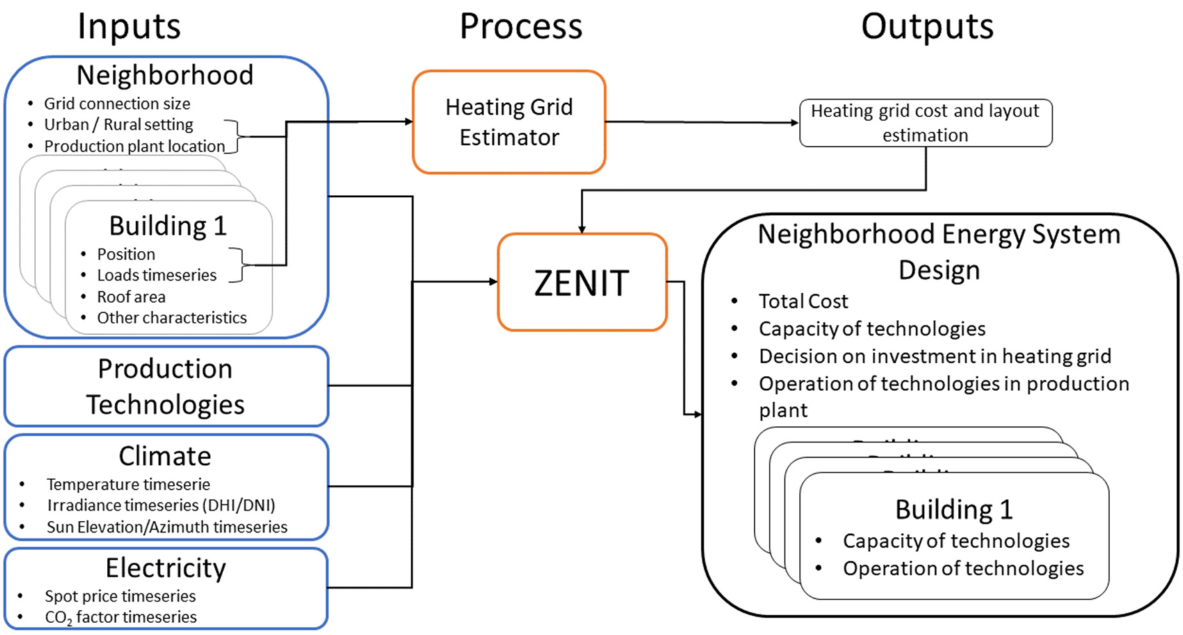


Figure 3 Schematic representation of the data flow using ZENIT.

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

To be considered a ZEN, the neighborhoods need to have net-zero emissions in their lifetime. In the ZEN framework, we assume that the electricity exports from renewable sources in the neighborhood reduce the emissions in the bidding zone by replacing some of the more carbon-intensive power generation. Therefore, such local electricity export is counted as compensations (or negative emissions) in the net emission calculation.

When it comes to the operation of the neighborhood, we consider the same hourly timesteps as in EMPIRE: three scenarios of one week per season and two peak days. Load balances for electricicity, separate 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, an efficiency links the fuel use and the generation of heat or electricity. Solar technologies (solar thermal collectors and PV panels) are modeled by a solar availability factor. For heat pumps, COP is used instead of the efficiency.

Heat and electric storages are modeled with their charge and discharge efficiencies and only consider the daily operation of the storage. Longer-term storages are not considered for the neighbourhood-level in this study.

3.3 Linking the models

Figure 4 presents the way the study is conducted and the articulation of the two models. Neighbourhoods in EMPIRE are equivalent to an electricity generation package, building heat generation, and conversion of electricity to heat. Thus, the single ZEN asset in EMPIRE consists of the neighbourhood's entire technology portfolio consisting of several ZEN assets. We further assume that 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 operation and maintenance costs, including fuel costs.

The study (and the linking of the models) happens as follows. The EMPIRE model is first run without ZEN as investment options. The results allow computation of emission factors and provide the spot price of electricity and the price of allowances needed in ZENIT. Subsequently, ZENIT is run for each node and each selected period (in this study, 36 nodes and three periods: 2030, 2040, 2050). The ZENIT runs give the input data necessary to include them as investment options in EMPIRE: the investment cost, the operational costs, heat and electricity generated, and the amount of allowances purchased. EMPIRE is then run once more including the option to invest in ZENs. EMPIRE only considers the possibility to invest in ZEN in the three periods considered in ZENIT (in this study: 2030, 2040, 2050).

Ideally, this process of back and forth between EMPIRE and ZENIT should be repeated multiple times until convergence. Indeed, the results from EMPIRE would impact the design of the ZENs and vice versa. However, in the study, we do not iterate until convergence because of the high number of nodes, periods, and cases resulting in many instances of ZENIT to run. At each step, until convergence, those runs would need to be repeated and result in unacceptable computation times. The convergence procedure may be better suited for studies where the scope is limited to a few countries or bidding zones.

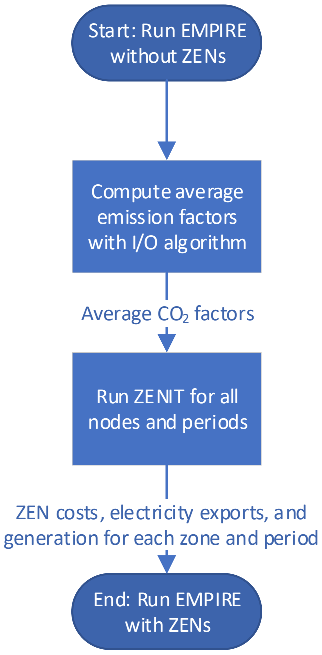


Figure 4 Flowchart of the process used in the study

4. Case study setup/design

4.1 EMPIRE Setup

At the European level, EMPIRE considers 35 nodes[2] , including Norway's five separate nodes defined by the Nord Pool market zones. 85 transmission lines connect the country nodes. The countries are illustrated in Figure 5: the green countries include electricity- and building heat markets that can develop ZEN, whereas the blue countries only include electricity markets.

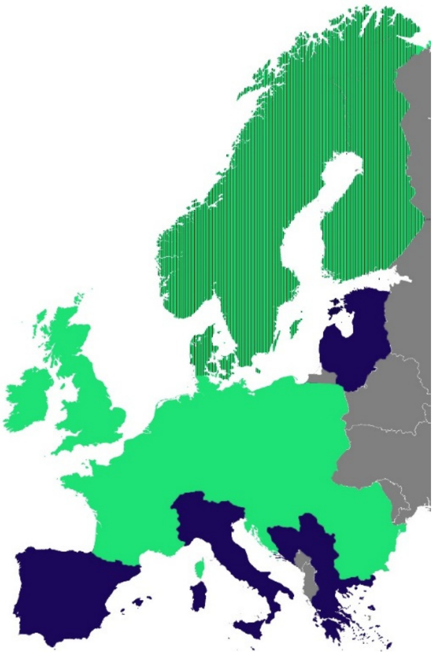


Figure 5 Countries considered in EMPIRE. Green = building heat markets. Blue = only electricity markets. The source for building heating profiles is [17] and [18] for striped countries and [19] for non-striped countries. Grey countries are not considered.

We consider the following electricity production technologies: Conventional turbines fuelled by lignite, coal, gas, biomass, nuclear, or geothermal; solar PV; hydropower (run-of-river and with reservoir); wave technology; and onshore and offshore windpower. For electricity storage, we consider pumped hydropower and lithium-ion batteries. For electricity generators and storage, costs and fuel efficiency are gathered from [20]. Fuel costs and future development of electricity demand are according to the EC decarbonization scenario presented in [21]. Current (initial) capacities of electricity generators in the different European countries are gathered from [22].

For heat production, we consider the following options: Combined heat- and power (CHP) plants fuelled by municipal waste or biomass; large-scale heat production with municipal waste, fossil gas, biomass, or geothermal; heat boilers fuelled by oil or fossil gas; direct electric heating; and air-sourced and ground-sourced heat pumps. We also consider small-scale and large-scale hot water storage. For building heat generators and storage, costs and fuel efficiencies are gathered from the Danish Energy

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[2] Austria, Bosnia H, Belgium, Bulgaria, Switzerland, Czech R, Germany, Denmark, Estonia, Spain, Finland, France, Great Brit., Greece, Croatia, Hungary, Ireland, Italy, Lithuania, Luxemb., Latvia, Macedonia, Netherlands, Norway (NO1-NO5), Poland, Portugal, Romania, Serbia, Sweden, Slovenia, and Slovakia

Agency[3]. Note that although the source for heat technologies reflect scale and connection to district heating, EMPIRE does not contain details that distinguish technology options beyond their assumed costs, fuel, and technological characteristics, and we allow the development of district heating units in any country. EMPIRE also does not separate between sanitary hot water demand and space heating demand.

A complete overview of cost assumptions related to technology options in EMPIRE, see Technology data in EMPIRE.

We have generated three scenarios representing different realizations of four seasons of a year in EMPIRE for this case study. Each season consists of 168 consecutive hours, making up representative weeks. The weeks have been sampled from historical data based on the scenario generation routine described in [15]. For wind and solar power generation, we have sampled time series based on historical satellite data available through renewables.ninja[4] [23] [24]. For hydro power generators, we have sampled from historical production data available through ENTSO-E Transparency Platform[5].

4.1.1 Emission cap in EMPIRE: Two scopes

The emission cap is a hard constraint in EMPIRE being an upper bound on total annual CO_2eq. by all considered energy generators in Europe in any stochastic scenario. We assume renewable energy generators to have zero emissions during operations (includes biomass in EMPIRE). We assume the emission cap follows the development illustrated in Figure 6 based on the needed emission reductions in the power sector according to a 1.5-degree scenario presented in [25], and a continued decrease to become 2 % of the 2020-2025 cap in 2060.

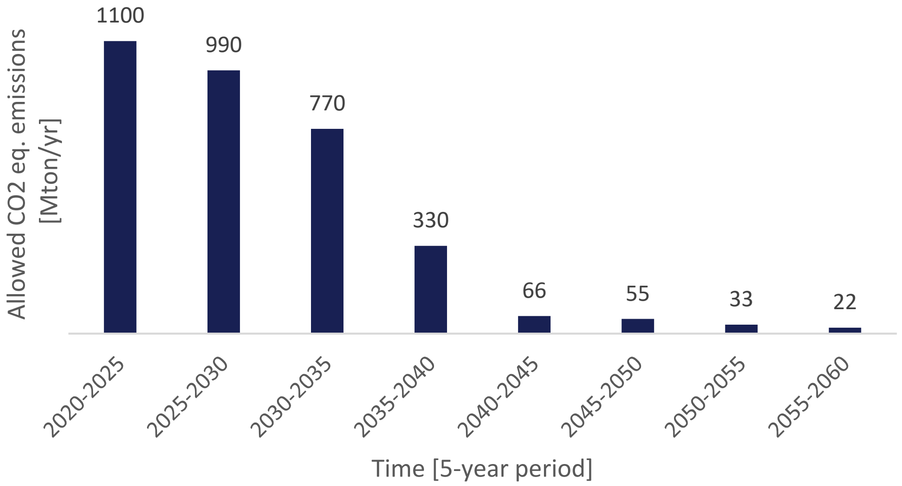

Figure 6: Assumed development of emission cap in EMPIRE according to a 1.5-degree scenario

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

[4] https://www.renewables.ninja/

[5] https://transparency.entsoe.eu/

We consider two different scopes for the European-wide emission cap in EMPIRE in two separate instances. The development of the emission cap is the same in both instances, but the assumption regarding which generators to include in the cap is different.

In the first instance, entitled business-as-usual (BAU), the emission cap in EMPIRE is assumed to cover emissions from large-scale power plants and district heating generators. This instance does not cap emissions from small-scale heat generators, e.g., individual gas boilers. Not counting emissions from small heat generators or biomass is in accordance with the emission trading directive [26] stating that: "[…] *Units with a rated thermal input under 3 MW and units which use exclusively biomass shall not be taken into account* […]".

In the second instance, entitled ALL, EMPIRE caps *all* operational emissions from *all* generators. This instance represents an "ideal" regulation where all CO2eq. emissions need allowances, even emissions from small-scale generators. To compare with BAU, we do not assume the emission cap to be less strict in ALL, even though it would cover more emissions.

4.1.2 Load profiles in EMPIRE: Electric-specific and building heat

Load profiles are provided with an hourly resolution for both heat and electricity demand. The same hours of a year are used for both electricity and heat load in the different seasons and scenarios, and we also use the same hours for every node. Electricity load profiles are gathered from historical data for European countries from the ENTSO-E Transparency platform. Building heat load profiles are gathered from two sources. The first source is the When2Heat project [19], where the aggregated total building heat load profiles are used for 16 central European countries[6] from the year 2016. The second source is the load profile generation tool presented in [27]. The load simulation tool's 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[7] for Norway and Open Power System Weather Data[8] for Finland, Sweden, and Denmark. The building areas were estimated based on the EU building observatory[9] and, for Norway, estimations by the Norwegian Energy Regulator [28]. The area estimates by building type are presented in Figure 7.

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[6] Countries in When2Heat data set include Austria, Belgium, Bulgaria, Switzerland, Germany, France, Great Britain, Croatia, Hungary, Ireland, Luxemburg, Netherlands, Poland, Romania, Slovenia, and Slovakia.

[7] https://klimaservicesenter.no/observations/

[8] https://doi.org/10.25832/weather_data/2019-04-09

[9] https://ec.europa.eu/energy/eu-buildings-database_en

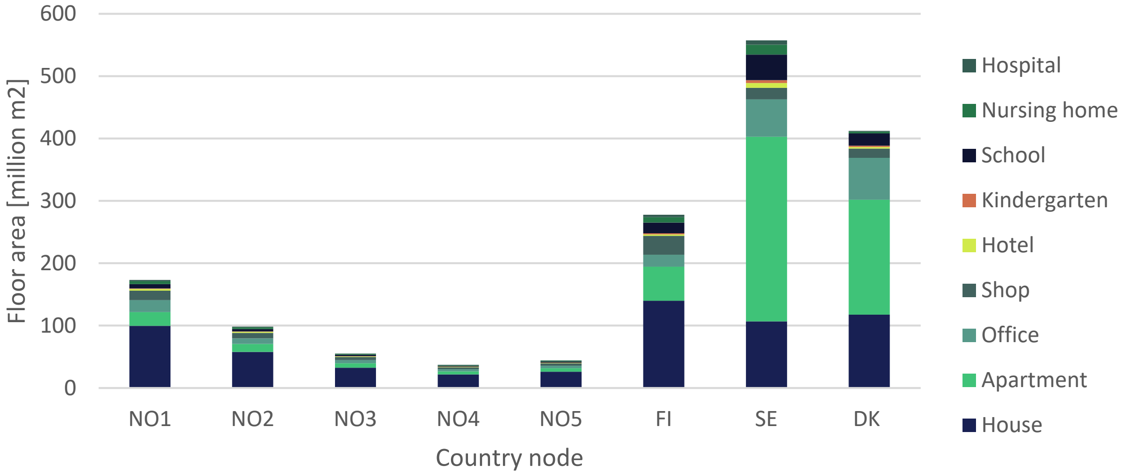

Figure 7: Assumed total building area in Norway, Sweden, Finland, and Denmark

In some countries, e.g. in Norway, electricity has been used to cover a significant share of the building heat demand . Some historical electricity load profiles, therefore, contain building heating demand. This study wants the electricity load to be electric-specific, representing a load that *must* be met with electricity as an energy carrier. Thus, we process the electricity load to represent electric-specific load by removing building heat demand through the following equation for every hour h and country n:

$$\xi_{\mathrm{h,n}}^{\text{el-specific}} = \xi_{h,n}^{\text{el-total}} - \alpha_{h,n}^{\text{el-heat}} \xi_{h,n}^{\text{heat}},$$

where $\xi_{h,n}^{\text{el-specific}}$ is the electric-specific load, $\xi_{h,n}^{\text{el-total}}$ is the historical total electricity load, $\alpha_{h,n}^{\text{el-heat}}$ is the average share of electric heating of all building heating, and $\xi_{h,n}^{\text{heat}}$ is the building heat load.

4.2 ZENIT Setup and Neighborhood description

The neighborhood that is used in this model is made up of 250000 m^2 ground floor area representing 100000 m^2 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, kindergarten, school, and nursing home. The load time-series of these buildings are obtained using the results from [17] and [18]. The main data regarding the neighborhood is presented in **Table 1**. We assume a lifetime of 60 years for the neighborhood and a discount rate of 4 %.

Table 1. Characteristics of the building types in the neighborhood

Type	Area (m^2)	Roof Area (m^2)
Houses1	13900	6950
Houses2	13900	6950
Apartments1	2205	4890
Apartments2	22005	4890
Offices	18948	3158
Shops	1230	1230
Kindergarten	460	490
School	5032	1677
Nursing Home	1062	531

Several technologies are included in the study:

- **At the building level:** Solar panels, solar thermal collectors, air-air heat pumps, air-water heat pumps, ground-source heat pumps, bio boilers (wood logs or wood pellets), electric heaters, electric boilers, biomethane boilers and gas, biogas, and biomethane CHPs.
- **At the neighborhood level:** CHPs (biogas, wood chips or pellets), boilers (wood chips or pellets or electricity) and ground-source heat pumps. The costs, efficiencies, and other technical data about these technologies is taken from the Danish Energy Agency[10] and can partly be found in [29].

Technologies at the neighborhood 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 type of building (apartment-complex or single-family house). The detailed data for the technologies is presented in Appendix B.

All time-series used correspond to the year 2016. The time-series for ambient temperature in Norway are gathered from measuring stations[11] and for the other countries from the Open Power System Data (OPSD) Project[12]. The solar irradiances also come from the OPSD project. The spot prices and 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 input-output methodology of [30].

The neighbourhood is designed according to the available data (spot prices, allowance prices, and emission factors) of the corresponding period. In practice, the model is run using the 2160 hours (4 weeks and two peak days in 3 scenarios) from EMPIRE scaling the operating costs and emissions accordingly.

ZENIT is implemented in Python and solved using Gurobi. The optimization is run on a server with a 12 core, 24 threads intel Core i9-9920X at 3.5GHz with 128 GB of RAM. Each run (for a single node and year) takes approximately 21 minutes.

The ZENIT model is run for the two EMPIRE cases: the cap comprising only large energy sources that we call the BAU case and the one comprising all energy sources that we name the ALL case. In each case, ZENIT is run for the nodes in EMPIRE where both the heat and electricity are taken into account: NO1, NO2, NO3, NO4, NO5, Austria, Belgium, Bulgaria, Croatia, Czech Republic,

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

[11] https://lmt.nibio.no/

[12] https://open-power-system-data.org/

Denmark, Finland, France, Germany, Great Britain, Hungary, Ireland, Luxembourg, Netherlands, Poland, Romania, Slovakia, Slovenia, Sweden, and Switzerland. The neighborhoods are built based on the actual condition resulting from EMPIRE in the years 2030, 2040, and 2050. Note that we also only consider ZEN as an investment option in EMPIRE in 2030, 2040, and 2050 to ensure that the ZEN option in EMPIRE is linked to the European situation in the respective period.

Contrary to [29], a mixed-integer linear program (MILP) approach is not used for the case studies in this report. Due to a large number of instances of the model to run, we reduce the number of binary variables to the bare minimum, which is only to have a binary for the investment in the heating grid. Further, we separate this MILP into two LP solved independently because this was found to be faster than solving a unique MILP. The same timesteps as the ones used in EMPIRE are used.

5. Results

This section describes the results based on the linking approach for two different carbon cap assumptions:

- **ALL:** EMPIRE caps *all* operational emissions from *all* generators.
- **BAU:** The emission cap in EMPIRE is assumed to cover emissions from large-scale power plants and district heating generators.

First, the initial EMPIRE results without a ZEN-option is presented. After that, we present the results from ZENIT when EMPIRE results are used to generate ZEN designs. Lastly, we present the results from EMPIRE after the model is run with the option of investing in ZENs.

5.1 EMPIRE without ZEN-option

5.1.1 ALL

The expected annual electricity and building heat production by source in Europe from 2020-2060 when all emissions are capped is presented in Figure 8 and Figure 9, respectively. The European power system has >50 % share of variable renewable energy sources (VRES) from 2030, with onshore wind making up the highest share. The growth in electricity demand is partly due to the electrification of building heat supply, where air-sourced heat pumps dominate the market. After 2040, > 50 % of European building heating is electricity based. Note that EMPIRE results mainly represents the building heat *sources*, and EMPIRE does not contain detailed features to represent *how* to distribute heat; electricity-based heating could be provided by in-building units or through district heating grids.

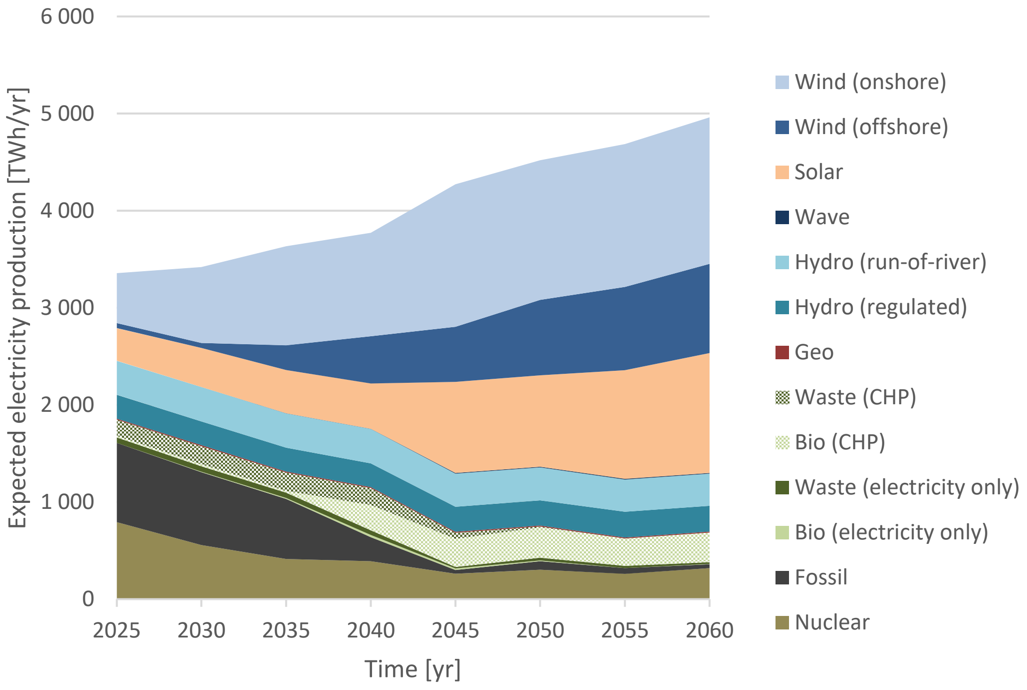

Figure 8 Expected annual electricity production by source in Europe in ALL when all emissions are capped.

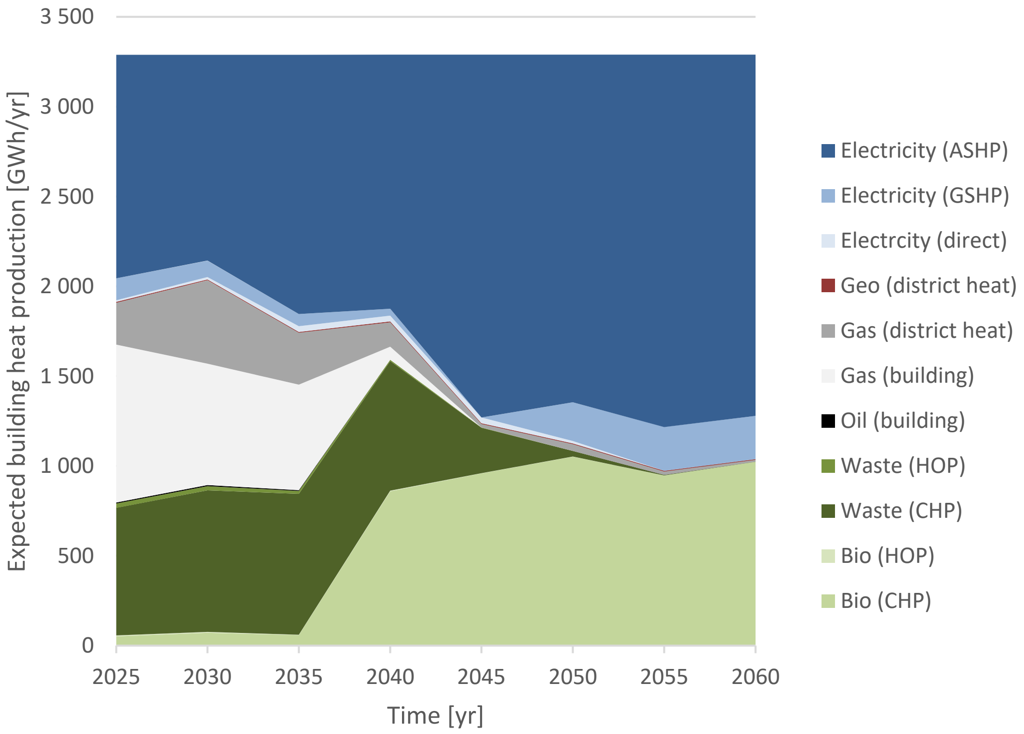

Figure 9 Expected annual building heat production by source in Europe in ALL when all emissions are capped.

Figure 10 presents the electricity production for the whole horizon by country and source. France and Germany are by far the largest electricity producers. Southern European countries, like Spain, Italy, and Portugal, all favour solar PV as the largest renewable source, while central and northern Europe favour wind as the largest VRES source. Also note that several European countries and regions, including France and the Nordics[13], produce more electricity than they consume (see Figure 10). This means those countries are net exporters of electricity. Other countries and regions, e.g. Italy and the British Isles, are net importers of electricity. Germany transitions from being a net importer of electricity before 2040 to becoming a net exporter after 2040, which is also the case for the North Carpathian[14] region. Note that Figure 10 only shows electric-specific consumption, which does not include electricity used for heat generation, e.g. in heat pumps. Electricity used for heating increases total electricity consumption by 7 % from what is presented in Figure 10.

Figure 11 presents the share of building heat sources by country and case. In both ALL and BAU, Slovakia has the lowest share of electric heating, while Sweden has 100 % electric heating. The difference in heat electrification among countries links to the electricity production in the respective countries: where Sweden develops a large share of VRES and regulated hydropower causing a low electricity price, Slovakia develops more nuclear electricity production and bio-based CHP. Although the Norwegian nodes has the lowest long-term average electricity prices in EMPIRE making it favorable with electricity-based heating, waste-based CHP supplies a significant amount of building heating which supports low-carbon electricity export from Norway.

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[13] Norway, Sweden, Denmark, and Finland
[14] Poland, Czech Republic, and Slovakia

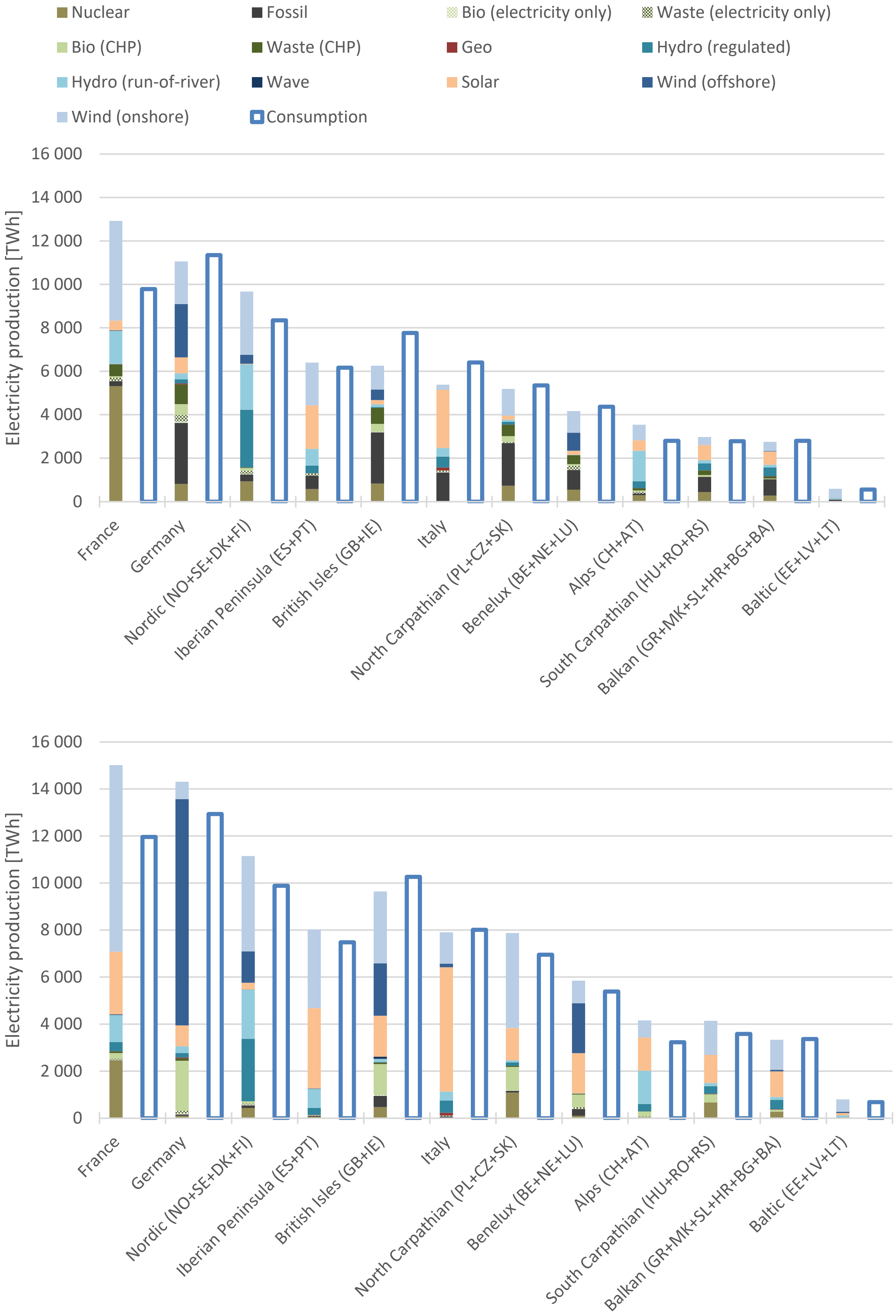


Figure 10 Electricity production (filled bars) and consumption (non-filled bars) for the whole horizon between 2020 and 2040 (top) and 2040 and 2060 (bottom) by region and source in ALL.

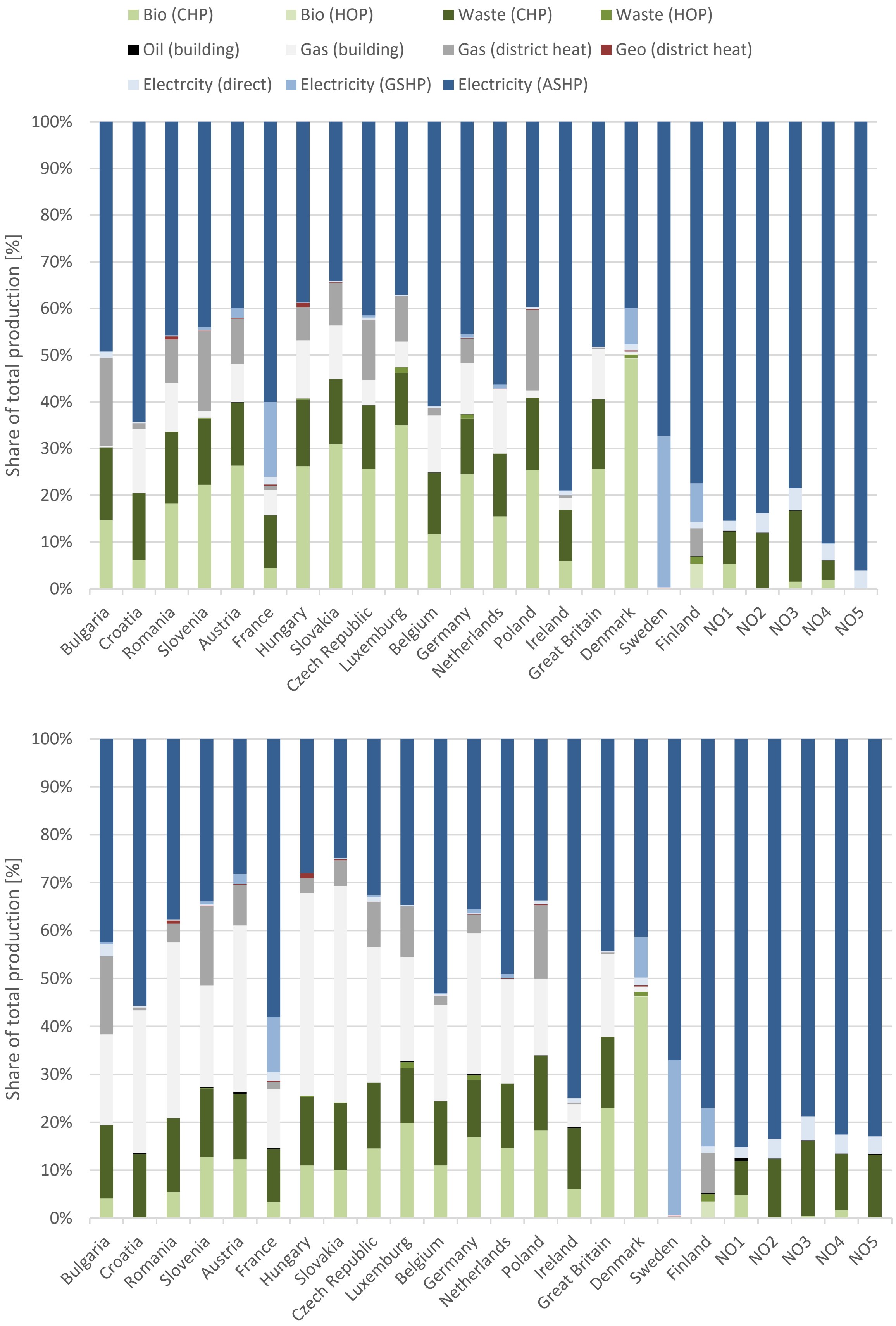


Figure 11 Source share of total building heat production for the entire horizon for ALL (top) and BAU (bottom).

5.1.2 BAU

The BAU case show a significantly higher share of fossil gas boilers because their emissions are not regulated, which causes the overall share of bio and electricity-based heating to decrease (see Figure 11). Not regulating emissions from fossil gas boilers also leaves room for more emissions from other sources as the emission allowances become cheaper, and we see a small increase in waste-to-energy heating in the Norwegian nodes (see Figure 11). This also leads Norway to develop less VRES and export more hydropower in BAU compared to ALL as less electricity is used for building heating.

Figure 12 presents the difference in expected electricity and heat production for the entire horizon compared with ALL (see Figure 8 and Figure 9). Recall that the difference in BAU from ALL is that more emissions are allowed because we assume the same emission regulation is covering a smaller scope of generators. Less renewables are therefore developed in BAU, including bio-based heating, which is partly replaced by more fossil and nuclear electricity generation. There is a net reduction in electricity generation in BAU as a consequence of electric heating being replaced by small-scale gas boilers (see Figure 12). The most considerable reduction in electricity production compared to ALL is onshore wind, followed by bio-based CHP. However, the increase in small-scale gas boilers in BAU compared to ALL still implies > 50 % of heating to be electric after 2040. The wide electrification of heating in both ALL and BAU is a consequence of heat pumps outcompeting gas boilers when VRES dominate the European power market. Note that we are assuming that the endogenous decisions related to investments or operations in EMPIRE do not impact any technology costs, including fossil fuel prices.

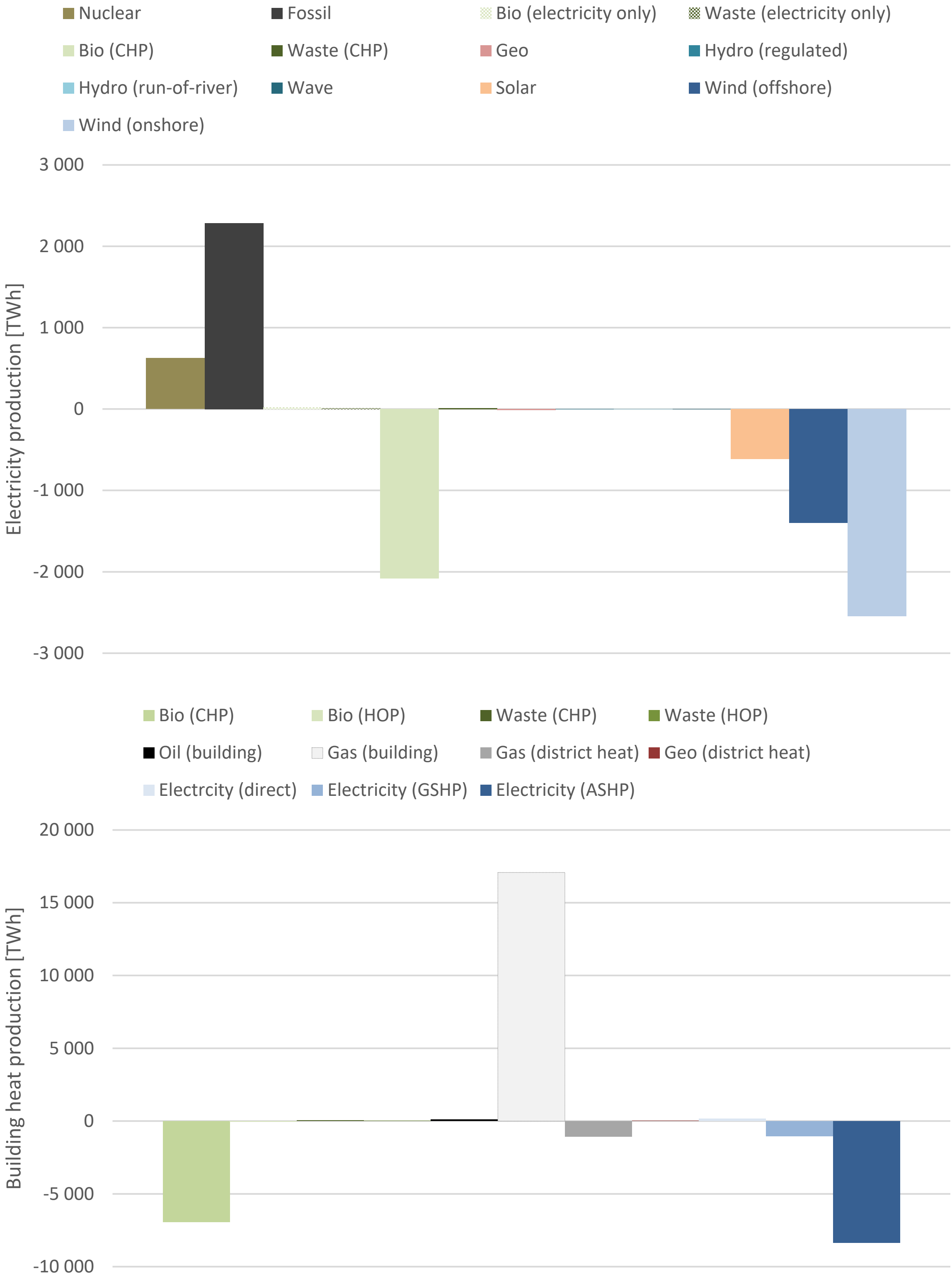


Figure 12 Difference in BAU from ALL in total expected electricity (top) and building heat (bottom) production by source in Europe for the entire time horizon (2020-2060).

5.2 ZENIT response to EMPIRE

The ZENIT runs using the results of both emission cap assumptions in EMPIRE are presented in this section. Different parameters will be used to differentiate the cases, such as the year used for the ZEN's energy system design, the latitude, or the average emission factor of electricity. The results using EMPIRE ALL and BAU cases are very similar, and only the latter is presented here, while the former is included in Appendix C.

First, to run ZENIT, the emission factors need to be calculated based on the results from the EMPIRE runs. The resulting emission factors are presented in Figure 13 and Figure 14. The evolution of the yearly average emission factors is similar in both cases, with reductions of the emission factors due to the reduction of the cap. However, the initial levels are different due to the difference in the definition of the cap. In both cases, the same cap is shared between the producing units. Still, small units are not included in the cap in the BAU case, thus leaving more of the cap available to units producing electricity and increasing the average emission factors.

The spot price of electricity has a very similar evolution in both cases. Overall, it seems to increase by about 30 €/MWh between 2020 and 2060. In some parts of northern Europe, the increase is smaller.

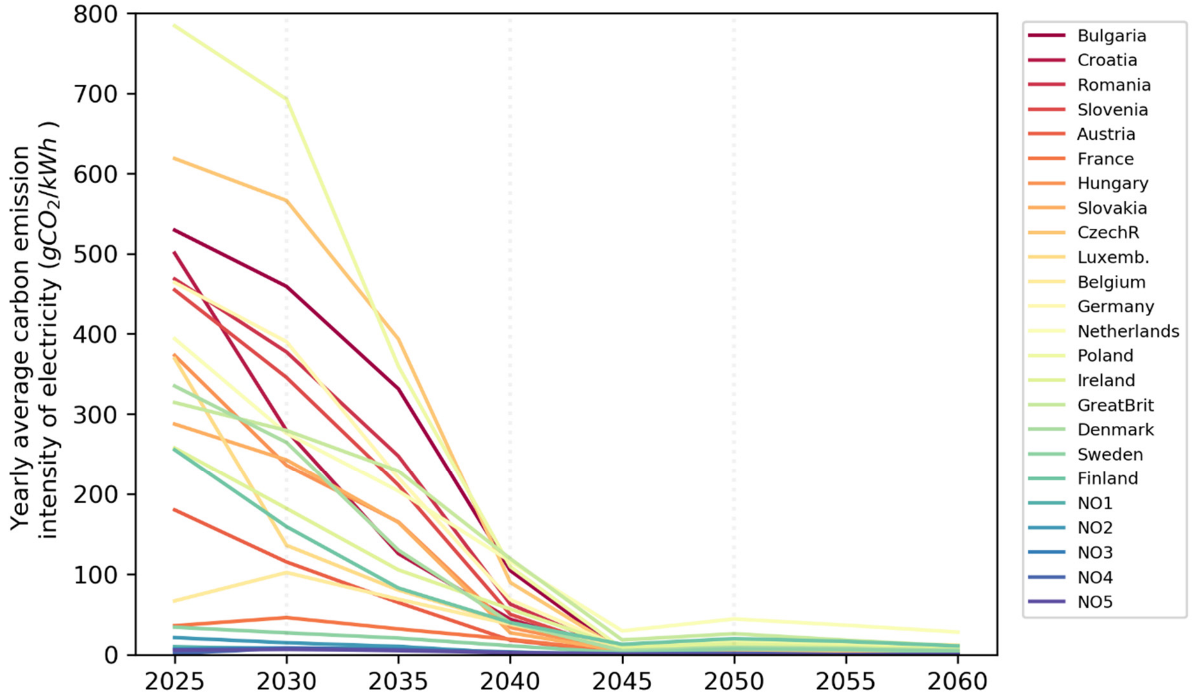


Figure 13 Evolution of the yearly average emission factor of electricity in the BAU EMPIRE case with countries coloured by latitude

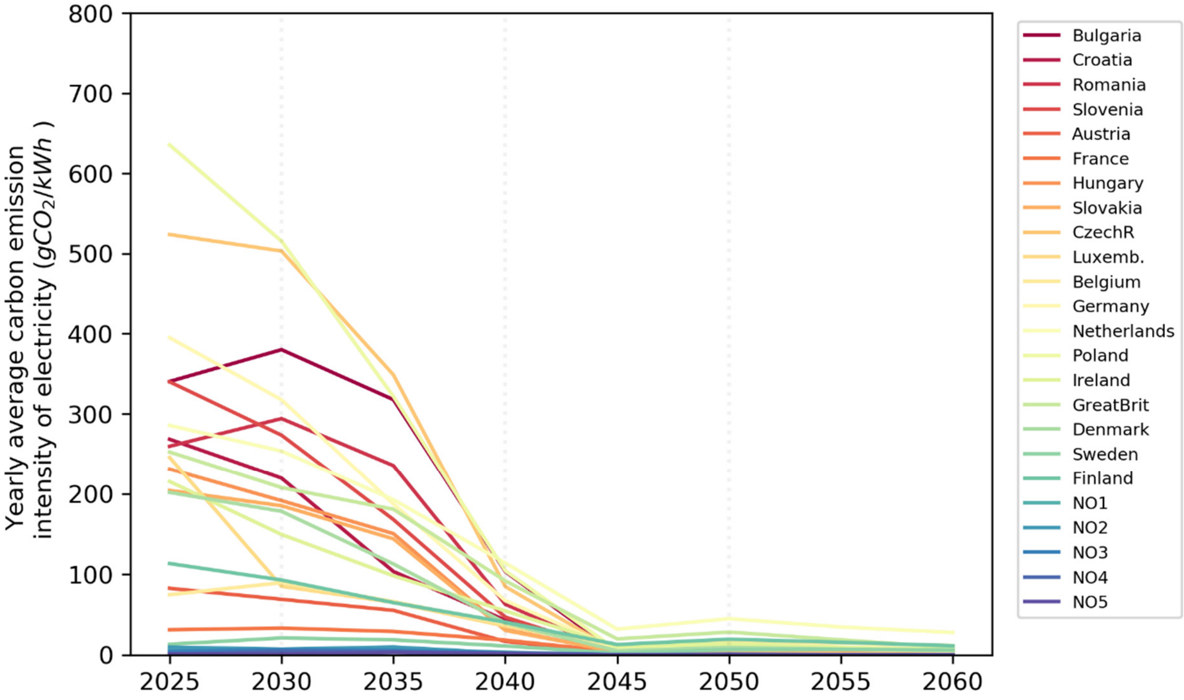


Figure 14 Evolution of the yearly average emission factor of electricity in the ALL EMPIRE case with countries coloured by latitude

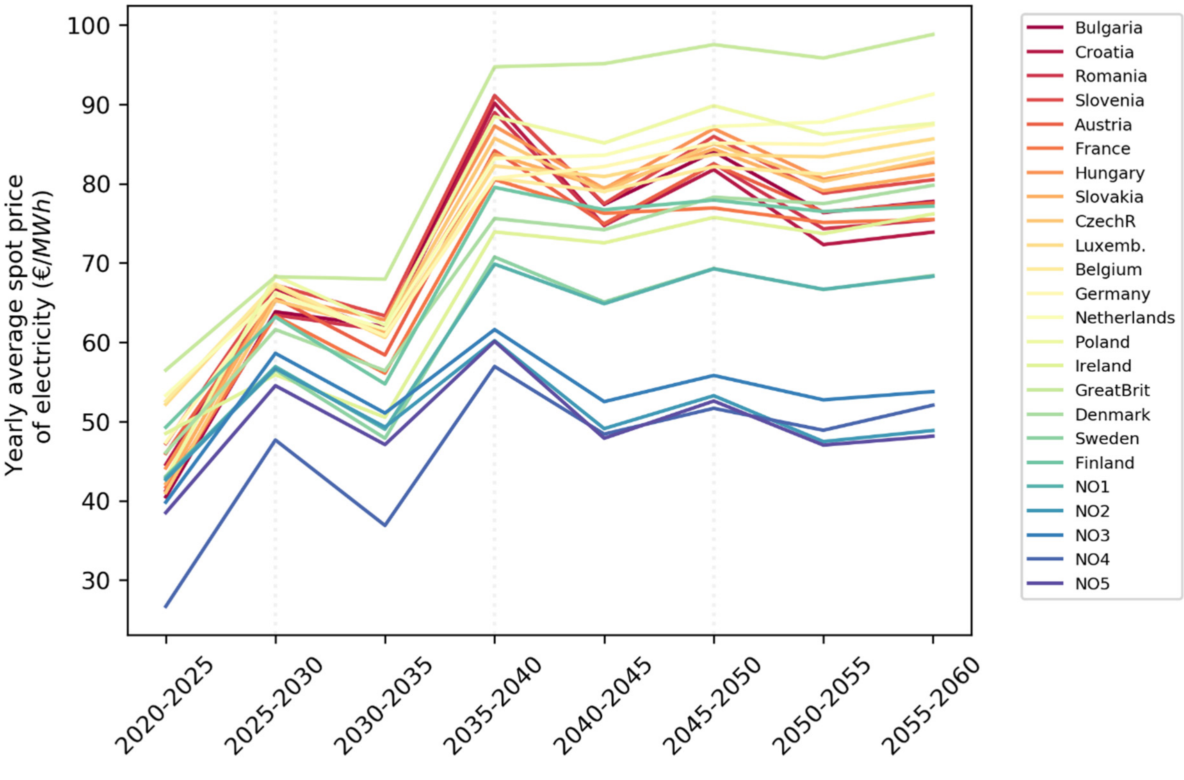


Figure 15 Evolution of the yearly average spot price of electricity in the BAU EMPIRE case with countries coloured by latitude

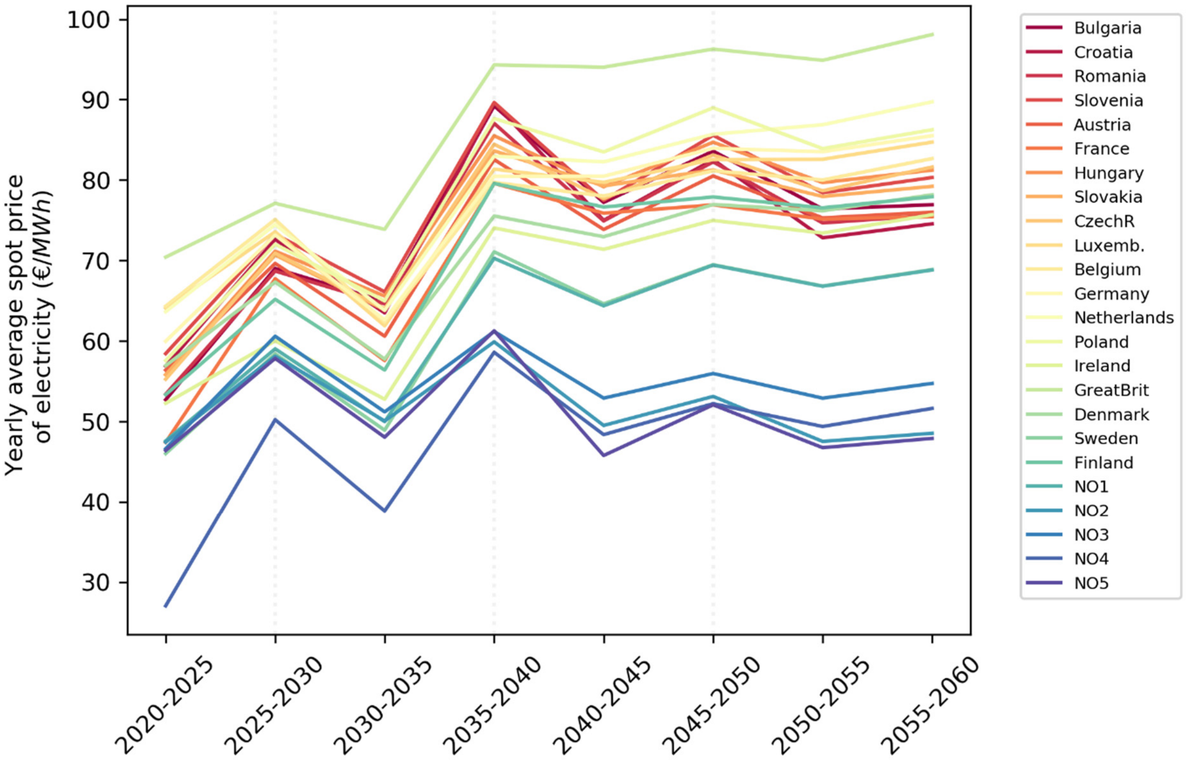


Figure 16 Evolution of the yearly average spot price of electricity in the ALL EMPIRE case with countries coloured by latitude

5.2.1 General Results

This subsection presents the results obtained in the BAU case. The number of countries included make it difficult to annalyze the results, so two different approaches are used to present the results. One of the approach tries to identify correlation between the results and the latitudes of the countries, and theircolor in the gradient of color is based on their latitude. The other seek to highlight correlation to the emission factor. The average emission factor in 2030 is used. Here shades of grey are used, with black being used for the country with the highest emission factor (here Poland) and a shade of grey based on the ratio of the emission factor divided by the maximuml emission factor is used for the other countries. A correlation to either of these is not always clear but only one version of each figure is presented below.

Figure 17 and Figure 18 present the investment results for each node and each period in the different technologies with different colors for the three years in the BAU case.

PV systems is the main energy system investment, which is almost always bought to the roof area limit. The rest of the energy system is more diverse, with certain technologies being chosen in only a few cases while others appear regularly. Among those, we can note the presence of some kind of heat pump, solar thermal collectors, wood boiler, biomethane boiler, biogas engine, gasified biomass stirling engine, solid oxide fuel cell, CHP, and storages. Electric storage seems to appear in later years, while heat storage is always present.

In the *ALL* case, the same technologies are chosen, and the investments are very similar.
More detailed results regarding specific technologies will be presented later in this section.

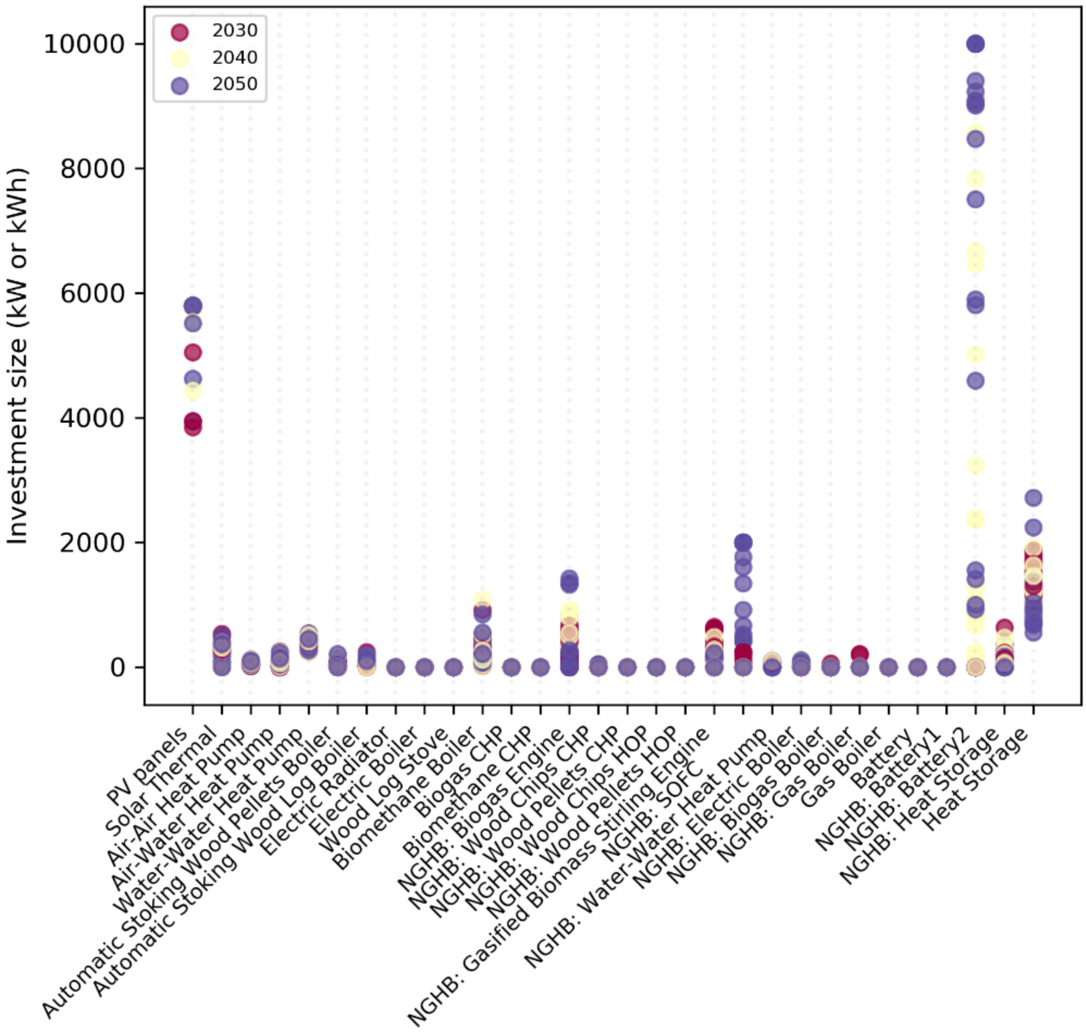


Figure 17 Resulting investment by technology and year resulting from the ZENIT runs using EMPIRE data from the *BAU* case

Figure 19 presents the total discounted costs of each ZEN. Those costs are varying by about 40% between the highest and lowest total discounted costs. In all countries, this cost decreases due to the evolution of the spot price of electricity, changes to the energy system design, and reduced technology costs over time.

The emissions of the ZENs are very dependent on the emission factor of electricity, as can be observed from Figure 20. Following the decarbonization of the energy system in EMPIRE, the neighborhoods' emissions are also reduced significantly. Indeed, electricity imports represent an important source of emissions for the neighborhoods. The local emissions (Figure 21) represent a higher share of the total emissions in the countries with low emission factors. However those local emissions are higher in absolute values in countries with high emission factors.

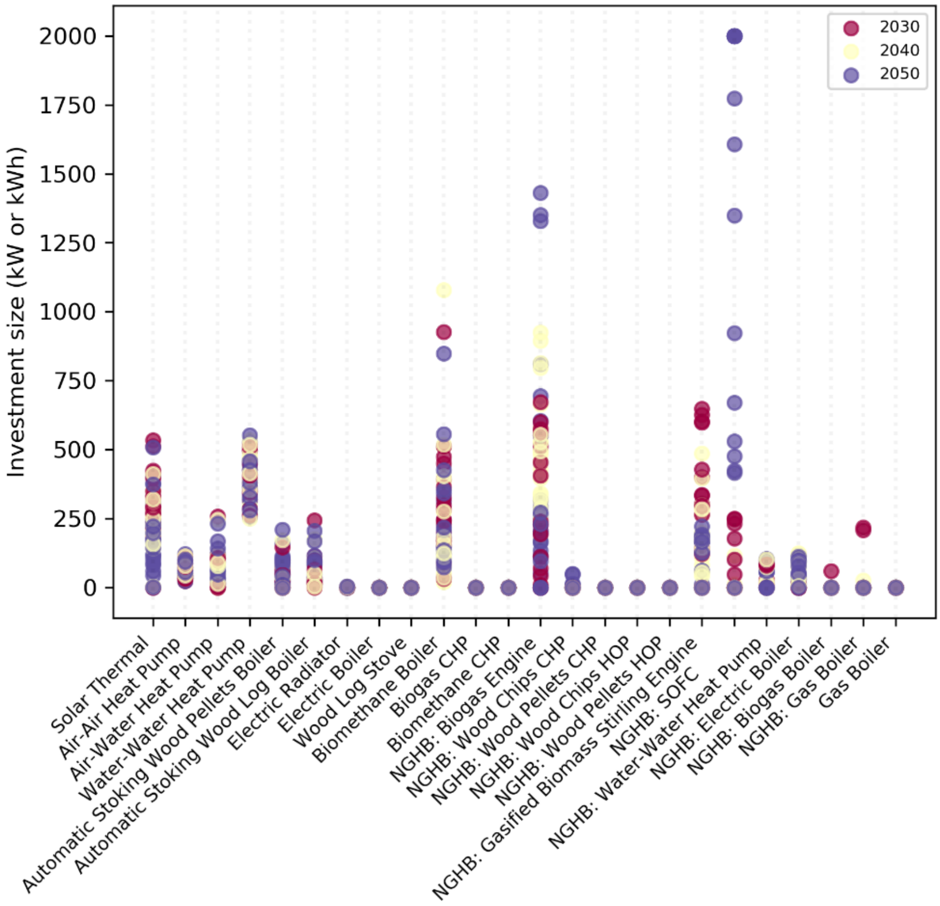


Figure 18 Extract of the resulting investment by technology and year resulting from the ZENIT runs using EMPIRE data from the *BAU* case

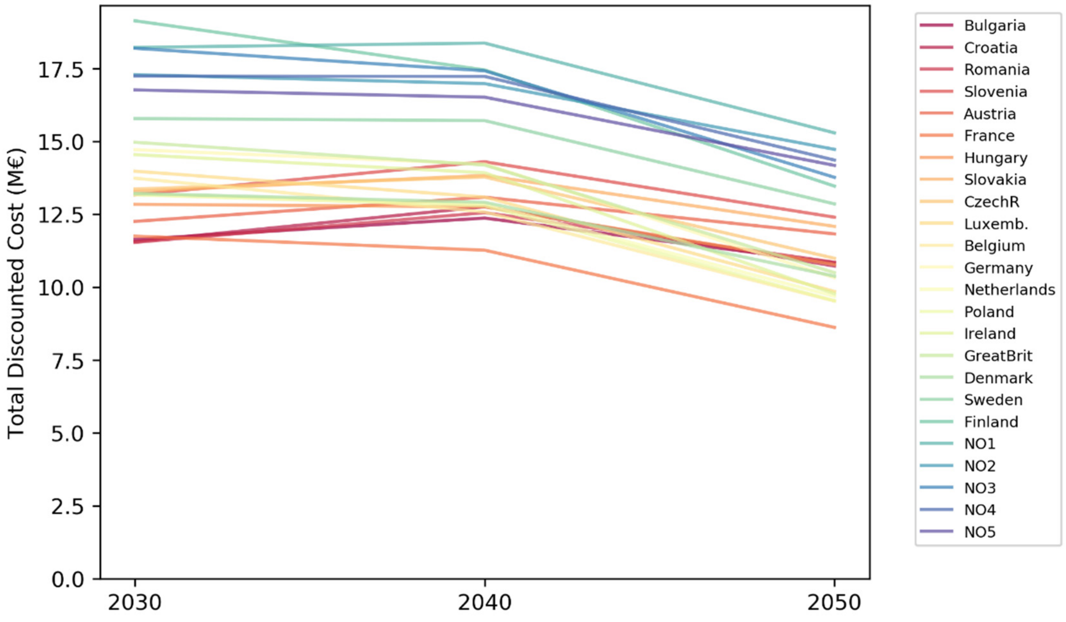


Figure 19 Total discounted costs for the energy system of a ZEN in different European countries in BAU case. The countries are coloured approximately from South to North.

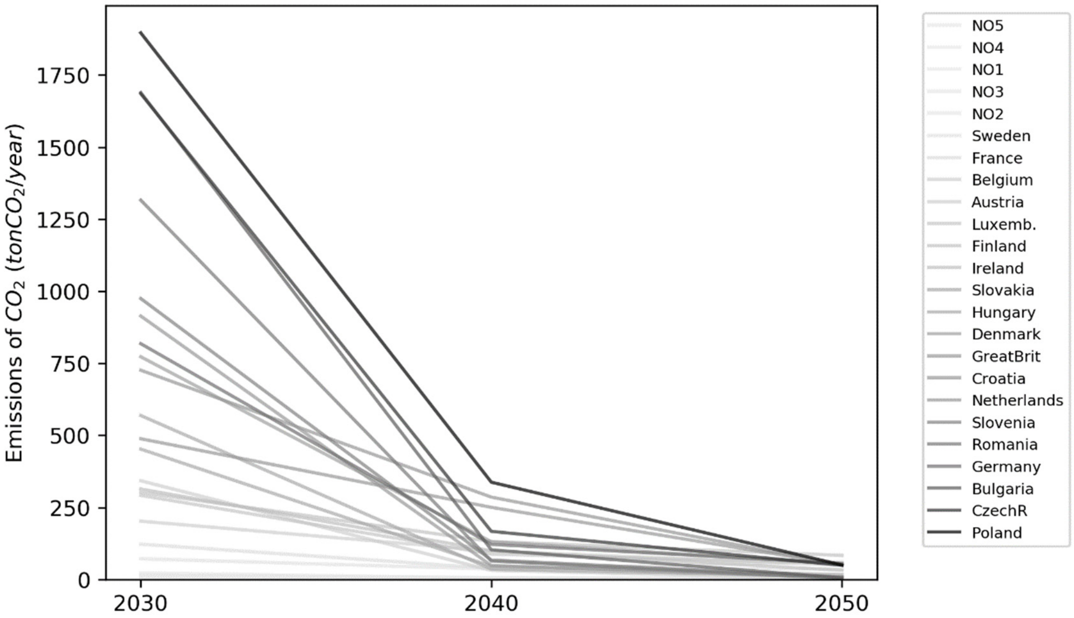


Figure 20 Total CO_2 emissions per year for the ZEN in each country coloured based on the average carbon intensity of the electricity in 2030 from lowest to highest in BAU case.

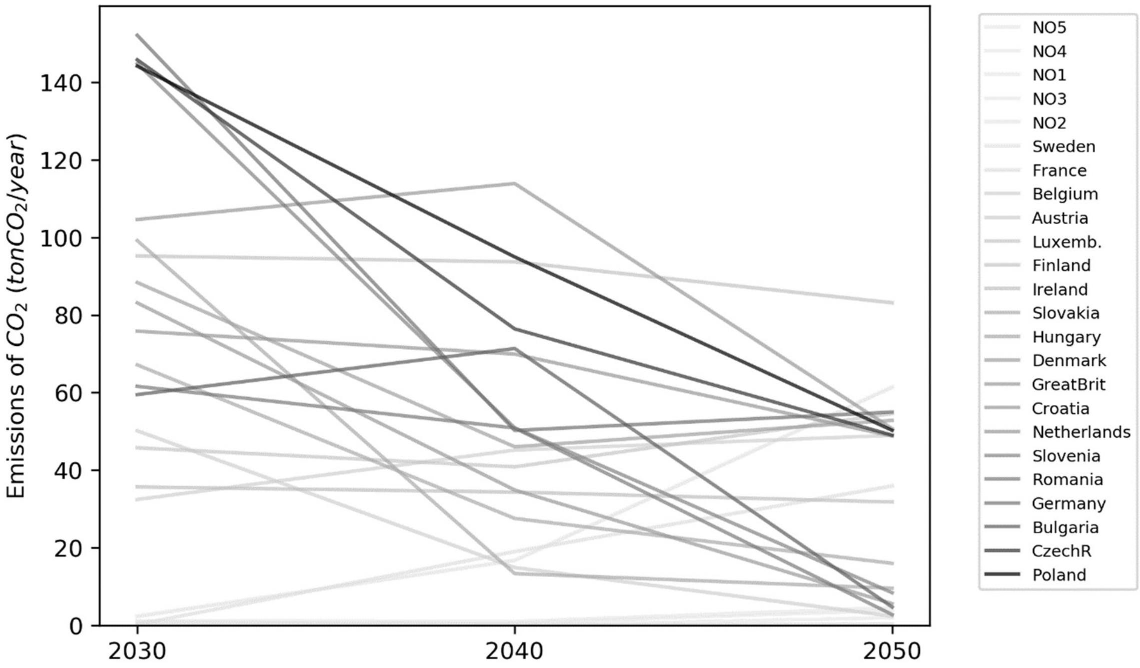


Figure 21 Local CO_2 emissions per year for the ZEN in each country coloured based on the average carbon intensity of the electricity in 2030 from lowest to highest in BAU case.

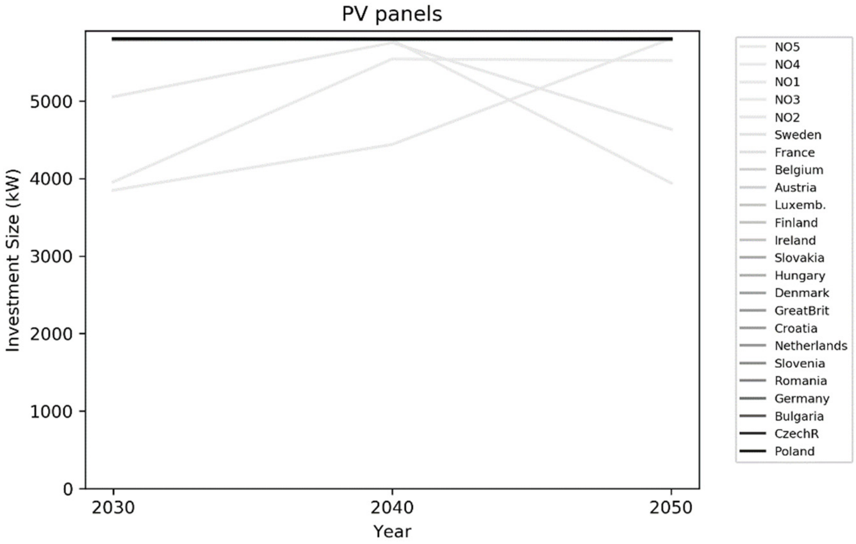


Figure 22 Installation of PV panels per year for the ZEN in each country coloured based on the average carbon intensity of the electricity in 2030 from lowest to highest in BAU case.

In certain countries with a low emission factor in 2030, local emissions are increasing in 2050. This is due to the investment in biomass technologies that see a sharp cost reduction in 2050 and replace other technologies such as PV.

Investments in PV panels (Figure 22) are almost always limited by the roof area, except in Norway. The heat pumps are also often selected. The size of the investment in heat pumps is linked to the emission factor of the electricity needed to power the heat pumps and the countries' heating needs.

A combination of the three available heat pumps is always present (Figure 23, Figure 24 and Figure 25). The brine-to-water heat pump seems to be favoured, with the highest installed capacity, while the air-to-air and air-to-water heat pump seem to be favoured in the north of Europe. This choice can appear strange due to the performance of those heat pumps in such low-temperature conditions. However, those investments do not replace the investments in water-water heat pumps but complement it.

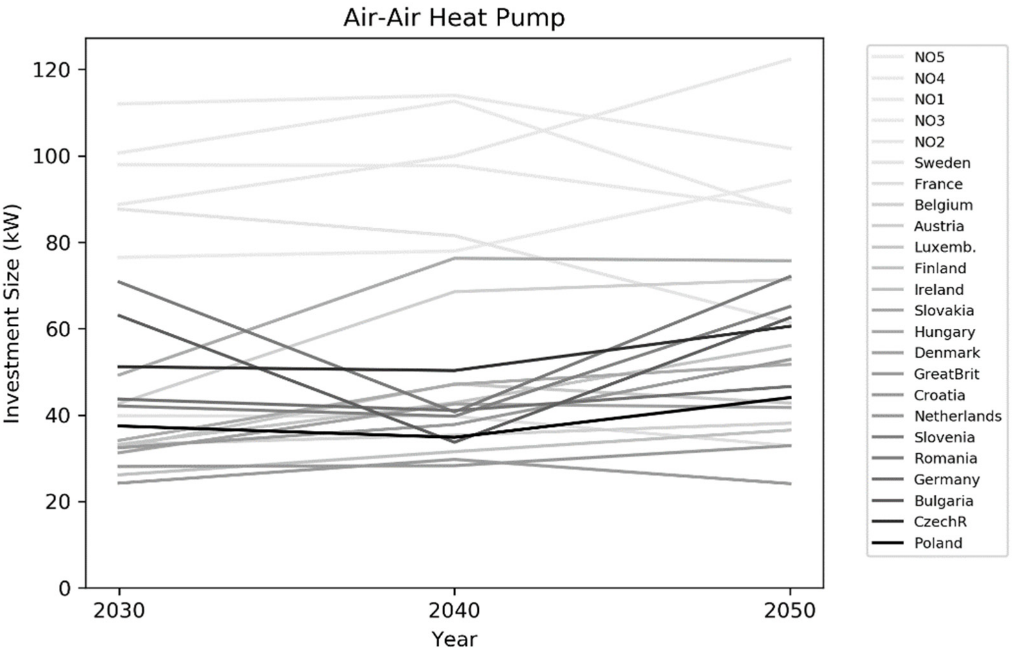


Figure 23 Installation of air-air heat pumps per year for the ZEN in each country coloured based on the average carbon intensity of the electricity in 2030 from lowest to highest in BAU case.

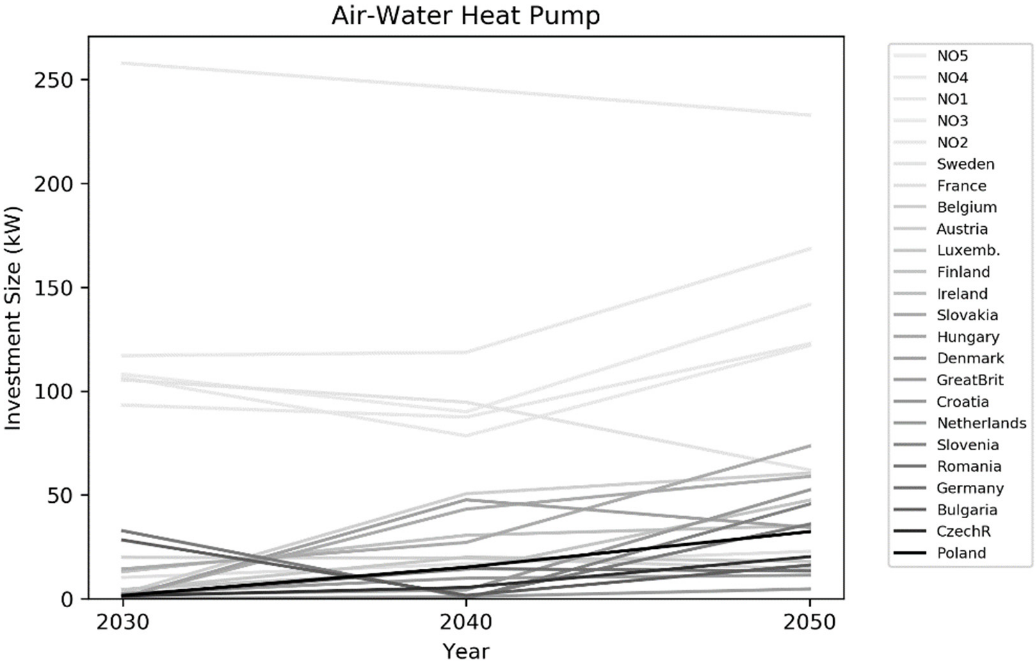


Figure 24 Installation of air-water heat pumps per year for the ZEN in each country coloured based on the average carbon intensity of the electricity in 2030 from lowest to highest in BAU case.

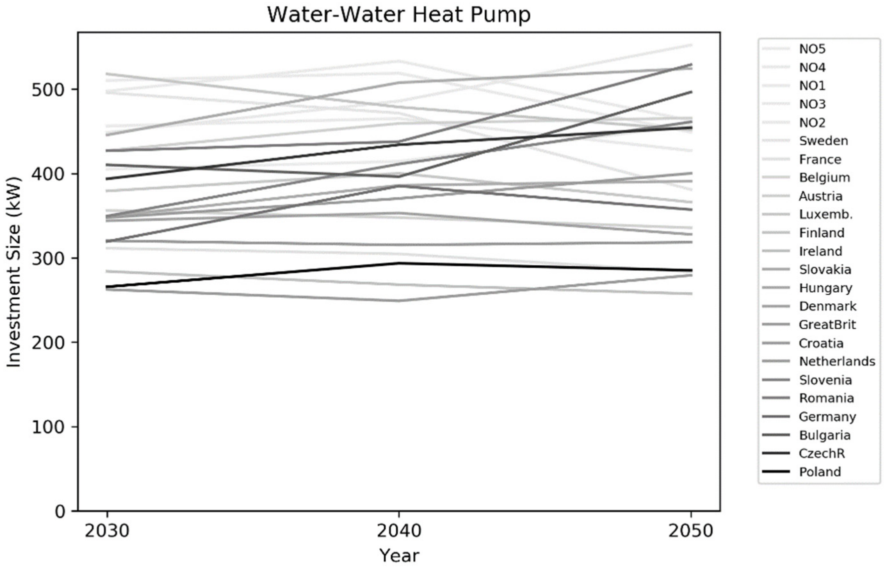


Figure 25 Installation of water-water heat pumps per year for the ZEN in each country coloured based on the average carbon intensity of the electricity in 2030 from lowest to highest in BAU case.

A gasified biomass stirling engine at the neighborhood level is chosen in particular in countries with higher electricity emission factors (Figure 26), and the size of the investment tends to decrease with the decarbonization of the electricity. Indeed, when the CO_2 factors of electricity decrease, the compensation obtained from technologies with local emissions also decrease. On the other hand, we observe an increase in the investment size in 2050 in a few countries with low emission factors in 2030.

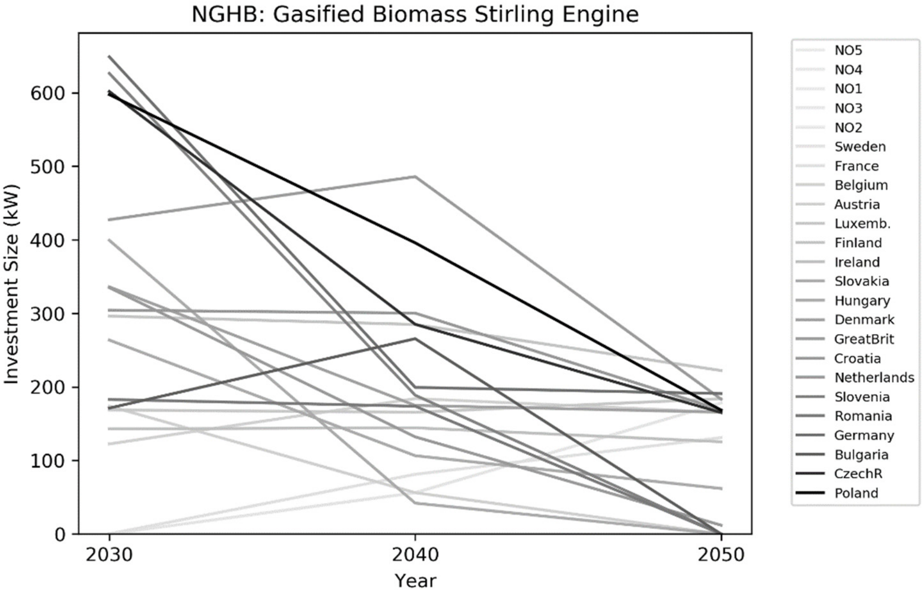


Figure 26 Installation of gasified biomass stirling engine per year for the ZEN in each country coloured based on the average carbon intensity of the electricity in 2030 from lowest to highest in BAU case.

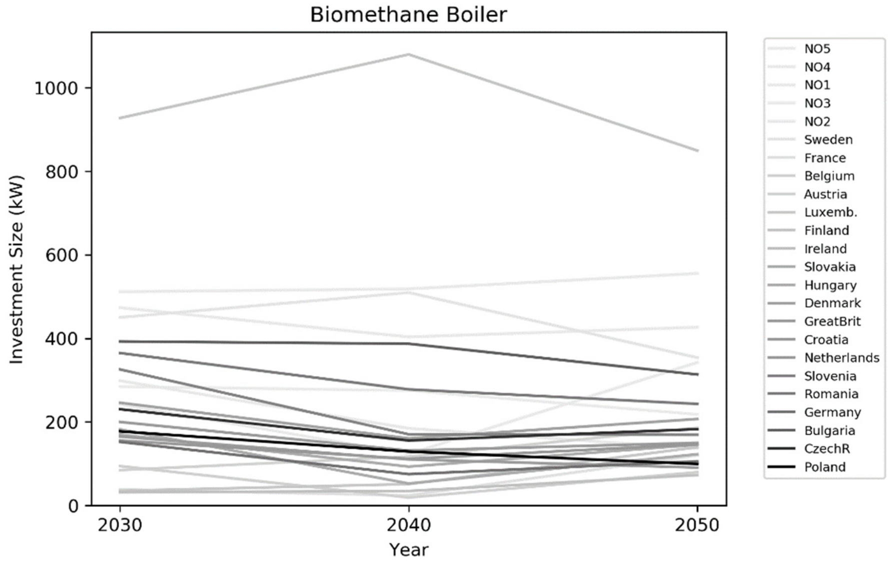


Figure 27 Installation of biomethane boiler per year for the ZEN in each country coloured based on the average carbon intensity of the electricity in 2030 from lowest to highest in BAU case.

The installation of biomethane boilers (Figure 27) remains relatively constant through the periods, with most investment sizes between 0 and 500 kW. The only exception is Finland, where between 800 and 1000 kW are installed.

There are significant investments in the SOFC in 2050 for several countries (Figure 28). This is partly due to a considerable cost reduction in 2050 compared to the previous periods and its low emissions. This technology also benefits from the simplification done to the model to solve faster, such as not accounting for its part load limitation.

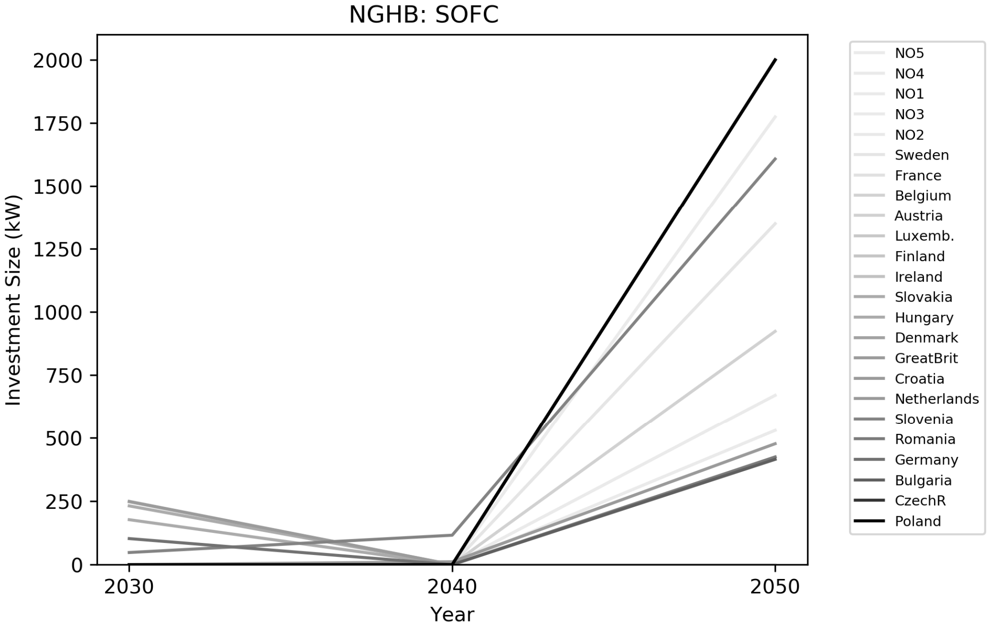


Figure 28 Installation of SOFC per year for the ZEN in each country coloured based on the average carbon intensity of the electricity in 2030 from lowest to highest in BAU case.

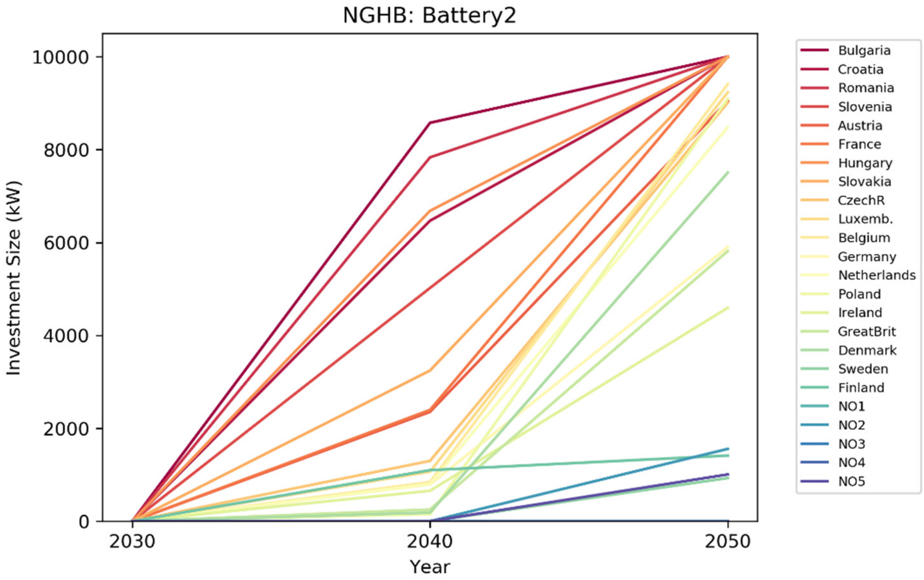


Figure 29 Installation of batteries per year for the ZEN in different European countries in the BAU case. The countries are coloured approximately from South to North

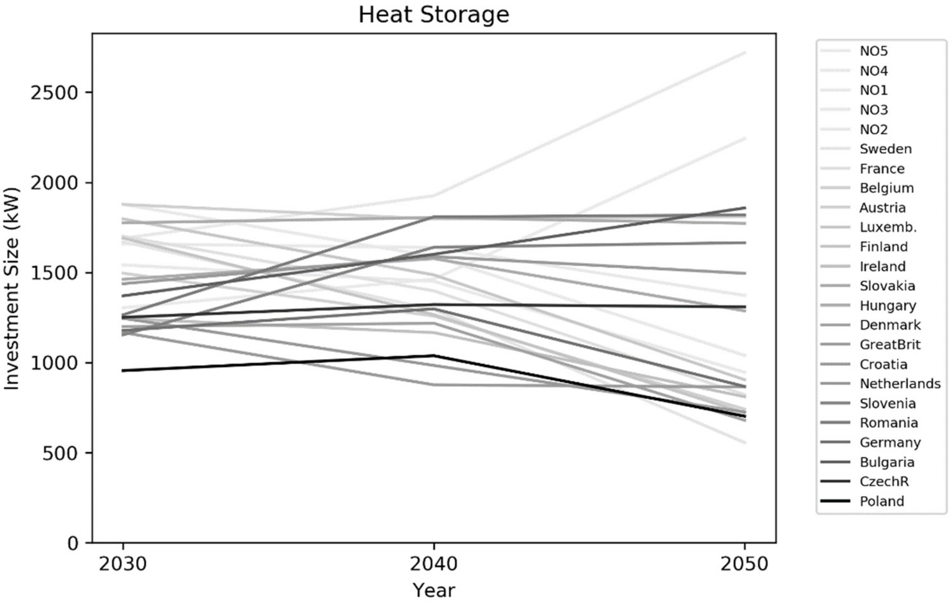


Figure 30 Installation of heat storage per year for the ZEN in each country coloured based on the average carbon intensity of the electricity in 2030 from lowest to highest in BAU case.

Batteries are too expensive to be used inside ZENs in 2030, but the expected cost reduction toward 2050 makes it profitable at that time (Figure 29). The batteries in our model can only be used to store and then export the local electricity production to increase profit and compensations.

The size of the investment in heat storage is between 1000 and 2000 kWh and stays constant or decreases for most countries except for NO5 and NO2 (Figure 30).

5.2.2 Focus on five nodes

In this part, we focus on five specific nodes to allow more detailed inspection of the results in the selected ccountries. We choose to focus on France, Germany, Great Britain, NO1, and Slovakia.

The investment resulting from the ZENIT runs for the five countries we focus on is presented in Figure 31. The investment in PV is at maximum in all nodes except for NO1 in 2050. The investment into a biogas engine at the neighborhood level shows more differences between the countries. In NO1, the investment in this technology increases to reach around 1500 kW in 2050 from around 800 kW in 2030. For the other countries, the investment size also seems to grow with the periods but stays below 800 kW.

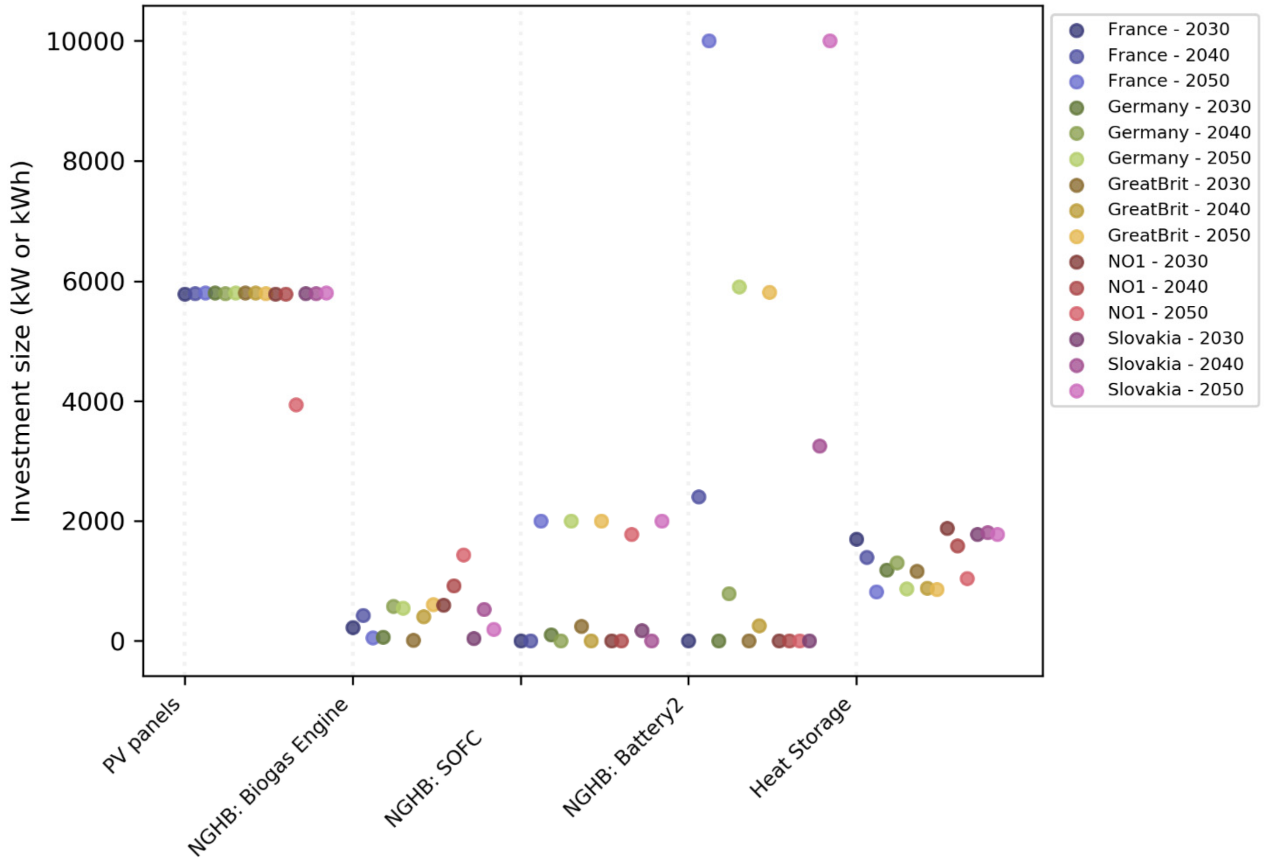


Figure 31 Resulting investment higher than 1000 kW by technology and year resulting from the ZENIT runs using EMPIRE data from the *BAU* case for the five nodes

SOFC is invested up to 2000 kW (the investment limit) in 2050 but is rare in earlier periods. Batteries are chosen from the second period in the five nodes except NO1. The investment during the second period remains limited, below 100 kWh for Germany and Great Britain and around 2000 and 3000 kWh for France and Slovakia. In 2050, the investment in those two countries reaches the limit of 1000 kWh while it is around 6000 kWh in Germany and Great Britain. The heat storage size lies between 1000 and 2000 kWh and seems to decrease with the periods except in Slovakia, where it stays constant at around 2000 kWh.

The other technologies (invested between 10 kW and 1000 kW) can be compared better from Figure 32. Solar thermal collectors investment size varies significantly from 100 to 400 kW. The variation is the biggest in France while Germany, Great Britain, and Slovakia have a smaller variation of around 70 kW. In NO1, they vary between 400 kW to 200 kW. Regarding heat pumps, all countries have air-air and water-water heat pumps, while air-water heat pumps are less common. The investment is, in general, lower for France, Germany, and Great Britain than for NO1 and Slovakia. A water-water heat pump at the neighborhood level is also chosen in NO1 even though the investment size is lower than the total of the ones invested in inside the buildings.

Wood log and wood pellets boiler are chosen more often in the last period and for sizes below 100 kW. Biomethane boilers are invested for up to 150 kW except in NO1, where it is a more critical component for the energy system and takes between 400 and 460 kW. Wood chips CHP is chosen only in Slovakia and in the last period. Gasified biomass stirling engines are predominantly chosen in Germany and Great Britain, though also in France and Slovakia. Electric boilers at the neighborhood level seem to be selected instead in the last two periods for about 100 kW.

The heat storage in the production plant varies more between the countries. In France, it decreases with time from 600 kWh to less than 100 kWh while in NO1, it varies from 200 to 300 and then 100 kWh.

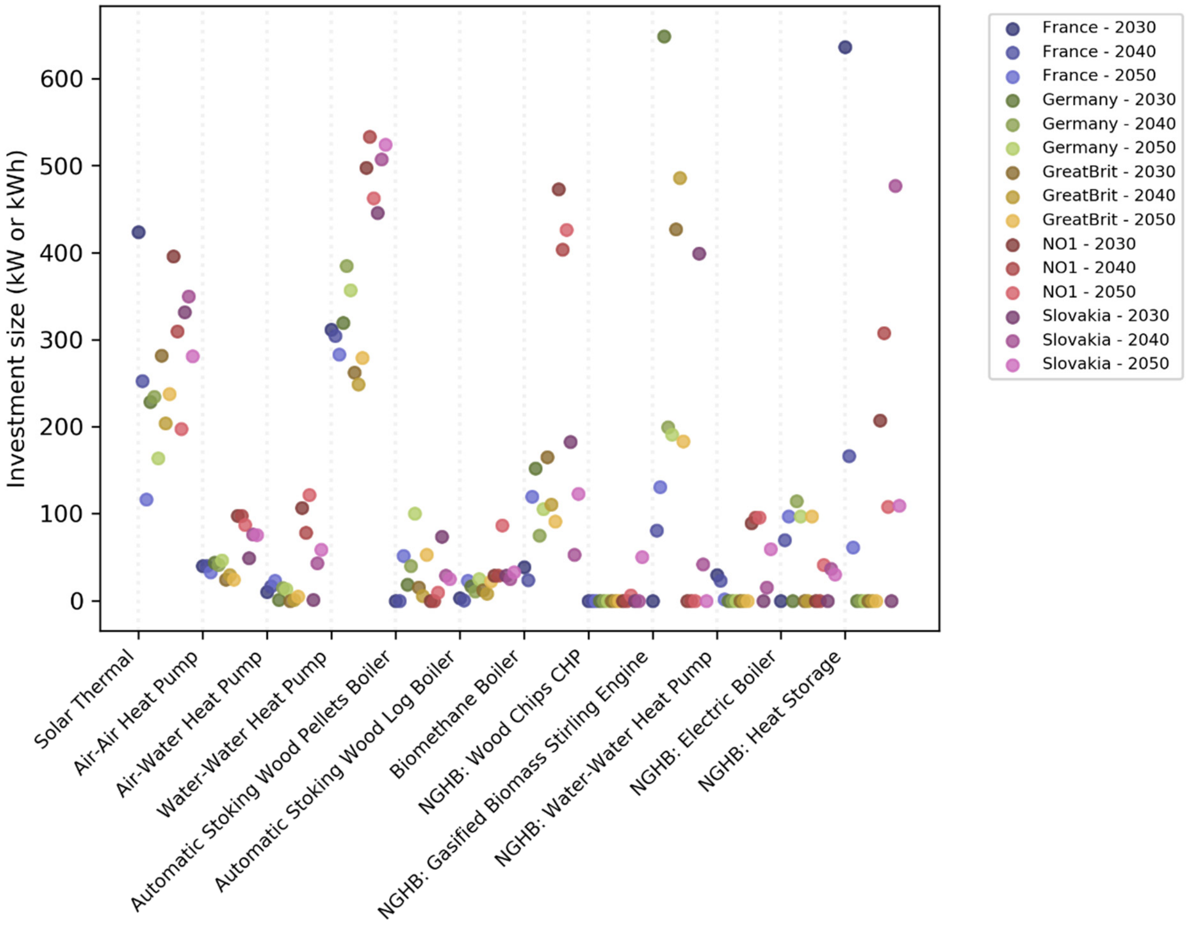


Figure 32 Resulting investment lower than 1000kW and higher than 10kW by technology and year resulting from the ZENIT runs using EMPIRE data from the *BAU* case for the five nodes

The breakdown of heat and electricity production are presented in Figure 33 and Figure 34. The electricity production is dominated in all countries by the PV panels, but the SOFC investment changes that in the last period. The output from PV is dependent on the latitude, which is reflected in the figure (the investment being at the maximum except in NO1 in the last period; the comparison is simplified). The total electricity production is relatively stable in the first two periods but increases between 30 and 50% in the last period with the investment in SOFC.

The production of heat is more diverse, in part because small investments can be made inside the buildings. The main contributors to the heat production are water-to-water heat pumps, biogas engine, and gasified biomass stirling engine.

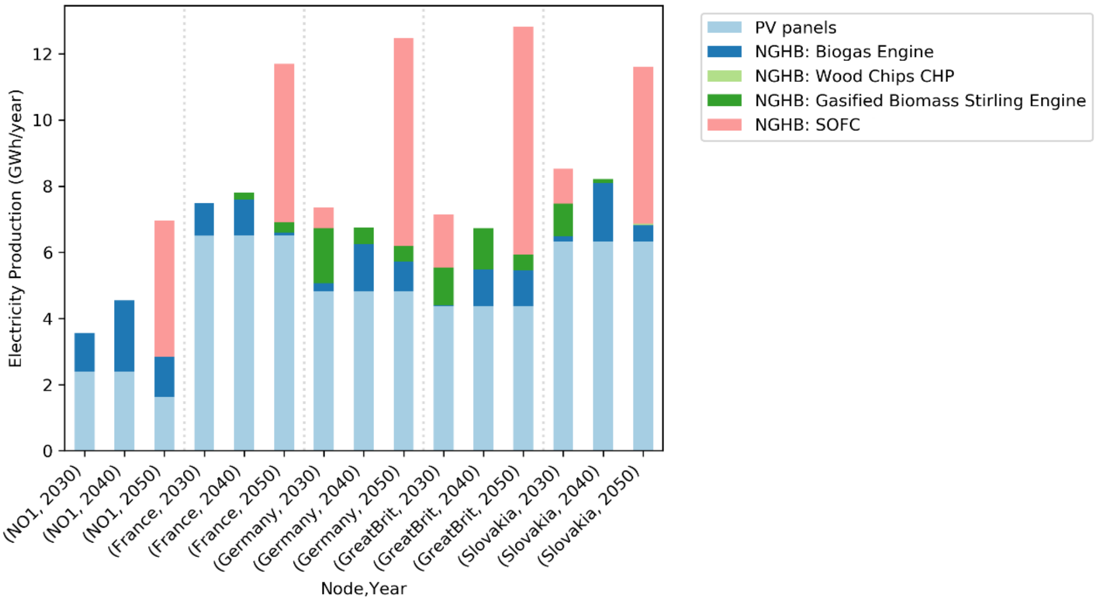


Figure 33 Breakdown of the electricity production in the ZEN by source in the five nodes in the BAU case

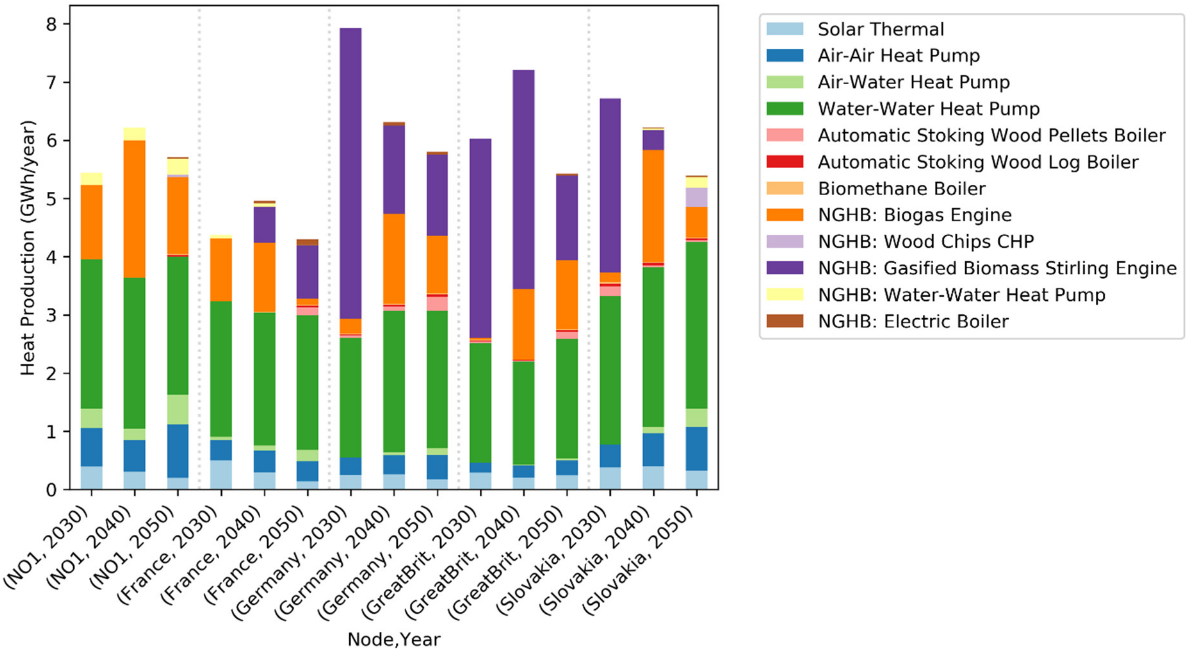


Figure 34 Breakdown of the heat production in the ZEN by source in the five nodes in the BAU case

The total discounted costs (Figure 35) are correlated to the latitude of the five countries. This can be assumed to be due to the higher production from PV panels allowing more compensation in France form the PV system while also having low emission factors.

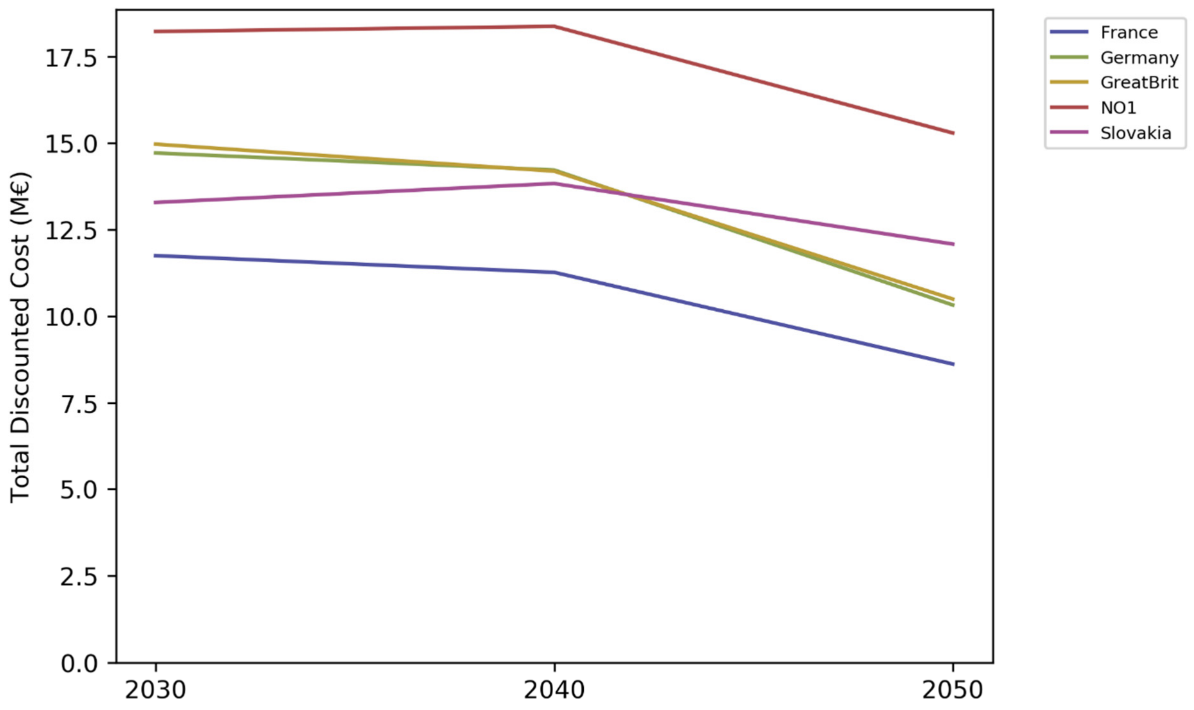


Figure 35 Total discounted costs for the energy system of a ZEN in five European countries in BAU case

5.3 EMPIRE response to ZENIT with fixed emission cap

The objective function of EMPIRE is reduced by 4% when ZEN is an option in the second EMPIRE run in both ALL and BAU (see Table 2). A reduction in total costs means that ZENs facilitate the achievement of the emission targets at a lower cost than without ZENs in the system. Based on this, it can be argued that even though ZENs do not directly reduce power system emissions, ZENs can be a factor that enables reaching the ambitious climate targets in Europe.

The ZENs are developed in many European countries, and it is most attractive in Germany followed by France. Figure 36 presents the number of ZENs developed in different European countries. The total number of ZENs is approximately 57 000 and 54 000 in ALL and BAU, respectively (see Section 4.2 for the definition of a ZEN unit). Slovakia is the only country to develop ZENs in 2030, while Bulgaria and Romania develop ZENs in 2040. The primary capacity expansion of ZENs is in 2050, where all countries with heating markets in EMPIRE develop ZEN, except Norway.

Norway does not develop ZEN because electricity costs are too low and ZEN costs are too high compared to other European countries. Instead, Norway expands wind power towards 2060 in all cases. However, Norway is still affected by ZEN development in other countries: Norway develops less wind power and less bio-based heating when ZENs are developed elsewhere. Bio-based heating in Norway is replaced by more heat pumps and waste-based heating, and Norway produces less electricity in total, mainly from wind, when other countries develop ZEN. This result confirms the substitution effect between wind power and building heating in Norway as identified in [2], [3], and [15].

Table 2 Key performance indicators for the entire horizon from the four EMPIRE runs with and without ZENs.

KPI	**ALL**		**BAU**	
[unit]	w/o ZEN	w/ ZEN	w/o ZEN	w/ ZEN
Total cost [billion (10^9) €]	3 693	3 553	3 623	3 481
Total curtailed VRES [TWh]	10 731	9 921	10 287	9 761
Total expected CO2eq. emissions [Mton]	16 752	16 749	22 358	21 932
Share of total electricity produced in ZENs [%]	-	6%	-	6%
Share of total heat produced in ZENs [%]	-	3%	-	3%
Total transmission capacity expansion [GW]	117	117	117	117
Total storage charging/discharging capacity expansion [GW] (electricity: central + ZEN, heat: central + ZEN)	568 + 0, 201 + 0	440 + 405, 205 + 54	581 + 0, 189 + 0	462 + 407, 192 + 52
Total storage energy capacity expansion [GWh] (electricity + heat)	1 127 + 12 142	870 + 12 388	1 151 + 11 402	911 + 11 573

Where and how much ZEN that is developed in each country is linked to a variety of reasons: (1) The energy mix in the country, (2) the energy mix in the ZEN, (3) the import/export balance, (4) the marginal energy cost in a country, (5) the energy demand and (6) the total cost of ZEN. Especially the two latter factors, the energy demand and the total cost of ZEN, seems to be crucial for the largest ZEN development: Countries with high energy demand tend to develop more ZENs (see Figure 10 and Figure 36), and the most developed ZEN designs are from 2050 when ZEN is least costly for all countries (see Figure 19 and Figure 36).

For electricity production by the ZENs developed in EMPIRE, solar PV makes up around 45 % (see Figure 37). Bio-based electricity generation in ZEN makes up the dominating share of 55 %, of which electricity generation by solid oxide fuel cell (SOFC) is the largest. Note that the SOFC uses biogas as fuel input, not hydrogen.

The development of ZEN in BAU reduces the overall expected emissions with 2 % compared to the case without ZEN, mainly after 2045 (see Figure 38). The reason for the emission reduction is that emissions from technologies within the ZEN-package are more economically attractive and less polluting than the alternative wide development of small-scale gas boilers. However, the emission reduction from developing ZEN in BAU is significantly smaller compared to ALL, where emissions are reduced by 25 % compared to BAU without ZEN. Because we assume that European climate targets are met in all cases, emission reductions in ALL are independent of the ZEN development.

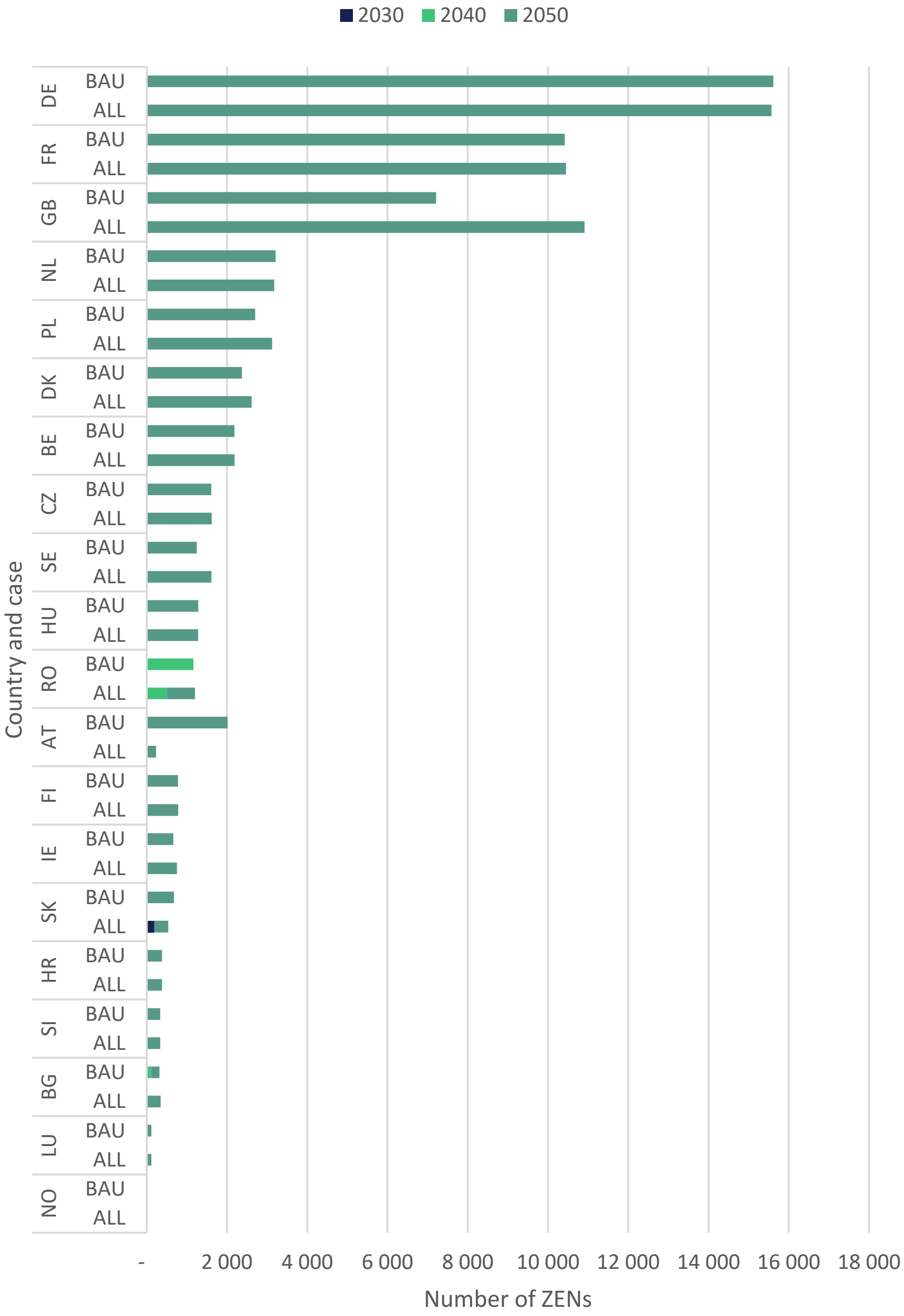


Figure 36 The number of ZENs developed in Europe by country, investment period, and case.

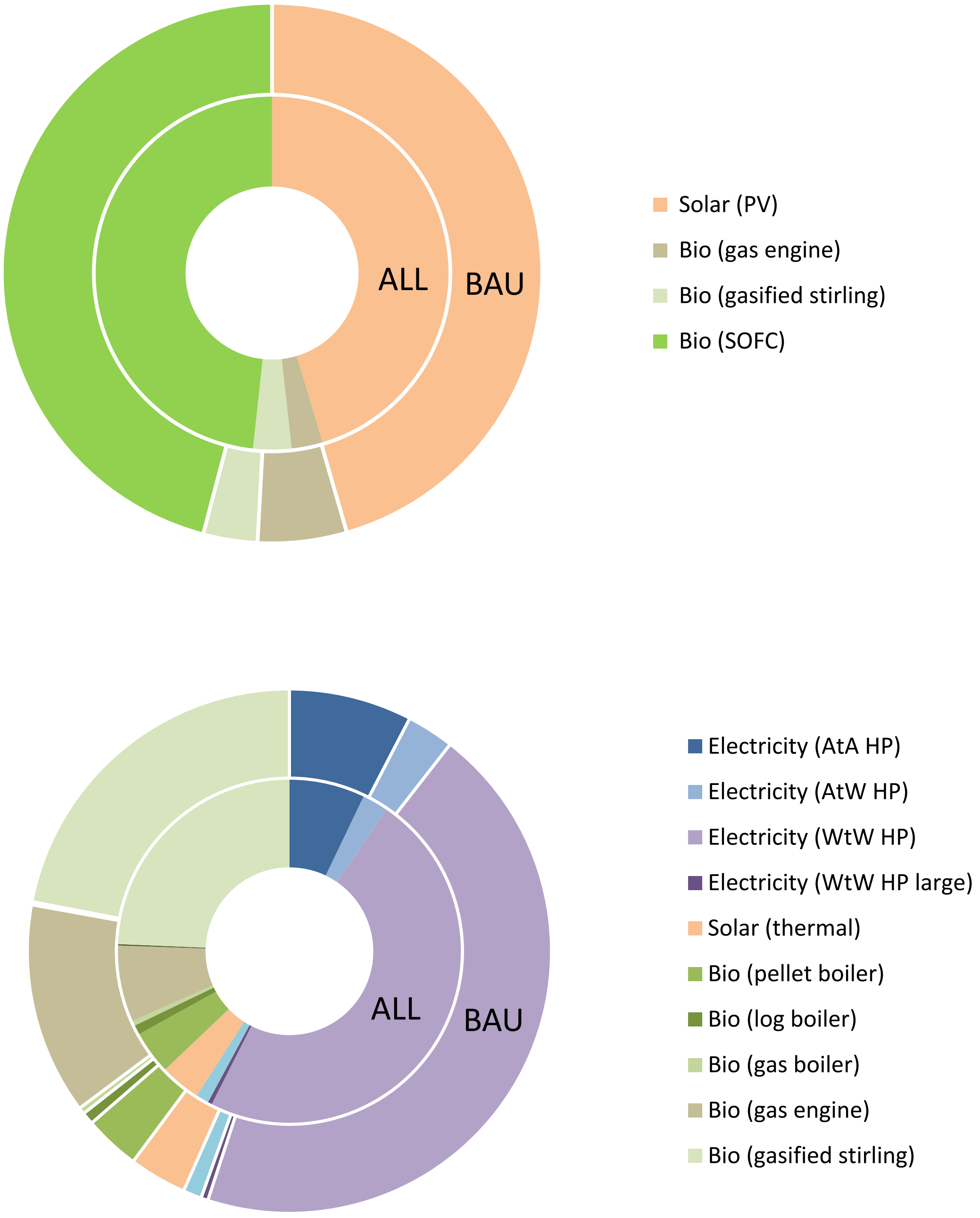


Figure 37 The share of heat and electricity generation from ZEN in EMPIRE by generation technology.

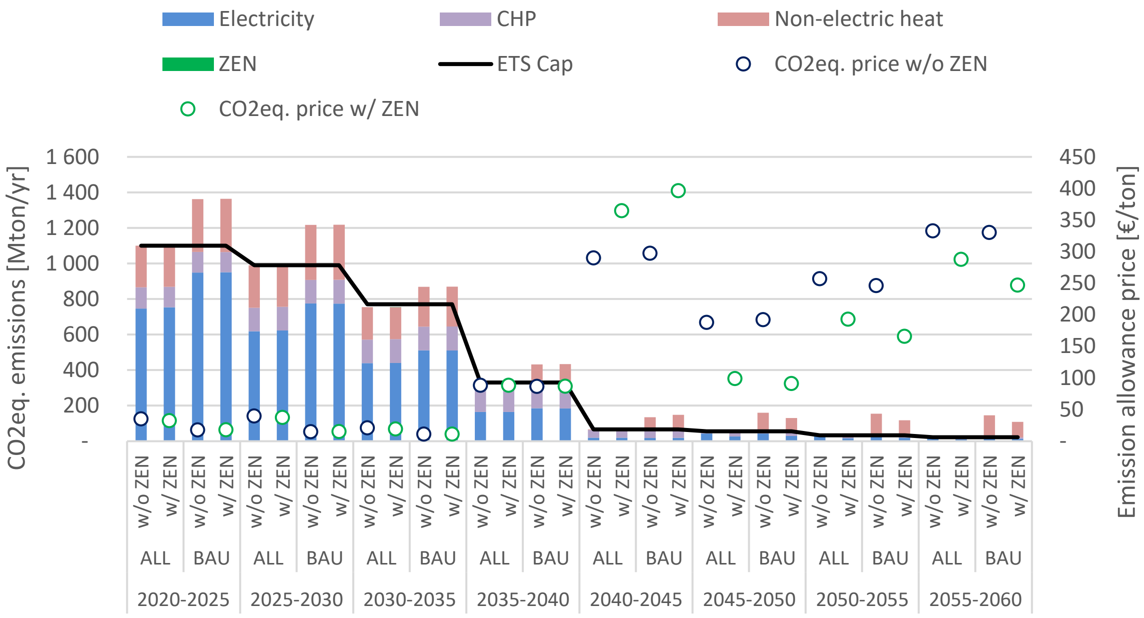


Figure 38 Expected annual CO2eq. emissions (right axis) and average CO2eq. allowance price (left axis) in EMPIRE by technology, investment period, and case.

Figure 38 shows the development of the expected price for emission allowances in different cases. We can classify the energy system transition into four different phases:

- **2020 – 2035:** Initially the effect of technology cost decreases dominate the policy impact. In this phase, the carbon price decreases because the effect of technology cost decrease is stronger than the effect of quota reductions.
- **2035 – 2045:** In this period, the table turns and the cost of enforcing the carbon limit has a stronger effect than technology cost reductions. The carbon price increases.
- **2045 – 2050:** In this period, the cost reductions again dominate the policy impact and the carbon price decreases. In addition, significant amounts of ZENs become competitive and further reduce the carbon price.
- **2050 - :** Again, the policy dominates the technology cost reductions since it becomes very expensive to remove the last few carbon emissions. The carbon price reaches its highest values.

One implication of these results is that the assumed emission cap development from [25] as presented in Figure 38 could be more ambitious from 2020-2035. If the emission cap would decrease from 2020-2035, the increase in allowance price after 2035 would potentially be less dramatic as more emissions could be allowed between 2035-2045.

Between 2040 and 2045 is the only period where the development of ZEN makes it more expensive to meet the emission targets. The increased allowance price with ZEN is because there is no option to invest in ZEN in the investment period 2040-2045; it is only possible to develop ZEN in ’25-’30, ’35-’40, and ’45-’60 because ZENIT designs the ZENs according to EMPIRE results from these periods. Because EMPIRE is solved for the entire horizon from 2020-2060, it plans for the introduction of ZEN in ’45-’50. The result is that EMPIRE allows higher system costs, and higher allowance price, in ’40-’45 with ZEN such that lower system costs can be achieved from 2045 to 2060.

After 2045, when most ZENs are developed in Europe (see Figure 36), the cases with ZEN included show a significantly lower allowance price than the cases without ZEN, which means that the total system cost of meeting the required reduction in emissions is reduced with ZEN. Since the political feasibility of reducing the emissions cap depends on the carbon price, introducing ZENs in the system makes it more likely that emission targets can be reached. Alternatively, although ZENs does not directly decrease carbon emissions in the system, the introduction of ZEN means that it is possible to reduce the emissions targets more aggressively at the same cost as without ZEN in the system.

The lack of emission reductions on the European level when developing ZEN and not including emissions from small-scale heat generation in the European emission cap is because of two reasons:

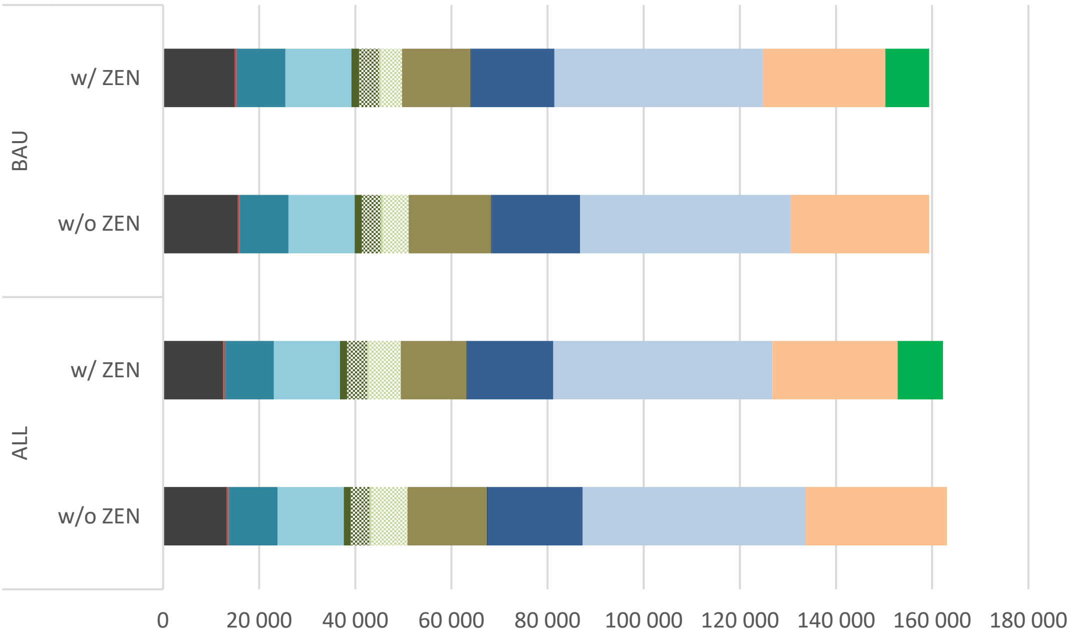
1) **Several ZEN-options produce emissions inside the neighborhood** that are compensated for according to the ZEN constraint (see Section 3.2). However, these emissions are not regulated when solving EMPIRE.
2) **The emission cap in EMPIRE is binding** in all investment periods in all four cases. A binding emission cap means that not regulating emissions from small-scale generators causes >600 Mton CO2eq. emissions over the entire horizon, even though the large-scale generators are capped. In other words, the increase in the availability of emission allowances in a perfectly competitive European electricity market makes emission-producing generators more cost-competitive, especially after 2040, when the cap is very strict.

The main takeaway from these results is that the idea of compensating emissions through local generation in ZEN fails to directly decrease European emissions when considering how emissions are regulated in the European power system. We observe either no impact on emissions (ALL) or a mild decrease in emissions when ZENs are developed (BAU). Note that no impact on emissions is a consequence of our assumption that the emission policy is the same in all instances with or without ZEN. For the ZEN compensation to reduce European emissions, the following "compensation"-assumption must hold:

Requirement for ZEN compensation to reduce emissions:
All energy production within the ZEN boundary replaces energy that would have been produced by generators with *higher* emissions somewhere else.

Our analysis indicates that this "compensation"-assumption is not valid unless all direct emissions within the ZEN boundary are part of the European emission cap. Even in that case, the fact that the emission cap is binding in Europe means that the ZEN development neither increases nor decreases total emissions. The failure of the "compensation"-assumption is a consequence of the cap-and-trade policy where the ZEN development reduces the cost of producing emissions such that it is more cost-efficient for other generators to emit more than they would if ZENs did not develop.

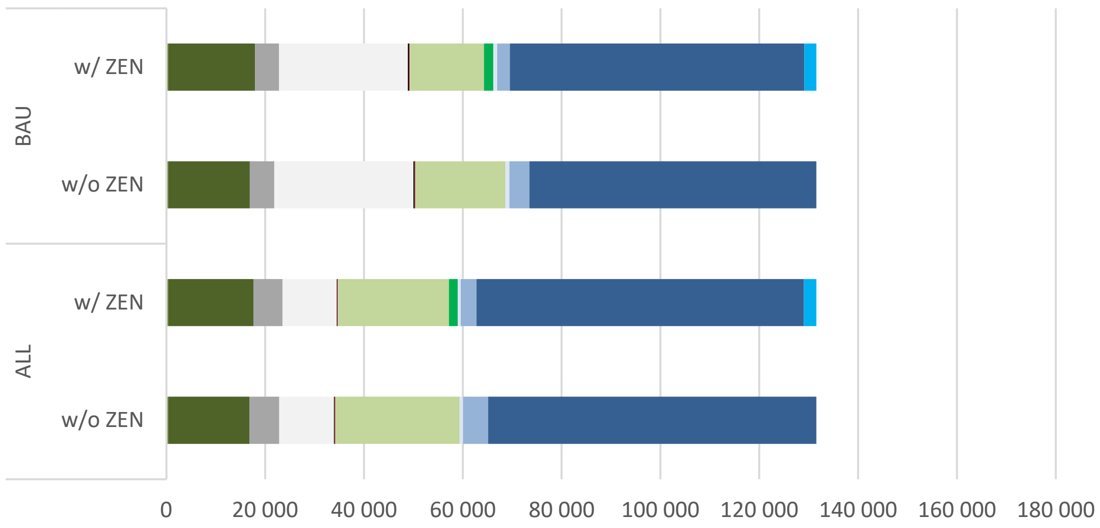
The ZEN development replaces wind energy (mainly offshore) (see Figure 39). The reduction in wind investments consequently leads to less curtailment of VRES (see Table 2), especially in investment periods after 2040. Although centralized solar investments decrease in EMPIRE with ZENs, there is about 3% more electricity generated by photovoltaics inside ZENs than without. ZENs also replace fossil and nuclear power, where nuclear decreases about three times more than fossil. Less nuclear with ZEN is mainly because nuclear is very expensive. The modest decrease in electricity production by fossil plants (see Figure 39) indicates that ZENs, as represented in this study, do not significantly decrease the need for conventional dispatchable supply in the system. The emission decrease from less electricity produced by fossil fuels is compensated by an emission increase from more waste-to-energy CHP plants.



	ALL		BAU	
	w/o ZEN	w/ ZEN	w/o ZEN	w/ ZEN
■ Fossil	13 278	12 499	15 564	14 895
■ Geo	416	417	402	405
■ Hydro (regulated)	10 146	10 167	10 144	10 179
■ Hydro (run-of-river)	13 771	13 734	13 772	13 721
■ Waste (electricity only)	1 470	1 512	1 480	1 586
▩ Waste (CHP)	3 922	4 132	3 934	4 195
■ Bio (electricity only)	339	271	361	265
▩ Bio (CHP)	7 537	6 729	5 456	4 503
■ Nuclear	16 489	13 698	17 115	14 248
■ Wave	148	148	148	148
■ Wind (offshore)	19 805	17 899	18 407	17 285
■ Wind (onshore)	46 338	45 575	43 790	43 357
■ Solar	29 431	26 055	28 820	25 472
■ ZEN	-	9 408	-	9 122

Figure 39 Total electricity produced in TWh in Europe for the entire horizon (2020-2060) by source for all cases.

Figure 40 shows building heat production for Europe with and without ZENs. The ZEN development leads to *more* electric heating by highly efficient heat pumps in both ALL and BAU across Europe, where the increase of electric heating is the largest in the BAU. Because the ZEN electric heating is highly energy-efficient, this result increases electricity generation in neither ALL nor BAU. On the contrary, the increased efficiency of water-to-water heat pumps in ZEN leads to a slight decrease in electricity generation for ALL and BAU, where ALL shows the largest decrease. ZEN heating mainly replaces bio-based CHP heating and gas boilers.



	ALL		BAU	
	w/o ZEN	w/ ZEN	w/o ZEN	w/ ZEN
🟩 Waste (HOP)	376	374	392	387
🟩 Waste (CHP)	16 455	17 289	16 500	17 541
⬜ Gas (district heat)	6 025	5 858	4 962	4 893
⬜ Gas (building)	11 069	10 964	28 151	26 046
⬛ Oil (building)	77	74	189	188
🟥 Geo (district heat)	199	205	200	205
🟩 Bio (HOP)	84	82	53	54
🟩 Bio (CHP)	25 094	22 362	18 162	14 971
🟩 ZEN (non-electric)	-	1 758	-	1 874
🟦 Electricity (direct)	655	639	823	812
🟦 Electricity (GSHP)	5 097	3 167	4 052	2 561
🟦 Electricity (ASHP)	66 434	66 251	58 078	59 581
🟦 ZEN (electric)	-	2 539	-	2 446

Figure 40 Total building heat produced in TWh in Europe for the entire horizon (2020-2060) by source for all cases.

The development of ZEN also replaces some capacity expansion of central electricity storage in EMPIRE (see Table 2). However, the aggregate charging/discharging capacity expansion of batteries in ZEN results in a +50% increase in battery capacity with ZEN in both cases. Similarly, for heat storage, the development of ZEN increases total heat storage capacity by +30% in both cases. Consequently, the ZEN profiles seem to fit better with demand profiles in EMPIRE, causing a decreased need for storage in the rest of the system. The fact that the ZEN development replaces wind production also reduces the capacity expansion of batteries in EMPIRE. Transmission expansion is not affected by a broad development of ZEN in this case study.

5.4 EMPIRE response to ZENIT with fixed emission tax

In this section, we present results from ALL w/ ZEN where we remove the emission cap and introduce an emission tax. In the previous section, we analyzed how ZENs impact European capacity expansion towards 2060. In both ALL and BAU, emissions are regulated like the EU ETS, where an upper bound on annually allowed emissions is defined for all investment periods. As the maximum allowed emissions are produced in all cases, ZENs do not avoid emissions with a fixed emission cap.

An alternative way to regulate GHG emissions is to introduce an *emission tax*. Where the cap-and-trade system politically defines the total quantity of allowed emissions, the emission tax politically enforces a fixed price of producing emissions. A similar feature to the emission tax in the cap-and-trade system is the allowance price, i.e., the marked-based price of acquiring the allowance to produce emissions. The allowance price is represented in EMPIRE as the shadow value of the emission cap constraint. The emission tax rate is equal to the average emission allowance price from ALL w/o ZEN in each investment period (see Figure 38).

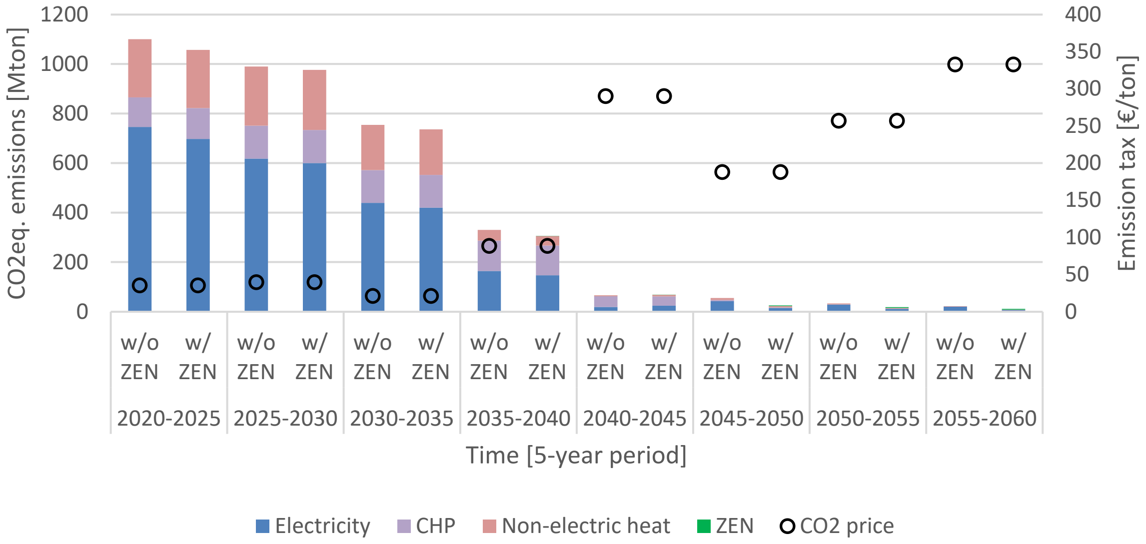


Figure 41 Expected annual emissions with emission tax in EMPIRE.

Annual expected emissions with a fixed emission tax are presented in Figure 41 where we also indicate the emission tax rate for each investment period. When ZEN is developed with a fixed emission tax, the ZEN development does not lower the CO2 price like in ALL with the emission cap. The ZEN development therefore does not make it more cost-efficient to produce emissions, and the development of ZEN leads to -5% GHG emissions across Europe compared to ALL w/o ZEN. Because most ZENs are still developed after 2045 with the emission tax, most emission reductions happen towards the end of the horizon in EMPIRE.

Bacause we keep the emission tax on the same level as the allowance price from ALL w/o ZEN, the total system costs are increased by 8% with the emission tax. The technologies that would bring the costs down in ALL w/ ZEN are not cost-efficient with the emission tax, because the emission tax is generally higher than the allowance price in ALL w/ ZEN (see Figure 38). With the emission tax, EMPIRE therefore develops ZEN along with technologies that yield higher system costs at the benefit of overall emission reductions below the emission cap defined in ALL.

5.5 Limitations

One limitation of this study is that it is not feasible to perform iterations until convergence due to the scope definition (in particular, the number of cases and nodes considered). A study focusing only on Norway or another country could perform this analysis with iterations to convergence. An iteration-based approach is illustrated in Figure 42, which also includes a procedure for marginal emission factors based on the origin of the electricity consumed in each node (obtained through the methodology of [30]), the merit order curve of marginal costs of the technologies in EMPIRE, and assumptions regarding the amount of electricity exports from the neighbourhood. Using much higher computational power than what is available for this study could also allow for iterations.

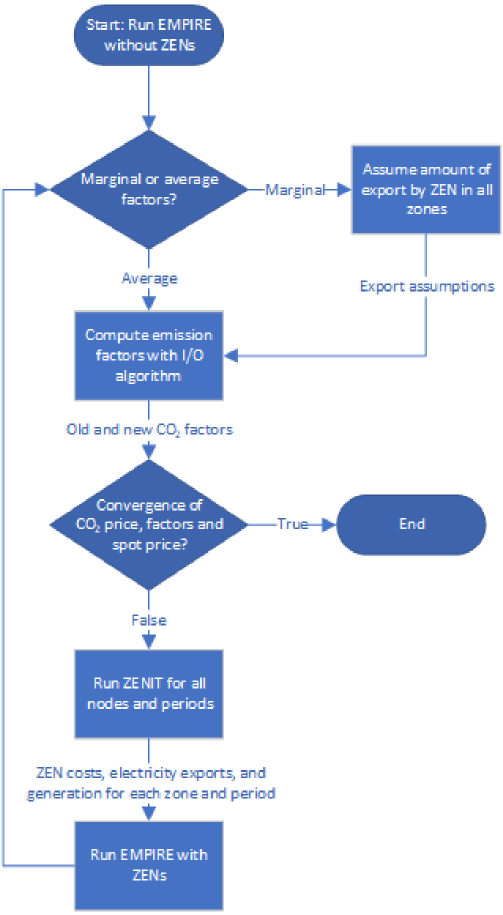


Figure 42: Possible computational procedure with an iteration-based approach

One convergence criterion that could be used is the root mean square deviation (RMSD) of the emission factors and spot prices below a certain threshold. In our study, the RMSD is relatively high, especially for the spot price: 70 and 62 €/MWh and 21 and 13 gCO_2/kWh for the cases ALL and BAU, respectively. It appears that the peak days are driving this number up significantly. There is no guarantee that a satisfactory convergence would be reached, but lower RMSD could be expected by repeating runs.

The average deviation should, however, contrast the RMSD. The average deviation values are much lower: -2.6 and -2.3 €/MWh and 2.2 and 0.04 gCO_2/kWh for the cases ALL and BAU, respectively. This indicates that even though the individual hours' deviations are high, they tend to compensate and indicate a time-shift of the spot prices and CO_2 factors rather than a deviation. These observations give a higher confidence in the quality of the results.

Figure 43 - Figure 46 present the RMSD and average deviation for each period in each node. Regarding the emissions factors, the deviations are mostly in the beginning and end of the study duration. The deviations seem to be affecting countries in the south of Europe the most at the beginning and of central Europe at the end. This means that in the runs including ZENs, the emission factor is higher in the south of Europe initially. Those deviations almost completely compensate, as can be seen from the average deviation figure. For the spot price, the deviations are practically non-existent until the second half of the study duration, except for nodes such as Sweden, Finland, and NO1, where the deviations are quite large and spikes in the 2040-2045 period. The other nodes see deviations only towards the end of the study, reaching RMSDs between 40 and 100 €/MWh. The average deviations, however, are almost zero for the entire first half. In 2050-2055, the run with ZENs give higher prices than in the run without ZEN in every node but then becomes lower in the following periods. Difference in spot prices are mostly due to temporal shift but an average deviation also happens from 2040. The most affected countries appear to be Sweden, Finland and NO1.

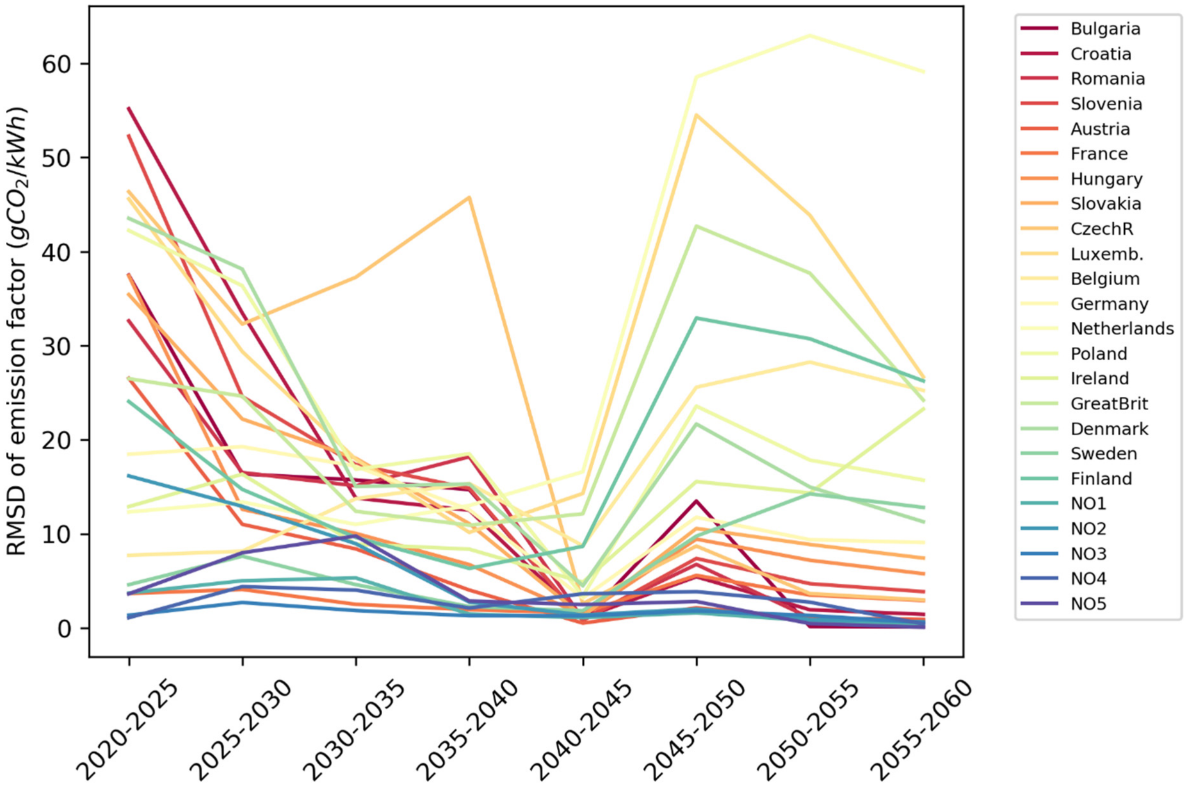


Figure 43 Yearly RMSD of emission factor in each node in each period in ALL case

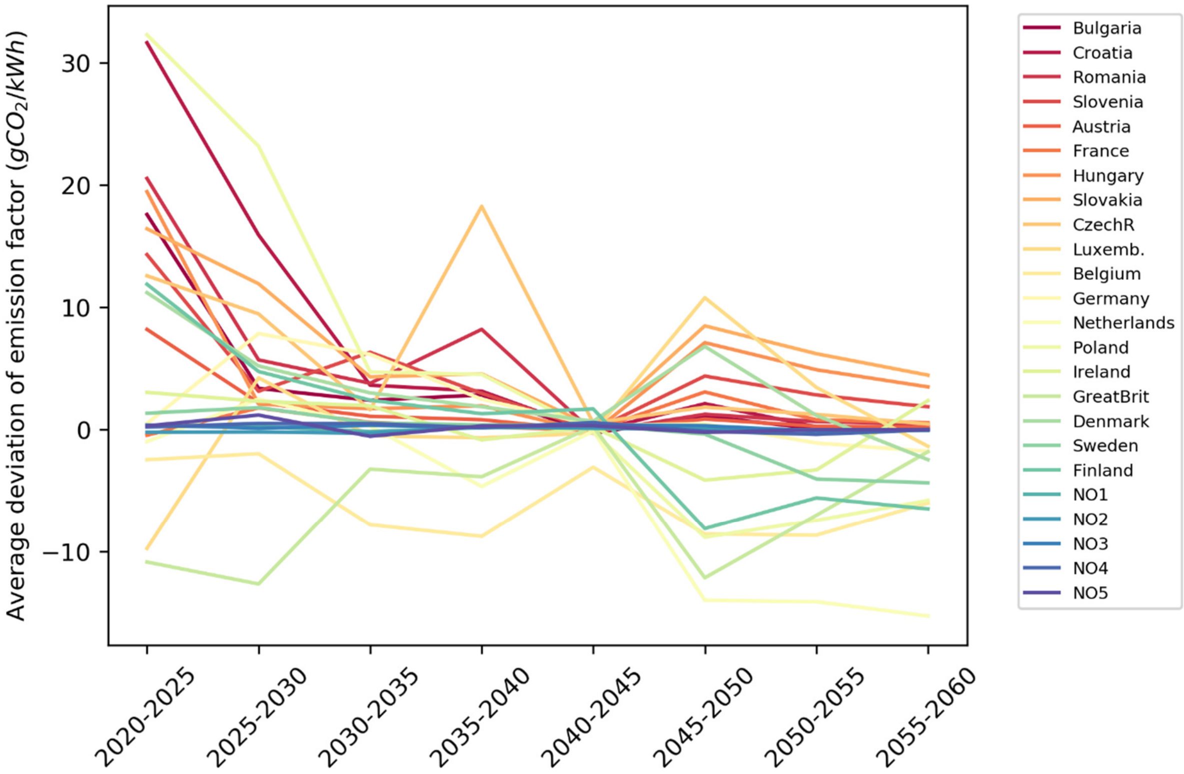


Figure 44 Yearly average deviation of emission factor in each node in each period in ALL case

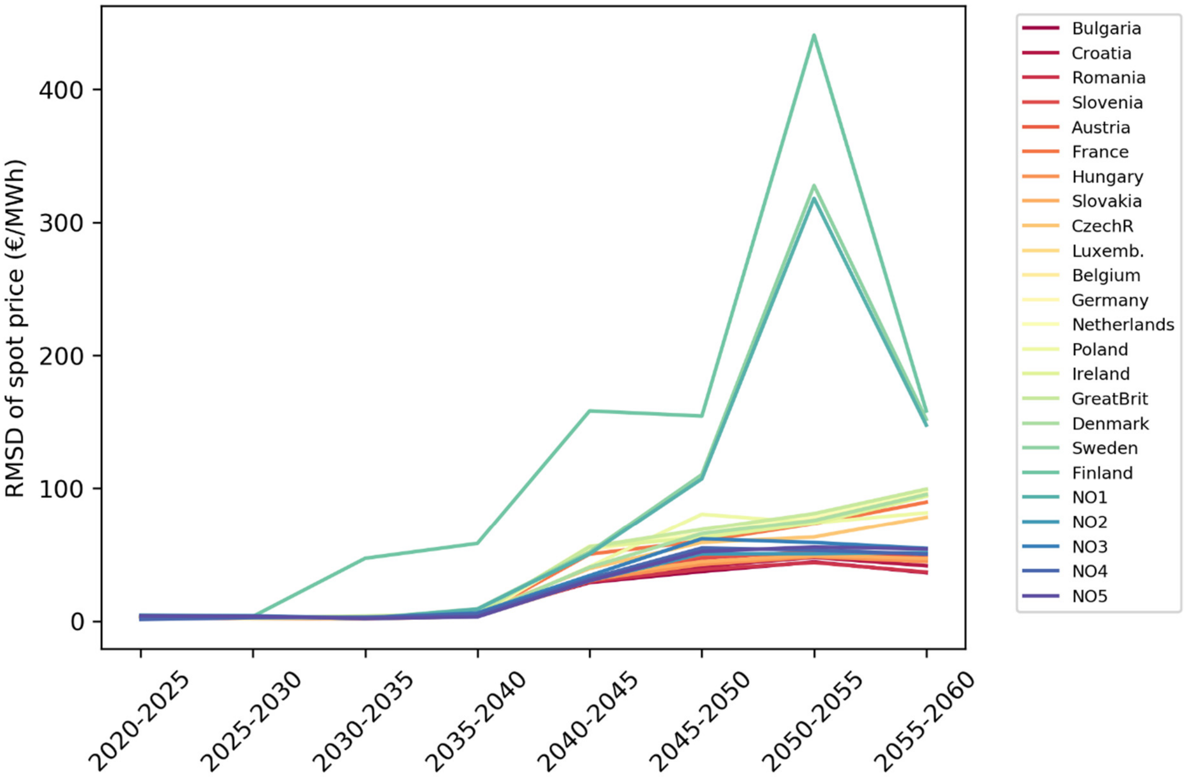


Figure 45 Yearly RMSD of spot price in each node in each period in ALL case

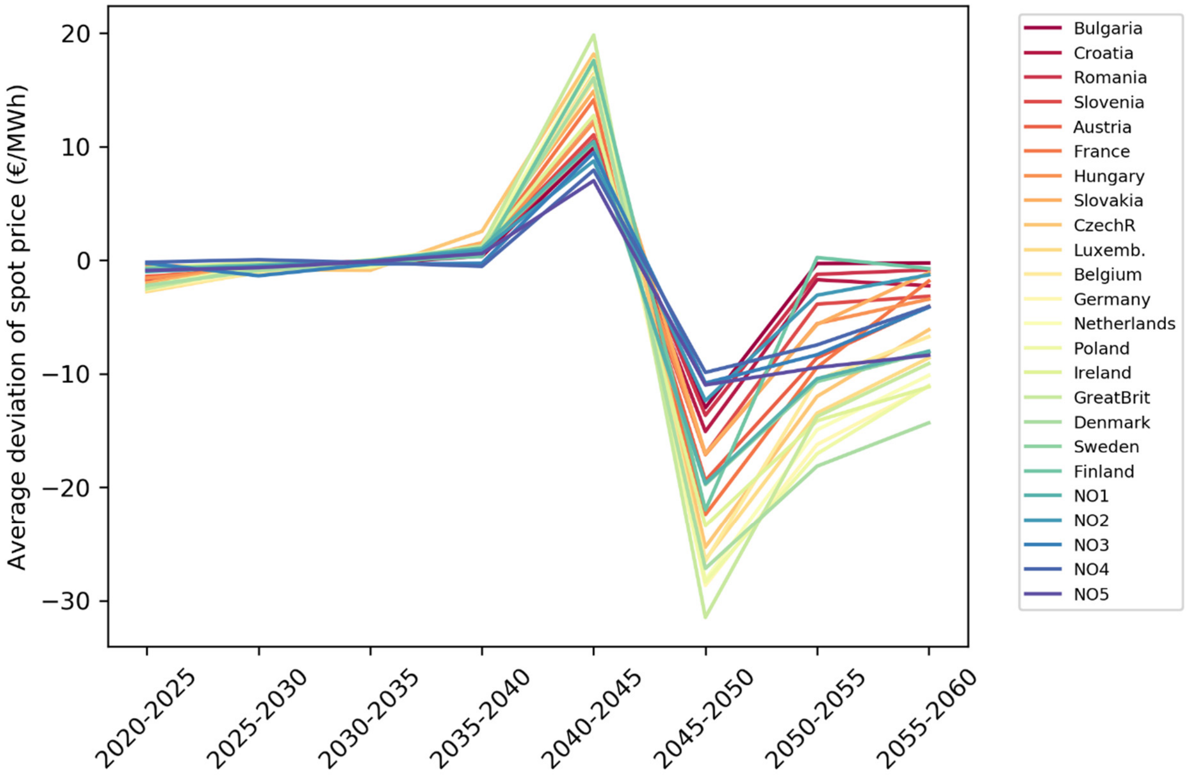


Figure 46 Yearly average deviation of spot price in each node in each period in ALL case

Another limitation is that the ZENIT neighborhood is designed only considering the information at the time it is designed. This ignores the future changes that could impact the costs of the neighborhood or even its design. For instance, the allowances' price could increase significantly during the neighborhood's lifetime, adding unexpected expenses. It would be possible to design the neighborhood with the information for all periods of EMPIRE. However, the lifetime of the neighborhood being 60 years, it would only be possible for the ZEN to be designed in the first period.

6. Conclusion

This report explores the link between the development of heat and electricity systems on the country level and the neighbourhood level across Europe. Two optimization models are used in a model linking framework where the output from one model is used as input to the other.

The main impact on meeting the ZEN requirement when the surrounding electricity system is decarbonized is a reduction of the investment in non-electric technologies in the neighborhoods. The emergence of SOFC and batteries is linked to the cost reduction of those technologies toward 2050. Technology cost reduction is the main reason for the overall cost reduction of the ZEN's energy system.

With ZENs in the heat and electricity system across Europe, less electricity is produced by nuclear and wind power plants. One important point is that surplus renewable energy produced within ZEN does not avoid GHG emissions with a European emission cap. This is because the energy generated by ZEN does not fully replace fossil fuels, and it mainly replaces energy produced by other low carbon sources.

A key assumption in our study is that the allowed GHG emissions per year are not affected by ZEN development. However, the resulting emission allowance prices and total system costs are decreased when ZENs are developed, which means that ZENs make it less costly for the system to achieve the same GHG emission reductions. Hence, the introduction of ZENs reduce the costs of obtaining climate targets instead of directly reducing system emissions with a cap-and-trade system.

We also run EMPIRE without specifying the allowed emissions per year according to European climate targets. Instead, we specify an emission tax equal to the allowance price without the ZEN option. When the emission tax is fixed, the ZEN development cause avoided system emissions that lead to higher system costs, and the European climate targets are exceeded. Higher system costs with a fixed emission tax are a consequence of more expensive and less polluting technologies developing alongside ZEN because the ZEN development does not lower the CO2eq. price.

Our study shows a clear dependency between local and international emission targets when planning energy systems on the European level and on the neighbourhood level. Future work could analyze the feedback effect of the wide-spread ZEN development on international emission policy. Our results indicate that the political feasibility of ambitious climate targets are strengthened by ZEN.

The energy demand in ZEN is not considered to be a part of the ZEN investment in EMPIRE. Instead, neighbourhood demand is assumed to be part of the aggregate demand for the respective market regions in EMPIRE. Therefore, investing in ZEN does not change the energy demand in EMPIRE, but rather it modifies the supply portfolio for a market region. It is possible to extend the neighbourhood contribution in EMPIRE to include a reduction in energy demand through the neighbourhood investment. Making energy savings a part of the ZEN investment in EMPIRE requires assumptions regarding building demand when no ZENs are developed, both in ZENIT and EMPIRE. Ideally, the energy efficiency investment(s) should be represented as an hourly net change in energy demand. We leave this development for future research.

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Appendices

A Complete ZENIT Model Description

The ZENIT (Zero Emission Neighborhood Investment Tool) is presented in [29] and this section presents the specific version used in this study. The model minimizes the energy system investment and operation cost for a given neighborhood that allows to be zero emission in the lifetime. On the contrary to [29], a MILP is not used. Indeed due to the large number of instances of the model to run, we reduce the number of binary variables to the bare minimum, that is only have a binary for the investment in the heating grid. Further, we separate this MILP into two LP solved independently because this was found to be faster than solving a unique MILP. The same timesteps as the ones used in EMPIRE are used.

The objective function is to minimize the following expression where $b^{HG}$is the binary controlling the investment in the heating grid:

$$b^{HG} \cdot C^{HG} + \sum_b \left(\sum_i \left(C_{i,b}^{disc} + \frac{C_{i,b}^{maint}}{\varepsilon_{r,D}^{tot}} \right) \cdot x_{i,b} \right) + \frac{1}{\varepsilon_{r,D}^{tot}} \sum_\kappa \sum_{t_\kappa} \sigma_\kappa \left(\sum_b \sum_f f_{f,t,b} \cdot P_f^{fuel} + \right.$$
$$\left. \left(P_t^{spot} + P^{grid} + P^{ret} \right) \cdot \left(y_t^{imp} + \sum_b \sum_{est} y_{t,b,est}^{imp} \right) - P_t^{spot} \cdot y_t^{exp} \right) + Em^{ETS} \cdot C^{ETS} \tag{1}$$

The C are the cost associated with it. The capacity of technology i in building b is $x_{i,b}$, the associated discounted investment cost is $C_{i,b}^{disc}$ and the operation and maintenance cost is $C_{i,b}^{maint}$. The discount factor for the lifetime of the neighborhood with the discount rate r is $\varepsilon_{r,D}^{tot}$. The timestep inside scenario κ is t_κ, and σ_κ is the representativity of the timestep inside the scenario. The fuel consumption of technology burning fuel f is $f_{f,t,b}$ and the cost of this fuel is P_f^{fuel}. P_t^{spot}, P^{grid} and P^{ret} are respectively the spot price of electricity, the grid tariff, and the retailer tariff. The import and export to the neighborhood are $y_t^{imp}$and y_t^{exp} while the import to battery est is $y_{t,b,est}^{imp}$. The imports and exports of electricity are limited by the size of the grid connection. Em^{ETS} is the amount of allowances bought on the EU ETS and C^{ETS} is the cost of allowances.

To be considered ZEN, the neighborhoods need to have net zero emissions in their lifetime. In the ZEN framework, we consider that the electricity exports from renewable sources in the neighborhood reduce the emissions in the bidding zone by replacing some of the more carbon intensive generation. The constraint representing this is:

$$\sum_\kappa \sum_{t_\kappa} \sigma_\kappa \left(\phi_t^{CO_2,el,imp} \cdot y_t^{imp} + \sum_b \sum_{est} \phi_t^{CO_2,el,exp} \cdot y_{t,b,est}^{imp} \right) + \sum_\kappa \sum_{t_\kappa} \sigma_\kappa \sum_b \sum_f \phi_f^{CO_2,f} \cdot$$
$$f_{f,t,b} \leq \phi_t^{CO_2,el,exp} \cdot \sum_\kappa \sum_{t_\kappa} \sigma_\kappa \left(\sum_b \sum_{est} \eta_{est} \cdot y_{t,est,b}^{exp} + \sum_b \sum_g y_{t,g,b}^{exp} \right) + Em^{ETS} \tag{2}$$

In this equation, $\phi_t^{CO_2,el,imp}$ and $\phi_t^{CO_2,el,exp}$ are the CO2 factors for electricity import and exports respectively and $\phi_f^{CO_2,f}$ are the factors for other fuels. The efficiency of the battery is η_{est}.
The electric, Space heating (SH) and Domestic Hot Water (DHW) load balances are:

$$y_t^{imp} + \sum_b \left(\sum_{est} y_{t,est,b}^{dch} \cdot \eta_{est} + \sum_g g_{g,t,b}^{selfc} \right) = \sum_b \left(\sum_e d_{e,t,b} + E_{t,b} \right), \quad \forall t \tag{3}$$

$$\sum_q q_{q,t,b}^{DHW} + \sum_{hst} \left(\eta_{hst} \cdot q_{t,hst,b}^{DHW,dch} - q_{t,hst,b}^{DHW,ch} \right) + q_{t,hst,b}^{HG,DHW} = \left(H_{b,t}^{DHW} \right) + q_{t,b}^{dump} \,, \quad \forall b,t \tag{4}$$

$$\sum_q q_{q,t,b}^{SH} + \sum_{hst} \left(\eta_{hst} \cdot q_{t,hst,b}^{SH,dch} - q_{t,hst,b}^{SH,ch} \right) + q_{t,hst,b}^{HG,SH} = \left(H_{b,t}^{SH} \right) \quad \forall b,t \tag{5}$$

The discharge from battery b to the neighborhood is $y_{t,est,b}^{dch}$ (similarly $q_{t,hst,b}^{dch}$ is the heat discharged from the heat storage hst to the neighborhood) and the electricity produced by technology g directly consumed is $g_{g,t,b}^{selfc}$. The electricity consumption of heat producing technology e is $d_{e,t,b}$ and the heat-independent electricity consumption is $E_{t,b}$. The heat produced by technology q is $q_{q,t,b}$, distinguished between Space Heating (SH) and Domestic Hot Water (DHW). The heat demand is $H_{b,t}$.

If the optimization invests in a heating grid, technologies at the neighborhood level, i.e. larger scale technologies, become available.

$$x_{i,PP} \leq X_i^{max} \cdot b^{HG} \tag{6}$$

The balance at the production plant (noted PP) where those technologies are located is then:

$$\sum_q q_{q,t,PP} + \sum_{hst}\left(\eta_{hst} \cdot q_{t,hst,PP}^{dch} - q_{t,hst,PP}^{ch}\right) = \sum_{b \setminus PP} q_{t,PP,b}^{HGtrans} + q_{t,PP}^{dump}\ , \quad \forall t \tag{7}$$

Where $q_{t,PP,b}^{HGtrans}$ is the heat transferred in the heating grid from the production plant to building *b* in timestep *t*.

The minimum investment capacity and part load limitations are not included in this model to limit the computational time.

The investment in *i* is limited by the existing capacity $X_{i,b}^{precap}$ and the maximum investment size X_i^{max}:

$$X_{i,b}^{precap} \leq x_{i,b} \leq X_i^{max}, \quad \forall i, b \tag{8}$$

The fuel or electricity used by technologies producing heat is:

$$f_{f,t,b} = \frac{q_{f,t,b}}{\eta_f}, \quad \forall f, t, b\ ;\ d_{e,t,b} = \frac{q_{e,t,b}}{\eta_e}, \quad \forall e, t, b \tag{9}$$

where η is the efficiency of the technology. The heat produced can fulfil SH and/or DHW depending on the technology; B_q^{DHW} and B_q^{SH} control which kind they can provide. An electric radiator for instance can only provide SH.

$$q_{f,t,b} = q_{q,t,b}^{DHW} + q_{q,t,b}^{SH}, \quad \forall q, t, b \tag{10}$$

$$q_{q,t,b}^{DHW} \leq M \cdot B_q^{DHW}, \quad \forall q, t, b \tag{11}$$

$$q_{q,t,b}^{SH} \leq M \cdot B_q^{SH}, \quad \forall q, t, b \tag{12}$$

For CHPs, the efficiency is the one related to heat and the electricity production is obtained with the heat-to-power ratio (α_{CHP}):

$$g_{f,t,b} = \frac{q_{f,t,b}}{\alpha_f}, \quad \forall CHP, t, b \tag{13}$$

The solar technologies (solar thermal collector and PV panels) are modelled by their efficiency and the solar irradiance.

For heat pumps, the COP is used instead of the efficiency. It is calculated based on a polynomial fit of manufacturer's data and the difference between the supply and the source temperature. The max electric consumption ($P^{in,max}$) is also obtained in the same way. The supply temperature is 65°C for DHW and for SH it differs between recent (or refurbished) and old houses.

The heat pumps are modelled in the following way:

$$d_{HP,t,b}^{SH} = \frac{q_{HP,t,b}^{SH}}{COP_{HP,t,b}^{SH}}, \quad \forall HP, t, b \tag{14}$$

$$d_{HP,t,b}^{DHW} = \frac{q_{HP,t,b}^{DHW}}{COP_{HP,t,b}^{DHW}}, \quad \forall HP, t, b \tag{15}$$

$$\frac{d_{HP,t,b}^{SH}}{P_{HP,t,b}^{in,max,SH}} + \frac{d_{HP,t,b}^{DHW}}{P_{HP,t,b}^{in,max,DHW}} \leq x_{HP,b}, \quad \forall HP, t, b \tag{16}$$

The heating grid is assumed to be radial and only fed by the central production plant, i.e. the buildings cannot feed heat into the heating grid.

$$q_{t,b}^{HGused} = \sum_{b''}\left(q_{t,b'',b}^{HGtrans} - Q_{b'',b}^{HGloss}\right) - \sum_{b'} q_{t,b,b'}^{HGtrans} \quad , \forall t, b \tag{17}$$

$$q_{t,b}^{HGused} \geq 0 \quad , \forall t, b \tag{18}$$

$$\boldsymbol{q_{t,b',b}^{HGtrans} \leq \dot{Q}_{b',b}^{max,pipe}} \quad ,\forall \boldsymbol{t, b, b'} \tag{19}$$

The size of the pipe limits the heat flow ($\dot{Q}_{b',b}^{max,pipe}$) in the pipe. The heat from the heating grid can only be used if a hydronic system is installed or for DHW in larger buildings if a hydronic system specifically for DHW already exists ($B_b^{DHWhyd} = 1$)

The operation of storage *st* (whether SH, DHW, or electric) is modelled as follows:
$\forall \kappa, t_\kappa \in [1,23], st, b$

$$\boldsymbol{v_{\kappa,t_\kappa,st,b}^{stor} = v_{\kappa,t_\kappa-1,st,b}^{stor} + \eta_{st} \cdot q_{\kappa,t_\kappa,st,b}^{ch} - q_{\kappa,t_\kappa,st,b}^{dch}} \tag{20}$$

$\forall \kappa, t_\kappa \in [0,23], st, b$

$$\boldsymbol{v_{\kappa,t_\kappa,st,b}^{stor} \leq x_{st,b}} \tag{21}$$

$$\boldsymbol{q_{\kappa,t_\kappa,st,b}^{ch} \leq \dot{Q}_{st}^{max} \;\; ; \;\; q_{\kappa,t_\kappa,st,b}^{dch} \leq \dot{Q}_{st}^{max}} \tag{22}$$

$\forall \kappa, st, b$

$$\boldsymbol{v_{\kappa,0,st,b}^{stor} = v_{\kappa,23,st,b}^{stor}} \tag{23}$$

The storages have a daily operation and a given limit on the charging rate $\dot{Q}_{st}^{max}$.

B Technology data in ZENIT

Table 3 Data of technologies in small buildings. The sub-columns represent, when relevant, the data for 2030, 2040 and 2050. A "-" means the value is the same as the previous year.

Tech.	η_{th}(%)			Inv. Cost (€/kWh)			Annual O&M Costs (% of Inv. Cost)			Lifetime (Year)	Fuel	α_{CHP}			El.	Heat
PV[15]	0.19	-	-	830	-	560	1.24	-	1.55	25					1	0
ST[16]	0.7	-	-	500	-	452	3.28	-	3.32	30					0	1
ASHP[17]	f(T)	-	-	514	-	486	8.12	-	7.77	12	Elec.				0	1
ASHP[18]	f(T)	-	-	1500	-	1250	4.25	-	4.78	18	Elec.				0	1
GSHP[19]	f(T)	-	-	2500	-	2249	2.55	-	2.66	20	Elec.				0	1
Boiler	0.8	-	0.85	812	-	737	7.42	-	7.43	20	Wood Pellets				0	1
Boiler	0.86	-	0.88	260	-	236	6.77	-	3.92	20	Wood Logs				0	1
Heater	1	-	1	933	-	833	0.82	-	0.84	30	Elec.				0	1
Boiler	0.75	-	-	875	-	775	5.71	-	6.13	20	Wood Logs				0	1
Boiler	0.96	-	0.97	300	-	270	6.61	-	6.67	20	Biomethane				0	1
Boiler	0.96	-	0.97	300	-	270	6.61	-	6.67	20	Gas				0	1
CHP	0.46	-	0.48	11428	-	8572	6.24	-	6.67	20	Biogas	0.92	-	-	1	1
CHP	0.6	-	0.61	7438	-	5785	6.11	-	6.42	20	Biomethane	1.73	-	1.76	1	1

Table 4 Data of technologies in large buildings. The sub-columns represent, when relevant, the data for 2030, 2040 and 2050. A "-" means the value is the same as the previous year.

Tech.	η_{th}(%)			Inv. Cost (€/kWh)			Annual O&M Costs (% of Inv. Cost)			Lifetime (Year)	Fuel	α_{CHP}	El.	Heat
PV	0.19	-	-	570	-	450	1.47	-	1.58	25			1	1
ST	0.7	-	-	478	-	429	0.65	-	0.67	30			0	1
ASHP	f(T)	-	-	393	-	356	2.94	-	4.32	20	Elec.		0	1
GSHP	f(T)	-	-	500	-	450	2.33	-	3.35	20	Elec.		0	1
Boiler	0.9	-	-	312	-	281	2.24	-	2.30	20	Wood Pellets		0	1
Heater	1	-	-	613	-	556	0.05	-	0.05	30	Elec.		0	1
Boiler	1.02	-	-	104	-	94	2.55	-	2.68	25	Biomethane		0	1
Boiler	1.02	-	-	104	-	94	2.55	-	2.68	25	Gas		0	1

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[15] Area Coefficient: 5.3m2/kW

[16] Area Coefficient: 1.43m2/kW

[17] Air-Air heat pump

[18] Air-Water heat pump

[19] Ground source heat pump

Table 5 Data of technologies at the neighborhood level. The sub-columns represent, when relevant, the data for 2030, 2040 and 2050. A "-" means the value is the same as the previous year.

Tech.	η_{th}(%)			Inv. Cost (€/kWh)			Annual O&M Costs (% of Inv. Cost)			Lifetime (Year)	Fuel	α_{CHP}			El.	Heat
CHP[20]	0.47	-	-	826	-	780	1.03	-	1.00	25	Biogas	1.09	-	-	1	1
CHP	0.98	-	-	915	-	863	4.54	-	4.66	25	Wood Chips	6.56	-	6.72	1	1
CHP	0.83	-	-	1077	-	1000	4.50	-	4.60	25	Wood Pellets	5.38	-	5.5	1	1
Boiler	1.14	-	-	658	-	596	4..78	-	4.96	25	Wood Chips				0	1
Boiler	1.01	-	-	652	-	614	4.75	-	4.56	25	Wood Pellets				0	1
CHP[21]	0.67	-	-	1267	-	1267	0.84	-	0.84	15	Wood Chips	3	-	3	1	1
Boiler[22]	0.6	-	-	2000	-	800	5.00	-	5.00	20	Biogas				0	
GSHP	f(T)	-	-	510	-	460	0.39	-	0.43	25	Elec.				0	1
Boiler	0.99	-	-	140	-	130	0.73	-	0.71	20	Elec.				0	1
Boiler	0.43	-	0.45	50	-	50	3.8	-	3.4	25	Biogas				0	1
Boiler	0.43	-	0.45	50	-	50	3.8	-	3.4	25	Gas				0	1

Table 6 Data of fuels used. The hourly data for electricity is taken from the output of the EMPIRE model.

Fuel	Fuel Cost (€/kWh)	CO2 factor (gCO_2/kWh)
Wood pellets	0.03664	40
Wood chips	0.02593	20
Wood logs	0.0504	20
Biogas	0.07	0
Biomethane	0.07	100
Gas (neighborhood level)	0.041	277
Gas (building level)	0.121	277

Table 7 Data of storage technologies

Index	One-way Eff. (%)	Inv. Cost (€/kWh)			O&M Cost (% of Inv. Cost)	Lifetime (Year)	Charge/Discharge rate (% of Cap.)
Battery							
1	95	577	-	-	0	10	0.37
2	93.8	500	-	-	0	15	0.234
3	96	622	394	255	0.125	30	0.5
Heat Storage							
1	0.95	75	-	-	0	20	0.2

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[20] Biogas Engine

[21] Gasified biomass stirling engine

[22] Solid oxide fuel cell

C ZENIT results in Empire All capped case

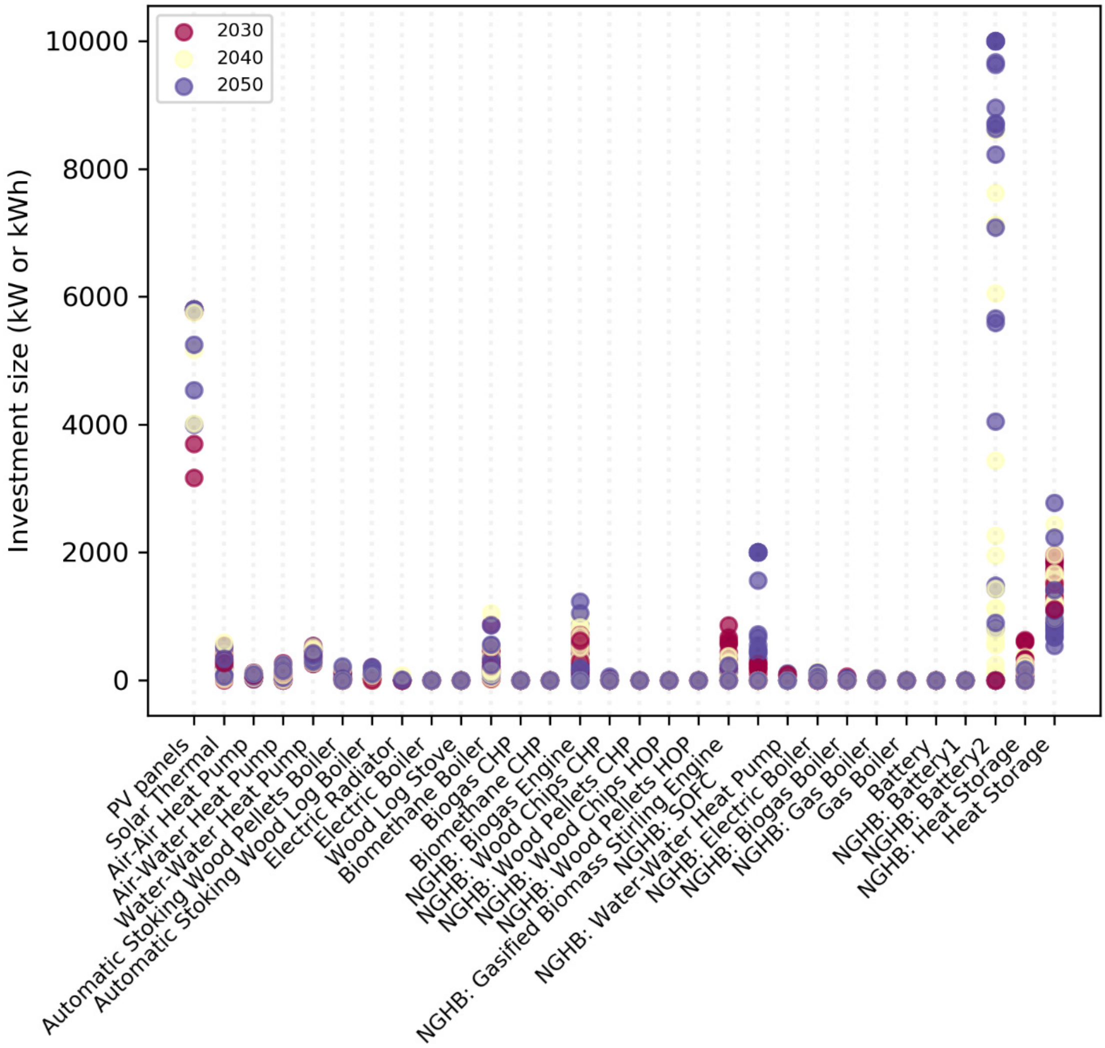

Figure 47 Resulting investment by technology and year resulting from the ZENIT runs using EMPIRE data from the *ALL* case

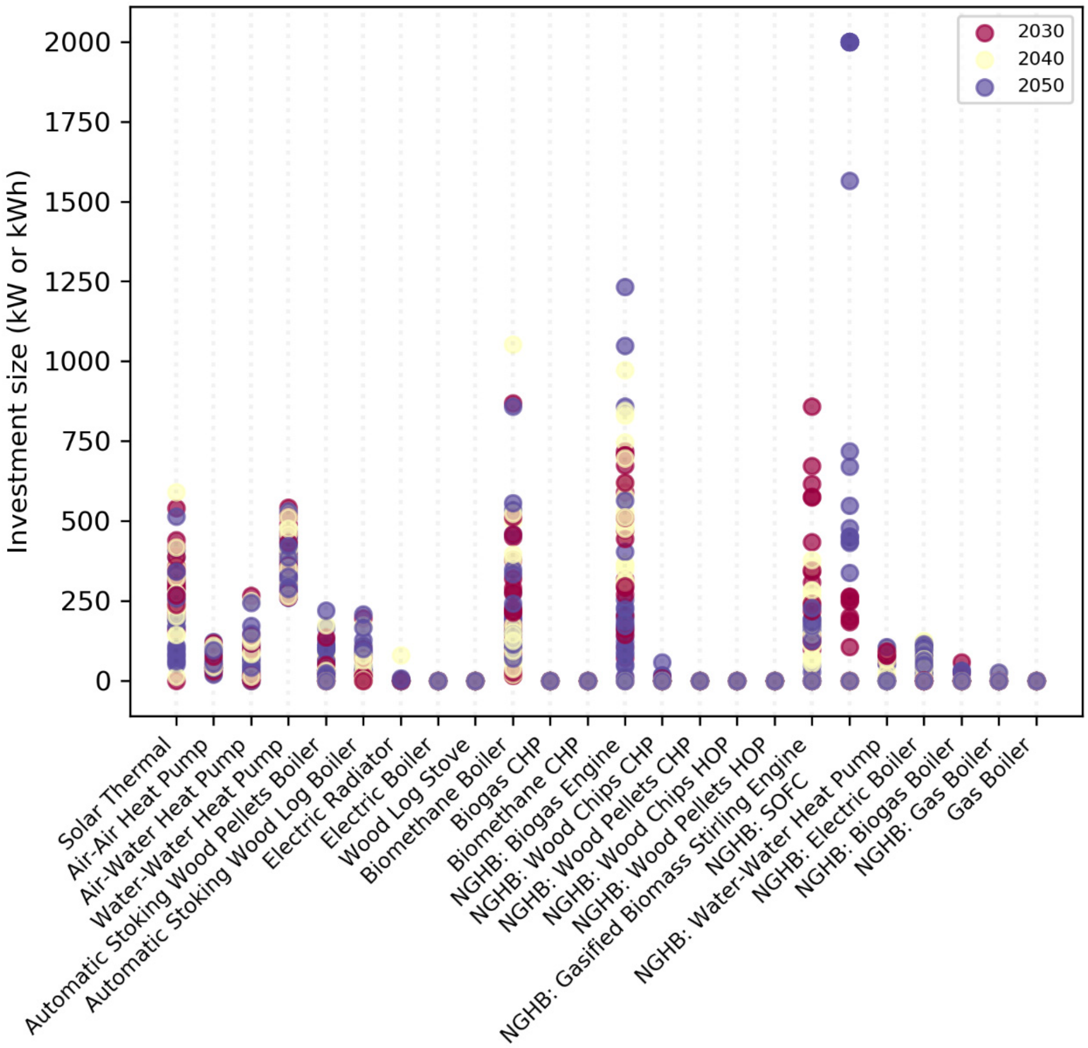

Figure 48 Extract of resulting investment by technology and year resulting from the ZENIT runs using EMPIRE data from the *ALL* case

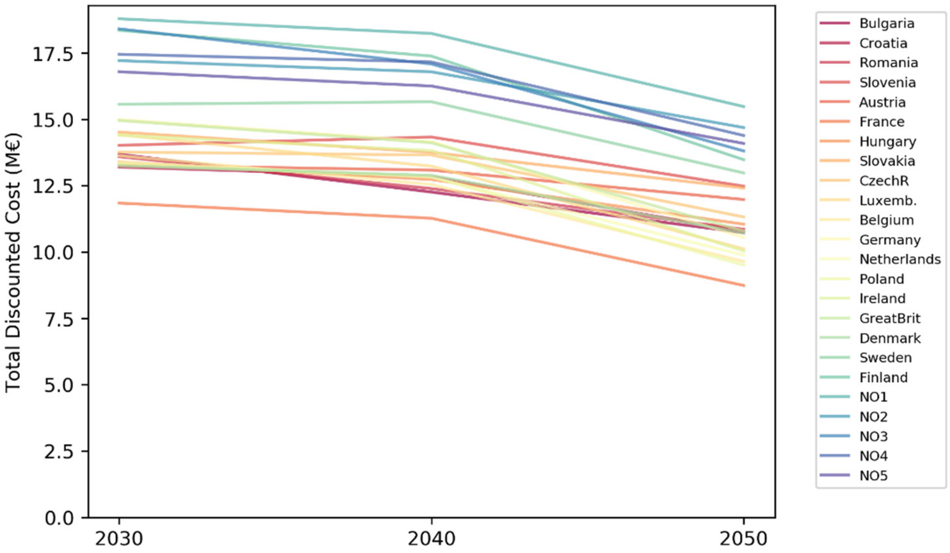

Figure 49 Total discounted costs for the energy system of a ZEN in different European countries. The countries are coloured approximately from South to North in ALL case.

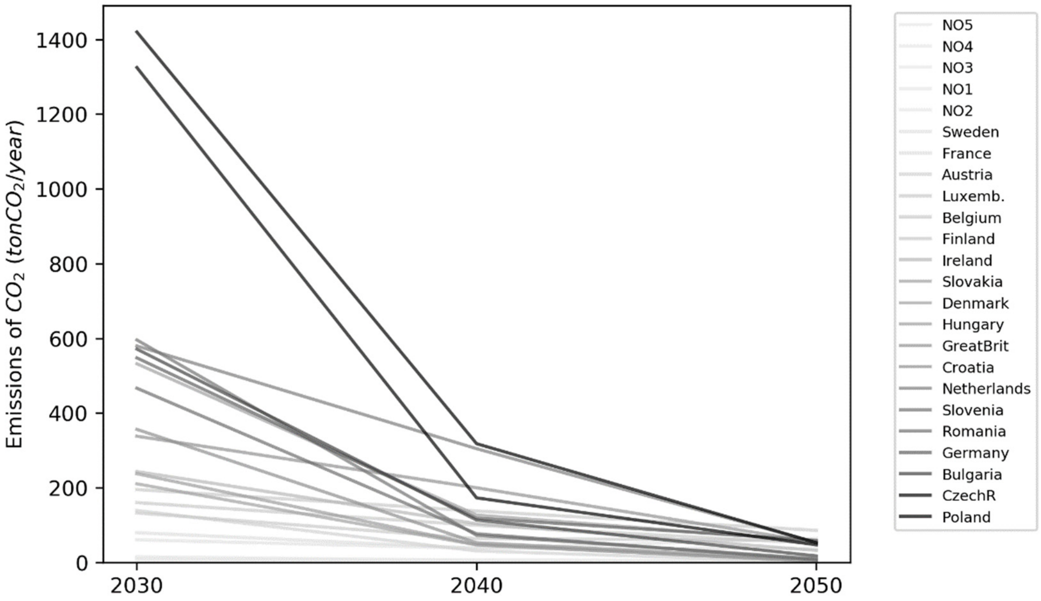

Figure 50 Total CO2 emissions per year for the ZEN in each country coloured based on the average carbon intensity of the electricity in 2030 from lowest to highest in ALL case.

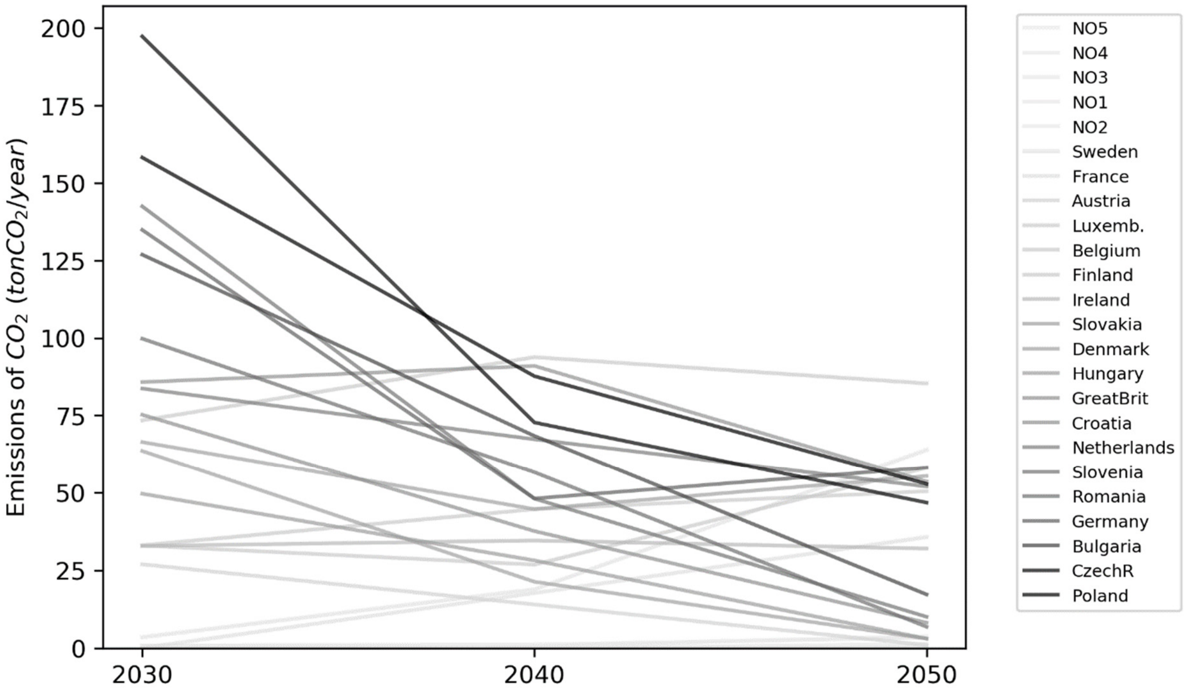

Figure 51 Local CO2 emissions per year for the ZEN in each country coloured based on the average carbon intensity of the electricity in 2030 from lowest to highest in ALL case.

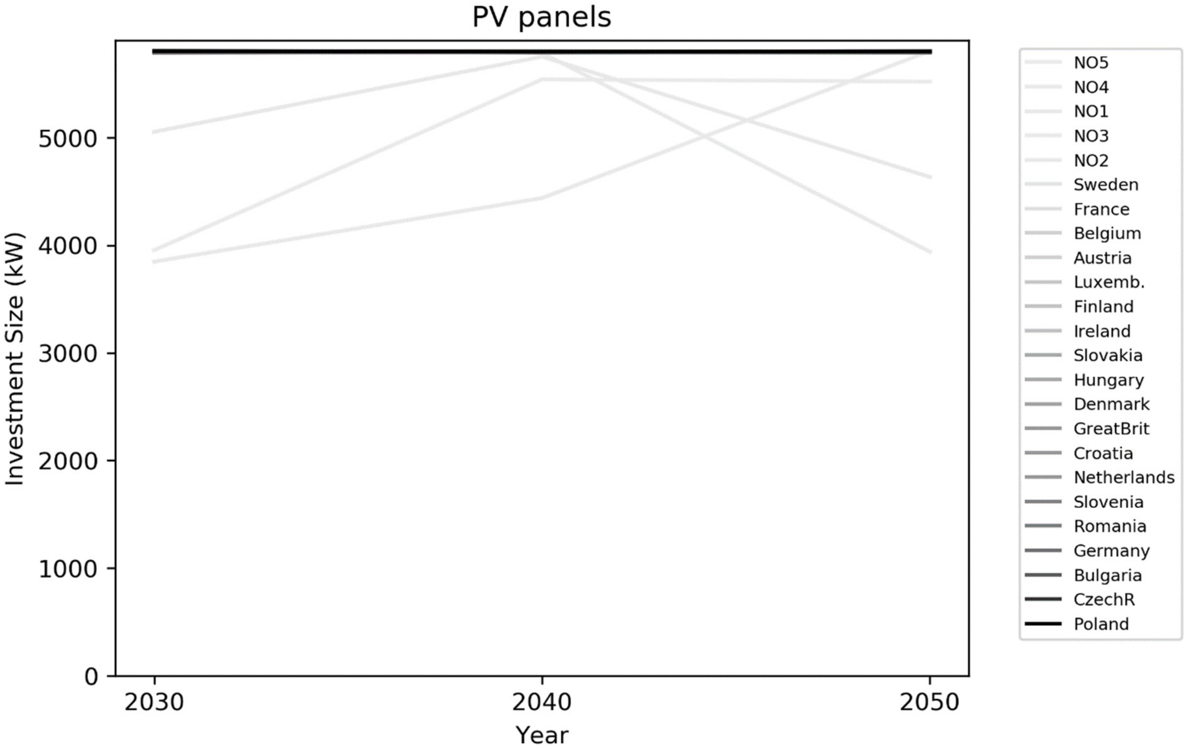

Figure 52 Installation of PV panels per year for the ZEN in each country coloured based on the average carbon intensity of the electricity in 2030 from lowest to highest in ALL case.

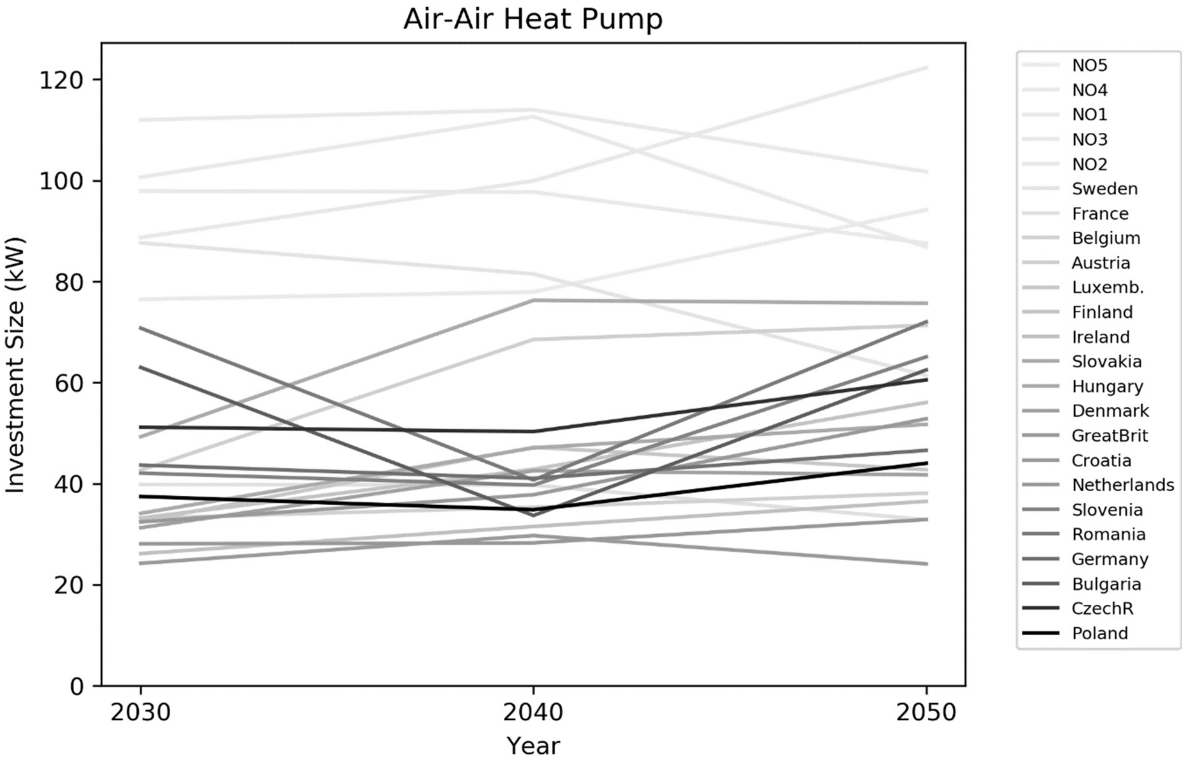

Figure 53 Installation of air-air heat pumps per year for the ZEN in each country coloured based on the average carbon intensity of the electricity in 2030 from lowest to highest in ALL case.

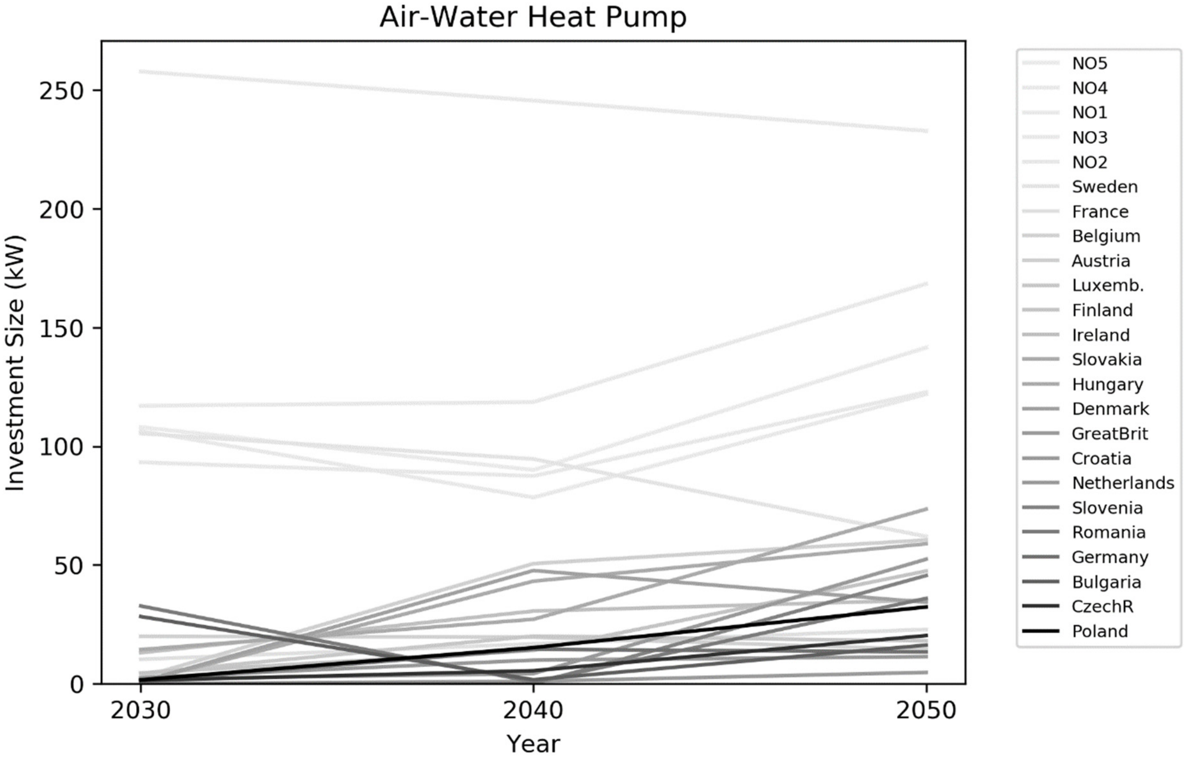

Figure 54 Installation of air-water heat pumps per year for the ZEN in each country coloured based on the average carbon intensity of the electricity in 2030 from lowest to highest in ALL case.

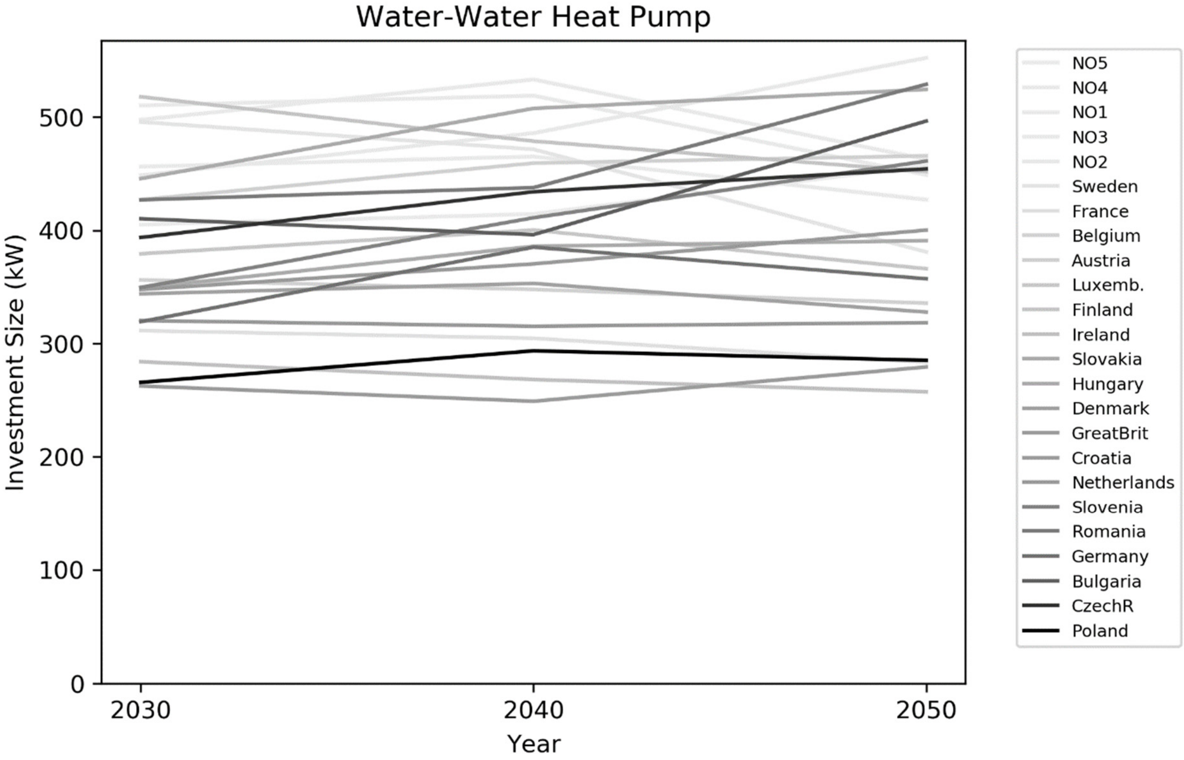

Figure 55 Installation of water-water heat pumps per year for the ZEN in each country coloured based on the average carbon intensity of the electricity in 2030 from lowest to highest in ALL case.

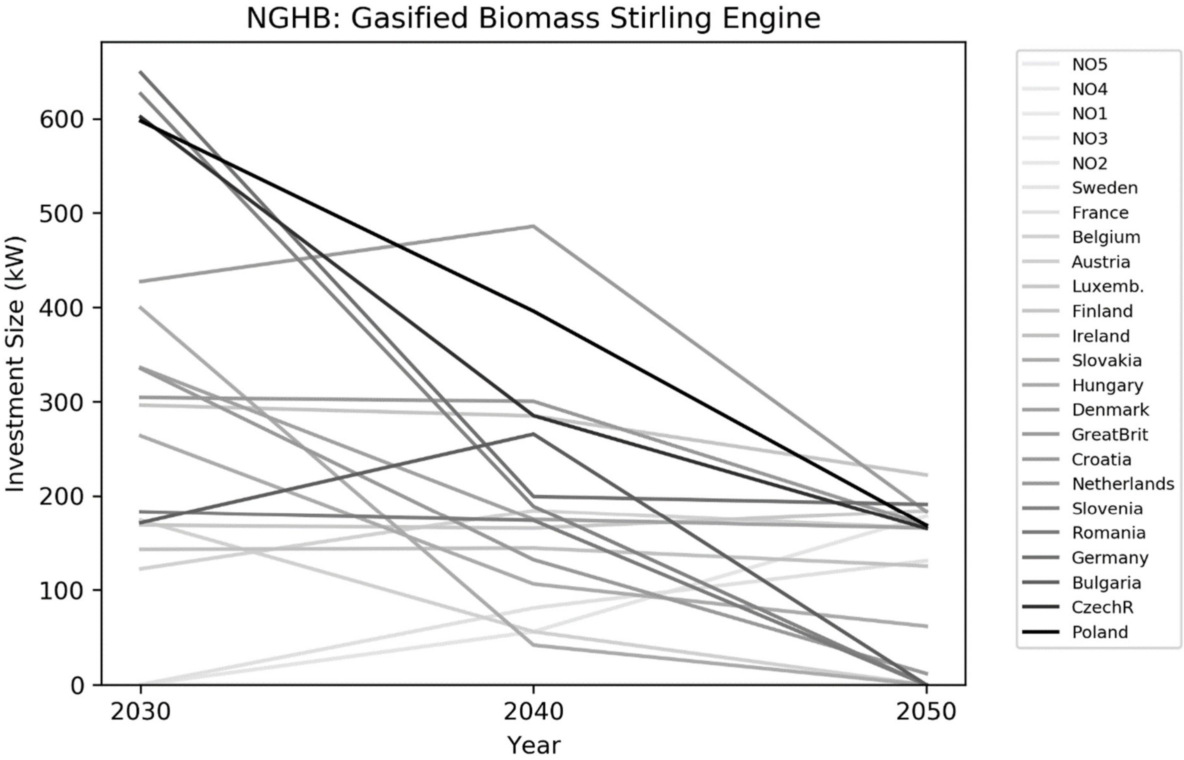

Figure 56 Installation of gasified biomass stirling engine per year for the ZEN in each country coloured based on the average carbon intensity of the electricity in 2030 from lowest to highest in ALL case.

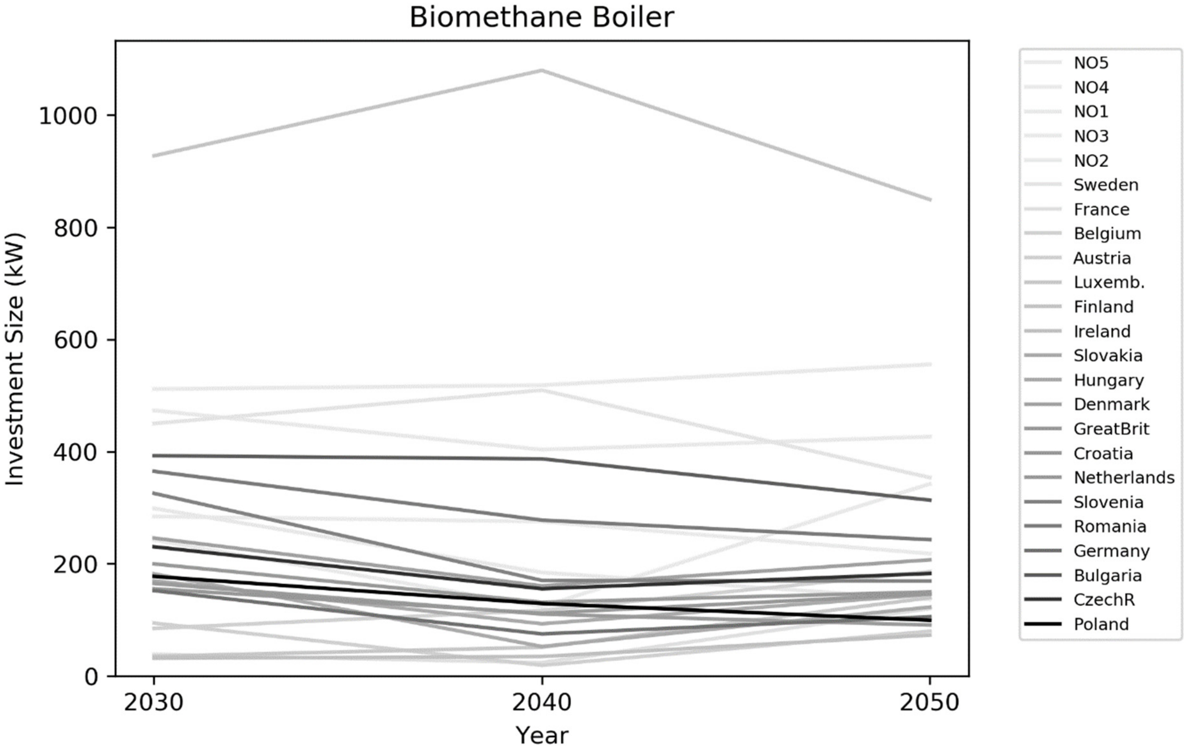

Figure 57 Installation of biomethane boiler per year for the ZEN in each country coloured based on the average carbon intensity of the electricity in 2030 from lowest to highest in ALL case.

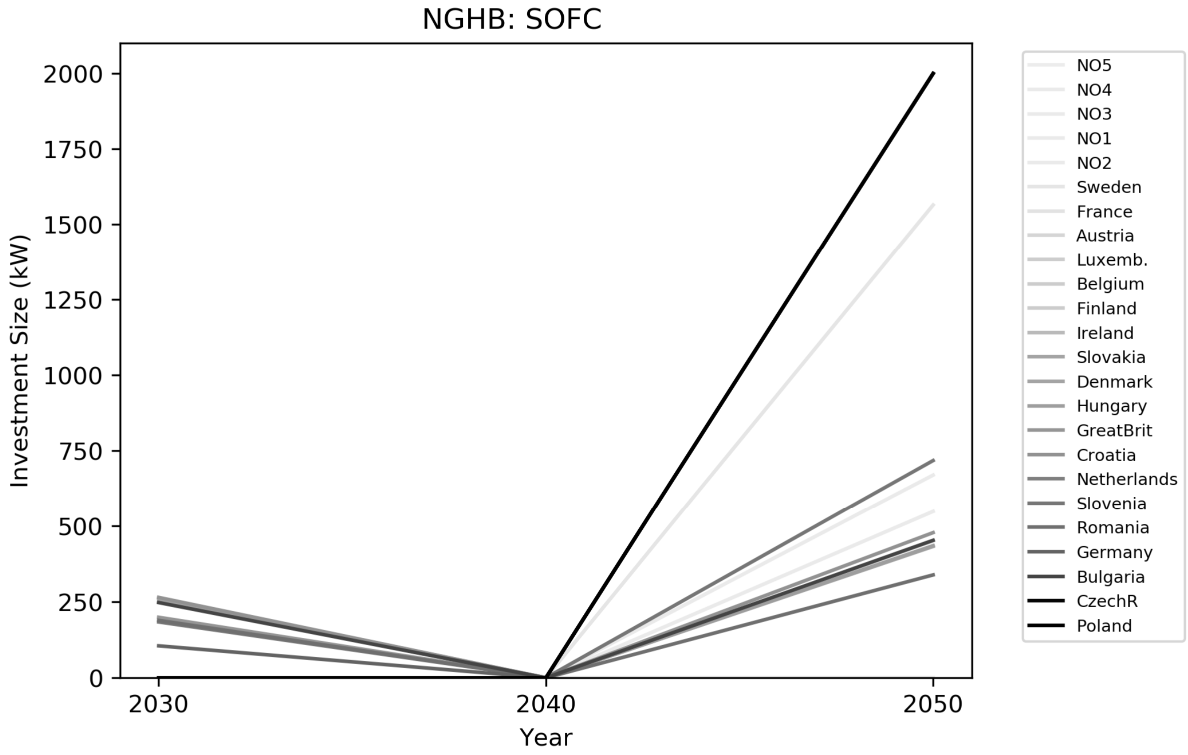

Figure 58 Installation of SOFC per year for the ZEN in each country coloured based on the average carbon intensity of the electricity in 2030 from lowest to highest in ALL case.

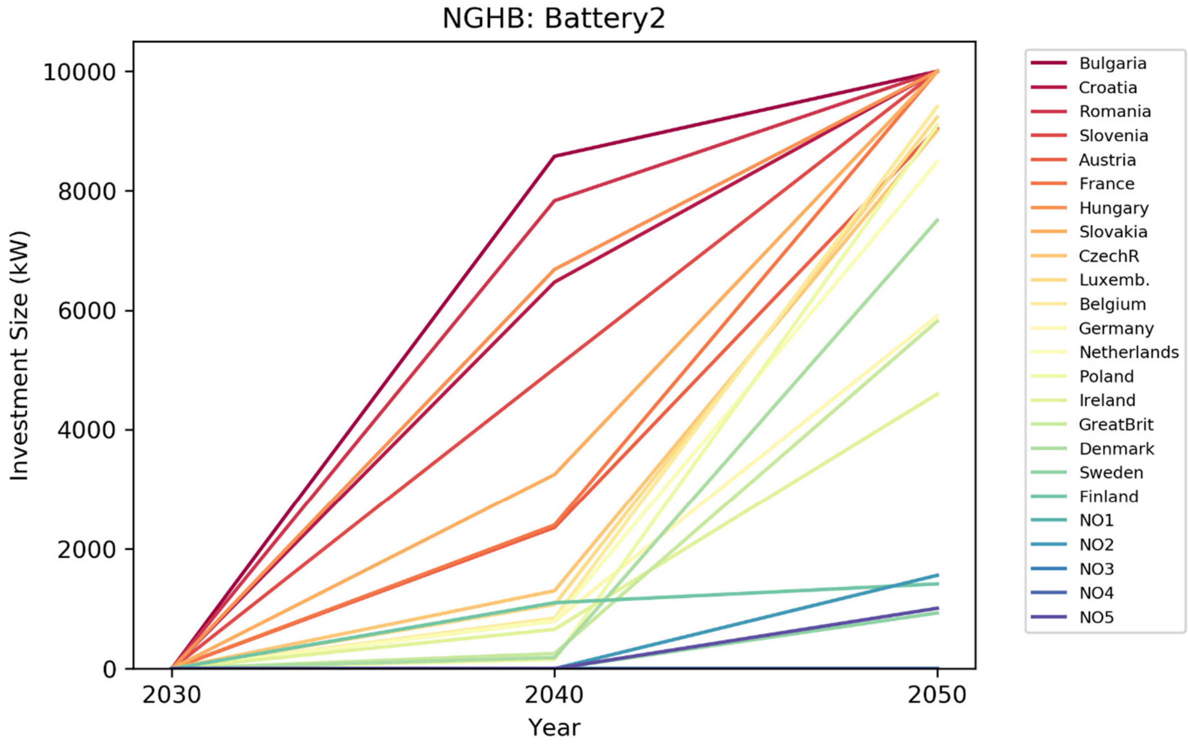

Figure 59 Installation of batteries per year for the ZEN in different European countries in ALL case. The countries are coloured approximately from South to North.

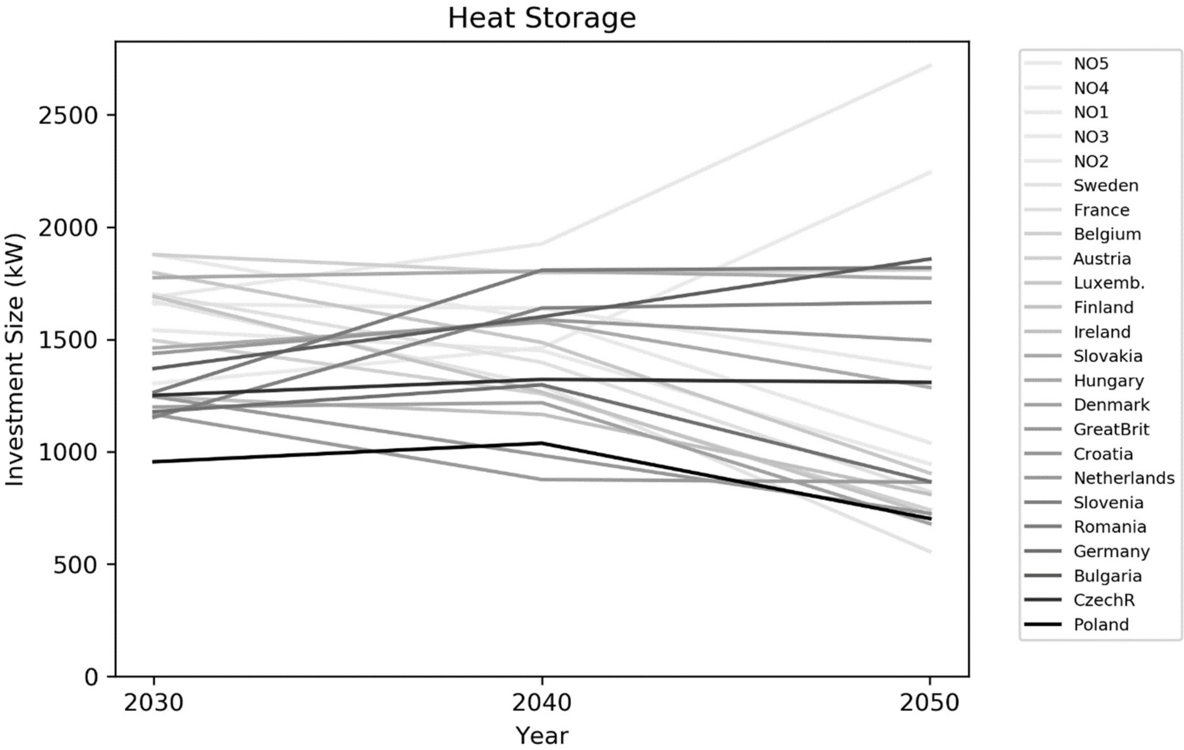

Figure 60 Installation of heat storage per year for the ZEN in each country coloured based on the average carbon intensity of the electricity in 2030 from lowest to highest in ALL case.

D Technology data in EMPIRE

Table 8 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
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 (10% co-firing bio)	2,183.8	49.1	2,083.9	55.7	1,956.4	47.0	1,793.7	94.7
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 9 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
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
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 (10% co-firing bio)	1,586.0	232.3	1,321.0	163.1	982.7	209.1	551.0	256.7
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

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