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Renewable energy transition, transmission system impacts and regional development – a mismatch between national planning and local development

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ABSTRACT

The energy transition rests on several pillars including the electrification of heating, transportation, and industry to enable the better exploitation of renewable energy sources. This changes the geography of the energy system, where power changes from being centrally produced to being more geographically distributed. The electrification will add new, large point demands to the electricity system. The distributed generation, point demands and a higher level of electricity transit all suggest grid impacts beyond design levels. Concurrently, the transition relies on coordinated actions at local and national levels with potential mismatch issues. This article probes into these developments for a larger Danish region. Based on a survey of local actions, it investigates whether the transmission grid can withstand the changes and to what extent grid limitations create barriers for industrial development. The work is based on geographical information system (GIS)-based analyses of production and demand, survey-based stakeholder consultation to unveil expected demand and production development, and grid analyses. Results indicate that the transmission system limits the development, and that permissions should not only be based on local conditions as reported by municipalities but should also factor in spatially distributed national targets. This thus calls for improved coordination between administrative levels.

1. Introduction

The transition to carbon-neutral or carbon-negative energy systems changes the general setup of the energy system. From a system characterized by few power producers and distributed demand, a system is evolving in which production is much more geographically dispersed while demands are growing fast due to ongoing electrification.

The electrification of transportation [1,2], heating demands, and industrial demands [3] is also changing the geography of the electricity system with increasing demands in dwellings for heating and home charging of electric vehicles and the potential production of synthetic fuels in power-to-x processes [4,5]. Depending on the fuel in question, such power-to-x facilities may appropriately be located near point sources of carbon dioxide. Thus, new electricity demands do not necessarily follow the population density and the main population centres.

There is already a substantial body of work on the geography of heating demands in, e.g., Europe [6] and Chile [7], as well as work with a more methodological focus on the approach to the assessment of the geographical distribution of heating demands [8,9]. However, there needs to be more focus on the geography of electricity systems as performed by e.g. Hülk et al. [10].

In terms of the production of electricity, there are different developments. On the one hand, there is the dispersion of small units such as home installations of photovoltaic (PV) panels and single or even domestic wind turbines. On the other hand, there is also an increase in larger wind farms and PV fields. For wind turbines, this includes offshore, typically implying the installation of new offshore transmission grids. As found in a review by Sarkar and Odyou, several issues are arising including issues regarding capacity, losses, and operation of the system [11].

A new survey underlines the uneven distribution of wind power and PV developments in Denmark with main development in sparsely populated areas [12], resulting in significant per-capita installations in the north and west of the country, while the east sees less development – see Fig. 1. There is more agricultural land for installations of PV and wind power projects in these western areas – but PV installations should not be ruled out in urban landscapes. Rooftops in the residential, service,

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and industrial sectors hold promise and would give a better spatial distribution of production compared to demands. Such an uneven and generally uncoordinated development impacts transmission needs[13].

Many energy system transition papers consider only electricity flows to and from the system while using a copper-plate representation of the object of the investigation, such as Šare's work on the Dubrovnik Region [14], Thellufsen's work on cross-border or cross-sector integration [15], Bamisile's work on Nigeria [16], Dorotic's island work [17], or Marczinkowski's island studies of Madeira, Samsø, and Orkney [18]. This is typical for model work using, e.g., the EnergyPLAN model that does not consider internal restrictions in the electricity system [19].

An area of importance is the integration of local and national energy systems to ensure that local actions and national targets are in compliance [20–23]. While the importance is stressed and case studies are analysed to support this in Refs. [20,21], we have not been able to identify work identifying actual mismatches in electricity grids in these articles or in the scientific literature in general. Another area of importance is that of sector or smart energy system integration. In smart energy systems, the development and operation of the electricity system is seen in conjunction with the rest of the energy system [24,25]. Thus, multiple sectors may be coordinated, including desalination [26–29], wastewater [30,31], industry [3,32], district cooling [33,34], district heating [35,36], and transportation [37]. One of the drivers in the trends towards smart energy systems is the exploitation of flexibility or low-cost storage outside the electricity system [38] – but in terms of transmission system, sector integration also enables a more local and controlled use, thus reducing transmission needs.

Transmission systems clearly set a barrier for the development of the energy system. A strong transmission system would enable a more diverse use of the electricity system; however, in addition to being costly, transmission grid expansions are also facing opposition [39,40].

Becker et al. analyse transmission system expansion on a European level from the perspective of renewable energy transition [41], finding that transmission may have to increase in the order of four-fold for a wind and PV-based Europe. This is supported by Taseska-Gjorgievska et al. finding that grid capacity limitations are underestimated in long-term energy planning [42]. On the other hand, Baecker and Candas [43] investigate the coordinated optimisation of transmission and distribution grids and how demand side flexibility can help reduce grid expansion needs.

Lund [44] previously assessed the impacts of a large-scale electrification of the energy system and used this as an argumentation for district heating and smart energy system integration, and Blarke presented a similar analysis regarding grid requirements in future renewable energy systems with his work on "Smart grid vs super grid" [45], finding that smart grids offered fewer requirements in terms of new grid infrastructure. Oropeza-Perez et al. [46] analysed the Mexican electricity system with dispersed PV on individual buildings finding that it would free *"the transmission and distribution grid [..] during certain hours of the days"*.

Different approaches to modelling transmission system expansion requirements have been presented [47] on a European level using the Balmorel model [48] – flow-based versus net transfer capacity as well integrating electricity market impacts. In another work, Østergaard investigated the geographical distribution of production and demand within the country finding that proper integration using local

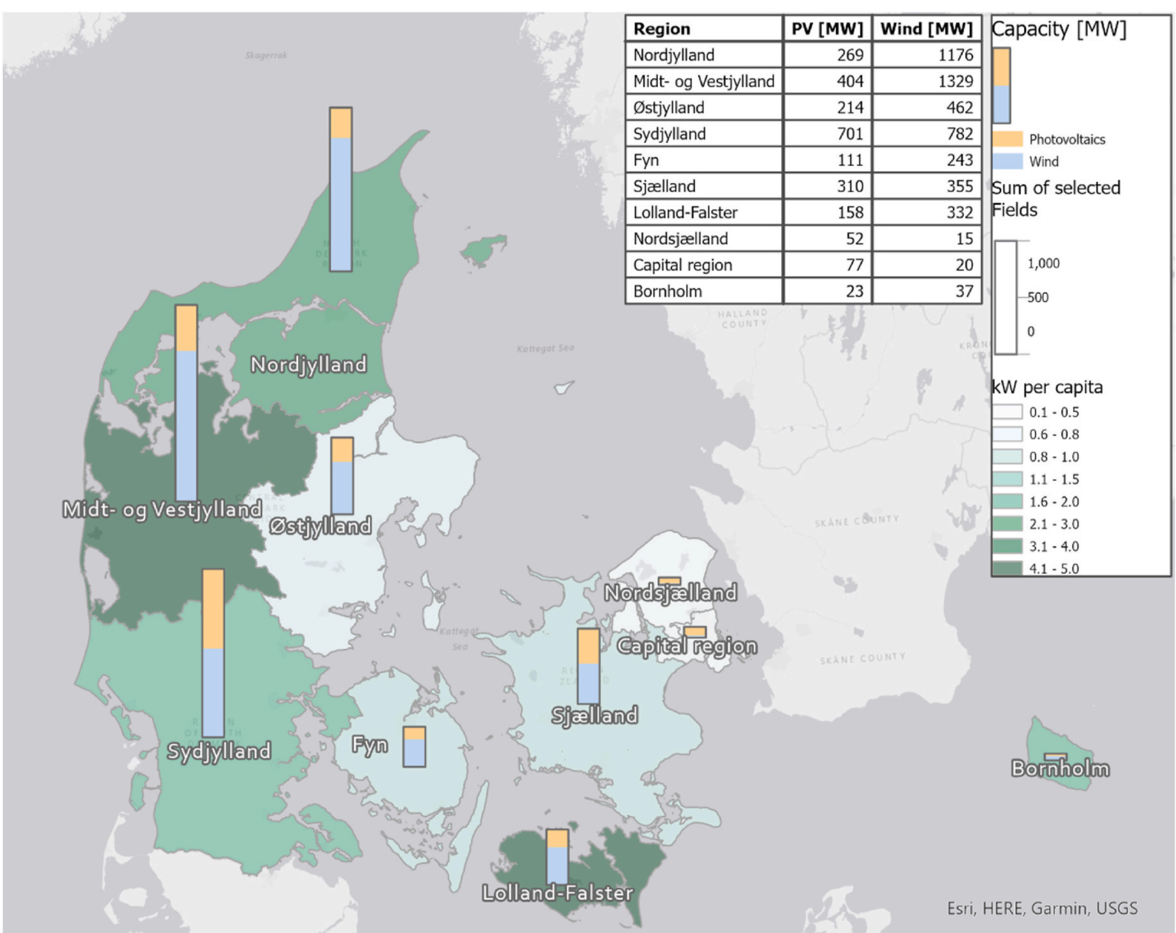

Fig. 1. Wind and PV capacity in Denmark in 2022. Note that the regions do not coincide with the political division of Denmark into regions – however the granularity here captures the uneven distribution of wind and PV better. Source of capacity data [12].

cogeneration of heat and power (CHP) stations actively [49,50] could limit transmission grid expansions to a level where underground cables could suffice. Menges demonstrated how underground cables are generally more accepted [51] – but also, that the willingness to pay among citizens does not necessarily match their cable preference.

Lastly, there is a discourse on microgrids [52] and their integration with distribution and transmission grids.

There is thus an important body of literature on transmission grid requirements for different energy system transition scenarios as well as on the spatial aspects of energy demand and supply, but much of the transition study work in general is copper-plate work. Also, much research focuses on large scale systems of, e.g., country, or continental scale. In addition, the studies primarily focus on researcher-based scenarios, and there is little if any work on actual developments in potential mismatches between national targets and local developments, or on questions whether transmission grids can accommodate the actual developments. This is thus leaving room for the development and analysis of co-designed scenarios and/or scenarios based on stakeholder consultation.

Any imbalances between the spatial distribution of production and demand will have impacts on transmission and distribution grid needs – and on the other side – the existence of a strong transmission grid allows for certain developments and modes of operation of energy systems. This calls for analyses with high temporal and spatial resolution as well as analyses coupling transmission system and energy system developments.

In this article, we investigate the link between regional development with a focus on actual plans among stakeholders and the constraints imposed on the system development through grid restrictions. A point of departure is taken in the North Denmark Region (see Fig. 2) with near-term scenarios in 2025 and 2030, respectively. This region provides a good representation of the Danish development in general, as it is characterized by an abundance of renewable energy sources as well as a larger urban area (Aalborg) with both central power production units and large industrial electricity demands. The region consists of 11 municipalities or varying characteristics.

The article proceeds with Section 2 where methods, tools and data are presented. Section 3 presents the analyses performed and, finally, the conclusions are synthesized in Section 4.

2. Methods and data

In this article, three approaches are combined. A stakeholder consultation based on a survey with all municipalities in Northern Jutland; simplified energy systems analyses; and transmission grid analyses. These approaches are further detailed in this section.

2.1. Stakeholder consultation

To be able to represent expected developments in the regional energy system as accurately as possible – both capacity wise and in terms of geography, a stakeholder consultation process was chosen, which involved a survey being sent to all municipalities. The objective was to increase the accuracy of the analysis and model, but also to increase the relevance of the model results for the participating municipalities.

The survey focused on the following topics: 1) plans for electrification of industry; 2) large new electricity consumers; 3) new electricity producing units. These topics were divided into a short (2025) and

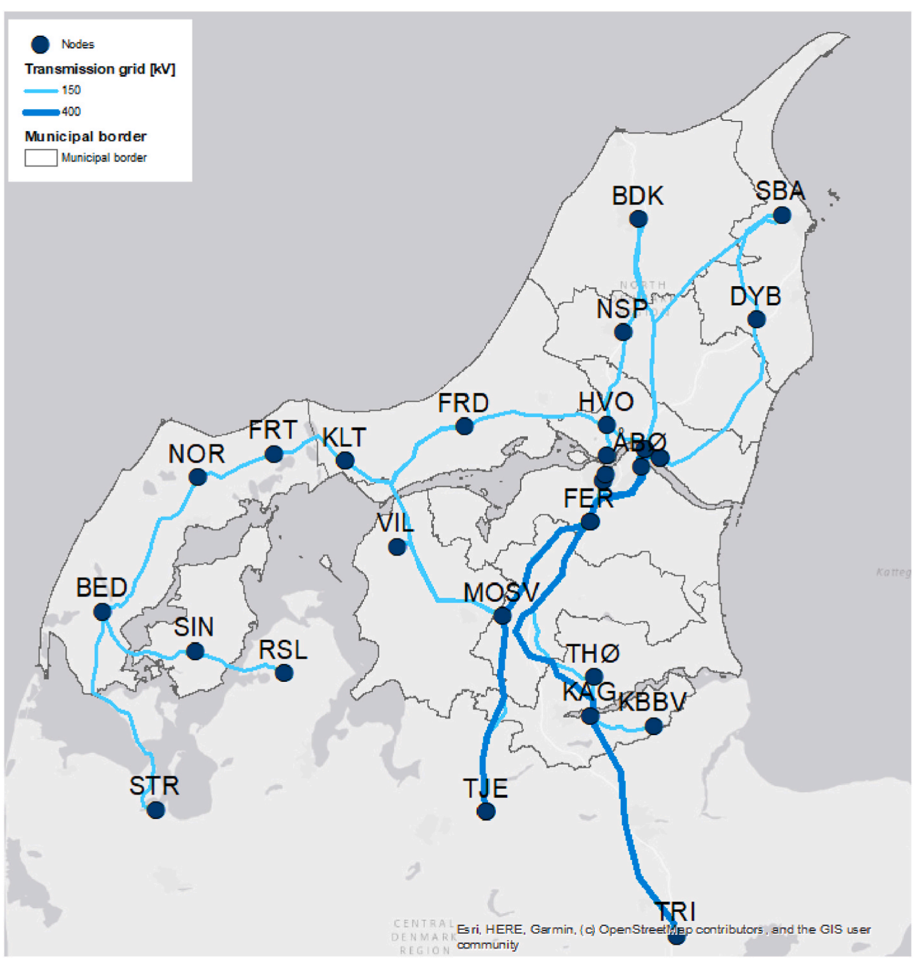

Fig. 2. Transmission grid of North Denmark Region with indication of lines, nodes and municipalities.

medium (2030) time horizon resulting in six survey questions. For each question three response categories were given: description; estimated demand/production; address/coordinates. The survey was sent as an editable document to the municipalities with the possibility to provide written answers instead of multiple-choice type of responses. This was to ensure that relevant additional information could be provided under each topic in the survey. The survey was sent out through North Denmark Region to relevant employees in the municipalities with a view to increasing the response rate. Earlier versions were discussed and updated in the project working group where, amongst others, three of the region's municipalities participated. This was done to minimize potential misunderstandings in the survey design. Moreover, North Denmark Region facilitated contact to the authors, which proved helpful in one case, where the survey was answered directly via email to one of the authors after prior consultation on the phone.

North Denmark Region was also helpful in following up on the survey request, which eventually resulted in a 100% response rate from the eleven municipalities. Also important for increasing the accuracy of the survey results was the possibility for iteratively following up on the provided information. Again, North Denmark Region was helpful in sending out clarifying questions from the authors to selected municipalities where necessary. Information from the returned survey documents was transferred to a spreadsheet and then used to make the electricity demand and production projections.

2.2. Transmission system analyses

The transmission system analyses are conducted using PandaPower [53]; a free software package that has previously been applied to, e.g., Sweden [54] but which has also formed the basis for more advanced tools as exemplified by Antic [55] and Wang [56].

PandaPower models a given grid as a series of connections in the form of lines or transformers between nodes. All components are described using their electrical parameters – e.g., impedance, susceptance, maximum current – and the resulting set of equations is solved numerically.

For these analyses, PandaPower is applied to the 150 and 400 kV grid in the area (See Fig. 2), thus distribution grids – here defined as 60 kV nominally and less – are not calculated. They are however considered as they are main connection points to more potential expansion sites.

Redundancy is not considered as would be in transmission system operator n-1 analyses. Thus, results are not worst-case contingency situations, but rather ordinary operations situations, but with analyses across the year, the variance in demands and productions show the system response to different development paths. Contingency and redundancy considerations are expected to impact different scenarios similarly.

The full list of node labels and full node names is included in Table 2 in the Appendix. The list also notes which nodes cannot be seen in, e.g., Fig. 2 due to graphical congestion.

2.3. Spatial and temporal energy systems analysis

Electricity demand and production are estimated in all nodes of the system with annual aggregated numbers with a basis in data from the Danish Transmission System Operator (TSO) Energinet [57]. Hourly values are not available from the TSO with the same nodal resolution, hence data are combined with more general data on hourly temporal resolution from Ref. [58] which is available with a much coarser spatial granularity – e.g., Western Denmark.

The two panels in Fig. 3 show the modelled hourly demand profile for the classical demand and heat pumps respectively. The classical demand is based on the TSO data while the heat pump demand data is based on outdoor temperature data. In addition to these demands, electric vehicles are modelled using the temporal profile of the classical demand and industry and electrolytic converters (power-to-x) are modelled with a constant rate.

Lund and Kempton [59] showed how the charging of electric vehicles affects energy system dynamics and that a smarter charging is beneficial for the system, however for the present analysis, it is decided not to consider a smart charging scheme – or vehicle-to-grid capability for that matter – in order to investigate plausible near-future scenarios. As for industry, the hourly demand is modelled with a flat rate due to the circumstance that energy intensive industry tends to be operated continuously.

Power-to-x is so far only installed in at limited scale in Denmark, and no data is available regarding temporal load profile, however, with high investment costs it is assumed that these units will be operated at near-constant load. If actual power-to-x stations are not operated at constant load, then the systems and grid analyses will indicate the need for curbing production and reducing electricity demand. I.e., if grid analyses indicate a grid overload of a certain duration per year, the same duration would be a reasonable indication of the need for curbing or shutting down power-to-x production entirely.

Fig. 4 shows the power production profiles which are based on TSO data as mentioned before. For the one large-scale central power station – the 400 MW Nordjyllandsværket – the temporal distribution is only relevant in the near-term 2025 scenario, as the station is planned to be decommissioned in 2028. Both local and central CHPs show some annual variation with higher productions during the colder seasons. As Andersen [60] found, CHP systems are important for load balancing, however their operation is clearly affected by heating needs. The temporal distributions also show that PV mainly produce in the summer months while the wind production is available all year, but with large fluctuations.

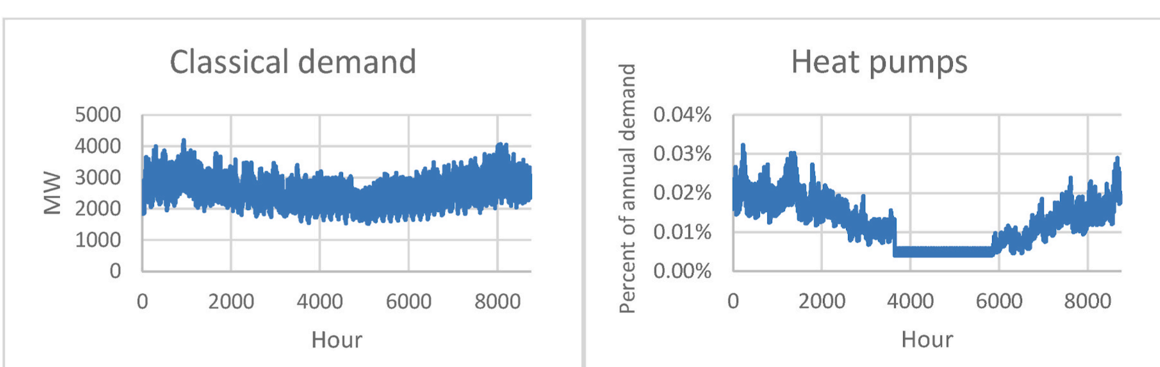

Fig. 3. Temporal distribution of electricity demands.

2.4. Demand and production projections

The classical electricity demand is modelled with a basis in 2020 data, and no evolution is modelled within the years modelled here in the existing buildings. Due to the construction of new buildings, however, the aggregate demand is modelled increasing at a rate of 0.42% per year [61]. For the electric vehicles, the evolution is based on assumptions from the Danish Energy Agency [62], with demand at 2.8% and 8.36% respectively of the classic electricity demands in 2025 and 2030 respectively. Outside district heating areas, heat pumps will be installed for individual house heating and at the same time, energy efficiency measures are carried out amounting to 20% savings in 2025 and 30% in 2030 [61].

Large new point demands in the form of industry (either new or electrification of existing industry), data centres or power-to-x are introduced based on the consultation with the municipalities in the areas. The same applies to new PV and wind power capacity. As the data from the municipalities is confidential, they have been aggregated for the purpose of this analysis. Not all the reported data from the municipalities has been included though, as some municipalities' expectations by far exceed reasonable levels as outlined in e.g. Ref. [63]. For instance, in terms of PV, the plan outlined in Ref. [63] calls for 5 GW in 2030 and 10 GW in 2045. The Danish Energy Agency assumes somewhat higher levels – 8.4 GW in 2045 and 13.1 GW in 2040 [62] on a Danish national scale. This corresponds to approx. 1.7 TWh from PV in 2030 in the modelled region – while the 2025 scenario already has an annual PV production of 2.3 TWh following the survey data from the municipalities.

An expected carbon dioxide storage facility was assessed, however prompting no relevant demand changes. This was for storage only – i.e., not for the more energy intensive capturing process, however the storage facility was expected by a municipality – but with no direct link to a site requiring capturing.

2.5. Yearly nodal balance

Table 1 shows yearly aggregated demands and production in the individual nodes of the 150 kV transmission grid. Numbers are aggregated across the aforementioned sectors and time. While the annual load in some nodes remains fairly constant over the years, it is also clear that for some nodes, productions and/or demands show strong developments, and also, that for some nodes, the annual imbalance between demand and production gets more pronounced – as shown graphically in Fig. 4. For the NNV node, corresponding to the city of Aalborg, for instance, production starts out in 2020 at a level of 260% of the demand and ends in 2030 at a level of 16% of the demand. This is due to the closing down of the power station Nordjyllandsværket in 2028, located in the vicinity of Aalborg.

On an aggregated level for the entire region, demand supersedes production by far as seen by the totals in Table 1. This is because some of the future capacity is planned as offshore wind farms not connected to the grid of this region. For these analyses, this offshore wind power contribution is neither quantified nor distributed spatially but will clearly reach the region through the transmission grid. Transmission grid loading from connecting the large demands with offshore wind farms will thus not differ from any other loading of the transmission grid caused by imbalances between production and demand within the region.

In Fig. 5, the development in production and consumption from 2020 to 2030 is presented. A strong demand increase is seen in BDK, DYB, KAG, NOR, SBA, THØ and NNV while production primarily increases in FRD, HVO, KAG, KLT, MOS, VHA and VIL.

The bar charts in Fig. 5 shows the differences in annual production and demand, which are then used to estimate hourly profiles for each node. Fig. 6 presents two examples of the hourly profiles for 2025 and 2030. The first example shows the BDK node, where the electricity demand increases by a factor three while production is constant, when comparing 2025 to 2030. The other example shows the NNV node, where the production is reduced significantly due to the expected closure of the central power station, which means that the production profile is dominated more by PV. For all nodes, similar hourly input profiles are established.

3. Analyses and results

In the following, the analysis starts with the reference situation in 2020, proceeds with the 2025 and 2030 scenarios, and concludes with a discussion on developments beyond the transmission grid area and, thus, areas only reached by distribution grids.

3.1. Analyses and results for the 2020 reference and the 2025 scenario

The analyses demonstrate that there unsurprisingly are not many issues with overloading in the reference situation. There are though some occurrences for a specific line in the western part of the region. This is a relatively sparsely populated area with good wind power

Table 1
Aggregated annual production and demand of electricity in the nodes of the electricity system in 2020, 2025 and 2030.

Node	2020		2025		2030	
	Demand [GWh]	Production [GWh]	Demand [GWh]	Production [GWh]	Demand [GWh]	Production [GWh]
BDK	416	415	503	485	1118	485
BED	362	213	406	213	425	213
DYB	176	220	1011	567	1019	367
FER	180	57	218	57	227	57
FRD	129	104	179	268	185	268
FRØ	134	173	146	173	154	173
HVO	140	181	159	509	166	509
KAG	275	658	538	658	891	924
KLT	36	447	46	473	48	473
MOS	265	164	317	627	330	627
NOR	202	262	238	262	2288	262
NIB	342	276	407	391	525	391
SBA	410	117	1359	117	3182	274
SIN	179	240	226	240	238	240
SKA	88	3	136	205	100	205
THØ	220	331	3703	331	3744	559
VHA	163	219	202	927	209	927
VIL	198	291	236	1153	243	1153
NVV	832	2.162	4195	2766	4216	659
Sum	**4746**	**6533**	**14,225**	**10,223**	**19,309**	**8766**

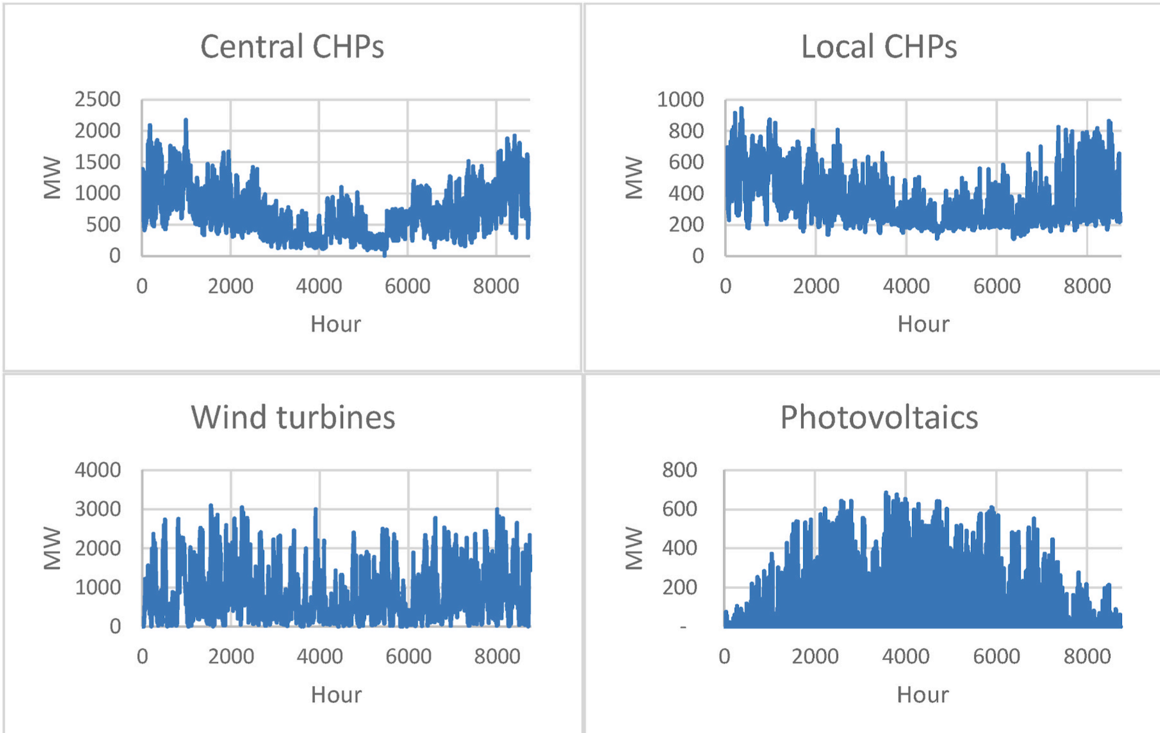

Fig. 4. Temporal distribution of power production. Note that the central power station is only present in the existing system as it is planned to be shut down in 2028.

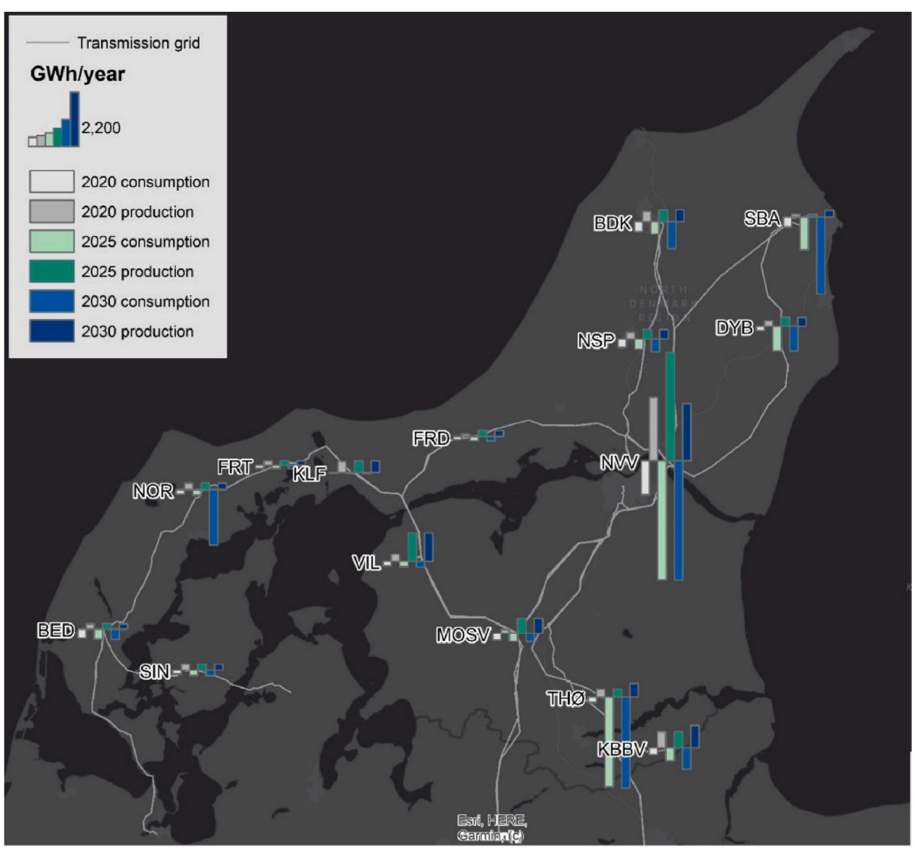

Fig. 5. Geographical distribution of the foreseen changes in electricity consumption and production at the transmission grid nodes. In the map the demand and production for NNV is a compilation of FER, HVO, NVV, SKA and VHA due to the proximity of these nodes and due to confidentiality concerns of some data in the area.

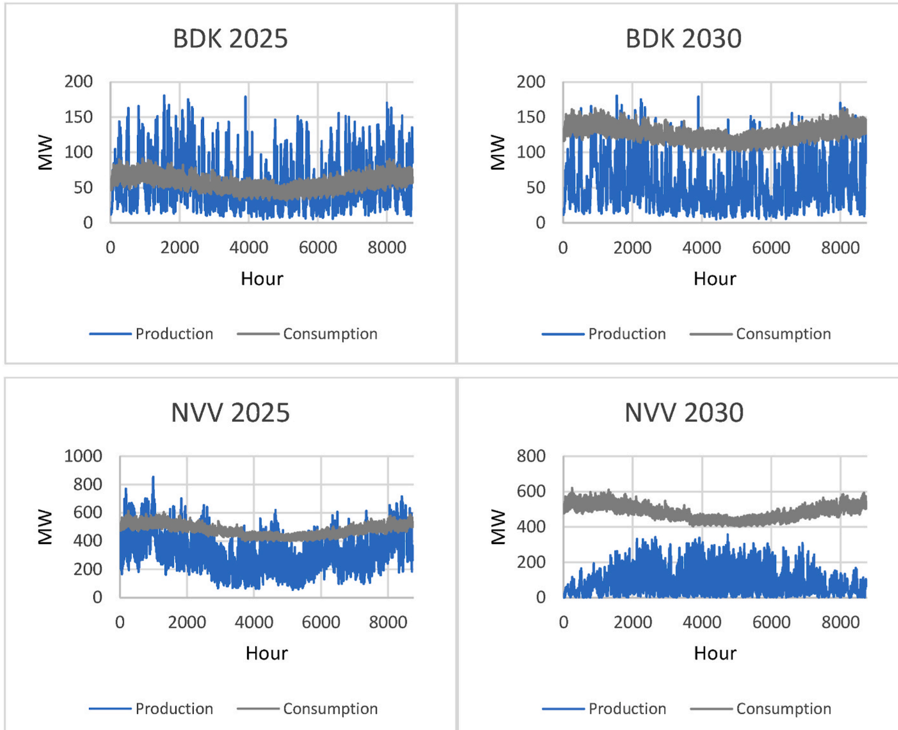

Fig. 6. Hourly production and demand in two sample nodes in 2025 and 2030.

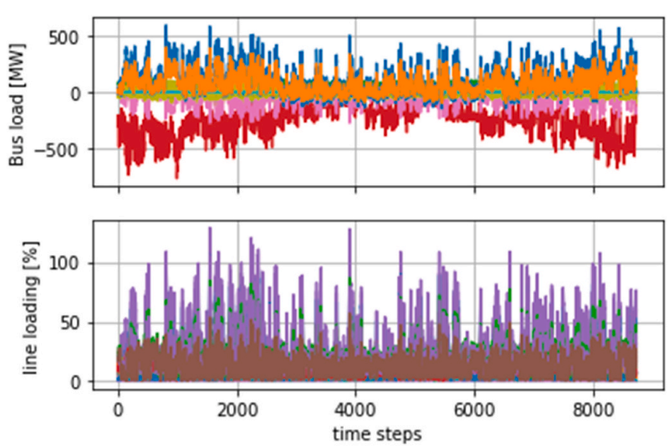

Fig. 7. Hourly node balance and line loading in the 2020 situation. All nodes and lines are shown with separate colours, but not all are visible due to graphical congestion.

resources.

Figs. 7 and 8 show the 2020 situation, which is the reference situation. As expected, most of the lines are not overloaded, only the line from BED to NOR shows overloading in 0.7% of the hours.

The 2025 scenario shows a more pronounced overloading with several lines exceeding a 100 %-line load during multiple hours of the year. Fifteen out of 35 lines are overloaded in some hours of the year. For most of these lines, however, overloading is limited to a few hours, while for specific lines overloading is a more consistent issue (See Figs. 9 and 10).

The FER-THØ line, for instance, is overloaded 100% of the time (see Fig. 11), while a line like VHA-ÅBØ is overloaded 31.2% of the time. The VHA-ABØ line is not shown in Fig. 11 as it is a relatively short line in the congested area under the ÅBØ label. The overloading on these lines is primarily due to a large demand increase in 2025. The demand also increases significantly in DYB and SBA from 2020 to 2025 but does not create overloaded lines.

3.2. Analyses and results for the 2030 scenario

For the 2030 situation (See Fig. 12), overloading increases further, with more lines overloaded in the west, in the centre and now also in the northern part of the area. A total of 22 out of 35 lines are overloaded for a smaller or larger part of the year, and some lines are overloaded more than half of the time. Again, as in the 2025 scenario, the line to THØ is always overloaded. The primary reason for the increase in the number overloaded lines are further demand increases in NOR, BDK, SBA between 2025 and 2030.

With the phasing out of the Nordjyllandsværket power station, more power is transmitted from outside to the region causing, e.g., the load to exceed the capacity for the 400 kV line from TJE to FER in some hours.

It should be noted, that for computational reasons, 6996 h are simulated here. For the remaining hours, PandaPower was unable to compute a solution – probably due to loading beyond model design parameters.

Fig. 13 shows as the same results as in Fig. 12 focusing on the average yearly load and standard deviation of line loads. It is noticed that some lines are hardly used – the 150 kV connection MOSV-TJE and the 400 kV line NVV-VHA. In the former case, this is a line running in parallel with a 400 kV line and in the latter case, this is due to simplifications of the assignment of loads in the Aalborg area. Note that the NVV-VHA line is not discernible in Fig. 12 due to graphical congestion in the Aalborg area. For other lines, the result is the same as in Fig. 12 with a few lines with consistent overloading - FER-THØ, BED-NOR and NVV-SBA.

3.3. Transmission and distribution grids

The grid analyses presented in the previous section only address the transmission grid at 150 and 400 kV levels, however, the transmission grid does not reach all corners of the region. A particular focus of the region's development plan is industrial ports and ferry ports where either power-to-x may find appropriate locations from a logistics'

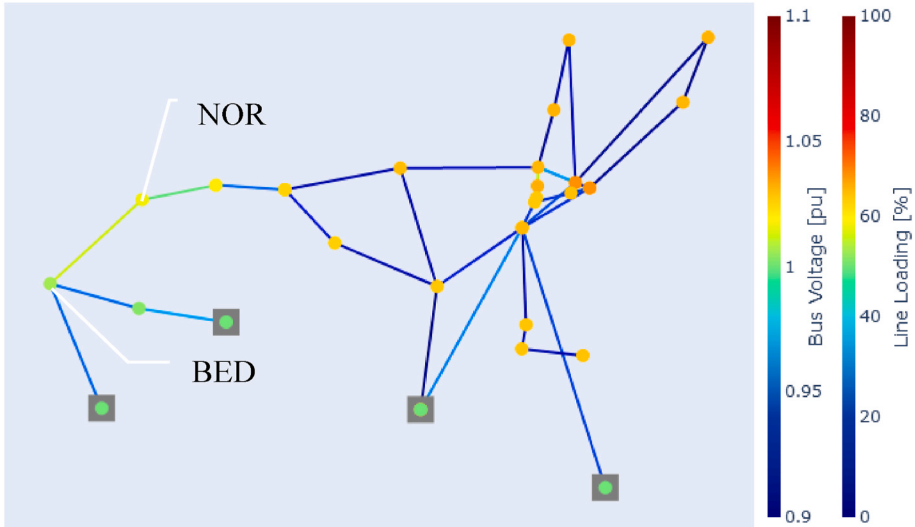

Fig. 8. Transmission grid of the modelled 2020 situation with colours representing nodal voltage (bus voltage) and line loading. Simulation results from hour 8735 are presented (a December evening).

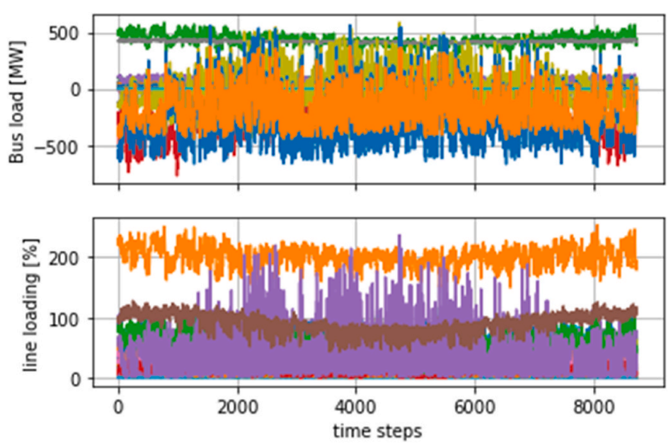

Fig. 9. Hourly node balance and line loading in the 2025 scenario. All nodes and lines are shown with separate colours, but not all are visible due to graphical congestion.

perspective or where ferries may demand power for charging in the future. Major ports lie in Hirtshals (mainly ferries), Skagen (Europe's largest landing site for pelagic fish [64]), Frederikshavn (ferries and industry [65]), Hanstholm (fishery [66]) and Aalborg (cement and an increasing focus on land-side activities [67]) (See Fig. 12). Of these, Port of Aalborg is the only one with relatively strong connections to the transmission grid. The port of Frederikshavn is connected to the SBA node through two 5–6 km 60 kV distribution lines. Port of Skagen – at the very tip of Denmark – is connected through 60 kV lines to SBA and BDK at a distance of 35–40 km. The Port of Hirtshals is also connected to BDK through 60 kV lines – both directly and meshed, and the Port of Hanstholm is similarly located 12 km north of NOR and 21 km west of FRT.

Where 150 kV lines under Danish conditions typically have a transmission capacity in the range of 200 MW, and a 400 kV transmission line a capacity of 1100 MW, distribution lines at 60 kV have far lower capacities. Here, the capacity is typically around 50 MW. As with other voltage levels, this of course depends on the conductors as well as the number of parallel systems, i.e., the number of systems on a line of transmission towers.

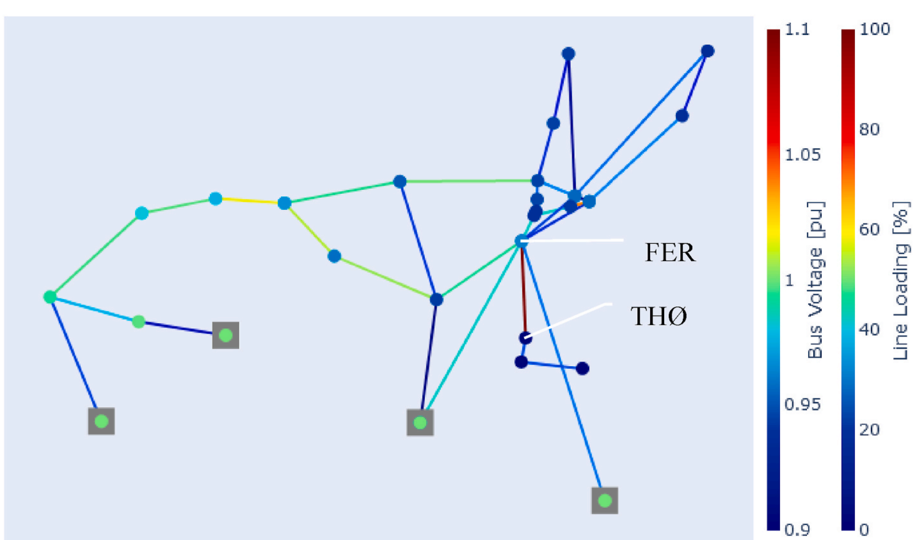

Fig. 10. Transmission grid of the modelled 2025 situation with colours representing nodal voltage (bus voltage) and line loading. Simulation results from hour 5000.

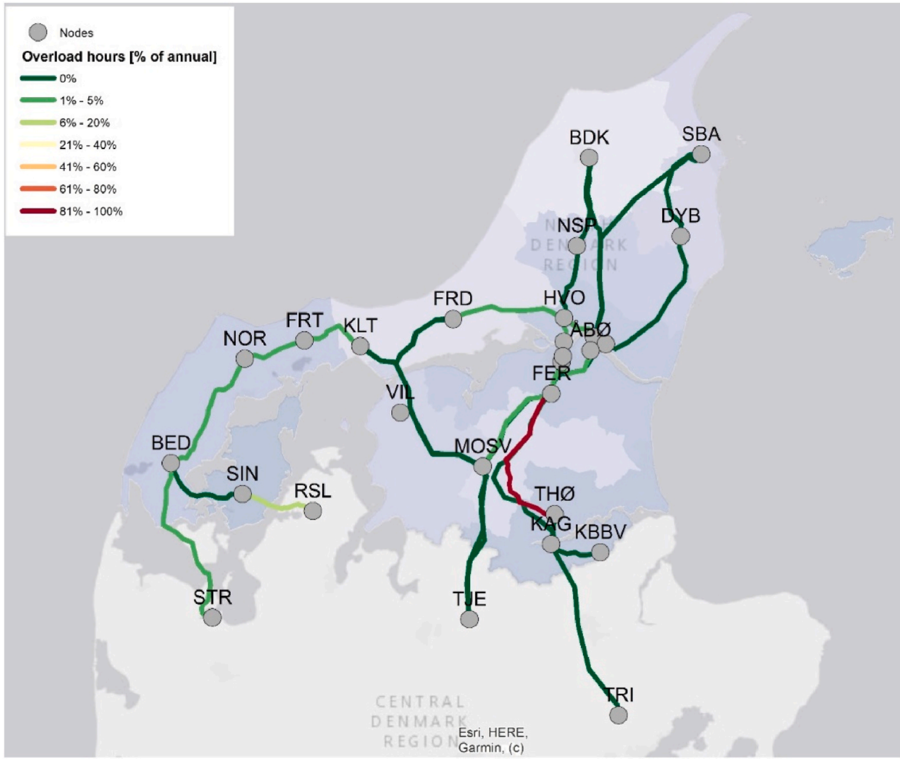

Fig. 11. Transmission grid of the modelled 2025 situation with colours representing the number of hours the individual lines are overloading during the entire year.

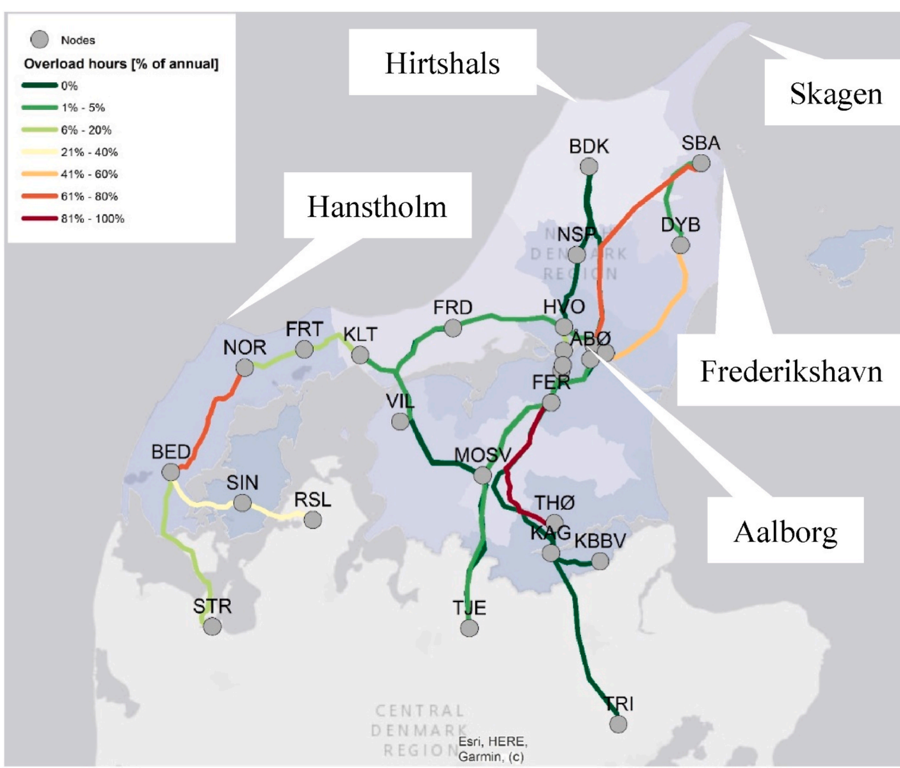

Fig. 12. Transmission grid of the modelled 2030 situation with colours representing the number of hours the individual lines are overloading during the entire year. It should be noted that the simulation is based on hours representing only about 80% of the year. In addition, major ports referred to in Section 3.3 are indicated.

The distribution grid thus also forms a barrier for development in a region like the one modelled here. There are definitive bottlenecks, but a closer survey of these issues has not been carried out. Whether ports can get an increased access to electricity through distribution or transmission grids is also not assessed, but clearly, the larger the demand, the more the motivation for expansion at transmission level. In terms of grid

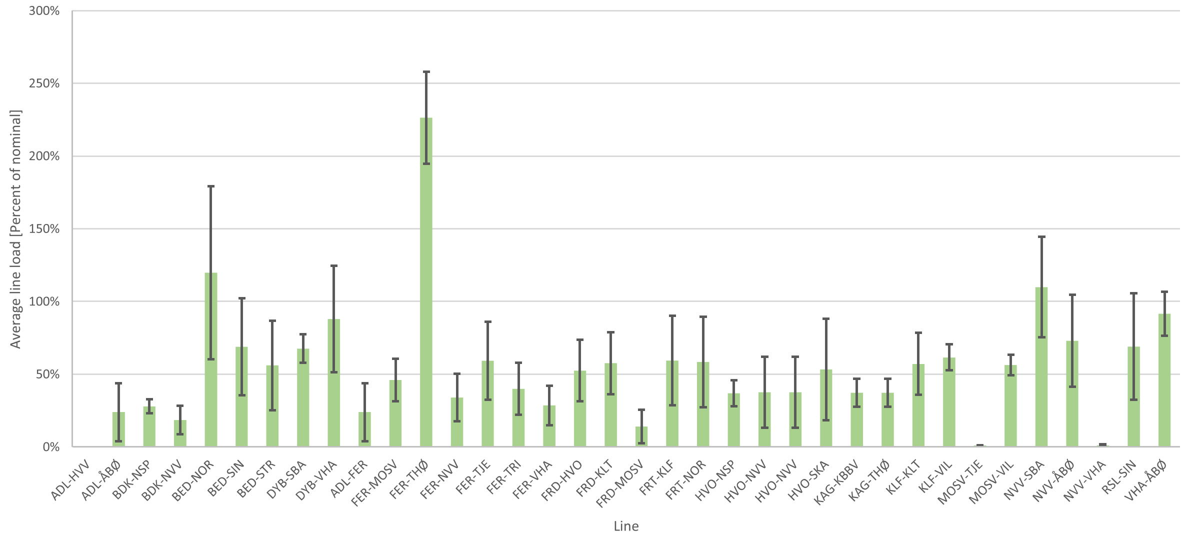

Fig. 13. Average yearly line loading of the transmission grid with the modelled 2030 situation with indication of standard deviation.

and energy system planning this is relevant, since ad-hoc (i.e., linked to new production) transmission grid upgrades or expansion by the transmission system operator typically take in the order of 3–5 years, while distribution grid expansions have shorter time horizons.

For the grid analyses conducted here, expected future demands and productions have been adhered to the nodes of the transmission grid, thus no higher spatial resolution is considered. Likewise, the transmission grid analyses have only addressed actual specific lines; not potential or planned, but currently non-existing lines. This issue could be addressed in further research on the topic.

4. Conclusion

This paper has presented a survey of future electricity productions and demands and assessed whether these expected developments are compatible with existing grid infrastructures. Most new demands are not problematic at the transmission system level. This applies to heat pumps for district heating or individual heating, electrification of the industry, and carbon dioxide storage facilities. On the other hand, if the ambitions of the eleven municipalities of the region are to be fulfilled in terms of electricity intensive processes like power-to-x, then demand will exceed present grid capacity. In some cases, even by far.

The analyses also suggest that several of the prime sites for development are beyond the feasible as they are only connected through distribution grids.

There are significant new productions planned from RES in the area – primarily PV. The production of these planned sites however does not only exceed what there is room for in the grid but also what is an appropriate share from a national perspective. A clear sign that not only should planning permission involve grid considerations, but it should also include consideration for national developments and appropriate shares across municipalities. If planning permissions are simply granted without regard for a reasonable spatial distribution of national aims or appropriate levels, then the survey shows that expansion can exceed the reasonable. A further coordination between administrative levels is thus also required and emphasized by the distributed nature of future energy systems and the good feasibility of, e.g., PV installations. Conversely, the analysis indicates that if new industrial developments involving electrification of energy-intensive industries and power-to-x should be supported at a more or less equal level in all municipalities, there may be a need to update the current "reactive" transmission grid expansion paradigm towards a more proactive paradigm.

Some of the areas where the analyses have identified particular issues – or mismatches between expected developments and current transmission capacity – is for the line leading south to THØ which shows significant overloading already in the 2025 scenario. In the 2030 scenario, also the line heading north to SBA, the line between BED and NOR in the western part of the area show overloading in more than 60% of the hours. Most other lines will be overloaded fewer hours.

It should be noted that this is without taking contingency into consideration, but perhaps grid resilience and contingency in the future will need to adapt to a new reality, i.e., not necessarily whether the system can operate without a critical line or transformer, but rather which loads needs to be shed under contingency situations.

It should also be noted that the calculation engine applied – PandaPower – has not been able to simulate all load situations. It is therefore expected that the duration of overloading is larger than what resulated from the simulations.

Taking the point of departure in one Danish region, the approach explored in this paper is applicable and relevant beyond the Danish context. Further work could explore the interfaces between transmission and distribution grids – especially, regarding the need to upgrade distribution lines to transmission lines, which has not been included in the present analysis, but is likely to become an issue in remote industrial areas, e.g., ports.

While the specific results clearly apply to the analysed case, there is no reason to assume that results would look different elsewhere with what may be labelled uncoordinated development. If investment decisions and planning permissions are only based on local conditions, good feasibility in e.g., wind power and PV projects can cause developments beyond appropriate levels and thus grid impacts that are unnecessarily significant.

Future studies could contrast this uncoordinated development with coordinated development, where local expansion plans are scaled to match national plans and targets. Furthermore, future studies could touch upon a more coordinated operation of the energy system, where the analyses in this study have not stressed the flexibility options of the energy system but has rather assumed e.g., constant power-to-x operation to optimise operating hours.

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.

Data availability

The data that has been used is confidential.

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Appendix

Table 2
Node labels and full names

Label	Full name	Note
ADL	Ådalen	Not shown on maps
BDK	Bredkær	
BED	Bedsted	
DYB	Dybvad	
FER	Ferslev	
FRD	Fredensdal	
FRØ	Frøstrup	
HVO	Hvorupgård	
HVV	Håndværkervej	Not shown on maps
KAG	Kærbybro	
KLF	Klimfjordholme 2	Not shown on maps
KLT	Klimfjordholme	
MOS	Mosbæk	
NVV	Nordjyllandsværket	Not shown on maps
NOR	Nors	
NSP	Nibstrup	
RSL	Roslev	
SBA	Starbakke	
SIN	Sindbjerg	
SKA	Skansen	
THØ	Tinghøj	
VHA	Vester Hassing	
VIL	Vilsted	
ÅBØ	Aalborg Øst	

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