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Impact of the CO_2 factor of electricity and the external CO_2 compensation price on zero emission neighborhoods' energy system design

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ABSTRACT

Existing literature on Zero Emission Neighborhoods (ZENs) and Buildings (ZEBs) only allow for reaching the zero emission target locally. This paper evaluates the impact of allowing to buy CO_2 compensation to reach that target in the design of ZENs. This is motivated by questions regarding the relevance of investing in local renewable production (mainly from PV) in a power system dominated by renewable hydropower. Further, it contributes to the existing literature regarding ZENs and ZEBs by highlighting the importance of the choice of the CO_2 factor of electricity for the design of ZENs' energy system.

A case study illustrates the impact of those choices on the resulting energy system design using the existing ZENIT model. Three CO_2 factors for electricity are used in the case study: a yearly average CO_2 factor for Norway (18 gCO_2/kWh), an hourly average CO_2 factor for Norway and a yearly average European factor (at 132 gCO_2/kWh). The energy system design of the ZEN is little affected when using hourly CO_2-factors compared to yearly average factors, while the European factor leads to less investment in PV. Hourly marginal CO_2 emission factors are also investigated using three accounting methods. There large differences in energy system design and emissions depending on where the factor is applied. The price of external compensation is varied between 0–2000 €/tonCO_2. A lower price of external CO_2 compensations mainly reduces the amount of PV investment. Allowing the purchase of CO_2 compensations at 250 €/tonCO_2 could reduce the total costs by more than 10%.

1. Introduction

Zero Emission Neighborhoods (ZEN) are gaining attention as a solution to the sustainability problem of current buildings and cities. To qualify as a ZEN, a neighborhood should have net zero emissions of CO_2 over the lifetime of its invested assets. Depending on the level of ambition, this can include only the operation part or, in addition, the construction, materials and deconstruction. The net zero emissions are reached when the emissions are completely compensated. To do this, it is necessary to make assumptions on the CO_2 factors, in particular for electricity, and on the compensation mechanism that allows to reach net zero emissions.

In order to guide the design of the energy system of such neighborhoods, a tool called ZENIT, which has been previously developed, is used in a case study. It uses a Mixed Integer Programming (MIP) optimization to minimize the cost of investing in and operating the energy system of a ZEN. In ZENIT, we consider that the electricity from on-site renewable sources exported to the grid prevents an amount of emissions corresponding to the electricity that would have been produced and fed to the grid from more carbon-intensive sources without this export. However, what should the CO_2 factor be for this replaced electricity, and in particular what is the impact of using annual average factors versus using hourly average or hourly marginal CO_2 factors? In addition to this question, we also discuss the value of using different compensation mechanisms in addition to the compensation by exportation of on-site electricity presented earlier. We discuss in particular the purchase of emission allowances on the European Emission Trading System (ETS), the compensation mechanism offered by carbon offsetting companies and finally carbon capture and storage (CCS). The impact on the design of the energy system of a ZEN is investigated analyzing the change in the results from variations of the price of carbon offsetting options.

The existing literature presented in Section 2 does not allow to have a good understanding of the factors to use in investments models for the energy system of ZENs in particular in Norway and does not explore the effects of modifying the definition of compensation to allow for more than only compensation from local sources. Indeed, the literature on designing energy system for Zero Emission Building,

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Nomenclature

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

Parameters

α_i	Part load limit as ratio of installed capacity
$\dot{Q}_{st}^{max}$	Maximum charge/discharge rate of est/hst [kWh/h]
η_{est}, η_{hst}	Efficiency of charge and discharge
η_{inv}	Efficiency of the inverter
η_i	Efficiency of i
$\phi_f^{CO_2}$	CO_2 factor of fuel type f [gCO_2/kWh]
$\phi_t^{CO_2,e}$	CO_2 factor of electricity at t [gCO_2/kWh]
σ_κ	Number of occurrences of cluster κ in the year
$\epsilon_{r,D}^{tot}$	discount factor for the duration of the study D with discount rate r
C^{HG}	Cost of investing in the heating grid [€]
$C_{i,b}^{maint}$	Annual maintenance cost of i in b [€/kWh]
$C_{i,b}^{var,disc}$, $C_{i,b}^{fix,disc}$	Variable/Fixed investment cost of i in b discounted to the beginning of the study including potential re-investments and salvage value [€/kWh]/[€]
C_{sl}	Cost of external carbon offsetting [€/gCO_2]
$COP_{hp,b,t}$	Coefficient of performance of heat pump hp
G^{stc}	Irradiance in standard test conditions: 1000 W/m^2
IRR_t^{tilt}	Total irradiance on a tilted plane [W/m^2]
M	Big M, taking a large value
P^{grid}	Electricity grid tariff [€/kWh]
$P_{hp,b,t}^{input,max}$	Maximum power consumption from manufacturer's data and output temperature [kW]
P^{ret}	Retailer tariff on electricity [€/kWh]
P_f^{fuel}	Price of fuel f [€/kWh]
P_t^{spot}	Spot price of electricity at t [€/kWh]
T^{coef}	Temperature coefficient
T^{noct}	Normal operating cell temperature [°C]
T^{stc}	Ambient temperature in standard test conditions [°C]
T_t	Ambient temperature at t [°C]
X_i^{max}	Maximum investment in i [kW]
X_i^{min}	Minimum investment in i [kW]

Variables

$\overline{x_{i,b,t}}$	Maximum production from i [kWh]
b^{HG}	Binary for the investment in the Heating Grid
$b_{i,b}$	Binary for the investment in i in b
$d_{e,t,b}$	Electricity consumed by e in b at t [kWh]
e^{sl}	Emission compensated via external carbon offsetting [gCO_2]
$f_{f,t,b}$	Fuel consumed by f in b at t [kWh]
$g_{g,t,b}$	Electricity generated by g at t [kWh]
$g_{t,g,b}^{ch}$	Electricity generated by g used to charge the 'prod' batteries at t [kWh]
$g_{t,g,b}^{selfc}$	Electricity generated by g self-consumed in the neighborhood at t [kWh]
$o_{i,t,b}$	Binary controlling if i in b is on or off at t
$q_{t,st,b}^{ch}$, $q_{t,st,b}^{dch}$	Energy charged/discharged from the neighborhood to the storage at t [kWh]
$q_{q,t,b}$	Heat generated by q in b at t [kWh]
$v_{t,st,b}^{stor}$	Level of the storage st in building b at t [kWh]
$x_{i,b}$	Capacity of i in b
$y_{t,est,b}^{ch}$	Electricity charged from on-site production to est at t [kWh]
$y_{t,est,b}^{dch}$	Electricity discharged from est to the neighborhood at t [kWh]
$y_{t,est,b}^{exp}$	Electricity exported from the est to the grid at t [kWh]
$y_{t,est,b}^{imp}$	Electricity imported from the grid to est at t [kWh]
$y_{t,g,b}^{exp}$	Electricity exported by g to the grid at t [kWh]
y_t^{imp}, y_t^{exp}	Electricity imported from the grid to the neighborhood/exported at t [kWh]

Zero Emission Neighborhood or other low emission buildings have only used yearly average [1–7] or monthly average [4] factors. Hourly average factors were used in [8] and [9] but not in the context of zero emission structures. Marginal factors are investigated by [9] but again not in the context of ZEN and with a questionable accounting of the emissions. Therefore, the literature does not provide good insights into the consequences of using hourly average and marginal emission factors for electricity for designing the energy system of ZENs. Moreover, the literature on ZEN only look at the relaxation of the ZEN criteria by reducing the ambition objective (by setting to compensate only a percentage of the emissions) such as in [2] but does not investigate a relaxation of the requirement for the compensation to be "local".

This paper extends the existing literature on low emission neighborhood energy system design, and in particular ZENs' energy system design, with new results on the impact of the CO_2 factor of electricity and relaxation of the "local" constraint on compensation on the design of the energy system of a ZEN.

In this paper, we perform a case study of a neighborhood in Norway, Evenstad, and use an optimization model, ZENIT, that minimizes total cost under the strong requirement of having zero CO2-emission over its entire lifetime. Section 3 presents the concept of ZEN and of compensation and goes into more detail in the calculation and choice of CO_2 factors of electricity. The model is presented in Section 4, the case study in Section 5 and the results in Section 6.

2. Literature review

Choosing the CO_2 factors for a generation type is not problematic thanks to the available data from, for instance, IPCC [10] or the Ecoinvent database [11]. The CO_2 factor of electricity for a country or a bidding zone is more complex. Indeed, not only is the production inside the zone important but also the imports from other zones. The origin of the power thus needs to be traced to obtain a good estimate of the emission factor. Another problem is how the factors change with a change in electricity demand. The marginal factors of CO_2 emissions can be defined as the change in emissions from producing or consuming 1 unit more (or 1 unit less) of electricity. One assumption that can be made is that it is the marginal unit in the merit order curve of the spot market for that hour that sets this marginal factor, but the units of the balancing market could also be considered.

The various possibilities of emission factors raise the question of which one to use. [12] made an algorithm to help select the appropriate emission factor of electricity based on one's application.

It is interesting to look at what emission factors are used in various studies and for different applications. In [13], marginal hourly emission factors are used to analyze the trade-offs between revenue and emission reduction for operating a battery system. The marginal emission factor is used to represent the emission reduction due to the battery intervention.

In [14], the consequences of the electrification of oil platforms on emissions of CO_2 were investigated using, in particular, the EMPS model. Different emission factors (Norway alone, Norway and countries it is connected to, Nordic countries and Europe), both average and marginal, are also presented in a scenario including new policies implemented by European countries.

[15] uses average factors and three different definition of marginal factors on industrial battery systems to study the impact on emissions and on operation. [16] and [17] investigate emission factors of electricity for electric vehicles in California. [16] defines emission factor on three dimension: average/marginal, aggregated/temporally explicit (hourly factors for instance) and retrospective/prospective; and discusses and compares them in the context of electric vehicles in California. [17] used marginal factors for investigating the impact of the additional load from electric vehicles on emissions and compared them with those of conventional vehicles.

The use of marginal factors in the case of electric vehicles or batteries is justified because they add or remove load from the system in a relatively unpredictable way. The use of hourly factors also allows to take advantage of the arbitraging potential of these units.

In the context of designing buildings' envelope (materials, thickness), [18] uses yearly average emission factors for the operation part of the analysis in the multi-objective optimization considering cost and emissions.

We can also look at what kinds of factors have been used in past studies for designing the energy system of neighborhoods or buildings.

The design of the energy system of ZEBs are investigated in [1,2] and [3]. The value of 130 gCO_2/kWh is used for the Nordic countries and 350 gCO_2/kWh when considering the European mix instead. In [1], it is found that using asymmetrical factors (different for imports and exports) in the context of ZEBs leads to a higher investment in PV panels.

It should be noted that ZEB can also stand for Zero Energy Buildings. We can refer to [19] for a review of the various definitions and calculation methodologies. More recently [20] also provides a review of the definitions and of the different existing optimization approaches to designing different aspects of Zero Energy and Emission Buildings.

[4] focuses on Zero Energy Buildings but also investigates the use of yearly and monthly average CO_2 factors for electricity, in a 2010 setting and a scenario for 2050. It finds that using CO_2 factors for the EU 2050, which are relatively low, makes it harder to be zero energy/zero emission because of the higher amount of PV needed, which is most often incompatible with available roof area. This results in systems using the grid as a seasonal storage. Those effects should be taken into account when selecting which factors to use.

In an optimization model investing in the energy system of a neighborhood and considering refurbishment [5] constrains the emissions and uses a yearly average CO_2 factor of Croatia for electricity as well as a carbon cost. A yearly average factor is also used in [6] in a sensitivity analysis on emission reduction for the design of the energy system of a neighborhood in the UK. For a similar model in Switzerland, [7] also uses yearly average value.

In a similar model, [8] uses half-hourly marginal electricity emission factors for the UK calculated based on the method of [21].

The consequences of using hourly factors instead of annual average in LCA (life cycle analysis) evaluation of houses have been demonstrated in [22].

An aggregate average factor is used in [23] in one of the objective functions of its multi-objective optimization model.

Very few instances of the use of marginal factors in the context of the investment in the energy system of neighborhood were found in the literature. For neighborhood energy systems, [9] compares accounting approaches with both hourly average and marginal factors of electricity. The marginal factors of Austria are derived from a merit order approach. When using marginal factors, the study however seems to account for all emissions of the energy system of the neighborhood with that factor. This is a questionable assumption as only the extra production or consumption from a base case scenario should use the marginal factor. [24] uses hourly marginal factors for accounting the carbon tax due to the imports of electricity to a microgrid in the objective function of its model that selects, size- and place-distributed energy resources in a microgrid.

The optimal choice of factors is dependent on the application. [12] is an example of a tool that can help with this choice. The choices and their consequences are not always justified in the literature. The literature on investments in the energy systems of neighborhoods presented above shows the use of many different emission factors. They are most often aggregated factors, in particular yearly, and prospective [4] or retrospective [2,3,5–7,23]. Only [8] and [9] use emission factors at a finer temporal resolution. The variety of choice indicates a lack of consensus on which factors to use for such applications. The higher representation of aggregated factor could be rather due to an ease of access than because they are the best solution. The hourly factors are harder to obtain but could improve the operation to take advantage of variations in hourly CO_2 factors. Marginal factors are even more difficult to obtain and often require many questionable assumptions that limit their use.

Despite the existing literature, there remains gaps in the knowledge regarding the factor to use specifically for the design of the energy system of ZENs. [2] and [4] considers non-symmetrical weighting factors but do not consider hourly factors. In addition, while [4] looks into the impact of different factors, it does so via a simulation and a calculation of the emissions of different existing energy systems, not always at a hourly resolution and finds the amount of PV needed to reach the net zero emissions. The factor to use in the context of ZENs' energy system's investment remains unclear. Another gap in the literature is on the definition of the ZENs and of what can be compensation in particular. The literature only considers strictly local compensations and do not explore the consequences of allowing other compensation means on the design of the energy system of ZENs.

This paper contributes to the existing literature by:

- Discussing the relevance of various compensation mechanisms that can help achieve net zero emission in neighborhoods inside or outside the local setting of the usual framework.
- Investigating the impact of the choice of CO_2 factors for electricity on the resulting energy system of ZENs
- Analyzing the impact of different emission compensation measures price points on the design of the energy system of ZENs

3. CO_2 Factors of electricity and compensations

3.1. ZEN/ZEB concept

Zero Emission Neighborhoods (ZENs) are neighborhoods that should have net zero emissions of CO_2 during their lifetime. This implies a carbon balance with on the one side the emissions and on the other the compensations. There are many sources of carbon emissions in the lifetime of a neighborhood: materials, construction, deconstruction, electricity use and heating of the buildings, transportation of people and goods are the main ones.

The research center on Zero Emission Buildings (ZEBs)[1] defined the CO_2 factors to be used in the design of buildings aiming to be ZEBs with a yearly average value of 132 gCO_2/kWh. This value was set based on the results from [25], and represents an average factor of the electricity mix in Europe for the period of 2010–2050 in a very optimistic European scenario.

Not emitting greenhouse gases is the best way to have a positive impact on the environment and reduce the need for compensations in the neighborhood. However, ZEBs and ZENs eventually do cause CO_2 emissions, and exporting renewable electricity to the grid, most often with PV, is necessary to compensate emissions locally. The concept of zero emission neighborhood (or building) considers that the export of electricity produced on-site from renewable sources and exported to the grid will replace the production of more carbon-intensive sources. In ZENIT, we count the emissions prevented in this way as the compensations. This causes challenges such as high additional investment costs, and, if the concept is generalized, grid stability and dimensioning issues. Thus this paper discusses the possibility of investing in CO_2-reducing measures outside of ZENs as an alternative to reach the balance locally.

3.2. Literature on calculation of CO_2 factors of electricity

The value of the CO_2 factor for electricity used is important for ZENs because it is involved in the accounting of the emissions from the imports of electricity as well as the compensations from exporting on-site renewable electricity.

The existing literature contains several methods for calculating the emission factors of countries. [26] gives an example of a methodology; *annual average* emissions for OECD countries were calculated with a production-based method and a consumption-based method, highlighting the differences in results for certain countries.

A methodology for calculating *hourly average* CO_2 emissions is presented in [27], where they were computed for Europe with a particular focus on Norway. It uses a multi-regional input–output approach to trace the origin of the electricity consumed in each bidding zone to a generation type and calculate the CO_2 factors. [28] and the electricityMap website[2] use a similar approach.

[29] calculates the *marginal* CO_2 factors for the UK by reconstructing the merit order curve using historical half-hourly generation from all plants and assuming that the marginal unit is the last one dispatched in the merit order curve.

Using historical data of actual generation per generator type, [21] calculates the *marginal* emission factor. The sum of the generation gives the demand while using the emission factor of each generation type gives the emissions. A regression is then performed on the emission as a function of the total demand to estimate the CO_2 factor variation when changing the demand. The method is applied to Great Britain. A similar method is applied to Spain in [30]. In [31], the long-run marginal CO_2 factors are calculated with the methodology of [21] but also considering the commissioning and decommissioning of plants, with marginal factors defined as the change in CO_2 emission in the system due to the commissioning or decommissioning of plants and to resulting changes in operation.

In New Zealand, [32] analyzed the average and marginal hourly CO_2 factors for the country, finding that hydropower was the main marginal element. They also make policy proposals based on their findings and argue, for instance, for the use of time-varying factors as a trigger for demand-side responses.

For Finland and the other Nordic countries, [33] calculated hourly average and marginal CO_2 factors for 2009, 2010, and also based on a scenario for 2030 for Europe, the Nordic countries together and each Nordic countries separately.

Both methods for calculating the marginal emissions factor have drawbacks. The method based on recreating the merit order needs to make assumptions and group generators into types and often cannot account for specific cases that arise due to ramping constraints or minimum up- and down-time. The other method is based on a linear regression which simplifies the actual marginal factors and cannot be applied to every countries, the fit of the regression depending on the specific power system. A third approach is to use Expansion planning and market models to obtain prospective marginal factors. Their precision then depends on the quality of the models used to obtain them and their assumptions.

In the case of Norway in particular, [25] also studied the CO_2 factors of electricity, both marginal and average, in a long-term approach based on scenarios from the European Union and the EMPS model. The EMPS models the European power system and market with a particular focus on hydropower production and Norway. However, the emission factors obtained do not allow to account for the hourly and seasonal variations in the electricity mix both now and in the future.

3.3. Considerations for selecting a CO_2 factor of electricity

Several considerations should be taken into account when making the decision on which CO_2 factors of electricity to use when designing a ZEN. One initial choice is whether this factor should be the same for the imported as for the exported electricity. Indeed, what is the carbon intensity of the electricity consumed and exported? When it comes to imported electricity, there should be no difference between the consumption from a ZEN and from any other standard building. In practice, since the electron cannot be traced back to a source at the consumer level, a more global factor needs to be used. The electricity mix of the bidding zone is relevant at the local level and can be computed (such as in [27]), thus making it a good choice for this role.

For the electricity exported, stricto-sensu, the emissions depend on the source and fuel that produced it. No emissions for PV panels, and the emissions corresponding to the burnt fuel for a gas CHP for example. Another approach is to consider the emissions in an LCA approach, i.e. considering the construction and other life cycles of the technology, it changes for example the emissions for PV, which are no longer zero. In the zero emission balance presented earlier, we consider the difference between the emissions from the electricity we export from on-site sources and the electricity it replaces in the grid. This electricity that is replaced also needs to be defined. Do we consider that the electricity replaced is based on the electricity mix, or do we replace the marginal unit, i.e. the last unit on the unit commitment curve, and should therefore use the carbon intensity of that unit?

It is also important to consider the case of a large number of ZENs in the power system. This changes the previous reasoning because it is now reasonable to consider that the ZENs are sufficiently numerous to influence the market. In this scenario, considering their significant power production, the ZENs would take part in the day-ahead market in the load forecast or as actors. In that case, the principle is the same but it becomes difficult to assess what the neighborhoods' electricity replaces. Indeed, the marginal intensity only holds in the vicinity of the clearing point. When moving away from the vicinity of the clearing

[1] https://www.zeb.no/

[2] https://www.electricitymap.org/

point, it is possible that several units have been "replaced" by the ZEN production. Those units are ordered in the market clearing by their costs, but their emissions are not following the same order. A possibility is to use the emission intensity of the replaced units weighted by the replaced amount of electricity. This, nevertheless, cannot easily be used in the investment optimization because the change in power production results in a change in the carbon intensity in a non-linear manner. Furthermore, this would require complete information of the market clearing and each bidding units.

In the same way, a large amount of ZEN would impact the average CO_2 factor of an area. Both of those impacts can be considered by coupling a model such as ZENIT and a European market and expansion planning model. The coupling could be a soft-linking iterating through each model or a hard-linking co-optimizing both the energy system and the ZENs. This approach would allow to obtain ZENs adapted to each zone and to the evolution of the power system, but can only produce generic neighborhoods and not reasonably be used to design the energy system of a specific one. [34] gives an example of such an approach.

4. Model presentation

ZENIT (Zero Emission Neighborhood Investment Tool) is presented in this section. ZENIT searches for the cost-optimal energy system for a given neighborhood to be zero emission through a MILP optimization. One representative year is used instead of the whole lifetime for computation reasons. This model is an extension of [2] and is partially presented in [35].

Minimize:

$$b^{HG}\cdot C^{HG}+\sum_b\sum_i\Bigg((C^{var,disc}_{i,b}+\frac{C^{maint}_{i,b}}{\varepsilon^{tot}_{r,D}})\cdot x_{i,b}+ C^{fix,disc}_{i,b}\cdot b_{i,b}\Bigg)+\sum_{t_\kappa}\frac{\sigma_\kappa}{\varepsilon^{tot}_{r,D}}\Bigg(\sum_b\sum_f f_{f,t,b}\cdot P^{fuel}_f + (P^{spot}_t+P^{grid}+P^{ret})\cdot(y^{imp}_t + \sum_b\sum_{est} y^{imp}_{t,est,b}) - P^{spot}_t\cdot y^{exp}_t\Bigg)+e^{sl}\cdot\frac{C^{sl}}{\varepsilon^{tot}_{r,D}} \tag{1}$$

The objective function (Eq. (1)) minimizes the cost of investing in and operating the energy system of the neighborhood as a whole and does not find the optimal investment of each building taken separately. It considers the fix and variable investment cost of the different technologies ($C^{var,disc}_{i,b}$, $C^{fix,disc}_{i,b}$) and the heating grid (C^{HG}), as well as operation- and maintenance-related costs ($C^{maint}_{i,b}$). A binary variable controls the investment in the heating grid (b^{HG}). The subscripts used in the equations are b for the buildings, i for the technologies, t for the timesteps, f for fuels and est for batteries. ε are the discount factors with interest rate r for the duration of the study D. $x_{i,b}$ is the capacity of the technologies and $b_{i,b}$ the binary related to whether it is invested in or not. σ_κ is the number of occurrences of cluster κ in the full year and t_κ is the timestep in the cluster. P are the prices of fuel, electricity on the spot market, grid tariff or retailer tariff. f is the consumption of fuel and y are the imports or exports of electricity. The external compensations that can be purchased are e^{sl}.

In ZENIT, the ZEN compensation framework introduced in Section 3.1 is used. In addition, the electric and heat loads of the buildings are inputs to the model so the impact of energy efficiency measures such as better insulation for refurbished houses needs to be accounted for in the load profiles given to the model. The zero emission balance constraint is used to enforce the Zero Emission requirement:

$$\phi^{CO_2}_{e,t}\sum_{t_\kappa}\sigma_\kappa\Big(y^{imp}_t+\sum_b\sum_{est}y^{imp}_{t,est,b}\Big) + \sum_{t_\kappa}\sigma_\kappa\sum_b\sum_f\phi^{CO_2}_f\cdot f_{f,t,b}\le\phi^{CO_2}_{e,t}\cdot\sum_{t_\kappa}\sigma_\kappa \Big(\sum_b\sum_{est}\eta_{est}\cdot y^{exp}_{t,est,b}+\sum_b\sum_g y^{exp}_{t,g,b}\Big)+e^{sl} \tag{2}$$

The CO_2 factors are represented by $\phi^{CO_2}_{e,t}$ for electricity and $\phi^{CO_2}_f$ for other fuels. η_{est} is the charging efficiency of the battery.

Other equations include load balances for electricity, Domestic Hot Water (DHW) and Space Heating (SH). They require the production and import to be equal to the consumption and exports for all timesteps.

The optimization model can choose to invest in a heating grid, giving access to other technologies. We assume that those technologies are located in a central production plant that feed the heating grid. The operation of the heating grid is then constrained by the flow limitation in the pipes and by a constraint preventing buildings from feeding heat into the grid.

The size of the connection to the electric grid limits the exports and imports.

For most technologies, the production of heat or electricity is linked to the fuel consumption using the efficiency of the technology.

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

$$f_{\gamma,t,b}=\frac{q_{\gamma,t,b}}{\eta_\gamma} \tag{3a}$$

$$d_{\gamma,t,b}=\frac{q_{\gamma,t,b}}{\eta_\gamma} \tag{3b}$$

For CHPs the electricity produced is the ratio of the heat produced and the heat to power ratio α_{CHP}.

The heat produced can be used for DHW or for SH but some technologies can only provide SH (such as electric radiators or wood stoves).

The production from PV and solar thermal collectors depends on the irradiance on a tilted surface IRR^{tilt}_t and their efficiency. The efficiency for the solar panel η^{PV}_t is defined based on [36] and accounts for the cell temperature T_c and inverter losses.

$$\eta_{PV,t}=\frac{\eta^{inv}}{G^{stc}}\cdot\left(1-T^{coef}\cdot(T^c-T^{stc})\right) \tag{4a}$$

$$T^c=T_t+(T^{noct}-20)\cdot\frac{IRR^{tilt}_t}{800} \tag{4b}$$

For the heat pumps in the buildings, the production and electrical consumption are defined as follows:

$$d^{SH}_{hp,b,t}=\frac{q^{SH}_{hp,b,t}}{COP^{SH}_{hp,b,t}} \tag{5a}$$

$$d^{DHW}_{hp,b,t}=\frac{q^{DHW}_{hp,b,t}}{COP^{DHW}_{hp,b,t}} \tag{5b}$$

$$\frac{d^{DHW}_{hp,b,t}}{P^{input,max,DHW}_{hp,b,t}}+\frac{d^{SH}_{hp,b,t}}{P^{input,max,SH}_{hp,b,t}}\le x_{hp,b} \tag{5c}$$

Eqs. (5a) and (5b) link the heat produced to the COP and the electrical consumption of the heat pump. The COPs are different for SH and DHW due to different temperature set points. They also depend on the outside temperature and they are calculated before the optimization. Eq. (5c) regulates how the heat pump can be used for both SH and DHW and enforces that the capacity invested is not exceeded. $P^{input,max}$ represents the maximum power input to the heat pump at the timestep based on the temperature set point and for a 1 kW unit. $d^{SH}_{hp,b,t}$ and $d^{SH}_{hp,b,t}$ represent the electric consumption of the heat pump for SH and DHW while $q^{DHW}_{hp,b,t}$ and $q^{DHW}_{hp,b,t}$ are the heat production. The data used to calculate the heat pumps COP and maximum power is based on manufacturer's data[3]

Other binary variables are used for part load limitations. These binary variables concern the operation and are defined for every timestep for each relevant technology, which can lead to a large number of binary variables. No minimum up- or downtime is used. $\forall i\setminus HP,t,b$:

[3] air–air HP: Bosch BMS500-AAM018-1CSXXA; air–water HP: Stiebel Eltron WPL23; water–water HP: Stiebel Eltron WPF10.

$$\overline{x_{i,b,t}} \leq X_{i,b}^{max} \cdot o_{i,t,b} \quad (6a) \qquad \overline{x_{i,b,t}} \leq x_{i,b} \quad (6b)$$

$$\overline{x_{i,b,t}} \geq x_{i,b} - X_{i,b}^{max} \cdot (1 - o_{i,t,b}) \quad (6c)$$

$$q_{i,b,t} \leq \overline{x_{i,b,t}} \quad (6d) \qquad q_{i,b,t} \geq \alpha_{i,b} \cdot \overline{x_{i,b,t}} \quad (6e)$$

The size of the investment in each technology type is bounded, from below to represent the larger scale of some technologies (Eq. (7)) and from above to limit the size of the research space. $\forall i, b$:

$$X_{i,b}^{min} \cdot b_{i,b} \leq x_{i,b} \leq X_{i,b}^{max} \cdot b_{i,b} \quad (7)$$

Technologies producing electricity can feed this electricity to the neighborhood directly, store it in batteries, export it or dump it.$\forall t, g, b$:

$$g_{g,t,b} = y_{t,g,b}^{exp} + g_{g,t,b}^{selfc} + g_{t,g,b}^{ch} + g_{t,g,b}^{dump} \quad (8)$$

The storage operation, whether heat or electrical storage, is modeled as follows: $\forall \kappa, t_\kappa \in [1, 23], st, b$

$$v_{\kappa,t_\kappa,st,b}^{stor} = v_{\kappa,t_\kappa-1,st,b}^{stor} + \eta_{st,b}^{stor} \cdot q_{\kappa,t_\kappa,st,b}^{ch} - q_{\kappa,t_\kappa,st,b}^{dch} \quad (9)$$

$\forall t \in [0, 23], st, b$

$$v_{\kappa,t_\kappa,st,b}^{stor} \leq x_{st,b} \quad (10)$$

$$q_{\kappa,t_\kappa,st,b}^{ch} \leq \dot{Q}_{st}^{max} \quad (11) \qquad q_{\kappa,t_\kappa,st,b}^{dch} \leq \dot{Q}_{st}^{max} \quad (12)$$

$\forall p, st, b, \kappa$

$$v_{\kappa,0,st,b}^{stor} = v_{\kappa,23,st,b}^{stor} \quad (13)$$

The state of charge of the storage st (either heat or electric storage) is represented by v^{stor} while qch and $qdch$ are the energy charged and discharged. The maximum charge and discharge rate is Q_{st}^{max}. This model only allows for the use of representative days and daily storage operation. Details of the process of clustering and choosing an appropriate number of clusters can be found in [35]. Some additional equations can be found in Appendix C.

5. Case study presentation

The model is implemented on a test case based on a small neighborhood, a campus at Evenstad in the Innlandet county in Norway where three building types represent the different buildings there. We use the same implementation as in [35]. All the buildings are aggregated into three building types: student housing, normal offices and passive offices. The student housing is a single building of 4200 m^2 of floor area and 1000 m^2 of roof area. The passive offices are buildings built at the ZEB and passive standard and represent 1141 m^2 of floor area and 900 m^2 of roof area. The normal offices comprise the remaining buildings for 3375 m^2 of floor area and 2000 m^2 of roof area. The location of the buildings are also used to create a grid layout that is used inside the optimization. The buildings' envelopes are not necessary as the energy consumption and building dynamics are exogenous to the optimization. In our case, we assume that they are part of the hourly Domestic Hot Water (DHW) and Space Heating (SH) load profiles.

The electric and heat hourly load profiles for the campus are derived from [37]. The share of DHW and SH in the heat load are then based on the time series from a passive building in Finland [38]. The annual loads are presented in Table 1.

Refurbishment of the building envelope is not considered in this study. It can be accounted for exogenously by adapting the timeseries and could also be endogenously integrated to the model but we choose to limit our scope strictly to the energy system of the neighborhood.

Table 1
Yearly total electricity, DHW and SH load for the three buildings groups considered in the optimization of their energy system.

Building group	Electricity load	DHW load	SH load
Student housing	161 414 kWh	45 238 kWh	199 752 kWh
Normal offices	612 336 kWh	45 562 kWh	300 476 kWh
Passive offices	146 092 kWh	6 456 kWh	44 748 kWh

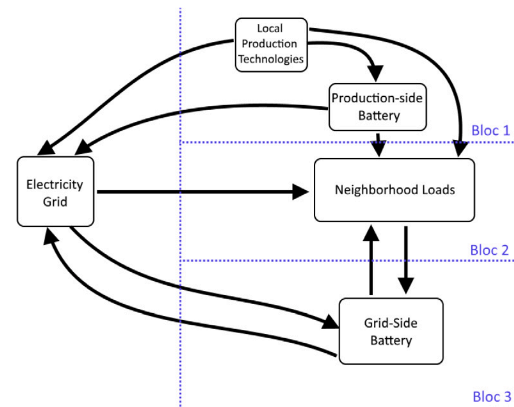


Fig. 1. Representation of the flows of electricity in the neighborhood and in particular between the neighborhood elements and the electricity grid. Three blocs are represented to facilitate the comprehension of the different approaches.

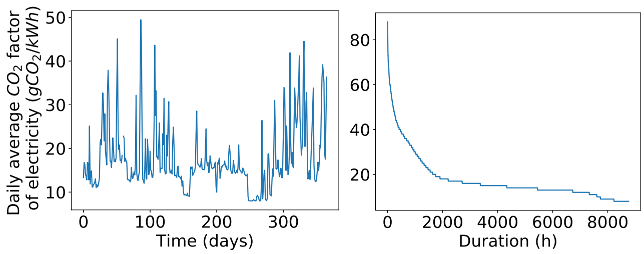
Table 2
Summary of the emission factors used in the three cases when investigating marginal emission factors. M: marginal; A: average.

Case name	Bloc 1	Bloc 2	Bloc 3
Case 1: *All*	M	M	M
Case 2: *Local Prod*	M	A	A
Case 3: *Local Prod + Grid Storage*	M	A	M

We compare the results using a yearly average factor of 18 gCO_2/kWh, a yearly average value of 132 gCO_2/kWh and hourly average values for NO1. In addition, for each of the electricity CO_2 factors, two alternatives are investigated in relation to the solar technologies. The first one considers that the investments in solar technologies are limited by the roof area available. The second one considers that other areas in the proximity of the neighborhoods can be used and thus does not take the roof area as a limiting factor. Further, we investigate the use of hourly marginal factors using different accounting approaches, i.e. different combinations of marginal and average electricity emission factors. Fig. 1 represents the flow of electricity in the neighborhood and the blocs that will be used to describe the accounting approaches. In the first approach, we account all the electricity exchanges between the neighborhood and the grid using the marginal factors (bloc 1, 2 and 3). In a second approach, we consider marginal factors only for bloc 1 and average factors for the rest. In the last approach, we consider marginal factors for bloc 1 and 3 and average for bloc 2. The factors are hourly in all cases. Table 2 summarizes the cases in this study.

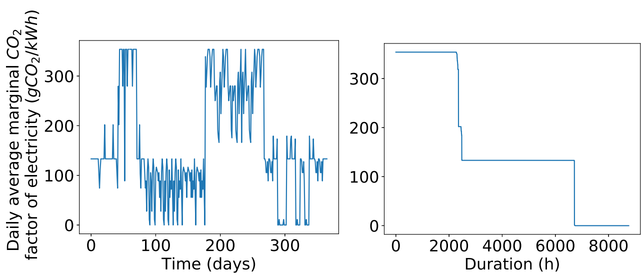
The hourly average CO_2 factor in NO1 is presented in Fig. 2. The yearly average corresponds to the value of 18 gCO_2/kWh introduced earlier but it goes as high as 90 gCO_2/kWh. From the daily average figure, it is clear that there are lower CO_2 factors in the summer months.

The hourly marginal CO_2 factor in NO1 is presented in Fig. 3. This factor is very different from the average one. Indeed, the summer seems to have relatively higher factor than the rest of the year, which should help compensating emissions with PV. Overall the marginal factors are higher than the average factors. Those patterns are not only due to the nature of marginal emission factors but also very specific to Norway where the operation of the high share of hydropower and the



(a) Daily Average (b) Duration Curve

Fig. 2. Daily average and duration curve of the CO_2 factor of electricity in NO1.



(a) Daily Average (b) Duration Curve

Fig. 3. Daily average and duration curve of the marginal CO_2 factor of electricity in NO1.

connection to central Europe leads to electricity imports to Norway when the prices are low.

The three different cases represent different accounting approaches. Case 1 is what is used in [9] but the fact that the whole electricity load of the neighborhood is considered as marginal is dubious. Case 3 addresses that but could lead to the optimization investing in a battery to bypass the average emissions of the neighborhood imports in some cases. This is mostly not relevant in our case due to the particular marginal and average emission factors in NO1 but could be important in other countries. Case 2 does not have this potential bypass but ignore the "unpredictability" of grid side battery operation which would suggest the use of marginal factors. Ultimately the question of what really should be considered marginal remains, and this paper instead shows the outcome of the three approaches.

We also investigate the possibility of external means to reach the necessary amount of compensation. Table 3 presents examples of such means. Carbon offset companies offer the possibility for private individuals and companies to offset their emissions of CO_2 by financing projects such as reforestation, preventing deforestation, or renewable energy in developing countries. There are several companies offering those services[4,5,6,7,8,9] but it is important to note that the efficiency of those companies in reducing CO_2 emissions is debated [39] and depends on specific projects.

The EU Emission Trading System (EU ETS) may also be used as a compensation mechanism. Indeed, if neighborhoods were to buy allowances from the EU ETS and given that the cap on the emission is fixed, this would reduce the amount of available allowances on the market and potentially push more entities towards carbon reduction measures. In the last year, the CO_2 price on the EU ETS has been in the 20 to 30 €/tonCO_2 range.

[4] https://compensate.com/
[5] https://www.atmosfair.de/en/
[6] https://nativeenergy.com/
[7] https://cotap.org/
[8] https://www.myclimate.org/
[9] https://www.cooleffect.org/

Table 3
Examples of external compensation options and their estimated carbon prices.

Compensation type	Compensation price (€/tonCO_2)
Carbon Offset Companies	3–25
EU ETS	20–30
CCS	18–250

Financing carbon capture and storage (CCS) could be another compensation mechanism by financing its use for cases where fossil fuels are still necessary. One of the drawbacks is that it can incentivize to continue using fossil fuels. Various costs from 18 to 250 €/tonCO_2 are reported in the literature [40–42].

The price of the identified external CO_2 compensations (Table 3) may vary between 3 to 250 €/tonCO_2, and to investigate the impact of different price levels, each of the six cases are performed with a price of 0, 15, 30, 50, 75, 100, 250, 500, 1000 and 2000 €/tonCO_2. Those cases are only done with average emission factors.

In the emission balance, we consider only the emissions from the operation phase of the buildings in the neighborhood with a focus on the energy system. This includes the emissions from the use of appliances and for heating. The other emissions could also be included by adding a term to the emission in the zero emission balance, but a good estimate would be necessary. In this study we limit ourselves to the case of a single ZEN, small enough not to influence the clearing of the market. We consider the carbon intensity of on-site sources solely on their production phase (not the LCA approach) and we compare yearly average and hourly average electricity mix carbon intensity both for import and export on the resulting ZEN design. The hourly CO_2 factors for electricity for NO1 are obtained by tracing back the origin of the electricity using the methodology presented in [27]. The production of each generation type and the exchanges between bidding zones are used to determine the resulting mix inside each zone and their corresponding hourly average carbon intensity. This data mainly comes from the ENTSO-E transparency platform and the year 2016 is used. The method presented in [21] for deriving the marginal emission factors does not appear to be suitable for Norway. Applying the same methodology results in a linear regression with a r^2 lower than 0.1. The methodology is not suitable for Norway due to the specificity of the Norwegian electricity market, and in particular the high share of hydropower and the imports of more carbon-intensive electricity. We use results from the EMPIRE model [43], in particular the share of each generation type each hour in NO1 (also considering imports in the same way as for deriving the hourly average emission factors) combined with assumptions on marginal costs of units to find the hourly marginal emissions of electricity in NO1.

The economic and technical data of the technologies are taken from the Danish Energy Agency.[10] In total, 22 technologies are implemented with, at the building level: solar panel, solar thermal, air–air heat pump, air–water heat-pump, ground source heat pump, bio boiler with wood logs or pellets, electric heater and electric boiler, biomethane boiler, biogas and biomethane CHP; and at the neighborhood level: biogas boiler, wood chips and pellets boiler and CHPs, ground-source heat pump and electric boiler. In addition, electric and heat storages are available. Appendix A contains the data used for the different technologies.

The spot price of electricity is obtained from Nordpool's website.[11] The temperature data comes from Agrometeorology Norway.[12] The solar irradiance (diffuse horizontal (DHI) and direct normal (DNI)) are obtained from Solcast.[13] The irradiance on a tilted surface IRR^{Tilt}

[10] https://ens.dk/en/our-services/projections-and-models/technology-data
[11] https://www.nordpoolgroup.com/Market-data1/#/nordic/table
[12] https://lmt.nibio.no, Fåvang station.
[13] https://solcast.com.au

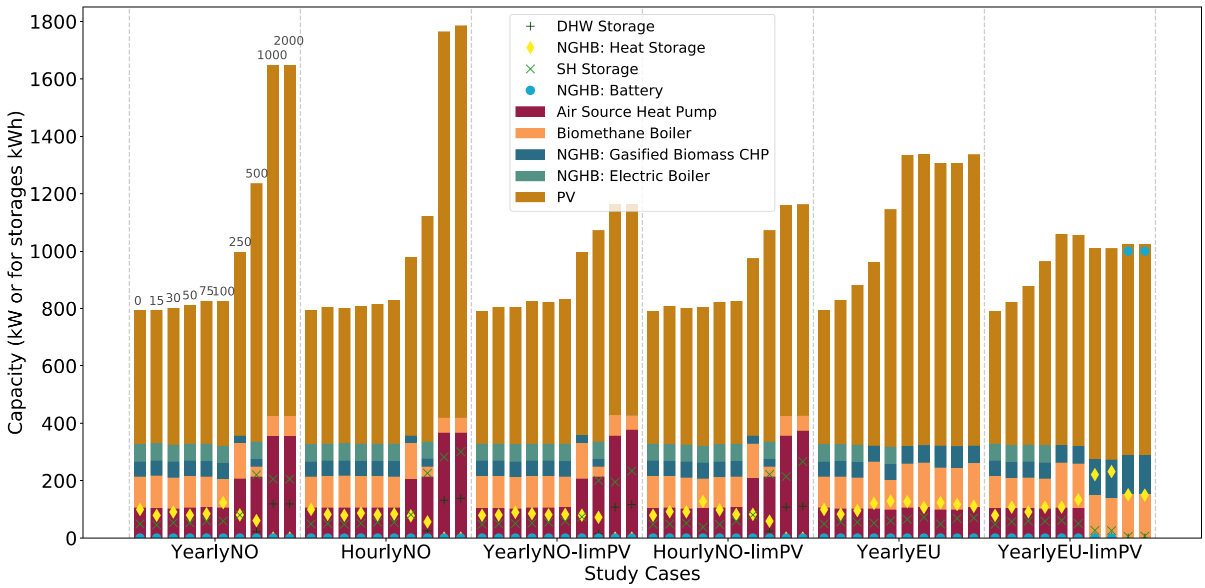


Fig. 4. Investments resulting from the runs grouped by case. The numbers above the bars in the *YearlyNo* case show the CO_2 compensation prices in €/tonCO_2. The same order of prices is used for the other cases. When the technology is at the neighborhood level, its name is preceded by NGHB.

which is an input of the clustering is derived from the DHI and DNI with:

$$IRR_t^{Tilt} = DHI_t \frac{1+\cos(\phi_1)}{2} + \alpha \cdot \left(DNI_t + DHI_t\right)\frac{1-\cos(\phi_1)}{2} + DNI_t\left(\frac{\cos(\varphi_t)\cdot\sin(\phi_1)\cdot\cos(\phi_2-\psi_t)}{\sin(\varphi_t)} + \frac{\sin(\varphi_t)\cdot\cos(\phi_1)}{\sin(\varphi_t)}\right) \tag{14}$$

We assume that for some sun positions (sun elevations (φ) below 1 degree and sun azimuths (ψ) between −90 and 90 degrees), no direct beam reaches the panels. This means that the last term of Eq. (14) is removed at such times. We use a constant albedo factor (α) of 0.3 for the whole year. Hourly albedo values could also be used to better represent the reflection of light on the ground in different conditions, in particular snow in the winter. The tilt angle of the solar panel is ϕ_1; the orientation of the solar panel regarding the azimuth is ϕ_2. We use data from year 2016 for those timeseries as it has been identified as suitable for the investment process [44]. Indeed, out of the years for which the data necessary to compute hourly emission factors are available (i.e. from year 2015), 2016 has electricity prices, temperatures, emission factors and solar irradiance around the average and also has quite low minimum winter temperatures for a good representation of the peak loads.

The price of wood pellets comes from [45], the price of wood logs from [46], the price of wood chips from [47] and the price of biogas from [48].

The model is implemented in Python and is solved using Gurobi. It is run on a laptop with an Intel Core i7-7600U dual core processor at 2.8 Ghz and 16 GB of RAM.

6. Results

6.1. Norwegian CO_2 factors for electricity

Starting with the case using yearly average Norwegian CO_2 factors, *YearlyNO*, and no possibility of external CO_2 compensation (which corresponds in this case to CO_2 compensation prices from 1000 €/ton) we find that the energy system of the neighborhood (Fig. 4) is comprised of around 1 200 kW PV, 350 kW air–water heat pumps and 70 kW biomethane boiler with 200 kWh SH storage and 120 kWh DHW storage. The heat in the neighborhood (Fig. 7) originates almost exclusively from the heat pump. The heat storage is comprised of both SH and DHW with, respectively 205 and 120 kWh.

As the external CO_2 compensation becomes cheaper (below 1000 €/ton for *YearlyNO*), the ZEN's energy system emits more CO_2 locally (Fig. 9) and increases the external CO_2 compensations purchased (Fig. 5). The major change of the energy system design occurs for the PV size, which is drastically reduced. For the heating system, Fig. 4 shows how the size of the heat pump decreases and the biomethane boiler increases. A gasified biomass CHP and electric boiler also appear. This reduces the share of the heat pump in the supplied heat, which only supplies around 35% when the external compensation is free. This heat is principally replaced by the gasified biomass CHP (around 50% of total) and the rest is covered by a mix of the heat from the biomethane and the electric boilers. The heat storage also changes. The DHW disappears and the SH storage is reduced and replaced by storage at the central plant, coinciding with the investment in technologies at the neighborhood level.

Similar results are obtained in the case using hourly Norwegian CO_2 factors *HourlyNO* (Fig. 4). The only difference is the slightly larger PV and heat storage, in particular, above 1000 €/tonCO_2. The reason lies in the hourly CO_2 factors, which are low in summer, when the PV exports occur, but significantly higher than in the *YearlyNO* in the rest of the year (see Fig. 2). In the winter, more CO_2 is emitted due to the difference in CO_2 factor of electricity while the compensation potential of PV is around the same in the *HourlyNO* and *YearlyNO* cases. This leads to a higher amount of installed PV in the *HourlyNO* case. The resulting designs remain comparable because the variations in the CO_2 factors of electricity can be limited by using the heat storage wisely. This also explains the slightly higher heat storage investment, when no external compensation is bought (above 1000 €/tonCO_2).

When the PV size is limited, in the *YearlyNO-limPV* case and *HourlyNO-PVlim* case, the results are also very similar. Compared to the cases when PV is not limited, the amount of PV is reduced by around a third for the cases above 1000 €/tonCO_2. With CO_2 prices below 500 €/tonCO_2, the results are the same as in the cases with unlimited PV (which we will call base cases from here on). This makes sense as the PV restriction is not binding for CO_2 prices below 500 (the limited PV installation is around 750 kW).

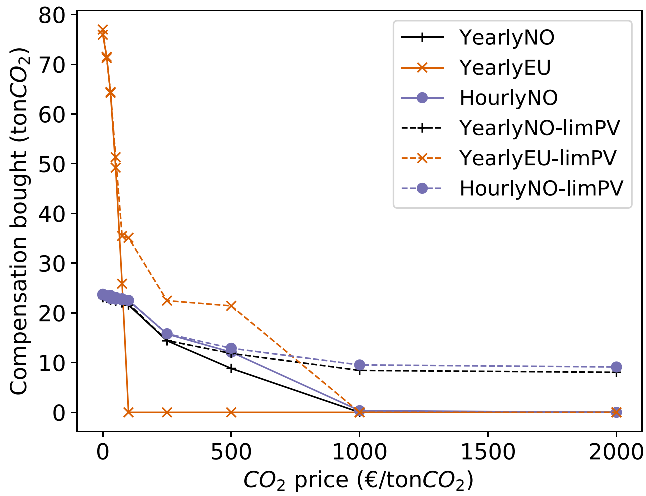


Fig. 5. CO_2 compensations bought for different CO_2 compensation price. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

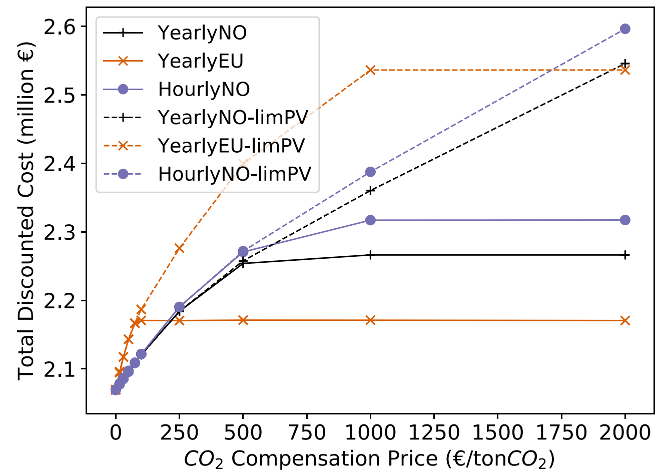


Fig. 6. Total discounted costs of energy system and operation for different CO_2 compensation price.

In all four cases with Norwegian factors, the heating grid and technologies at the neighborhood level are chosen for compensation prices between 0 and 500 €/tonCO_2. The principal reason to invest in technologies at the neighborhood level is the same as for technologies inside buildings, i.e. the cost (investment and operation) and the associated emissions; the main difference is that an additional cost for the heating grid is necessary together with some transmission losses that need to be compensated. Here, for that external CO_2 price range, it invests in an electric boiler and a gasified biomass CHP, thus indicating that they are cost effective to invest in and operate in comparison with the other technologies inside the buildings.

The annual average CO_2 factor of the *HourlyNO* case and the one used in the *YearlyNO* cases are the same, which explains the similarity of the results. PV is found to be the cheapest option to reach the balance with the cost assumptions made in this paper.

In regard to the amount of CO_2 compensations bought, as can be observed from Fig. 5, the four cases with Norwegian CO_2 factors (in blue and green) behave very similarly up to 250 €/tonCO_2. Above that the limPV cases converge towards 10 tons of bought compensation while the base cases go down to zero at 1000 €/tonCO_2. There are still compensations bought at such a price in the limPV cases because no more PV can be installed (the limit is reached) and the external compensation is still the cheapest option to achieve net zero emissions. If we had increased the price of external compensations further, we can expect that the external compensations bought would also have gone to zero and that another technology would have been installed, such as a CHP for instance (and possibly also replacing other technologies).

The amount of CO_2 emitted from the ZEN and the CO_2 compensations (Fig. 9) is also similar across the cases using Norwegian CO_2 factors, with the exception of the limPV cases that we covered above. Overall, when buying external compensation becomes more expensive, lower overall emissions are achieved.

The total discounted costs (Fig. 6) are similar across the four NO cases until 500 €/tonCO_2, after which they diverge. In the limPV cases, they continue to increase linearly with the price of external compensations (the amount of compensation bought remains the same), while in the base cases, they converge at 2.26 and 2.31 million euros for, respectively the *YearlyNO* and the *HourlyNo* case.

6.2. European CO_2 factors for electricity

To investigate the impact of a higher CO_2 factor for the European condition at 132 g/kWh, we compare the cases with Norwegian factors to the *YearlyEU* case. When no external compensation is available (at 2000 €/tonCO_2), Fig. 4 shows that the investments in PV is around 1300 kW, 400 kW lower than in the *YearlyNO* and *HourlyNO*. There is also a 155 kW biomethane boiler, a 60 kW gasified biomass CHP, and an 107 kW air-source heat pump. Moreover, the heat storage is a combination of SH storage and storage at the neighborhood level.

The lower amount of PV in comparison to the Norwegian factor cases is due to the relatively higher CO_2 factor used, allowing to obtain more compensations from the PV production in the summer. In both the *YearlyEU* and the *HourlyNO* the CO_2 factors are high in the winter. However, in the *YearlyEU* case it is also high in the summer, thus making compensating easier. The comparison between the *YearlyNO* and the *YearlyEU* cases is slightly different. Indeed, in both cases the electricity emission factor is constant throughout the year. If their heating systems were only electricity based, there should be no difference between the energy systems in both cases as the imports of electricity and the exports have the same emission value. This would mean that the amount of PV in both cases should be the same. However, our results show that this is not the case here and this is due to the heating technologies using fuels other than electricity. In the *YearlyEU* case, the heat pump is significantly smaller, leading to relatively less production of heat from it (Fig. 7) and thus less electricity imports and fewer emissions. In addition, the biomethane boiler is significantly larger and there is a gasified biomass CHP. The biomethane boiler is used more than in the *YearlyNO* case and the gasified biomass CHP provides around two-thirds of the heat. In the *YearlyEU* case, the CO_2 factor of electricity is higher than the CO_2 factors of those technologies, thus allowing the exported electricity to compensate for producing heat with these technologies more easily. Moreover, this is amplified by the fact that the CHP also produces electricity that can reduce the imports or be exported, and contribute to the compensations/reduction of emissions.

When the external compensation price is reduced, nothing happens until 75 €/tonCO_2, except for a small reduction of around 30 kW in the amount of PV for 1000 and 500 €/tonCO_2. From 75 €/tonCO_2 and below, external compensations are bought (Fig. 5). It principally affects the amount of PV which gradually reduces to reach the same level as in the other base cases. The size of the biomethane boiler is also reduced to a similar amount as in the other base cases.

In the *YearlyEU* case with PV limitation and when no compensation can be bought (at 2000 €/tonCO_2), PV is still the best technology available to the model to reach net zero emissions and so the amount of PV is similar to the other limPV cases. However, the air-source heat pump is replaced completely by a 150 kW biomethane boiler. The heat storage is covered by a 150 kWh heat storage at the neighborhood

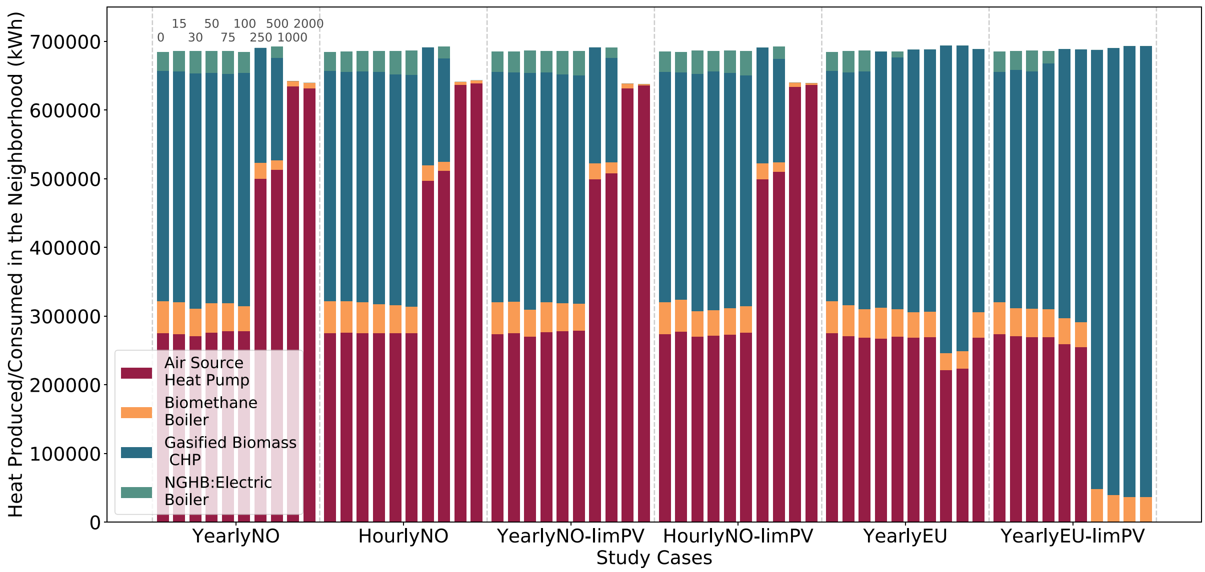


Fig. 7. Heat produced in the neighborhood by each technology in the runs grouped by case.

level. A grid-scale battery of 1000 kWh is also installed. With a higher and constant CO_2 factor, and as it cannot invest in more PV, the optimization chooses to rely on the CHP for the additional electricity exports needed to reach the emission balance. The CHP use (which can be seen in Fig. 7) is primarily driven by the need for electricity and the heat is the by-product. The battery is used to store the electricity from the CHP that cannot be directly exported and/or to maximize the profit from selling the electricity.

At 1000 €/tonCO_2, the system is the same. As the external compensation price is reduced further to 500 and 250 €/tonCO_2, the battery is no longer chosen, and it is replaced by more heat storage and by purchasing external compensations (Fig. 5). Going even further to 75 and 100 €/tonCO_2, the size of the gasified biomass CHP is reduced, some of the neighborhood scale heat storage is converted to SH storage, and an air-source heat pump appears, taking over around 40% of the heat production (Fig. 7). Lowering the price of external compensations further leads to a reduction of the amount of PV invested, replaced by purchasing more external compensations (Fig. 5).

The cost of the system in the *YearlyEU* cases with and without the PV limitation (Fig. 6) is the same up to 75 €/tonCO_2 at which point it is no longer possible to increase the amount of PV in the limPV case, leading to more purchase of external compensations. The cost of the system stays constant from this point in the base case while it continues increasing in the limPV case due to the need of external compensation and from 1000 €/tonCO_2, due to the investment in the battery.

The heating grid is always chosen.

6.3. *Marginal emission factors for electricity*

The cases using the marginal emission factors for electricity give the following results.

As a reminder, *Case 1* accounts all exchanges of electricity using marginal factors, *Case 2* uses marginal factors only for the exports of locally produced electricity and *Case 3* uses marginal factors for local batteries in addition to the local production of electricity. Fig. 8, shows the resulting energy system investment for the runs using marginal emission factors. The first observation is that *Case 2* and *Case 3* are very similar. Indeed, investment in the battery is not optimal according to the optimization, meaning that both cases are equal. The minor difference in investment illustrates that close to optimality (here within a MIP gap of 0.1%), there can be different solutions.

The investments in the heating system are very similar and the size of PV is the main differentiation, with *Case 1* having a 70% bigger

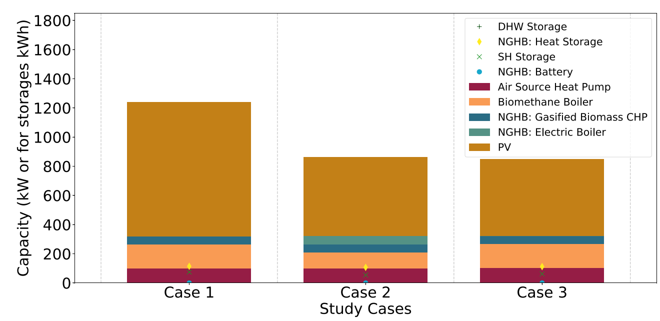


Fig. 8. Investments resulting from the runs with marginal factors. When the technology is at the neighborhood level, its name is preceded by NGHB.

Table 4
Other results from the three marginal cases, including annual emissions, total discounted costs and external compensation bought.

	Case 1	*Case 2*	*Case 3*
Emissions (tonCO_2/year)	83.261	23.964	25.498
Total discounted costs (€)	2 137 299	2 060 269	2 058 756
External compensation bought	0	0	0

PV system. The marginal factors being overall higher than the average factors in NO1, this result was expected.

When comparing the results using marginal factors to the one using average factors, the impact of higher factors, and in particular in the summer, with marginal factors is clear and results in a smaller PV system. The energy system also uses more carbon intensive technologies. Those results are comparable to the investments obtained when decreasing the external compensation price with average emission factors.

Table 4 presents the total discounted costs and the emissions for the three marginal cases. No external compensation is bought in those cases (as intended, the price of external compensation being 10000 €/tonCO_2). This means that the emissions presented in this table also corresponds to the local and total compensations. The overall higher marginal emission factors lead to very high emissions in *Case 1*, due to accounting local imports of electricity with the marginal factors. This number is in a similar range to the amount of emissions in the case *YearlyEU*. This can be explained by the fact that the marginal factor in NO1 is most often driven by imports from Europe. *Case 2* and *Case*

3 have slightly higher emissions than in the case *HourlyNO* due to the extra compensations that they get by using marginal factors on their electricity exports. In terms of total discounted costs, all three cases end up being less expensive than the ones using only average emission factors and a similar price of external compensation, but also for Case 2 and Case 3 lower by about 10000€ than the cases with free external compensation and average emission factors. This minor difference can most likely be attributed to the differences between the clusters of the cases using average and marginal factors.

7. Limitations

This paper's objective is to discuss and highlight the impact of the choice of CO_2 factor of electricity and alternative compensation mechanisms on the design of the energy system of ZENs. The results presented in this paper are only valid under the cost assumptions made and the context of the case study.

Another limitation is that storage operation is only intra-day, and does not consider inter-day or seasonal storage. This limitation arises from the computational complexity of the problem leading to the modeling choice of using clustering and of leaving these storage operations out. Making a model accounting for those storage operations is possible, for example by operating one or several continuous years, at the cost of much higher computational times. It is also possible to model seasonal storage and inter-day storage when using clustering, but again with an addition computational burden [7,35]. There are other ways to reduce the computational complexity of the model, for example by limiting the number of binary variables associated with the technology costs or the part-load limitation. If including those storage applications is important in your particular case, a different trade-off than the one chosen in this paper might be more suitable when designing the model for your application.

The results focus on the compensation obtained from the energy system of the neighborhood and do not consider the load reduction impact that refurbishing the buildings would have on the amount of CO_2 to compensate. There is a competition between the investment in the refurbishment and the energy system. In particular, the refurbishment would reduce the SH load and lead to smaller heating units also leading to less need for compensation and a smaller size of PV. It being chosen by the model would depend highly on the expected load reduction and cost of the refurbishment. Evaluating the potential of refurbishment for older building stock when designing ZENs remains as future work.

The lack of major changes in the choices of technologies when reducing the price of external compensations to zero can appear strange. This is a result of the technology options and their cost and emission assumptions making the same technologies cost-optimal with and without the emission constraint.

8. Discussion

In this paper we discuss and investigate the impact of the CO_2 factors and of altering the ZEN definition to allow for external compensation on the energy system of ZENs.

The carbon offset companies, introduced in Section 5, offer a way to compensate emissions but the real impact of the compensation bought in terms of emission reduction and additiveness is hard to measure. In addition, it might be politically difficult to justify. Indeed, relying on such measures would create a flow of money towards the emission reduction and the development in places other than Norway, which could be seen negatively by a share of the population. A solution to this would be to have compensations paid for emissions reduction inside the country. In the case of Norway, this could mean that the compensation bought could, for instance be used to incentivize EV, incentivize refurbishment of older houses or to finance emission-reduction measures in some carbon-intensive industry. This would allow a refocus of some part of the objective of being a ZEN from an already low emission power system, where gains are hard to achieve, to other more problematic areas where a bigger impact can be made. The main problem of this approach is to quantify the price of CO_2 reduction and the actual emission reduction achieved.

We advocate the use of hourly CO_2 factors which allow the possibility to consider and incentivize, in the optimization, to produce when the carbon intensity is the highest. However, it is not straightforward to compute those emissions for historical years and it is difficult to take into account the changes in the hourly carbon intensity profiles that will arise due to the changing European power system. With the increase of wind and solar capacity, which have significant seasonal and daily variations, as well as the introduction of means to deal with their limited dispatchability, the hourly carbon intensity timeseries is likely to be significantly modified. This can be overcome by using European market and capacity expansion models to extract future CO_2 factor timeseries. Another solution that appears acceptable in Norway is to use yearly average factors, as they give a good approximation of the investments obtained with hourly average factors and make it easier to include future changes in the power system. The use of hourly factors may still be preferable when it comes to the actual operation of the neighborhood.

The limPV cases with Norwegian factors illustrate the difficulty to reach the zero emission balance. In the limPV cases, even with very high external compensation prices, external compensation remains the most cost-effective way to reach net zero emissions along with PV. In this paper, we only included the carbon emissions from the operation of the ZEN's energy system, but the carbon emissions from materials, construction and deconstruction of the neighborhood could also be taken into account depending on the ambition of the project. This would increase the amount of CO_2 to compensate, in turns increasing the investment in PV panels until it reaches the limit. This indicates that for ZENs considering all the emissions in the project life-cycle, the external compensations would be part of the solution (at the price points considered in this study) if they were allowed by the framework.

The results presented in this paper focus only on the Norwegian case and it is important to remember the unique nature of the Norwegian power system when considering the results, and before translating them to other situations. In general, the break-even cost of external CO_2 compensations will depend on their price and on the climatic conditions (in particular the solar irradiance) and the spot price of electricity which affects the investment and compensation obtained from PV panels. From Fig. 5, a lower CO_2 factor of electricity leads to a higher break-even cost of external compensation. We can expect a similar behavior in other countries but the specific costs will depend on the parameters mentioned previously. No conclusions regarding the impact of the choice of an hourly or annual factor can be made for the countries other than Norway based on this paper. The impact of this choice will depend on the level of the yearly factor and on the variations in hourly factors due to the specific power system of the area.

The results obtained using marginal factors and the difference between the marginal and average emission factor profile are very dependent on the area. The results obtained in this study are valid for NO1 and can somewhat be extended to the whole of Norway and to a lesser extent to the Nordic countries.

9. Conclusion

This paper discusses the importance of the choice of the CO_2 factor of electricity for the design of ZENs' energy systems as well as the different compensation mechanisms that can be used to reach the zero emission target. A case study is used to illustrate the impact of the CO_2 factor choice and how different CO_2 compensations' price points would affect the resulting energy system design in Norway. The results suggest that the investments using *YearlyNO* and *HourlyNO* factors are very similar, while using the *YearlyEU* factor results in less investment in PV but assigns more emissions to the neighborhood. The total cost

Table 5
Data of technologies producing heat and/or electricity.

Tech.	η_{th} (%)	Fix. Inv. Cost (€)	Var. Inv. Cost (€/kW)	α_i (% Inst. Cap.)	Min. Cap. (kW)	Annual O&M Costs (% of Var Inv. Cost)	Lifetime (year)	Fuel	α_{CHP}	El.	Heat
At building level											
PV[a]		0	730	0	50	1.42	35			1	0
ST[b]	70	28350	376	0	100	0.74	25			0	1
ASHP[c]	f(T_t)	42300	247	0	100	0.95	20	Elec.		0	1
GSHP[d]	f(T_t)	99600	373	0	100	0.63	20	Elec.		0	1
Boiler[e]	85	32200	176	30	100	2.22	20	Wood Pellets		0	1
Heater	100	15450	451	0	100	1.18	30	Elec.		0	1
Boiler	100	3936	52	20	35	2.99	25	Biomethane		0	1
Boiler	100	3936	52	20	35	2.99	25	Gas		0	1
At neighborhood level											
CHP[f]	47	0	1035	50	200	1.03	25	Biogas	1.09	1	1
CHP	98	0	894	20	1000	4.4	25	Wood Chips	7.27	1	1
CHP	83	0	1076	20	1000	4.45	25	Wood Pellets	5.76	1	1
Boiler[g]	115	0	680	20	1000	4.74	25	Wood Chips		0	1
Boiler[g]	100	0	720	40	1000	4.58	25	Wood Pellets		0	1
CHP[h]	66	0	1267	10	10	0.84	15	Wood Chips	3	1	1
Boiler[i]	58	0	3300	70	50	5	20	Biogas		0	1
GSHP[d]	f(T_t)	0	660	010	1000	0.3	25	Elec.		0	1
Boiler	99	0	150	5	60	0.71	20	Elec.		0	1
Boiler	100	0	60	15	500	3.25	25	Biogas		0	1
Boiler	100	0	60	15	500	3.25	25	Gas		0	1

[a]Area Coefficient: 5.3 m^2/kW.
[b]Area Coefficient: 1.43 m^2/kW.
[c]Air Source Heat Pump.
[d]Ground Source Heat Pump.
[e]Automatic stoking of pellets.
[f]Gas Engine.
[g]HOP.
[h]Gasified Biomass Stirling Engine Plant.
[i]Solid Oxide Fuel Cell (SOFC).

of the system depends on the limitation of PV investment. In addition, when using marginal factors, extra care need to be given to the details of the emission accounting.

The yearly factors ignore the hourly, daily and seasonal variations of the CO_2 factor of electricity but make it easier to implement in regulatory frameworks. The choice of a factor centered on Norway or on Europe depends on the system boundaries that are required. Choosing hourly factors ensures a better representation of the time variability of the factor but obtaining accurate hourly factors with a long-term perspective is more challenging. Yearly Norwegian factors represent a good approximation of the hourly case and can be used to simplify models or regulatory frameworks. This remains true even when considering the possibility to rely on external compensation for reaching the zero emission balance. Furthermore, allowing for external compensation at a price of 250 gCO_2/kWh would reduce the overall cost of ZEN energy systems by more than 10% with the technology options investigated in this paper and in a setting with limited roof area and no additional available space for PV. The price and type of this external compensation as well as whether it makes sense from a global CO_2 reduction perspective has been briefly discussed but it remains beyond the scope of this paper to draw definitive conclusions on this matter. However, the fact that the neighborhood is resorting to buying external compensations even for prices up to 1000 €/tonCO_2, questions the relevance of standards forcing strictly local compensations in reducing the emission in Norway and whether other less costly measures, either external compensations as in this paper or completely unrelated to neighborhood, would allow to have a bigger impact on CO_2 emissions. The use of marginal factors in NO1 leads to reduced energy system costs and different amount of emissions. However, the relevance of its use in the context of ZENs and its impact in other countries remain open questions.

Declaration of competing interest

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

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Appendix A. Technology data

The data for those technologies come from the Danish Energy Agency and Energinet.[14] A summary of the data used is presented in Table 5. The data for storages is presented in Table 7.

The data for prices of fuels come from different sources. For the wood pellets and wood chips, they come from the Norwegian Bioenergy Association.[15] The data for the biogas and biomethane come from the European Biogas Association.[16] The price for gas is estimated based

[14] https://ens.dk/en/our-services/projections-and-models/technology-data
[15] http://nobio.no/wp-content/uploads/2018/01/Veien-til-biovarme.pdf
[16] https://www.europeanbiogas.eu/wp-content/uploads/2019/07/Biomethane-in-transport.pdf

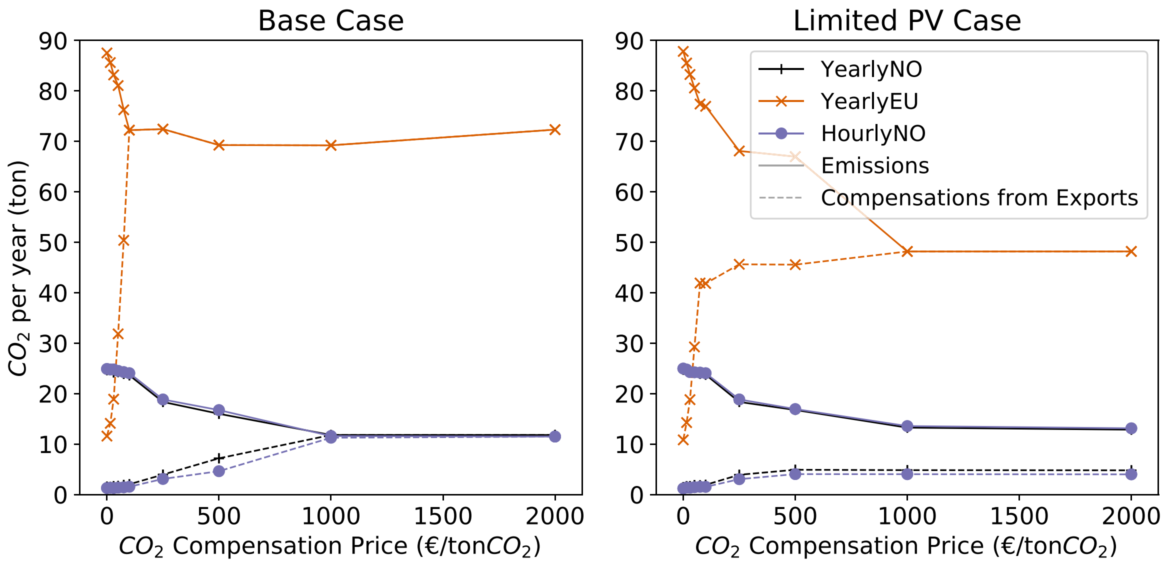

Fig. 9. CO_2 emissions and compensations for different CO_2 compensation price.

Table 6
Data of fuels.

Fuel	Fuel cost (€/kWh)	CO_2 factor (gCO_2/kWh)
Electricity	$f(t)$	$f(t)$
Wood pellets	0.03664	40
Wood chips	0.02592	20
Biogas	0.07	0
Biomethane	0.07	100
Gas (neighborhood level)	0.041	277
Gas (building level)	0.121	277

on the statistics of natural gas price in Europe for non-household consumers[17] (neighborhood level) and households consumers[18] (building level).

The data for CO_2 factor of fuels come from a report from Cundall.[19] A summary of the data for fuel is presented in Table 6.

Appendix B. Additional results

Fig. 9 shows the emissions and compensations for the different cases. The difference between the emissions and compensations are the external compensation bought.

Appendix C. Additional model's equation

Load balances for electricity (Eq. (15a)), Domestic Hot Water (DHW) (Eq. (15b)) and Space Heating (SH) (Eq. (15c)): $\forall t$:

$$y^{imp}_t + \sum_b \left(\sum_{est} y^{dch}_{t,est,b} \cdot \eta_{est} + \sum_g g^{selfc}_{g,t,b} \right) = \sum_b \left(\sum_e d_{e,t,b} + E_{b,t} \right) \tag{15a}$$

$\forall t, b$:

$$\sum_q q^{DHW}_{q,t,b} + \sum_{hst} (\eta_{hst} \cdot q^{DHWdch}_{t,hst,b} - q^{DHWch}_{t,hst,b}) + q^{HGusedDHW}_{t,b} = H^{DHW}_{b,t} + q^{dump}_{t,b} \tag{15b}$$

$$\sum_q q^{SH}_{q,t,b} + \sum_{hst} (\eta_{hst} \cdot q^{SHdch}_{t,hst,b} - q^{SHch}_{t,hst,b}) \quad + q^{HGusedSH}_{t,b} = H^{SH}_{b,t} \tag{15c}$$

The operation of the heating grid is constrained by the following equations: $\forall t$

$$\sum_q q_{q,t,'PP'} + \sum_{hst} (\eta_{hst} \cdot q^{dch}_{t,hst,'PP'} - q^{ch}_{t,hst,'PP'}) = \sum_{b \backslash 'PP'} q^{HGtrans}_{t,'PP',b} + q^{dump}_{t,'PP'} \tag{16a}$$

$\forall b, b', t$

$$q^{HGtrans}_{t,b',b} \leq \dot{Q}^{MaxPipe}_{b',b} \tag{16b}$$

$\forall b, t$

$$\sum_{b'} q^{HGtrans}_{t,b,b'} \leq \sum_{b''} \left(q^{HGtrans}_{t,b'',b} - Q^{HGloss}_{b'',b} \right) \tag{16c}$$

$$q^{HGused}_{t,b} = q^{HGusedSH}_{t,b} + q^{HGusedDHW}_{t,b} \tag{16d}$$

$$q^{HGused}_{t,b} = \sum_{b''} \left(q^{HGtrans}_{t,b'',b} - Q^{HGloss}_{b'',b} \right) - \sum_{b'} q^{HGtrans}_{t,b,b'} \tag{16e}$$

$\forall i$

$$x_{i,'ProductionPlant'} \leq X^{max}_i \cdot b^{HG} \tag{16f}$$

The size of the connection to the electric grid limits the exports and imports.: $\forall t$

$$y^{imp}_t + \sum_b \sum_{est} y^{imp}_{t,est,b} + \sum_b \sum_g y^{exp}_{t,g,b} \leq GC \tag{17}$$

The CHP operation use a heat-to-power ratio: $\forall t,' CHP', b$:

$$g_{CHP,t,b} = \frac{q_{CHP,t,b}}{\alpha_{CHP}} \tag{18}$$

Heat can be DHW or SH and some technologies can only provide SH: $\forall q, t, b$:

$$q_{q,t,b} = q^{DHW}_{q,t,b} + q^{SH}_{q,t,b} \tag{19}$$

$$q^{DHW}_{q,t,b} <= M \cdot B^{DHW}_q \tag{20}$$

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

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

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

Table 7
Data of storage.

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

[a]Based on Tesla Powerwall.
[b]Based on Tesla Powerpack.
[c]Based on Danish energy agency data.
[d]Same data are used for the heat storage at the building or neighborhood level and for both SH and DHW.

PV and Solar thermal operation uses the units efficiency and irradiance:

$$g_{PV,t} + g_t^{curt} = \eta_{PV,t} \cdot x_{PV} \cdot IRR_t^{tilt} \tag{21}$$

$$q_{ST,t} = \eta_{ST} \cdot x_{ST} \cdot IRR_t^{tilt} \tag{22}$$

Batteries and local production technologies are connected: $\forall t, b$:

$$\sum_g g_{t,g,b}^{ch} = \sum_{est} y_{t,est,b}^{ch} \tag{23}$$

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