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Roles of local and national energy systems in the integration of renewable energy

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HIGHLIGHTS

- A method is suggested to link local and national energy systems.
- The method analyses excess electricity.
- The goal is to see how much excess can be integrated in each energy system.
- The method is tested on two Danish examples towards 100% renewable energy.

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ABSTRACT

In the transition to renewable energy systems, national plans are being created for several countries around the world. Concurrently, regions, municipalities and cities are planning for CO_2 neutral and renewable energy systems. Both developments are necessary, which raises the question whether these two types of energy planning are coordinated. How should national plans specify local actions, and how should local plans take into account the surrounding development of the energy system? Most local plans rely on the surrounding energy systems as they need to integrate with the energy system to export excess production or import during demands with insufficient capacity. This paper suggests a methodology to analyse how well these local plans integrate with the surrounding national energy system. The methodology is applied to the two Danish examples of Copenhagen and Sønderborg. Both examples connect to the Danish 2030 scenario defined in the Coherent Energy and Environmental System Analysis study. Based on the results the study concludes that the suggested methodology is applicable for evaluating how well local and national energy systems integrate, and can potentially be used in bettering energy planning to include the benefits of local action and national coordination.

1. Introduction

In the wake of climate change due to CO_2 emissions from fossil fuels in energy systems [1], countries and states are setting targets, plans and milestones for future renewable energy systems. For instance, Denmark [2] and Sweden [3] with 100% renewable energy by 2050, the state of California's Clean Energy Future [4] and the European Union's Energy Roadmap 2050 [5]. Alongside these governmental targets and plans are detailed plans for future 100% renewable energy systems made by university researchers. These are for instance Heat Roadmap Europe, which investigates increased district heating in future European energy systems [6], renewable energy systems in Portugal [7,8], a model of an Irish 100% renewable energy system [9], a plan for each state in the US [10] and a Danish plan for transition to a 100% renewable energy system [11]. Other examples are a model of large-scale integration of wind energy in Croatia [12], and the potential of renewable energy in China [13]. These studies have a national or state level emphasis. This means that the studies find suitable energy systems for each country or state but they do not identify the local implementation of the systems. This is an important point since future 100% renewable energy systems rely on resources where local planning is necessary such as decentral combined heat and power, wind power and photovoltaics.

On the other hand, cities and municipalities are increasingly looking into climate and renewable energy targets, for example in Sweden [14]. This could be through strategic energy planning [15,16] or the application of smart cities concepts [17]. Even though these might be rooted in the national renewable energy targets, they do not necessarily take the specific national plans for a renewable energy transition into account. Danish examples

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Nomenclature

Abbreviations

CHP	combined heat and power
PP	Power Plant
CEESA	Coherent Energy and Environmental System Analysis
CTR	Central Municipalities' Transmission Company (Centralkommunernes Transmissionsselskab I/S)
CPH	Copenhagen
CPH2025	Copenhagen 2025 Plan

Parameters

P_{imp1}	hourly potential import in system 1
P_{imp2}	hourly potential import in system 2
PP_{prod1}	hourly electricity produced at power plants in system 1
PP_{prod2}	hourly electricity produced at power plants in system 2
$import_{demand1}$	hourly import output from EnergyPLAN in system 1
$import_{demand2}$	hourly import output from EnergyPLAN in system 2
$export_{total}$	hourly sum of potential export from system 1 and system 2
$export_1$	hourly export output from EnergyPLAN in system 1
$export_2$	hourly export output from EnergyPLAN in system 2
$Import_1$	hourly import demand in system 1 based on when potential import matches potential export
$Import_2$	hourly import demand in system 2 based on when potential import matches potential export
$Balance_1$	hourly balance of export and import for system 1 calculated based on the suggested methodology

of this are Copenhagen, which has a target of CO_2 neutrality by 2025 [18], Sønderborg with a target of CO_2 neutrality by 2029 [19], and Aalborg with a vision of a local 100% renewable energy system by 2050 [20]. Other examples are a plan for CO_2 neutrality in Flensburg by 2050 [21] and a plan setting the path for CO_2 neutrality in Seattle, WA by 2050 [22]. The focus of all these plans is to fulfil local targets; however, the steps they suggest might not align with the national renewable energy plans. The right local development is key to achieving national renewable energy systems, which is also pointed out in [23]. Otherwise, the risk is that decisions are being made which hinder 100% renewable energy scenarios. This raises the question of the degree to which the transition to renewable energy should be handled locally and the degree to which it should be handled nationally. In principle, this equals the balance between national energy systems and transnational systems, for instance a country and the European Union.

Thus, there is a need for a methodology that can link and quantify the connection between local energy plans and national energy systems, as a potential misalignment exists. For instance in a Danish context, little coordination exists between the local and national energy planning [16], and the investigated studies suggests the same in other countries.

This potential misalignment can be reduced to two main issues. The first relates to the balance between local and national resources and the extent to which a certain energy system affects the use of such resources. This is important as local actions might change the overall resources available for the remaining national energy system. This was briefly investigated in [24] and is possible to estimate when the plants and fuels related to the local and national energy systems are known; thus, it will not be further investigated in this paper. The second issue is that these local systems have to integrate with the remaining national energy system. This applies to exporting excess electricity production, and importing electricity when needed. It is important to estimate the level of integration for two reasons: on the one hand it is not feasible to have many island-mode operating local systems; on the other hand, neither is it feasible to have situations where local action in one place is dependent on local action in another place.

The investigated studies of Aalborg [20] and Frederikshavn [25], show two different methodologies to account for the integration between the local and national energy system. One is to allocate shares and then balance the system locally without investigating the consequences of import and export [20]. The other is to include import and export by including the surrounding electricity grid as a single technology [25]. This might be an oversimplification as illustrated in [26]. Both of the methodologies take offset in the local system, and either disregard or simplifies the surrounding energy system. This calls for a different approach and a new methodology that can include both the local and the national scope. This paper suggests such a methodology within the framework of the energy system analysis tool EnergyPLAN.

The goal of the methodology is to measure how well the local and national energy system integrate by investigating the level of interaction in the electricity grid between them. The approach includes the complete energy systems to take into account synergies with the transport and heat sectors. By investigating how well the systems interact, it is possible to identify how compatible they are and possibly making coordination between them easier. The paper will however not investigate the design of energy systems to reach the right level of integration. The developed methodology is in principle applicable to investigating the interaction between countries as well.

The methodology is applied to two Danish examples: (1) the municipality of Copenhagen and how their Copenhagen 2025 plan fits with a Danish transition to 100% renewable energy and (2) the municipality of Sønderborg's plan for 2029 and how it fits with the same Danish transition. Both examples investigate how well the municipalities integrate with the national energy system in terms of electricity production and consumption. These examples illustrate the application of the methodology on respectively a smaller municipality and an urban municipality, thus the methodology is applied to two very different energy system layouts. The examples should however not be seen as representative cases.

2. Methodology

To create a methodology that investigates the level of integration between local and national energy systems, the key parameter becomes the potential over production of electricity in the two energy systems. As [27] argues, the amount of excess electricity can be used as a measure to identify how well a system can integrate renewable energy. Thus this is also seen as a parameter for integrating energy systems. One overall concept behind transmission cables is to utilise excess electricity from one system in another. Thus, the excess electricity can be seen as a parameter that also indicates how well two systems with excess electricity integrates. In this specific study, the reduction in critical excess electricity [28] is used. Thus it is important to work within a framework that can measure both of these energy systems and identify the electricity grid balance when the local and national energy systems integrate. Fig. 1 shows this concept. Concretely, this study uses the primary energy supply and the electricity that can be imported and exported on an hourly basis as measure points.

The methodology has to be developed within a framework that can handle hourly operation of energy systems and include the whole energy system and not only the electricity sector. The hourly operation is necessary to include fluctuations in energy demands and in production by renewable energy technologies such as wind turbines. By modelling the whole energy system, it allows for the inclusion of the heat and transport sectors, which become important in systems with heat pumps and electric vehicles that can utilise excess electricity. Therefore, the methodology suggested in this paper is built on top of the advanced energy system analysis tool EnergyPLAN since EnergyPLAN performs hourly simulations of energy systems. Currently, EnergyPLAN does not have the capability of linking and combining hourly simulations of two energy systems. The suggested methodology would allow EnergyPLAN to do this.

2.1. EnergyPLAN

EnergyPLAN is an analytically programmed energy system analysis tool; it is an input/output model that simulates hourly operation of an energy system [29]. EnergyPLAN includes transport, heating, electricity, gas, and industry in its energy system analyses and can thus be seen as a holistic model [30]. By simulating the whole energy system on hourly operation, EnergyPLAN enables the inclusion of fluctuating renewable energy such as wind and solar, but also the operation of storages, which are important in renewable smart energy systems [31]. Fig. 2 shows the overall schematic of EnergyPLAN.

EnergyPLAN has been used to analyse energy systems at various scales. This includes analysis at the European scale in the Heat Roadmap Europe studies [6], of countries such as Denmark [32], Portugal [7], and Ireland [9,33], and of counties, municipalities and cities such as Inland Norway [34], Aalborg [20], Frederikshavn [35], and Copenhagen [36]. Besides analyses of energy systems at different scales, EnergyPLAN has also been utilised to simulate how different initiatives influence energy systems, for instance how different types of energy savings affect each other and the performance of the energy system [37,38], and the influence of heat pumps in renewable energy systems [39].

2.2. Connecting EnergyPLAN analyses

When creating a methodology for linking EnergyPLAN analyses, the importance is that the result says something about both the local energy systems, the national energy systems and the transmission between them. Therefore, an EnergyPLAN model is needed for both the local energy system and the remaining national energy system.

First, the methodology has to be able to identify when there is a need for import in an energy system and when there is a possibility of exporting electricity from each energy system. Second, the methodology has to be able to use this information to identify when each system can export and import and finally input this into a new model for each system. Fig. 3 shows this overall thinking.

To identify each energy system's potential for import and export, the first step is to run each as island mode operation [40]. By doing this, each analysis identifies hours with import demand and export opportunities. These are seen as:

- Lack of capacity in power producing units
- Electricity production at power plants

Eqs. (1) and (2) shows this principle:

$$P_{imp1} = import_{demand1} + PP_{prod1} \tag{1}$$

$$P_{imp2} = import_{demand2} + PP_{prod2} \tag{2}$$

A system has a possibility of export in situations with over-delivery of electricity for instance from too much production from wind turbines, or excess electricity production from CHP plants. In each scenario, EnergyPLAN is set to balance CHP units based on heat demand only, which enables as much exportable electricity as possible in each system. EnergyPLAN outputs the hourly export production from each system. These system exports are summarized into a total hourly export between the systems, shown in Eq. (3):

$$export_{total} = export_1 + export_2 \tag{3}$$

This hourly export is the total sum of critical excess electricity, and thus is the first indicator of the demand for integration.

Each system can only export electricity an import demand exists in the other system, and similarly a system cannot import and export during the same hours. This is acceptable since all systems are connected to the same electricity grid. Thus, there is no situation where one region acts as a transmission line between two other regions. Overall, this is labelled as usable import and export. This principle is illustrated for system 1 in Eq. (4). The equation is applied to all hours in a year.

$$\textbf{\textit{if}}\,(P_{imp1} > export_{total})\,\textbf{\textit{then}}\ Import_1 = export_{total}\ \textbf{\textit{else}}\ Import_1 = P_{imp1} \tag{4}$$

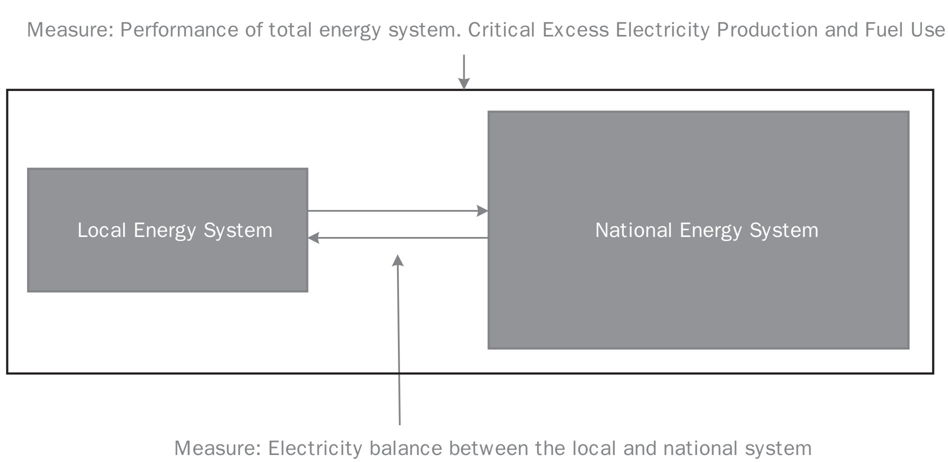

Fig. 1. Concept for analysing the link between local energy systems and national energy systems.

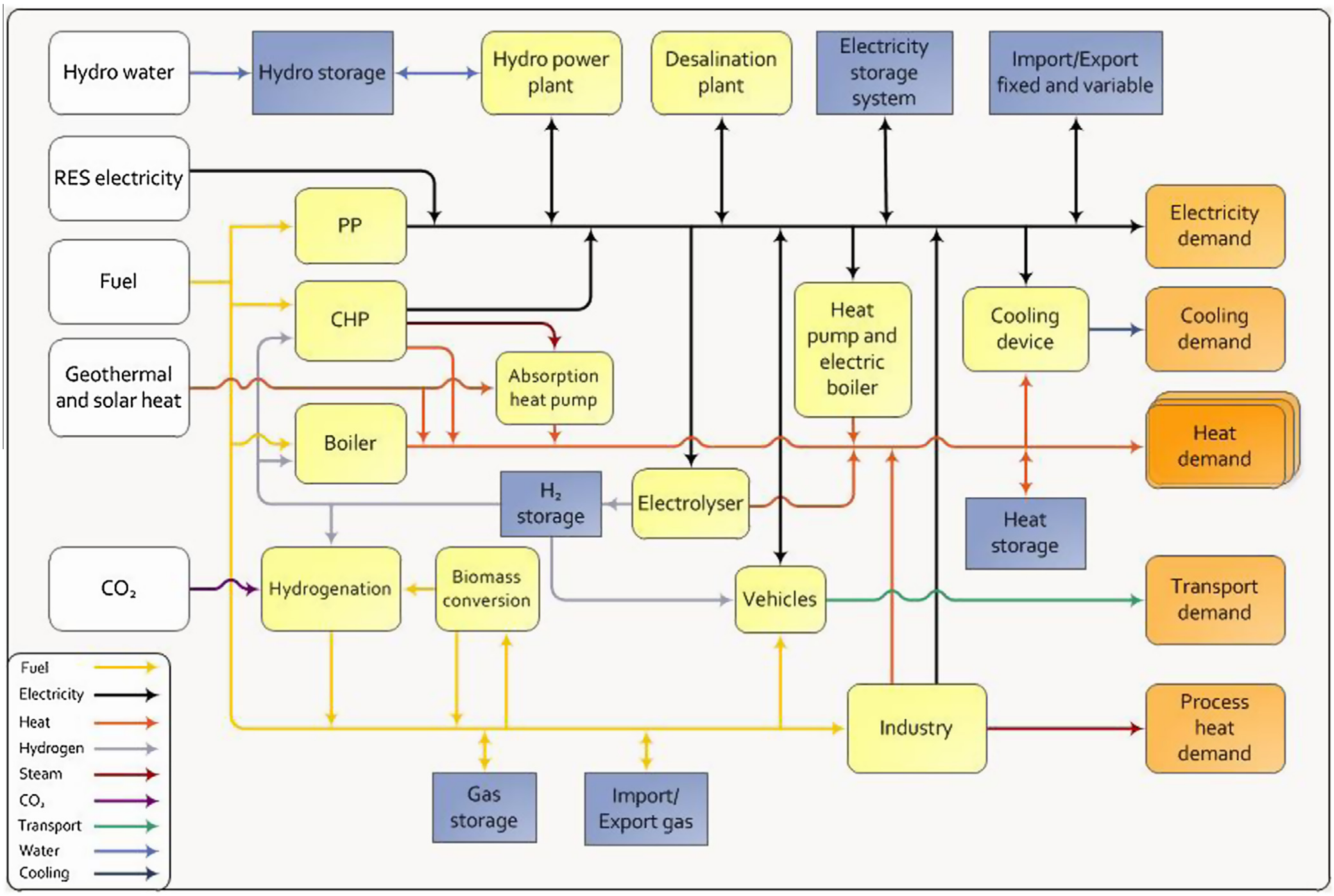

Fig. 2. Overview of how EnergyPLAN simulates energy systems [28].

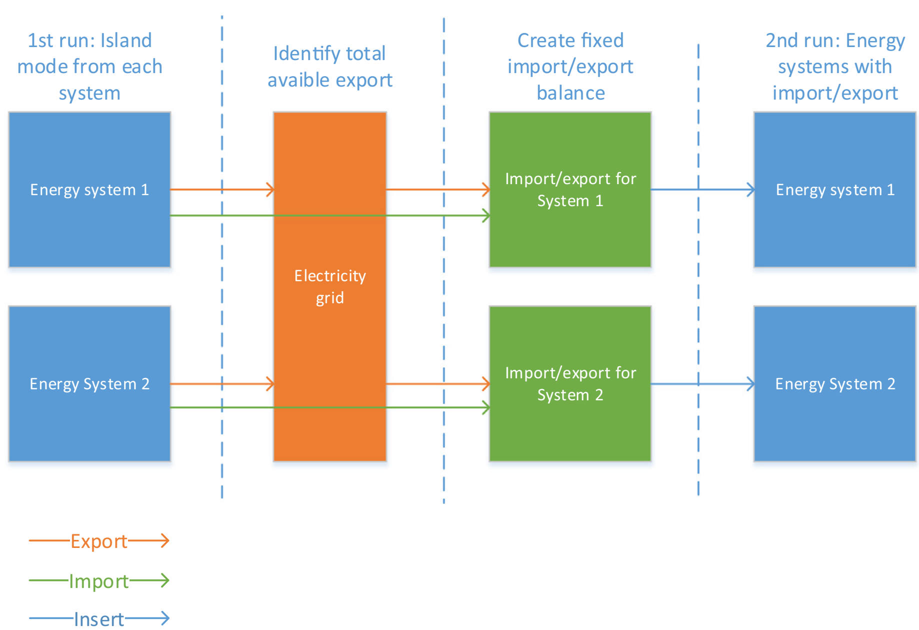

Fig. 3. Overall methodology behind the tool that calculates how well the systems integrate [41].

By matching the export with the import, it is possible to identify how much of the excess electricity that can be used in the other system. From this the methodology creates a balance for each system. Eq. (5) shows the principle of system 1. The balance is for every hour in the year, where a positive value describes export and a negative value describes import in a given hour.

$$Balance_1 = import_2 - import_1 \tag{5}$$

Since it has been ensured that export and import cannot occur in the same hour and the import cannot exceed the total available excess electricity, Eq. (5) results in that every hourly value has either a positive or a negative value.

By including the balance for each system as a fixed import and export in EnergyPLAN, a second EnergyPLAN run of each system is made. This run takes into account that power plant production can be reduced, or that there is less excess electricity since it is exported to the connected region.

By utilising this methodology, it is possible to investigate the integration between the energy systems. This is done by using the potential exportable electricity and the potential importable electricity in each system. This export/import balance is divided into two segments:

(1) Integrable excess electricity: The excess electricity production in a system that can be utilised in the other system without altering the production profiles. The integrable excess electricity is expressed through the balance for each system described in Eqs. (1)–(5).
(2) Non-integrable excess electricity: The excess electricity production in a system that cannot be utilised in the other system. This indicates that the given system changes its production profile or that other energy systems import the electricity. The non-integrable excess electricity equals the excess production that Eqs. (1)–(5) does not capture.

In other terms the methodology investigates first the amount of critical excess electricity produced. Thereafter, it identifies to what extent this excess electricity can be utilised in the other system. Therefore, the key indicator becomes how much of this excess electricity can used in the other system. In other words, how much of the excess electricity is integrable. Overall, this translates into, that the amount which the total excess electricity drops equals how well the energy systems integrate.

The main measure in this study becomes the relation between the amount of integrable excess electricity and non-integrable excess electricity and the level total excess electricity drops in the systems.

2.3. Examples

To test the presented methodology the study investigates two Danish examples: the example of Copenhagen and its 2025 plan, and Sønderborg and its 2029 plan. Both examples are linked to a Danish 2030 energy system based on the Coherent Energy and Environmental System Analysis (CEESA) study [11].

The following Sections 2.3.1,2.3.2, and 2.3.3 describe the Danish energy system and each local system.

2.3.1. Danish energy system

The study uses the CEESA model to define the reference for the Danish energy system [11]. The CEESA analysis explores the possibility of a transition to 100% renewable energy in the Danish energy system. The CEESA study approaches this problem by looking at Denmark as a whole. Thus, it does not take into account different regions. The energy system analyses in the CEESA study were made in EnergyPLAN, making it easier to transfer to the study in this paper. One of the main findings in CEESA is that total national biomass consumption should not exceed 67 TW h.

Since most of the local studies do not set targets for fuel use in industry nor for transport, these demands are still modelled in the national model. Therefore, industry and transportation follow the CEESA development in all examples, even if the local plans might have other suggestions.

Adjustments have been made to the CEESA 2030 model to make it easier to compare the different scenarios.

- The system operates in a manner to balance the CHP plants only according to heat demands (technical regulation strategy 1). This is to create the most opportunities for import and export.
- Boiler and power plant capacities reflect peak demands. CHP plant capacities reflect average heat demands. This makes it easier to split the CEESA 2030 national system into two parts. Table 1 shows the different input values.

To be able to compare each of the individual plans in the examples with a reference scenario, the first step is to create a CEESA development for Copenhagen and Sønderborg, and, by using the methodology described in Section 2.2, link it to the remainder of the Danish energy system as modelled on the basis of CEESA. This works as the reference scenario. To split the CEESA 2030 model, the demands and installed renewables are split into shares based on the population in each municipality. Based on these changes in demand, the boiler and CHP capacities are changed to reflect peak demands in each area. Finally, for the Sønderborg example, biogas production is also split based on population share. To validate these scenarios based on the national CEESA model, total fuel use is used as a parameter. Fig. 4 shows that the new split models are a good representation of CEESA 2030.

2.3.2. Copenhagen

The first example is the city of Copenhagen. The starting point is Copenhagen Municipality's plan for a CO_2 neutral municipality by 2025 [18]. This plan only covers the area of Copenhagen Municipality and therefore does not take into account the extension of the city of Copenhagen beyond the municipal borders. This means that the district heating system expands beyond the Copenhagen plans, which Copenhagen uses to its benefit by expecting a plant outside its jurisdiction to convert to biomass, but does not include the heat demands associated with the remaining system. Since the approach defined Section 2.2 cannot split the district heating grid, the smallest scale of the system boundary is the district heating grid. Therefore, the Copenhagen model is based on the CTR district heating grid [42].

Thus, the Copenhagen model includes not only the heat and electricity demands and production units specified in the Copenhagen Climate Plan for 2025, but also the heat and electricity demands associated with the remaining area connected to the CTR grid outside of Copenhagen Municipality. For this latter area, a CEESA 2030 development is applied. The Copenhagen system links to the remaining Danish energy system modelled based on CEESA 2030. Table 2 shows the key parameters for the systems.

2.3.3. Sønderborg

Sønderborg is a municipality in Southern Denmark. The municipality runs the project ProjectZero that seeks to create a zero emission Sønderborg Municipality by 2029 [19]. This only includes emissions from energy units. To reach the target of zero emissions, Sønderborg will implement steps to supply the municipality's heat

Table 1
Changes in capacities in the CEESA reference system for Denmark.

	Original CEESA value	New value based on demand
Boiler 2 capacity (MW)	3484	3896
Boiler 3 capacity (MW)	7574	8392
CHP 2 Electric Capacity (MW)	1945	1379
CHP 3 Electric Capacity (MW)	2500	2820
PP1 Electric Capacity (MW)	6094	6115

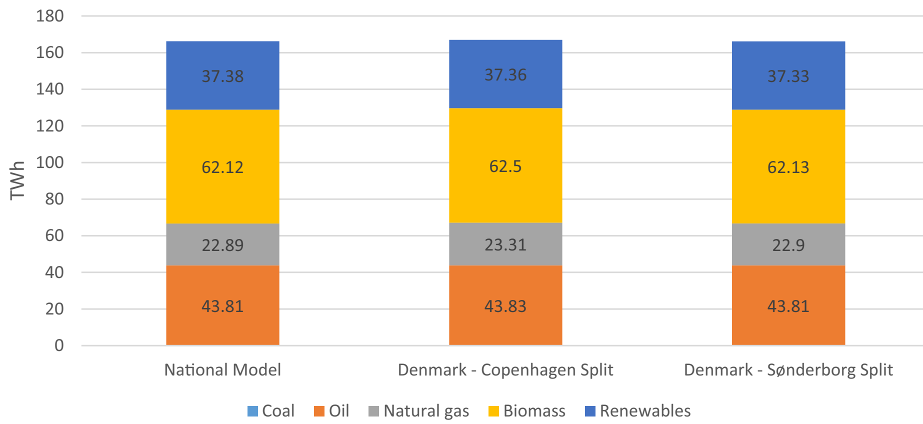

Fig. 4. Validation of the reference Copenhagen and Sønderborg systems compared to the original CEESA 2030 scenario.

and electricity demand. This includes demand reductions in both the electricity and heat sectors. Changing the district heating in the city of Sønderborg to biogas CHP and heat pumps, combined with biomass boilers, instead of the current natural gas engine CHP. Another step is basing the individual heating on heat pumps and biomass boilers. Solar thermal units will help provide both individual and district heating. The electricity demand is then covered by the biogas CHP, waste incineration, onshore and offshore wind power, and solar power. Interconnection will handle the remaining imbalances. All of these elements combined should remove the use of oil and gas in the electricity and heat supply. This study does not include Sønderborg's plan for transitioning the industry sector, instead the CEESA strategy for industry is used. The same applies to transport. The study uses an EnergyPLAN model for Sønderborg developed by PlanEnergi, altered according to Section 2.3 to fit this study. Table 3 shows the main inputs for the Sønderborg example.

3. Analysis and results

The first parameter to test is whether the local plans achieve the goal of zero CO_2 emissions without accounting for transport and industry working in island mode operation [40]. Table 4 shows that fuel used for providing heat and power only comes from biomass, biogas and fluctuating renewable energy in both Copenhagen and Sønderborg. However, the fuel mix is different in the two plans. Copenhagen has a biomass share of 94% and fluctuating renewables of 6%, whereas the fuel mix in Sønderborg is 64% fluctuating renewable energy, and 36% biomass and biogas. One of the reasons for this difference is the fact that Copenhagen only has district heating heat demand, whereas Sønderborg Municipality has 20% individual heat demand. Another reason is that the Copenhagen plan, to a large extent, focuses on converting existing large-scale CHP plants to biomass. Due to this fuel mix, both local systems have zero CO_2 emissions. From a national perspective, the Copenhagen plan leads to total CO_2 emissions of 15.73 Mton and the Sønderborg plan leads to national CO_2 emissions of 16.72 Mton. This compares to the national CEESA reference of 16.87 Mton. However, the Copenhagen plant results in national biomass consumption that is 7 TW h higher than the reference CEESA scenario.

Both of these scenarios result in excess electricity production: Sønderborg due to the high amount of fluctuating renewable energy production and Copenhagen because of a high CHP production that runs according to the heat demand in Copenhagen. In Sønderborg, this results in an excess production of 0.24 TW h

Table 2
Primary inputs for the Copenhagen 2025 plan and the Copenhagen CEESA reference.

	Copenhagen 2025	Copenhagen reference
District heating demand (TW h)	7.19	7.68
CHP 3 capacity (electricity) (MW)	1295	828
Group 3 heat pumps (electricity) (MW)	0	61
Boiler 3 capacity (MW)	1747	2606
Electricity demand (TW h)	4.25	4.15
Wind + offshore wind (MW)	361.5	0
Power plant capacity (MW)	1400	1667

Table 3
Primary inputs for the Sønderborg 2029 plan and the Sønderborg CEESA reference.

	Sønderborg 2029	Sønderborg reference
District heating demand (TW h)	0.56	0.45
CHP 2 capacity (electricity) (MW)	17.25	61
Group 2 heat pumps (electricity) (MW)	20.66	7
Boiler 2 capacity (MW)	150	180
Electricity demand (TW h)	0.31	0.27
Onshore + offshore wind (MW)	149.6	92.8
PV Capacity (MW)	40	44.7
Power plant capacity (MW)	0	0
Individual heating demand (TW h)	0.12	0.14

Table 4
Fuel use and CO_2 emissions in the local energy plans for Copenhagen 2025 plan and Sønderborg 2029 plan.

	Copenhagen 2025	Sønderborg 2029
CO_2 emission (Mton)	0.00	−0.03
Fuel consumption for district heating boilers (TW h)	0.09	0.02
– Biomass	*0.09*	*0.02*
Fuel consumption for combined heat and power (TW h)	11.89	0.28
– Biomass	*11.89*	*0.17*
– Biogas	*0.00*	*0.11*
Fuel for power production (TW h)	2.89	0.72
– Biomass	*2.07*	*0.00*
– Variable renewable energy	*0.82*	*0.72*
Fuel consumption for individual heating (TW h)	0.00	0.05
– Biomass	*0.00*	*0.05*
Surplus biomass consumption (TW h)	0.00	0.04
Total fuel use (TW h)	14.87	1.11

(35% of the total electricity production). In Copenhagen, the excess electricity production is 1.28 TW h (20% of the total electricity production). As highlighted in the methodology, the goal is to utilise this excess production in relation to the surrounding Danish energy system. Thus identifying to what level the systems integrate. This is done by identifying how much the excess electricity production is reduced. This reduction occurs because the remaining Danish system is able to utilise it.

Since Copenhagen has sufficient capacity of power plants and CHP plants, they are not affected by time periods with no wind production, and as such they do not require import of electricity from a technical point of view. Sønderborg needs electricity imports of 0.02 TW h annually from a technical point of view.

What these analyses do not clearly show is how well the plans integrate with the CEESA system. Therefore, each system based on the Copenhagen 2025 plan and the Sønderborg 2029 plan, respectively, is linked to the remaining Danish energy system as described in Section 2.

Both systems result in a large exportable amount of energy. The study shows that the Danish system cannot integrate this overproduction in all hours. Figs. 5 and 6, respectively, show how the reference Copenhagen system and the Copenhagen 2025 system integrate with the remaining Danish system, and how much is non-integrable. Figs. 8 and 9 show the same for the reference Sønderborg system and the Sønderborg 2029 plan, respectively. The goal of Figs. 5,6 and Figs. 8,9 is to illustrate the hourly annual behaviour of the interaction between the local and national energy systems. Tables 5 and 6 shows the annual summarised export balance from respectively the Copenhagen and Sønderborg example.

In the reference energy system, the Copenhagen system annually exports 0.14 TW h to the surrounding Danish energy system. On top of that, the reference Copenhagen system produces an excess of 0.68 TW h that cannot be integrated in the Danish energy system due to Denmark also producing excess electricity. This means that Denmark can integrate 17% of the reference Copenhagen system's excess electricity production. In the reference scenario, the Copenhagen reference imports 0.15 TW h from the Danish system. In total, Denmark produces 5.94 TW h excess electricity where Copenhagen integrates 3% of the excess production. In other words, the critical excess production in the Copenhagen system is reduced by 14% in the reference scenario as seen in Fig. 7. These 14% can be utilised in the remaining Danish energy system.

If Copenhagen implements the Copenhagen 2025 plan, the Copenhagen energy system will produce excess electricity of 1.28 TW h. In this example, Denmark can integrate 0.13 TW h, or 10%, of this excess production while 1.15 TW h would have to be handled elsewhere. The surrounding Danish system produces 5.93 TW h of excess electricity; here Copenhagen imports and integrates 2%, 0.14 TW h of the Danish excess electricity production. Thus, by integrating with the Danish energy system, the critical excess production from the Copenhagen 2025 system is reduced by 10%, as seen in Fig. 7, and instead utilised in the Danish energy system.

Copenhagen does not have an import demand due to sufficient CHP and PP capacities.

Overall, this shows that the amount of exchange that can be integrated by the surrounding Danish energy system does not change depending on the reference or the CPH2025 Copenhagen energy system. However, it shows that the Copenhagen 2025 plan leads to a larger production of excess electricity compared to the reference system. A larger production that the Danish energy system cannot integrate without compromising its own production. Thus, the remaining 90% of the excess production from the CPH2025 would have to be integrated elsewhere. In total, the integration reduces the total critical excess production in Copenhagen and Denmark from 6.76 TW h to 6.47 TW h in the reference systems and from 7.21 TW h to 6.94 TW h in the 2025 scenario.

In the reference Sønderborg energy system, the total excess electricity production amounts to 0.072 TW h. Of this, 33% is handled by the surrounding Danish energy system and 67% has to be integrated elsewhere. The reference Sønderborg system an import demand of 0.002 TW h of the demand for import is primarily caused by lack of capacity in hours with little wind and little operation on the decentralised CHP plant. This means that by integrating with Denmark, the critical excess electricity from the Sønderborg reference is reduced by 33%, according to Fig. 10. This excess is utilised by the surrounding Danish system.

If Sønderborg transitions to the Sønderborg 2029 plan, the excess electricity production in Sønderborg Municipality increases to 0.24 TW h. The surrounding Danish energy system has the possibility of integrating 0.12 TW h if they operate without taking Sønderborg Municipality into account. This means that Denmark can integrate 50% of the excess production in Sønderborg Municipality if they plan according to the Sønderborg 2029 plan. The remaining 50% has to be handled elsewhere or by Denmark altering production to accommodate Sønderborg. From Fig. 10, it is seen that the critical excess in the Sønderborg 2029 plan can be reduced by 50% and utilised in the remaining Danish energy system. In the Sønderborg 2029 plan, Sønderborg imports 0.02 TW h of electricity due to lack of production at the decentralised CHP plant and low wind production. The surrounding Danish energy system can provide 0.01 TW h of this lack of production without altering its production profile. The remaining 0.01 TW h has to be imported from other places, or the Danish system has to change its production profile.

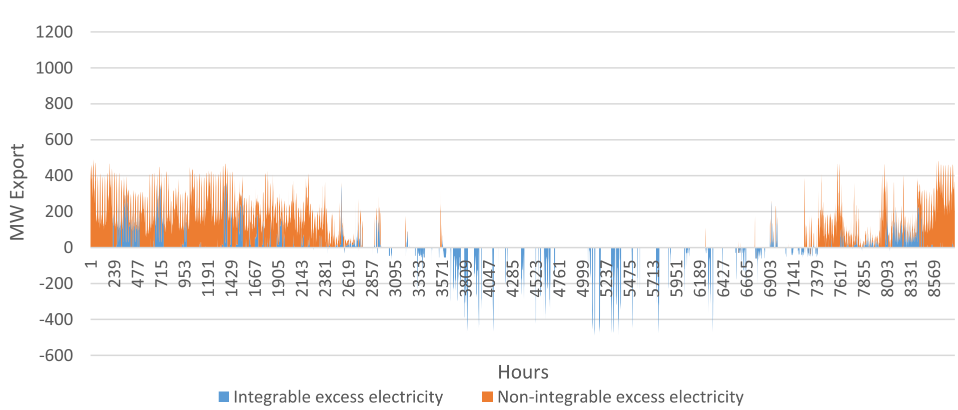

Fig. 5. Interaction measured as exportable electricity between the reference Copenhagen energy system and the Danish energy system.

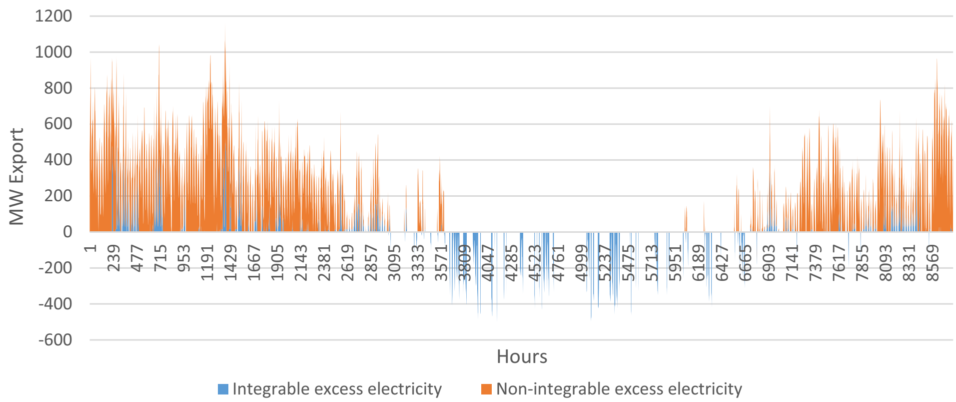

Fig. 6. Interaction measured as exportable electricity between the Copenhagen 2025 energy system and the Danish energy system.

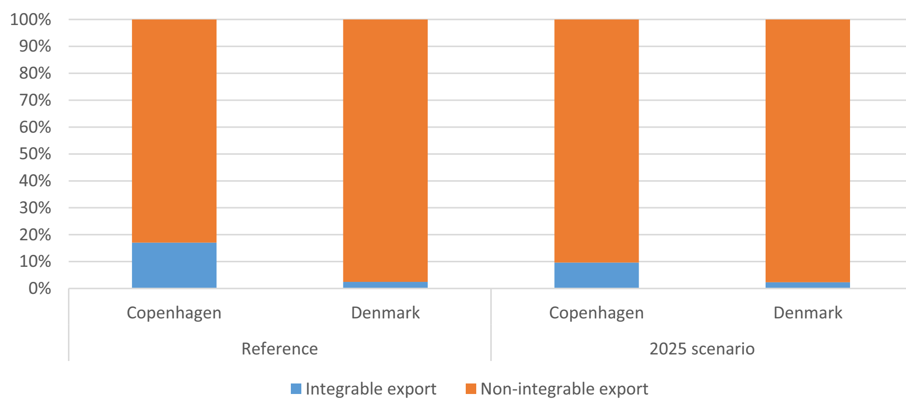

Fig. 7. Share of annual excess electricity production that can be integrated between the Sønderborg and Denmark system.

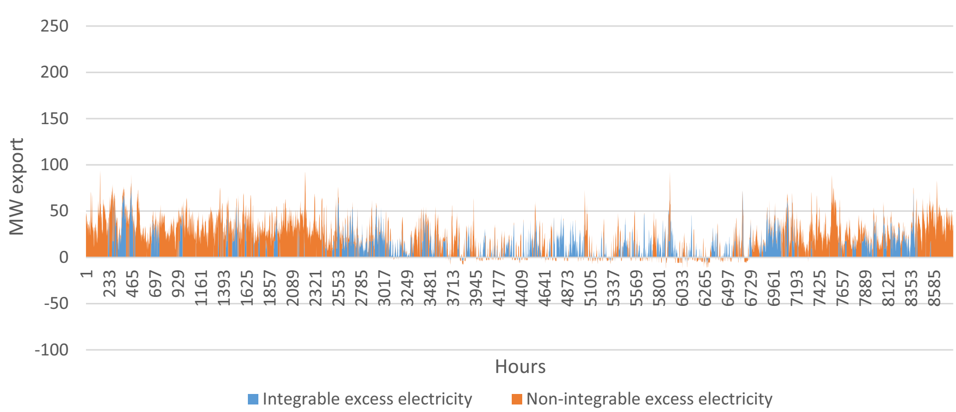

Fig. 8. Interaction measured as exportable electricity between the reference Sønderborg energy system and the Danish energy system.

Due to Sønderborg being a rather small energy system compared to the national energy demand and national energy production, they only integrate very small amounts of the total Danish excess production. This is less than 1% in both the reference and the Sønderborg 2029 example.

The integration between Sønderborg and Denmark reduces the total critical excess electricity 6.06 TW h to 5.99 TW h in the reference systems and from 6.09 TW h to 5.97 TW h in the 2029 scenario.

When comparing the reference with the Sønderborg 2029 example, the reference has less interaction, but in both the reference and the 2029 plan over 33% of the excess production can be integrated by Denmark. The higher export in the Sønderborg 2029 example is due to more wind turbine capacity and less capacity on the decentralised CHP plant. For the same reason, the Sønderborg 2029 system has to import more electricity from the surrounding energy system.

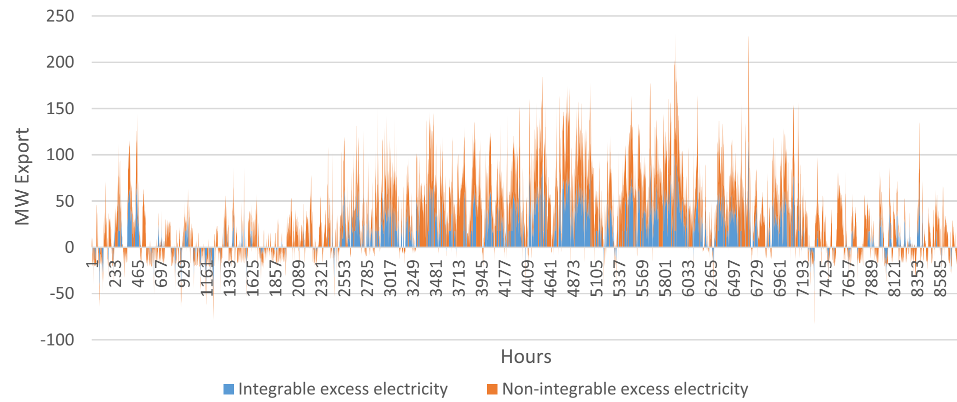

Fig. 9. Interaction measured as exportable electricity between the Sønderborg 2029 energy system and the Danish energy system.

Table 5
Annual export integration between the Copenhagen systems and the Danish energy system.

	Copenhagen reference	Copenhagen 2025
Total excess production from the Copenhagen system (TW h)	0.82	1.28
– *Integrable*	*0.14*	*0.13*
– *Non-integrable*	*0.68*	*1.15*
Total excess production from the Danish system (TW h)	5.94	5.93
– *Integrable*	*0.15*	*0.14*
– *Non-integrable*	*5.79*	*5.79*

Table 6
Annual export integration between the Sønderborg systems and the Danish energy system.

	Sønderborg reference	Sønderborg 2029
Total excess production from the Sønderborg system (TW h)	0.21	0.24
– *Integrable*	*0.07*	*0.12*
– *Non-integrable*	*0.14*	*0.12*
Total excess production from the Danish system (TW h)	5.85	5.85
– *Integrable*	*0.00*	*0.00*
– *Non-integrable*	*5.85*	*5.85*

When looking at the excess production, it can be seen that Copenhagen produces 1.28 TW h of excess electricity if they develop according to their plans. However, the Danish system has very little option of integrating this excess production, and can only integrate 10% of Copenhagen's excess production without changing its production profile. To handle the non-integrable excess electricity, the surrounding Danish system would have to operate differently to integrate more, the Copenhagen system would have to change its production profile, or other energy systems would have to import the excess production from Copenhagen. In the example of Sønderborg, it also produces higher amounts of excess electricity if developing according to their 2029 plan compared to the reference development. In this example, however, the Danish system is able to integrate it, by 0.12 TW h of the total 0.24 TW h of excess production from Sønderborg being integrable. The remaining 0.12 TW h has to be integrated through changes in the Danish system, the Sønderborg system or other energy systems. It is important to note that this study is set up to maximise excess production from all systems. For further studies, it would therefore be interesting to see how these systems can be altered to better integrate with the surrounding energy systems.

In that regard, one point of further discussion and investigation is how to coordinate local and national energy planning, as all parts of a country are likely to increase the excess production, thus making it more difficult to integrate between the systems. It is therefore important that local systems take into account the developments of the surrounding energy systems, as they cannot rely on their ability to integrate their excess production. This requires a coordinated national energy planning that takes into account freedom at the local level. This type of energy planning requires further investigation. This study suggests a methodology for using EnergyPLAN for such analyses, but does not try to optimise between the local and national system

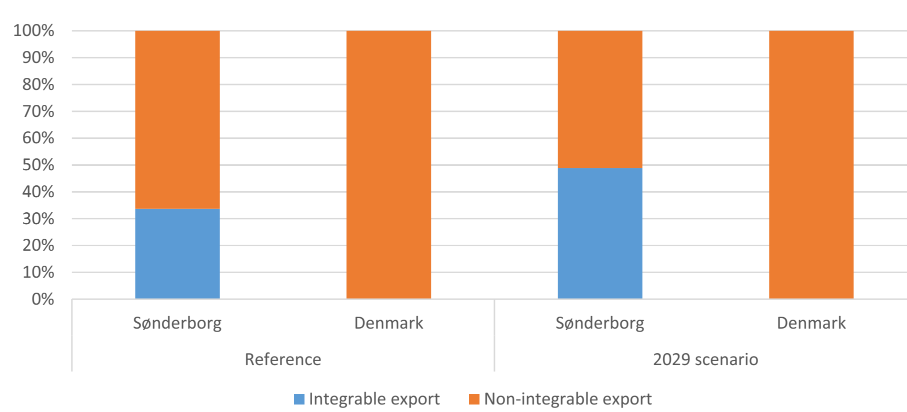

Fig. 10. Share of annual excess electricity production that can be integrated between the Copenhagen and Denmark system.

4. Conclusion

Currently, energy planning for future energy systems is divided into two branches: National planning and local municipal or city planning. This study investigated a methodology to link these two branches.

The methodology enables the use of the advanced energy system analysis tool EnergyPLAN to connect a local energy system model with a model of the surrounding national energy system. The paper studied the connection between the local and national system by investigating how well the systems integrate. The level of integration was measured by investigating how well the systems can exchange excess electricity. The study divided the excess electricity into (1) integrable excess electricity and (2) non-integrable excess electricity. Integrable excess electricity is the excess electricity that can be handled between the local and national system, while non-integrable excess electricity is the remaining excess production that has to be handled in a different manner, for instance by changing production profiles in the systems or exported to other energy systems. The study argues that by measuring the level of integration it enables researchers and planners to identify how well a local and national energy plan can work together. As such, the methodology can help towards linking local and national energy planning.

To test the application of the methodology, and illustrate the use excess electricity as a parameter to test integration, the study investigated two Danish examples. An urban area in Copenhagen and a smaller city in a rural area in Sønderborg, both connect to a national Danish system. In both examples it was possible to create a local and national energy system model, and by applying the methodology possible to investigate the level of integration between the local energy system and the national energy system. The Copenhagen example shows a situation with little integration between the local plan and the national plan, whereas the Sønderborg example shows a plan much more suited to integrate with the surrounding Danish energy system.

The examples show that the methodology can work as a measure for how well the local and national systems integrate. In both examples the tool enables utilisation of the critical excess electricity from each individual system, thus by integration enabling better performance of energy systems. Thus, the methodology can potentially be applied in designing energy plans that can utilise the benefits of local action and national coordination. In such cases the plans should evaluate to what extent the total critical excess electricity can be reduced due to interconnection. Such kind of application would be the next step in developing the suggested methodology.

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