Towards Zero Emission Neighbourhoods: Implications for the Power System

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***Abstract*—This paper investigates the development of neighbourhoods with ambitious emission targets in the Nordic countries and their value for the power system. The targets relate to compensating for emissions in neighbourhoods through local low-carbon electricity and heat production. The first part of our analysis investigates local generation expansion with a neighbourhood perspective using a mixed integer linear programming model. The second part investigates the value of representative neighbourhoods with a country perspective using a generation and transmission capacity expansion model. When coupling the models, results indicate that neighbourhoods with co-generation of electricity and heat are most attractive for the power system in the Nordics, while neighbourhoods with solar PV provide most emission reduction.**

***Index Terms*—Soft-linking models, mathematical programming, sustainable neighborhoods, climate and energy policy**

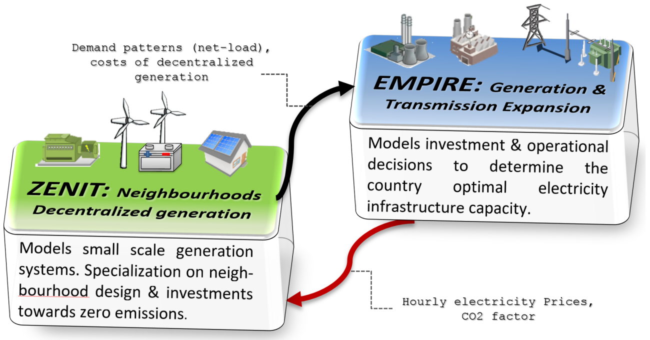

Fig. 1. Modelling approach to connect neighbourhood and country perspectives

I. INTRODUCTION

A. Motivation

As the world debates actions to combat climate change, the success of reducing greenhouse gas (GHG) emissions might rely on two main developments: the transition to a low-carbon energy system and improvements in energy efficiency. To some extent, both options have put the end-user at the centre of the energy transition. This has translated into the adoption of distributed generation technologies and policies directed to promote sustainable solutions for buildings and neighbourhoods.

Buildings represent a major contributor to GHG emissions with an estimated 33% of the worldwide energy related GHG emissions [1]. However, it is unclear which solutions and technologies will be cost optimal in the energy transition, whether energy demand is best met locally or centrally and how the power system is affected by developments on a neighbourhood level.

The representation of decentralized electricity and heat generation in country-scale power system models is challenging. From a neighbourhood perspective, the factors that affect the local units are hard to accurately represent with a national perspective. Hence, two models with different granularity might provide different results regarding: (1) The need for flexibility (related to temporal and spatial resolution) and (2) the synergy between energy carriers (e.g. heat, gas and electricity).

A better understanding of flexibility and synergy using different models is key to support RES deployment, integrate decentralized generation systems, study electricity market designs and propose sounded policy recommendations. Reviews of different methodologies [2] for combining energy models suggest two main approaches:

1) Soft-linking individual models with different granularity, and
2) Direct extension of one model with more detailed granularity.

The exercise of soft-linking models is useful when they have different temporal, spatial and technological detail, as well as different energy carrier options. The link could be one-directional (one model's output inspires input to another model) or bi-directional (iterative process where output inspires input to both models, see [3]). The main goal of using a soft-linking approach is to investigate how results from a somehow limited and simplified model are affected when its assumptions are challenged.

Direct extension of models is computationally challenging and requires a careful choice of granularity. It removes the need to work with two models, but the representation of short-term variations will be simplified to keep a tractable problem. In this work, the soft-linking approach is used.

B. State-of-the-art

Some work has been done on connecting flexibility and synergy aspects of the power system in optimization problems with different granularity.

The TIMES model [4] has been soft-linked with several models with different perspectives, including the electricity and gas system model PLEXOS and the residential energy system model ArDEM [5]. Where TIMES has a wide energy carrier resolution, the soft-linked models have a higher temporal and spatial resolution allowing a more detailed representation of technologies. A similar soft-linking approach has also been used with the energy system model MARKAL and the unit commitment model REPOWERS to analyze the need for flexibility in the Dutch power system [6]. Results from the soft linkings point to an overestimation of investments in renewable capacity when only using the aggregated energy system model. Results from the energy system model alone also underestimate the need for flexibility due to a simplified representation of short-term variations (low temporal granularity). TIMES has also been used to investigate the introduction of Zero Energy Buildings (ZEBs) in Scandinavia. In [7], the authors assumed a large introduction of buildings with a low heat demand and on-site solar PV production compensating for nearly all energy consumption. A similar analysis was done using the EMPS model [8]. In these analyses, the models did not directly support investment decisions in ZEBs, but rather optimized the energy system development given a certain roll-out of such buildings.

C. Contribution

The main goal of this work is (1) to investigate the development of distributed energy production in neighbourhoods with ambitious local emission targets, and (2) to investigate the value of this development for the larger power system.

We have analyzed investments in energy assets with two models described in Section II. Section III presents the results from our soft-linking approach and these are discussed in Section IV. Future work is suggested in Section V, and Section VI concludes the paper.

II. MODELS

A. EMPIRE

The EMPIRE model is a capacity expansion model for the power system that has been extensively used and developed in various research projects, e.g. [9]. EMPIRE is formulated as a multi-horizon stochastic program that optimizes investments under uncertainty of hourly supply from intermittent generators and electric demand. EMPIRE represents uncertainty by incorporating stochastic scenarios with representative seasons. Hence, EMPIRE's main strength is the representation of joint short- and long-term decisions (operations and investments), i.e. multiple investment decisions co-exist with hourly operational decisions. EMPIRE assumes capacity expansion under perfect competition. Generators are subject to upward ramping constraints. There are also details on hydro power and pumped storage. Transmission is modelled as a transport network between countries.

The EMPIRE model's geographical coverage takes into consideration the EU countries plus Switzerland, Norway and some Balkan states. For each country, we have collected information on existing generation and transmission capabilities. We have also gathered technology costs, fuel prices and other parameters from different publicly available sources[1]. Our EMPIRE implementation follows the EU commission decarbonization scenario based on PRIMES data [10].

B. ZENIT

The ZENIT (Zero Emission Neighbourhoods Investment Tool) model's objective is to design and plan energy systems in neighbourhoods. It models a neighbourhood at an aggregated level to determine the cost optimal investments in heat and electricity supply based on mixed integer linear programming (MILP). The model considers hourly operation of the neighbourhood energy system over one representative year.

An important feature in ZENIT is the "zero emission"-constraint:

$$\sum_t (y_t^{imp} - y_t^{exp}) \cdot \alpha^{CO_2,\text{el}} + \sum_t \sum_f \alpha_f^{CO_2,\text{fuel}} \cdot q_{f,t} = 0,$$

where y_t represents the import and export of electricity in the neighbourhood at time t; the factors $\alpha^{CO_2,\text{el}}$ and $\alpha_f^{CO_2,\text{fuel}}$ represent, respectively, the CO_2 factors of electricity and fuel type f; and $q_{f,t}$ represents the amount of fuel f consumed at time t. The equation above is an annual emission compensation constraint for operation. The neighbourhood must at least produce the same amount of electricity as imported, and also produce electricity compensating for any emissions from local heat generation. The smaller the CO_2 factor from the grid, the more local electricity must be produced to balance the constraint. In [11], a description of the model that inspired the development of ZENIT is given, where the system boundary is for single buildings (not neighbourhood, see also [12]).

The technology options for the neighbourhood energy system are: solar photovoltaics (PV), solar thermal collectors, boilers, combined heat and power (CHP), district heating, heat pumps and energy storages. CHPs and boilers are considered both at the neighbourhood scale and at the building scale with different possible fuel (electricity, gas and bio pellets). Data related to each option were gathered from different sources: in particular IEA-ETSAP[2] and the Danish Energy Agency[3]. The cost assumption for batteries are based on an IRENA publication [13]. For this study, we consider residential neighbourhoods of $10,000$ m^2 as reference neighbourhoods. Climate data and load profiles were also gathered for each country. Electric peak load per neighbourhood varies between countries, and ranges from $65 - 77$ kWh/h.

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[1] For a more detailed explanation on sources and inputs refer to [9]

[2] https://iea-etsap.org/index.php/energy-technology-data

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

C. Linking models in a Nordic market setting

A reference case of EMPIRE has been used as input to ZENIT to optimize neighbourhood development under ambitious goals in the Nordic countries. ZENIT is run three times for Denmark, Finland, Norway and Sweden using electricity costs and CO_2 factors from years 2025, 2030 and 2035 from the reference case. The electricity prices and CO_2 factors from EMPIRE affects the choice of technologies and the investments in local energy supply. In addition, the cost of PV panels is set to reduce through time in order to follow the cost of PV in EMPIRE. The other technologies (including batteries) keeps a constant cost through the different years of the study.

Linking back, the results from ZENIT has been used as input to EMPIRE. ZENIT functions as a tool to generate country specific *representative neighbourhoods*. The neighbourhoods provide new investment options in EMPIRE represented as intermittent generators with fixed investment- and operational costs. Investments in neighbourhood capacity provide a certain availability of supply depending on the output from ZENIT. The supply input to EMPIRE includes the electric self-consumption (consumption of locally produced electricity) plus the export of electricity to the grid. This contributes to meeting demand in EMPIRE. Investments in representative neighbourhoods are based on linearly scaling the neighbourhood reference size of $10,000$ m^2.

Because ZENIT has the option of investing in solar PV, the choice of investing in PV in the Nordic countries in EMPIRE is replaced by the choice of investing in representative neighbourhoods. Investment cost for neighbourhoods in EMPIRE relates only to units producing electricity in the ZENIT design since EMPIRE models the power system. This assumption means that units not generating electricity cover their costs in a different market.

III. RESULTS

The results consist of three parts: (A) a reference case of EMPIRE, (B) the ZENIT analysis of neighbourhood designs and (C) running EMPIRE with the option of investing in neighbourhoods. Part (A) produces input from EMPIRE to ZENIT and part (B) produces input from ZENIT to EMPIRE.

A. Reference case in EMPIRE

Our EMPIRE reference case assumes the European power system is decarbonized towards 2050 without the development of Carbon Capture and Storage (CCS) nor nuclear expansion, i.e. a scenario with strong RES deployment. It also assumes that no major transmission expansion takes place among EU countries (see details in [14]). Energy sources like gas, hydro and biomass are key sources of flexibility to manage a large RES capacity. As Figure 2 illustrates, coal technologies are phased out due to emission targets and a high carbon price. This is substituted by gas and the increase in RES generation from 2025 onward. From 2030, gas declines progressively its annual generation in favour of solar PV and wind. At the EU level in 2050, RES generation represents 64% with an average electricity price of 91.5 €/MWh and the CO_2 price reaches $1,920$ €’$10/tCO_2$.

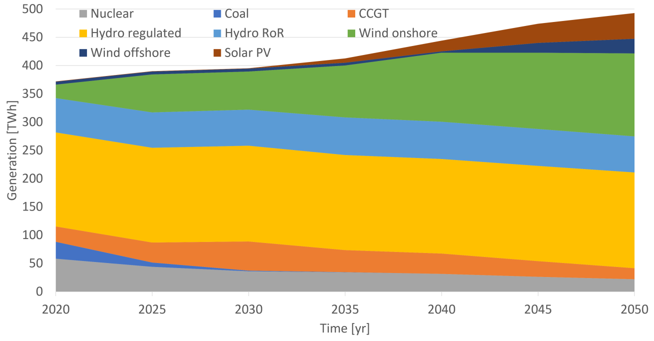

Fig. 2. Generation mix (TWh) for the Nordics in the reference.

B. Neighbourhood designs in ZENIT

ZENIT is run with reference data for each country and year. The designs are responses to the electricity prices and grid CO_2 factors resulting from the EMPIRE reference case (see Table I).

TABLE I
CO_2 FACTORS RESULTING FROM EMPIRE

[gCO2/kWh]	Denmark	Finland	Norway	Sweden
2025	264.8	141.7	17.0	44.0
2030	247.3	112.5	17.0	40.0
2035	170.1	86.3	17.0	40.0

The optimal ZEN design is based on a combination of batteries and solar PV for the electric part of the system in every country. For the heat part, a combination of heat pumps, boilers and heat storage is optimal. The complete designs for each case are presented in Figure 3.

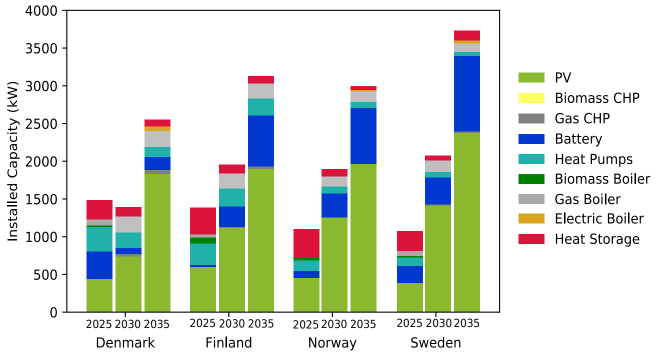

Fig. 3. Design of the ZEN for each country and each year

The electric part of the system is based on PV and batteries in each case, and with a small CHP in a few cases. There is no case of a design solely based on biomass CHP without PV, which could also fulfill the zero emission constraint. It is not optimal due to high costs compared to the PV design.

To be able to compare a CHP design and a PV design, an optimization is run with an investment cost for PV 5 times higher than in the previous case. The resulting design is based on biomass CHP in Denmark and Finland in the year 2025 and 2030. It remains PV-based for the other cases.

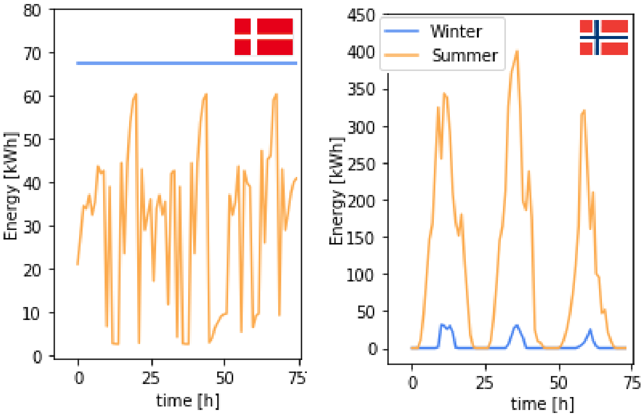

Fig. 4. Contribution from neighbourhoods in Denmark (CHP design) and Norway (PV design) in 2025

Figure 4 shows a sampled supply profile for 3 days used in EMPIRE to represent the contribution from investment in ZENs. In the CHP design (see Figure 4, left), the load contribution is constant in the winter. The CHP is a base load for heat production, and the electricity is a by-product used either locally or sold to the grid. In the summer, the profile is volatile due to varying heat- and electric demand and varying electricity price. Ramping constraints are not included in this version of ZENIT, and it should be noted that this volatility might be unrealistic. In the PV design (see Figure 4, right), the profile is dominated by PV and follows insolation conditions in winter and summer.

C. Choice of neighbourhood design in ZENIT-EMPIRE

EMPIRE is run twice, using the outputs of the two runs presented in Section III-B (Optimal PV designs and non-optimal CHP designs).

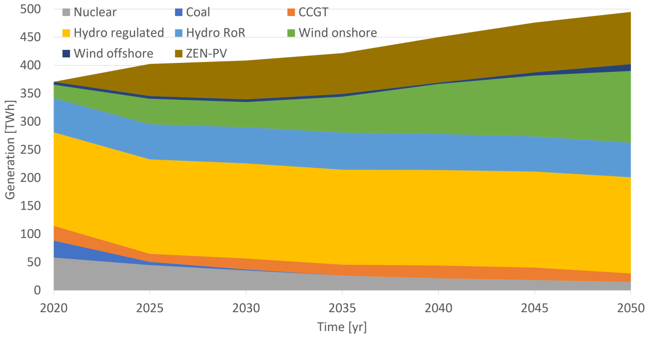

Fig. 5. Generation mix (TWh) for the Nordics with ZEN-PV.

In the first run, all PV designs for year 2035 from Section III-B are developed in the four countries, where neighbourhoods in Sweden makes the biggest contribution. Investments in ZEN mainly decrease closed cycle gas turbine (CCGT) investments and some wind investments in the Nordics compared to our reference (see Figure 2 and 5). Investments in ZEN-PV are also larger than in solar PV alone in the reference, and they contribute with about 93 TWh/yr by 2050. Emissions and costs decrease in all Nordic countries except Sweden compared to the reference in 2050, and emissions decrease in the Nordics by around 20% (from 6.2 to 5.0 MtCO2).

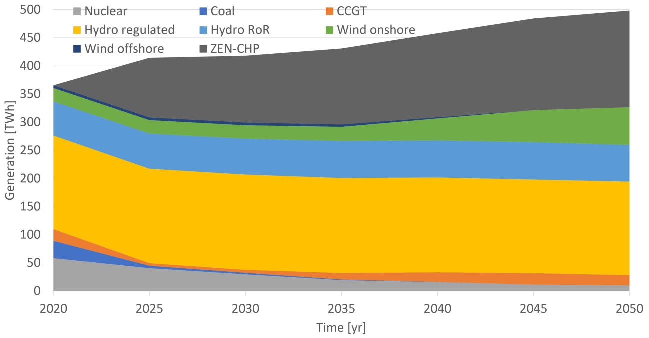

Fig. 6. Generation mix (TWh) for the Nordics with ZEN-CHP.

In the second run, EMPIRE invests in the CHP design in Denmark and Finland (see Figure 6). No PV designs are optimal in this case. Again, investments in CCGT decrease, and more wind investments are replaced with ZEN compared to when the PV designs are developed (see Figure 5 and 6). ZEN-CHP investments are biggest in Finland, and the total generation by ZEN-CHP in 2050 correspond to about 170 TWh/yr. Total emissions in the Nordics decrease by around 10% with emissions in the Nordics dropping from 6.2 to 5.5 MtCO2 compared to the reference in 2050. Emissions and costs decrease in Finland and Denmark, but increase in Norway and Sweden.

IV. DISCUSSION

The two main designs (ZEN-PV and ZEN-CHP) from Section III-B have their own advantages and drawbacks. ZEN-PV imports electricity in the winter to fuel the heat pumps and exports electricity in the summer. It benefits from the low investment cost of heat pumps. ZEN-CHP needs a big investment in a biomass CHP unit, and it has higher operational cost. However, it can operate with little import from the grid. This is beneficial in Denmark where the CO_2 factors of electricity is relatively high. The two designs are interesting to compare because EMPIRE only has an electric view. Even though ZEN-CHP is not optimal when considering the whole energy system of a neighbourhood, it provides stable electricity output and has a low cost in EMPIRE (since only the electrical part is accounted for). On the other hand, ZEN-PV has most of its cost related to the electric part of the system.

With investments in ZEN-PV, emissions decrease and more PV is introduced compared to the reference case. This can be due to two factors: (1) different solar profiles used in EMPIRE and ZENIT and (2) batteries contributing to a more attractive profile in EMPIRE. More integrated data for the two models could identify the most contributing factor.

Our results assume investments in neighbourhoods in EMPIRE does not contribute to emissions. It should be noted that ZENIT is optimizing the cost with a CO_2 balance (not minimizing CO_2 emissions). In 2035, the least expensive ZEN design consists massively of PV (due to its low cost) and is thus able to produce heat from cheap gas units to a larger extent (see Figure 3). However, the electrical part of both designs provide very low emissions.

The investment costs for ZEN in EMPIRE only represent the cost of supplying electricity from the neighbourhoods. This cost assumption is made because EMPIRE only considers capacity expansion of the power system. The cost of providing electricity from a CHP unit depends on what the generated heat is used for. Here, we assume that the cost of providing heat is covered in a separate market, and that the electricity provided is a rather cheap by-product of producing heat for neighbourhoods.

Results providing large investments in ZEN-CHP raises the question of feasibility of these investments. The total potential for biomass in the Nordics exceed the annual need by 2050 [15] (see Section III-C). However, the demand for biomass in other sectors (e.g. transportation and food) could challenge the availability of fuel for CHP plants. Further, burning biomass in urban areas might cause a lot of unwanted local pollution [16].

V. FUTURE WORK

Some potential contribution from neighbourhoods are not captured by this study. One part relates to the synergy between electricity and other energy carriers providing heat. Gain can be obtained by reducing the heat demand of buildings through investment in building performance measures such as insulation. The extent to which the electric load would be affected by changes in heat demand (using for example biomass rather than electricity) is not captured in this analysis. These aspects would play a role in countries were electricity is providing a big part of the heat demand, such as in Norway.

Moreover, the effects of investing in more efficient technologies (i.e. decreased electric demand in neighbourhoods) will affect the electric load. The effects of local energy efficiency measures on local electric load profiles needs to be investigated, and could be incorporated in future work.

A more computationally demanding part relates to the flexibility provided by neighbourhoods. Due to soft-linking limitations, the current method can only investigate the value of local development independent of the larger power system. To investigate the extended flexibility potential in neighbourhoods, decisions locally and centrally must be coordinated in a common model framework.

VI. CONCLUSION

In this study, we focused on investments in the energy system of neighbourhoods and showed how distributed energy production could help reach CO_2 targets. Results indicate the development of distributed energy generation in neighbourhoods in the Nordics is attractive for the power system under certain assumptions.

This work is a demonstration of the soft-linking of two models to better understand different aspects of the energy transition. Future work can better include three aspects in the model framework: (1) synergy between demand and supply of heat and electricity, (2) local energy efficiency investments and (3) coordinated flexibility options. Including these aspects can alter both the optimal ZEN design and their value in the larger power system.

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