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STUDENTERRAPPORT

Hydrogen Production Curtailment from Transmission Line Overloading – A PandaPower Study on PtX Grid-Connection Scenarios in the Region of Northern Jutland, Denmark

Full name of student	Frederick Sebastian Marcus Stender
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Name of supervisor	Jakob Zinck Thellufsen
Student number	20175390
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Abstract

The deployment of hydrogen production via electrolysers in power-to-X (PtX) facilities can be refined into synthetic fuels, which enables abating greenhouse gas emissions in otherwise hard-to-abate sectors such as heavy transportation and industry. However, with increasing electrification occurring in energy systems and changes to the nature of electricity generation, the impact on potential overloading of electricity transmission lines come into question with the high level of electricity consumption needed from grid connected PtX facilities. Curtailment of hydrogen production in PtX facilities may be needed as to not induce overloading of transmission systems. This study performs a power flow analysis in the modelling tool of *PandaPower* to the electricity transmission grid in the case study area in the region of Northern Jutland, Denmark. Different strategies of varying grid connection versus direct electricity generation from directly connected onshore wind turbines are simulated to evaluate curtailment of hydrogen production of PtX facilities with varying capacities in preliminary pipeline to the region. Results indicate that grid connection of two 1 GW PtX facilities to the region will induce overloading of transmission lines to a degree with which the existing electricity transmission grid in the region can't withstand the transported electricity and potentially undermine the hydrogen production of other, smaller PtX grid connected facilities in the region by inducing transmission line overloading. By assuming no grid connection of the two 1 GW PtX facilities in pipeline to the region of Northern Jutland, can the smaller PtX facilities – amounting to 570 MW of electrolyser capacity – achieve full hydrogen production in all hours of the year, whilst effectively offsetting 188 GWh of excess electricity production from directly connected onshore wind turbines.

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Summary, general audience

The deployment of hydrogen production via electrolysers in power-to-X (PtX) facilities can be refined into synthetic fuels, which enables abating greenhouse gas emissions in otherwise hard-to-abate sectors in the energy system such as heavy transportation and industry. However, with increasing electrification occurring in energy systems and changes to the nature of electricity generation, the impact on potential overloading of electricity transmission lines come into question with the high level of electricity consumption needed from grid connected PtX facilities.

By investigating four different scenarios i.e., strategically different pathways that simulate different strategies of supplying PtX facilities by respectively directly connected onshore wind turbines and the electricity transmission grid, this study investigates the needed decrease of hydrogen production as overloading of electricity transmission lines occur. The overloading of electricity transmission lines can lead to short-circuits and other critical errors in electrical grids. Thus, the overloading of electricity transmission lines is to be avoided.

Initially, the study determines the annual electricity consumption of *1)* classic electricity consumption of four major building types, *2)* the charging of electric vehicles and plug-in hybrid vehicles, and *3)* individual heat pumps to each transmission bus of the electricity transmission grid. Then, the electricity generation from *1)* combined heat- and power plants, *2)* photovoltaics, and *3)* existing onshore wind turbines is determined to each transmission bus of the electricity transmission grid. To allocate the different types of electricity generation- and consumption to the appropriate electricity transmission grid buses of the grid, Voronoi polygons are extended from each transmission bus inside the boundaries of the region of Northern Jutland. This process is also called Voronoi tessellation and is to determine the geographically, Euclidean-distance nearest electricity transmission bus of the different types of above-mentioned energy system components, thus allocating electricity generation- and consumption in the electricity transmission grid of Northern Jutland. By creating Voronoi polygons inside the boundaries of the region of Northern Jutland, the geographical location of respectively buildings, combined heat- and power plants, photovoltaics, and existing onshore wind turbines are utilised to determine the capacities of these technologies to the appropriate transmission buses of the grid. Buildings are used to determine both the electricity consumption of individual heat pumps- and the classic electricity consumption. As the number of electric vehicles- and plug-in hybrid vehicles is in the utilised data of the 2024-number of the respective types of vehicles at municipal level, the intersecting areas between the municipalities in the region of Northern Jutland and the Voronoi polygons are utilised as to determine, by assuming land area is the proxy of the geographical distribution of electric vehicles- and plug-in hybrid vehicles.

By applying distributions of the hourly share of electricity consumption to each of the three types of electricity consumption, the hourly electricity consumption needed satisfied in the power flow analysis model is determined. Correspondingly, hourly distributions of the electricity generation are coupled with each of the three types of electricity generation to determine the hourly electricity generation to each transmission bus of the electricity grid. The modelling of the hourly electricity generation- and consumption is initially done to existing levels of electricity generation- and consumption to each transmission bus of the electricity grid. To most components the 2024-level is identified and is then projected to the years of respectively 2030, 2040, and 2050 utilising the Danish Energy Agency's expectation of development to each of these types of components in the energy system. This expected development of the different components in the energy system reflects the Danish Energy Agency's expectation to the development in the entire of Western Denmark (price zone of DK1) i.e., Jutland, Fyn, and various other and smaller areas West of Zealand. The expected development is provided in relative developments, which is transferred to the current (2024) levels of electricity generation- and consumption to each of the components of the energy system. A few exceptions to this transferral of the Danish Energy Agency's expectation to the relative development of the above-mentioned components of the energy system are utilised in this study:

1) additional onshore wind turbines are only modelled in the PtX grid-connection scenarios in which onshore wind turbines are connected by a direct power line to the respective PtX facilities modelled.

2) individual heating is assumed to completely replaced by individual air-to-water heat pumps in all buildings outside existing district heating areas in the region.

The *PandaPower* power flow modelling tool is then able to simulate the flow of power, balancing electricity generation- and consumption in all hours of the year – respectively to the years of 2024 (to reflect the current level of strain on electricity transmission lines), 2030 (to reflect the short-term development of the underlying energy system), 2040 (to reflect the medium-term development of the underlying energy system), and 2050 (to reflect the long-term development of the underlying energy system) – with the aim of not exceeding transmission line loading capacities. In hours of excess electricity generation, the model will offset excess electricity out of the region of Northern Jutland via four external grid transmission buses (export). In hours of an electricity consumption not being satisfied, and the model determine the flow of power would overall be lessened with the import of electricity elsewhere and/or the total electricity generation of the model can't provide the electricity consumption, the model will import electricity from the external grid (import). The simultaneous import and export of electricity respectively to and from the region can occur in the model, as some transmission lines will require electricity to cover consumption in one part of the region, whilst another part of the region may be in excess of electricity generation.

The PtX facilities in pipeline to the region of Northern Jutland – including their locations and electrolyser capacities – are derived from a pipeline list by the association Hydrogen Denmark. Depending on the preliminary location, the geographically nearest electricity transmission bus (medium- or high voltage transformer) is assumed to be the point of grid connection point of the respective PtX facilities. Specifically, six PtX facilities in pipeline to the region of Northern Jutland are identified: Two PtX facilities each at 50 MW, one PtX facility at 120 MW, one PtX facility at 350 MW, and two PtX facilities each at 1 GW. Thus, the summarised electrolyser capacity modelled in the electricity transmission grid of Northern Jutland is 2,570 MW. If only the four smaller PtX facilities were deployed in the electricity transmission grid of Northern Jutland, the summarised electrolyser capacity is 570 MW. Utilising data from the Danish Energy Agency's *Technology Catalogue for Renewable Fuels* provides the information that the average hydrogen production of electrolysers is 519 kg hydrogen per day per MW electrolyser, the theoretically highest level of deploying all 2,570 MW in the region of Northern Jutland is determined to be 486.8 kilo tons of hydrogen annually. Deploying the four smaller PtX projects at a summarised electrolyser capacity at 570 MW can annually produce x kilo tons of hydrogen at the theoretically highest level.

By assuming that the PtX facilities are not connected to the electricity transmission grid at all – and will thus not contribute to the overloading of electricity transmission lines at all – but instead are supplied with electricity from directly connected onshore wind turbines, the six PtX facilities can annually provide around 46% of the theoretically highest level. Only 150-metre hub height, 7.2 MW_e onshore wind turbines are modelled for this study, and thus there are hours in which the electricity production can't cover the electricity consumption of the PtX facilities, that are modelled to try to operate at full capacity in all hours of the year.

The annual hydrogen production can be increased from the PtX facilities by assuming they are connected to the electricity transmission grid. In the first of three PtX grid-connection scenarios – *only grid* – the PtX facilities can only draw power from the grid. By modelling the deployment of the four smaller PtX facilities, the annual hydrogen production is increased from 47.9 kilo tons of hydrogen (*44% of the theoretically highest level of the four smaller PtX facilities*) by 125% to ~108 kilo tons which is 100% of the theoretically highest level of hydrogen production of the four smaller PtX facilities. However, when the two 1 GW PtX facilities are deployed in the grid by the *no grid*-scenario, overloading of electricity transmission lines occur in a lot of electricity transmission lines: Many transmission lines are utilised above their line loading capacities in some hours of the year, and several of these transmission lines are utilised above their line loading capacities in *all* hours of the year. In fact, the overloading of transmission lines in the electricity transmission grid (partially) undermines the hydrogen production from the four smaller PtX facilities, as *1)* none of the transmission lines supplying the two 1 GW PtX facilities are in the flow of power utilised under their line loading capacities, and thus no hydrogen production can occur at these sites, and *2)* some transmission lines supply the same PtX facilities which then in turn cannot be provided with power as the lines are utilised above their line loading capacities – which they only were to a slim extent prior to the deployment of the two 1 GW PtX facilities.

The second of three PtX grid-connection scenarios in which the PtX facilities in pipeline to the region are connected to the electricity transmission grid – *partial grid* – assumes the electricity consumption of the PtX facilities to be initially covered by directly connected onshore wind turbines that offset their excess electricity production. Excess electricity production from the directly connected onshore wind turbines occur, as the capacity of the onshore wind turbines is annually set to produce the same amount of electricity equal to that of the annual electricity production of the respective PtX facilities were they to utilise full capacity in all hours of the year. Thus, the directly connected onshore wind turbines will in some hours of the year produce electricity above the respective PtX facilities' capacities. The deployment of the four smaller PtX facilities to this scenario shows to induce a near insignificant increase of overloading of electricity transmission lines in the electricity transmission lines. Thus, the four smaller PtX projects will still – as was also the case in the *only grid*-scenario – produce hydrogen at full capacity utilisation whilst effectively integrating 188 GWh of surplus electricity into the electricity transmission grid. However, the deployment of all six PtX facilities to the *partial grid*-scenario induces overloading of electricity transmission line loading.

In the last of the three PtX grid-connection scenarios entailing some level of grid connection of the PtX facilities in pipeline to the region – *partial grid full wind curtailment* – the impact of possibly decreasing the overloading of electricity transmission lines by curtailing all excess electricity production from the directly connected onshore wind turbines. To this PtX grid-connection scenario it is concluded as goes for the deployment of all six PtX facilities in the region, that the overloading of electricity transmission lines is also too high for the scenario to prove possible for all six PtX facilities to be connected. Applying the *partial grid full wind curtailment*-scenario to the four smaller PtX projects shows the same level of annual hydrogen production, but curtailment of wind power production increases to ~22% of the directly connected onshore wind turbines.

The study concludes as goes specifically for the planning of both PtX facilities and onshore wind turbines directly connected to said PtX facilities in the region of Northern Jutland, and possibly delivering excess electricity production to the electricity transmission grid, that: by the current state of the electricity transmission grid in the region of Northern Jutland it is likely that any scenario of grid connection of the two 1 GW PtX facilities in pipeline to the region of Northern Jutland will induce extensive overloading of electricity transmission lines. Thus, these 1 GW PtX facilities in pipeline to the region ought to be connected to the PtX grid-connection scenario of *no grid* in which only directly connected onshore wind turbines supply power to these facilities. This would allow for the production of 174.4 kilo tons of hydrogen annually, which translates to 46% of the theoretically highest level of annual production achieved. Subsequently, the four smaller PtX facilities in pipeline to the region – amounting to total of 570 MW electrolyser capacity – ought to be connected by the *partial grid* scenario in which case 100% capacity utilisation can be achieved which translates to 108 kilo tons hydrogen annually. Additionally, 188 GWh of surplus electricity production from onshore wind turbines can be integrated in the electricity transmission grid. In summary, it is determined that the combination of PtX grid-connection scenarios to the PtX facilities in pipeline to the region of Northern Jutland is by not grid connecting the two 1 GW PtX projects and applying the *partial grid*-scenario to the four smaller PtX facilities in pipeline entails an annual hydrogen production of 282.4 kilo tons of hydrogen annually. This translates into an overall utilisation of the theoretically highest level of the PtX facilities in pipeline to the region of 58%.

The study concludes on a more general basis, that the deployment of grid connected PtX facilities must be carefully considered with respect to potentially induce electricity transmission line overloading, and that the implementation of PtX facilities being grid connected can potentially (partially) undermine the hydrogen production of grid connected PtX facilities elsewhere in the electricity grid.

The contribution of this study to the field of science on the subject of grid- versus direct wind-power supply strategies for PtX facilities is the proposal of a method that combines methodological approaches of *1)* directly connecting onshore wind turbines to grid connected PtX facility and *2)* considering the potential overloading of electricity transmission lines that can entail curtailment of hydrogen production at grid connected PtX facilities.

1 Introduction

1.1 Motivation

Electricity can be stored in the form of hydrogen via the process of electrolysis in power-to-X (PtX) facilities **Fejl! Henvisningskilde ikke fundet.**. This hydrogen can then be further refined into synthetic fuels that can help abate greenhouse gas emissions from the fuel consumption of the otherwise hard-to-abate sectors of industry- and heavy transportation [1]. Additionally, the electricity consumption of the PtX facility in on its own can provide peak shaving in hours of excess electricity production / a high share of renewables in the electricity grid, effectively enacting as an energy storage [2]. For the very same reason, PtX facilities bear the potential to provide grid stability if connected to the electricity grid [3]. These are amongst possible positive effects to the energy system with the deployment of PtX facilities.

However, the electricity consumption of PtX facilities can risk increasing the utilisation of electricity transmission lines above line loading capacities. The overloading of transmission lines' capacity can lead to blackouts, short-circuits, and other operational issues of electricity grids [4]. At the same time, as general electrification leads to higher electricity consumption via, amongst other, the shift towards electric vehicles, deployment of individual heat pumps to replace biomass- and fossil fuel based individual heating, and electrification of industry [5], [6], [7], this potentially contributes as well to the overloading of electricity transmission lines' capacity. All the while, increasing capacities of electricity production from renewable energy-based sources are also projected to potentially contribute to the overloading of transmission line capacities [8]. This questions the deployment of grid connected PtX facilities in the face of other projected changes in the energy system that can induce overloading of electricity transmission lines well.

One of such strategies to supply PtX facilities with electricity – without connecting to a transmission grid – is via directly connected renewable electricity production e.g., onshore wind turbines and photovoltaics [9]. However, such a strategy can result in a loss of hydrogen production when electricity cannot be supplied by the inherently intermittent electricity production from renewables. Thus, a hybrid-grid operation strategy could potentially offer a higher hydrogen yield. This calls for the uncovering of additional research on the topic of hybrid grid-renewables connection strategies with which PtX facilities can be supplied with electricity from both directly connected renewables and the electricity transmission grid.

As to further add to the complexity of hybrid grid-renewables operational strategies of supplying PtX facilities with electricity, it is not clear as to what level of renewable electricity production to connect directly to a PtX facility is appropriate for decreasing the possible curtailment of hydrogen production in case of transmission line overloading. In the case of directly connected renewable electricity production producing electricity higher than that of the capacity of the connected PtX facility's capacity, can the excess electricity production be offset to the electricity transmission grid – and all other things considered, what is of higher prioritisation: Curtailment of hydrogen production, or curtailment of wind power production?

1.2 Literature review

As to summarise on the *Motivation* of this study, some questions and uncertainties make themselves apparent: *1)* Embedded in energy systems of changes in consumption- and production, how will grid-connected PtX facilities impact utilisation of transmission lines? *2)* How will curtailment of hydrogen production vary to different strategies of power supply for grid connected PtX facilities? *3)* To what extent can any excess electricity production from an overcapacity of renewable electricity production directly connected to PtX facilities be offset to electricity transmission grids?

[10] proposes a method for estimating overloading of electricity transmission lines originating from errors of forecasting the electricity generation of renewable electricity production delivered to grid. [11] show that the expansion of a transmission line in the Southern Pakistan justifies the investment as the operation costs- and electricity sales of electricity generators (primarily gas) prices drop below that of the investment, due to the transmission line being uncongested after expansion. [12] proposes a method for decreasing wind power curtailment with respect to transmission line overloading in the New England electricity transmission bus system. However, none of these studies includes the modelling of hydrogen production from a grid connected- or a hybrid-grid connection of a PtX facility. [13] models different types of PtX facilities with dynamic operation in the transmission grid of Japan. The study finds that an annual utilization of PtX facilities' capacity factor of 30% - i.e., production curtailment of 70% annually – achieves the highest level of price reductions, by reducing the required capacities of respectively generators, transmission grids, and batteries. However, this study does not consider any renewable electricity production that can supply PtX facilities directly with power, that does not utilise the electricity transmission grid. While the study of [13] does model the electricity transmission grid of Japan, it is not clear as to whether potential overloading of transmission lines can lead to curtailment of PtX facilities' operation. [14] presents scenarios with different levels of additional deployment of renewable electricity generation, long distance transmission line capacities, and storage capacities in a power system model of Europe and Middle East/North Africa. They find that inadequate transmission line capacities lead to an increase in the required storage capacity in power systems and higher curtailment of power production from renewable electricity producing generators. The model of [14] includes electricity storages as a variable in their study and while a PtX facility could show some of the same characteristics and capabilities as an electricity storage, it is unlikely they would enact in the same ways to the electricity transmission system. While an electricity storage solely has the purpose of storing and/or curtailing excess electricity production to then resupply the electricity grid later with power, a PtX facility could initially absorb the same excess electricity production but would not resupply the grid with power. The latter would obviously only hold true is there no integration of e.g., fuel cells in the respective PtX facility, in which case the PtX facility could redeliver power to the electricity transmission grid. None the less, it is assumed that the modelled storages of [14] enact solely as electricity balancing components. Thus, [14] do consider overloading of transmission line capacities, the integration, and curtailment of electricity production from renewable energy generators but not the impact on potential overloading of transmission lines by the deployment of grid connected PtX facilities. [15] considers the operation- and hydrogen production costs of PtX facilities connected to the electricity transmission grid of Kramer Junction, California, USA whilst being supplied with directly connected renewable electricity generators. The directly connected renewable electricity generators can also offset surplus electricity generation to the electricity transmission grid as well. [15] concludes amongst other that the highest reduction of hydrogen production is seen in the scenario in which excess electricity production from the directly connected renewable electricity generators is offset to the electricity transmission grid, thus providing a reduction in hydrogen cost from electricity sales. However, [15] does not consider the potential overloading of transmission lines from neither the offsetting of excess electricity production nor the supply of power from the grid to the modelled PtX facilities.

[16] models PtX facilities of varying capacities at three different sites in Italy. To each PtX facility, a scenario of the initial power supply being provided by respectively photovoltaics, onshore wind turbines, and geothermal electricity production is simulated with the electricity transmission grid providing any remaining electricity consumption for the PtX facility to reach full utilization of the respective PtX facility's capacity of daily hydrogen production. The study finds amongst other that one of the modelled PtX facility sites with onshore wind turbines enacting as the directly connected renewable electricity generators, in combination with the electricity transmission grid providing the remaining of the PtX facility's needed electricity consumption to fulfil capacity, showed the lowest levelized costs of hydrogen production. However, [16] does not model the potential overloading of transmission lines in hours of drawing power from the electricity transmission grid to supply additional power to the modelled PtX facilities.

[17] demonstrates the annual hydrogen production and resulting levelized cost of hydrogen production to PtX facilities supplied with power from directly connected onshore wind turbines and photovoltaics, respectively. These metrics are also evaluated when the PtX facilities are provided – only – with power from the electricity transmission grid. However, this study also did not consider the potential overloading of transmission lines that could reduce the hydrogen production of grid connected PtX facilities.

[18] determines levelized costs of producing hydrogen (LCOH) in the energy systems of respectively Saudi-Arabia and Germany utilising the energy system modelling tool of PLEXOS. In the study, PtX facilities are assumed supplied with power from directly connected respectively onshore wind turbines and photovoltaics in the cases of respectively Germany and Saudi-Arabia. Curtailing the electricity production by 3.8% and 1.8% of the annual electricity production from respectively photovoltaics and onshore wind turbines showed a lowering of LOCH. Thus, [18] indicates that there could be a potential economic upside in terms of lowering the capacity of directly connected renewable electricity production. However, the study considered neither potential overloading of electricity transmission lines when curtailing excess electricity production from directly connected renewable electricity producing generators nor the impact of a grid-hybrid model to supply the PtX facility with electricity. [19] demonstrates the possible annual output of synthetic gases (power-to-gas) and synthetic fuels (PtX) from the utilisation of excess electricity production from the projected increase of renewable electricity generation in the German energy system by 2050. However, the study does not consider any scenarios of alleviating the needed power for electricity consumption at PtX facilities by modelling directly connected renewable electricity generation. Additionally, the study does not consider the possible overloading of transmission lines to supply PtX facilities with power from the electricity transmission grid.

[20] demonstrates "smart charging" of the politically set target number of five million electric vehicles in California, USA to reduce renewable electricity production curtailment by 40%. Though the study does consider the curtailment of renewable electricity production in the face of an increasing electricity consumption – that is not from PtX facilities – it neither considers transmission line overloading nor the integration of PtX facilities.

In conclusion, several studies demonstrate mechanisms and methods to decrease curtailment of electricity production from renewable electricity generators. Additionally, several studies show hydrogen production costs or curtailment of hydrogen production when insufficient electricity is provided to PtX facilities of varying capacities. Furthermore, few studies were found to consider the potential overloading of transmission lines as a proxy for the (necessary) curtailment of hydrogen production of grid connected PtX facilities.

However, no studies were found to include both approaches simultaneously, and thus there seems to be a research gap in which a study considers *a)* the curtailment of hydrogen production to grid connected PtX facilities due to overloading of transmission lines whilst considering both *b)* supplying the same grid connected PtX facilities with directly renewable electricity generators and *c)* – all at once.

This study will seek to bridge this gap in the current state-of-the-art by combining these considerations to an electricity transmission model in a power flow modelling tool.

1.3 Contributions

As was explained and summarised in *1.2 above*, no studies could be found that all at once considered *1)* the impact of general electrification on transmission line overloading, *2)* curtailment of hydrogen production from grid-connected PtX facilities in hours of transmission line overloading, and *3)* curtailment of excess electricity production from renewable electricity generators connected to PtX facilities both with and without electricity transmission grid connection.

This study will consider develop a novel approach of determining the impact on curtailment of hydrogen production to grid connected PtX facilities, with and without directly connected renewable electricity generators. Utilising the case study area of the region of Northern Jutland, Denmark, this study will demonstrate the impact on transmission line overloading in an existing electricity transmission grid embedded in an energy system with projections of electricity generation- and consumption.

2 Research question and theoretical framework of study

To seek bridging the gap in current literature as described in *1.2* by incorporating multiple approaches simultaneously and to address the multitude of issues addressed in *1.1*, a central research question to guide the present study is formulated:

Research question

How do different strategies for supplying power-to-X (PtX) facilities in Northern Jutland affect the curtailment of hydrogen production and electricity from onshore wind turbines, considering transmission line overloading?

As was addressed in *1.2 above*, several strategies of supplying PtX facilities can be considered in which the electricity to produce hydrogen can stem from

1) directly connected renewable electricity generators only (*no grid*),

2) the electricity transmission grid only (*only grid*),

3) both the electricity transmission grid and directly connected renewable electricity generators from which any excess electricity production is sought offset to the electricity transmission grid (*partial grid*), or

4) both the electricity transmission grid and directly connected renewable electricity generators from which any excess electricity production is curtailed (*partial grid full wind curtailment*).

Each of these four scenarios each represent a strategy with which PtX facilities are supplied with electricity to produce hydrogen and are visualised in *Figure 1*.

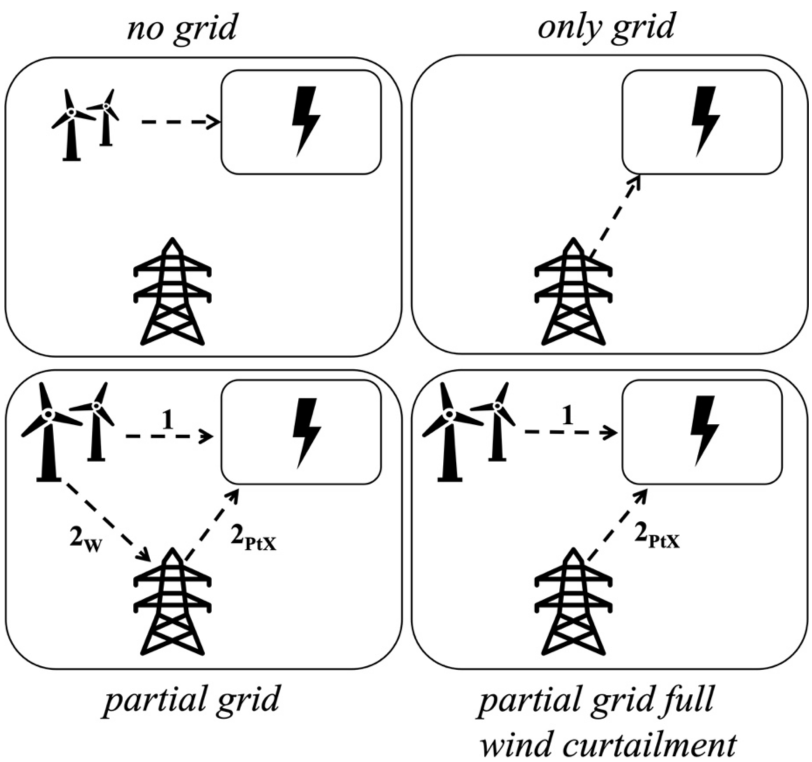

Figure 1: Visual representation of strategic pathways to supply PtX facilities with power including how potential excess electricity production is considered for this study.

2.1 Objective, case study area, and scenarios

The primary objective of this study is to bridge the gap between studies considering *1)* change in overloading of transmission lines resulting from the projected development of the energy system- and electricity sector, *2)* curtailment of hydrogen production due to transmission line overloading, and *3)* curtailment of excess electricity production offset to the electricity transmission grid due to transmission line overloading. The case study area in which the PtX facilities are modelled is the electricity transmission grid of Northern Jutland, as the *PandaPower* model for this region has already been created and investigated (for a slightly different purpose) by the authors of [21]. It can be contemplated that utilising the same code in PandaPower, and thus the same layout of the electricity transmission grid in the region of Northern Jutland as in [21], provides verification to the modelling of the power flow in this study as it has already been utilised with success in [21].

The scenario of *no grid* is of interest, as this scenario reflects that the modelled PtX facilities are not connected to the electricity transmission grid at all. Thus, there would be no curtailment of hydrogen production due to transmission line overloading – as the PtX facilities can't be supplied with power from any transmission lines. It is expected that there is a higher loss of hydrogen production to this scenario compared to that of the other scenarios. However, transmission line overloading may affect the possibility of supplying PtX facilities in the other scenarios to a degree that the *no grid* scenario will show to have a lower level of hydrogen production curtailment. Should this be the case for the modelled PtX facilities in the *no grid* scenario in either of the three years of projecting electricity generation- and consumption (2030, 2040, and 2050), this could indicate that the electricity transmission grid in the case study area of Northern Jutland can't withstand the additional electricity consumption that is required of the PtX facilities.

The scenario of *only grid* reflects a strategic pathway of installing no additional onshore wind turbines in the vicinity of the modelled PtX facilities. Additionally, it reflects a regime of energy planning in which the deployment of additional onshore wind turbines and PtX facilities are not coordinated.

In the scenario of *partial grid*, the energy system planning approach that is sought reflected is that of a combined planning approach of increasing the PtX capacity to the region whilst utilising areas in the vicinity of the preliminary locations of the PtX facilities. Additionally, any surplus/excess electricity production from the onshore wind turbines directly connected to the PtX facilities is sought offset to the electricity transmission grid. In hours of transmission line overloading, the excess/surplus electricity production is curtailed.

To reflect the energy system planning approach of *partial grid*, but all excess/surplus electricity production is curtailed. This is to show the full effect of the contribution towards transmission line overloading from the surplus electricity.

Each scenario will show variations on the potential overloading of electricity transmission lines, and thus to the potential curtailment of respectively hydrogen production and excess/surplus electricity production from any directly connected onshore wind turbines effectively delivered to the electricity transmission grid.

2.2 Data and projection of electricity generation- and consumption

To each transmission bus of the transmission system, the hourly level of electricity consumption- and generation from a variety of components in the energy system- and electricity sector are found to the year of 2024, and projected to 2030, 2040, and 2050. The majority of components of electricity generation- and consumption to each transmission bus is increased or decreased relatively to that of the Danish Energy Agency's expectation to Western Denmark – i.e., the entire price zone of DK1 – in their *Analyseforudsætninger til Energinet 2023* (AF23). AF23 is the Danish Energy Agency's expected development of the energy system in a fulfilled policies-scenario which means that all political ambitions at the time of AF23 being conducted are fulfilled. Depending on the energy system component, the projection of electricity generation- or consumption is weighted to either area or existing capacity. This approach, however, will assume that existing electricity generation- and consumption will to all geographically enclosed areas increase or decrease by the same relative projection. On the one hand, this approach does allow for a simple calculation in which spatial-geographically differences are not considered.

On the other hand, this approach is for that very same reason connected with some level of uncertainty, as the different components of the energy system will probably not develop relatively perfectly equal throughout the entirety of Western Denmark (DK1).

2.3 PandaPower

To determine the hourly load on electricity transmission lines, the open-source, Python-based library of *PandaPower* is utilised for this study. *PandaPower* is a power- and electricity system model that allows a user to define an electrical grid with electricity generation- and load. *PandaPower* will to each hour seek to offset all electricity production to either a load or to the external grid via an external grid transmission bus. The modelling of strain on the electricity transmission grid and its transmission lines is performed in the Python-based library of *PandaPower*. By modelling each individual medium- and high voltage transmission buses and the transmission lines connecting these transmission buses including, an hourly flow of power between each transmission bus via the connecting transmission lines is determined. The model also needs modelling of external grid buses to offset (i.e., export) any excess electricity production if generation is higher than the load, and vice versa if the electricity load is higher than that of the generation. While PandaPower does enable the possibility of modelling constant values of import- or export from/to external grid buses, this would remove the possibility of investigating the variable, hourly needed import/export of electricity to/from the region of Northern Jutland to the different PtX grid-connection scenarios.

The specific Python code for modelling the existing electricity transmission grid to the region of Northern Jutland is identical to that of [21] and was acquired through bilateral communication to the authors behind the study. The changes from the modelled electricity transmission grid of Northern Jutland in [21] to the modelled electricity transmission grid in the present study are: *1)* the hourly load and consumption to each transmission bus, and *2)* a single 400 kilovolts transmission line is assumed implemented to ensure the convergence of the model. The latter is elaborated in *3.2 below*.

The model of PandaPower is chosen as the tool for modelling power flow and thus transmission line overloading for this study. While there are several other modelling tools available for conducting power flow analyses, PandaPower is chosen as it is the only open-source tool for modelling of hourly transmission line loading that is also validated and easy to use for new users [22], [23].

The hourly values inputted to *PandaPower* – enabling an optimal flow of power to each hour of the year to the electricity transmission grid of Northern Jutland – are in this study fixated hourly values. While the hourly electricity generation- or consumption from the respective can be determined internally in *PandaPower* with the possibility of adding lower- and upper boundaries e.g., minimum- or maximum ramping of electricity production of electricity production by combined heat- and power plants. On the one hand, this could potentially show an electricity transmission system in which curtailment of combined heat- and power plants, photovoltaics could arise. In the same manner, demand-side management strategies of curtailing electricity consumption to different components of the energy system could be modelled. On the other hand, these fixated hourly values without considering possible up- and down-regulation of neither electricity producing- or consuming units allow to give a clearer evaluation on the needed curtailment of PtX facilities. Thus, both approaches are feasible to a study of this type, but the non-flexible hourly values are utilised for this study as to more clearly see the impact of the different grid-direct wind PtX strategies i.e., scenarios *no grid*, *only grid*, *partial grid*, and *partial grid full wind curtailment*.

2.4 Top-down versus bottom-up energy system modelling

On a more general, theoretical notion, this study applies a top-down energy system modelling- and planning approach to the answering of the research question. The top-down approach is typically associated with that of macro-economic energy system studies- and analyses, while the bottom-up approach is typically associated with a high level of technological detail, simulation strategies. In a non-economic sense, the top-down approach usually finds it application with energy system analyses on a greater geographical scale with a higher level of aggregation of energy system components in the modelled energy system [24]. Though this study will make no conclusions specifically on the economic implications – from different strategical pathways and scenarios of allowing for power supply for PtX facilities' hydrogen production and the offset of excess electricity production from PtX-connected renewable electricity generators – the aim of the study is to expand upon the knowledge of consequences from deploying a large capacity of PtX to a region. Additionally, no site-specific, dynamic effects are taken into consideration, nor is the implication on transmission line overloading from up- and down-regulating specific PtX facilities considered. A bottom-up approach to this study could have been to propose technical initiatives- and strategies with which the annual- and hourly curtailment of hydrogen production to a given grid connected PtX facility could be minimised with respect to transmission line overloading. In summary, the notion that this study applies a top-down energy system modelling approach is to acknowledge the fact that the applied hybrid grid-direct wind scenarios of deploying PtX facilities in the electricity transmission grid of Northern Jutland will ultimately not yield any results on evaluating the most feasible scenarios for specific PtX facilities or locations of connection in the electricity transmission grid of PtX facilities. Thus, the study is more suitable to conclude on the impact of regional energy planning including deployment of PtX facilities and possible connection of directly integrated renewable electricity generators.

3 Methodology

The methodology of this thesis is structured as follows:

Initially, subsection *3.1* will present the methods and data utilised in this study to project various types of electricity generation- and consumption that is not related to the deployment of PtX facilities nor any possible onshore wind turbines connected to these PtX facilities with the possibility of offsetting excess electricity production to the grid. As mentioned in *Research question and theoretical framework*, the purpose of projecting other types of electricity generation- and consumption is to consider that other developments of the energy system- and the electricity sector will also impact the electricity transmission system. These pillars of electricity generation- and consumption – that are not directly linked to the deployment of neither PtX projects in pipeline to the region of Northern Jutland nor any possible onshore wind turbines that can deliver electricity to the respective PtX facilities and excess electricity production to the transmission grid – are shown projected to respectively 2030-, 2040-, and 2050. These years are utilised to reflect the impact to a respectively short-term (2030), medium-term (2040), and long-term (2050) development. Additionally, the electricity generation- and consumption is derived to each transmission bus and modelled *only* in the existing electricity transmission grid to the present year of 2024. To the year of 2024, there is no modelling of any PtX projects nor additional onshore wind turbine capacity.

Then, subsection *3.2* will present the electricity transmission grid in the region of Northern Jutland that is modelled in the software of *PandaPower* to determine the change in line loading of transmission lines to the different PtX grid-scenarios. At the same time, the PtX projects in pipeline to the region of Northern Jutland are presented in the context of the electricity transmission grid. The specific transmission lines to supply the respective PtX projects in pipeline to the region are shown explicitly.

Finally, subsection *3.3* will in more detail present the PtX grid-connection scenarios. These are the same theoretically derived archetypes of strategies in which power can be delivered to the production of hydrogen from electrolysers at PtX facilities. However, in this part of the methodology, more detail is given to each of the PtX grid-connection scenarios and how the line loading of the transmission lines that supply the respective PtX projects in pipeline to the region of Northern Jutland affects the key metrics to evaluate the PtX grid-connection scenarios' impact on the electricity transmission grid of the region: *1)* The loss of annual hydrogen production relative to the theoretical maximum of the respective PtX projects' capacities, and *2)* the curtailment of electricity production from additional wind turbines to supply power to the PtX projects in pipeline.

3.1 Modelling of electricity production- and consumption to transmission buses

3.1.1 Classic electricity consumption

The first type of electricity consumption modelled at hourly load of the respective transmission buses is the classic electricity consumption of buildings. The classic electricity consumption is typically defined as electricity consumption not affiliated with heating nor charging of electric vehicles.

The Danish electricity- and gas transmission system operator (TSO) 'Energinet' displays in publicly available data online the hourly electricity consumption of respectively: *1)* single-family homes and terraced houses, *2)* multi-storey residential buildings, *3)* leisure homes, and *4)* commercial buildings. The data can be seen to its fullest online in [25].

The specific building application codes as derived from the Danish building registry to each of the four categories of buildings can be seen in *Table 1*.

	Categories of building types			
	Single-family homes and terraced houses	**Multi-storey residential buildings**	**Leisure homes**	**Commercial buildings**
Application codes of buildings as seen in the Danish Building Registry (BBR)	110	140	510	210-229
	120	150	520	290-449
	121	160	521	490
	122		530	522
	130		540	530-539
	131		585	
	132		590	
	185			
	190			

Table 1: Building codes from the Danish Building Registry used to determine classic electricity consumption across four major building types.

The explanation for each of the building type codes shown in *Table 1* can be seen in appendix *7.3 below*. By not considering buildings heated by a heat pump or electric heating, the average classic electricity consumption is found at an hourly level in a three-year period (2021/01/01-2024/01/01). This allows for determining an hourly distribution of classic electricity consumption for each of these four types of buildings. However, as goes specifically for commercial buildings, it is not included in the data if the building is heated by an individual heat pump or otherwise electrically heated. This serves as an uncertainty utilising the dataset of [25]. The annual electricity consumption summarised per building type is of all buildings in the region of Northern Jutland is shown in *Figure 2*.

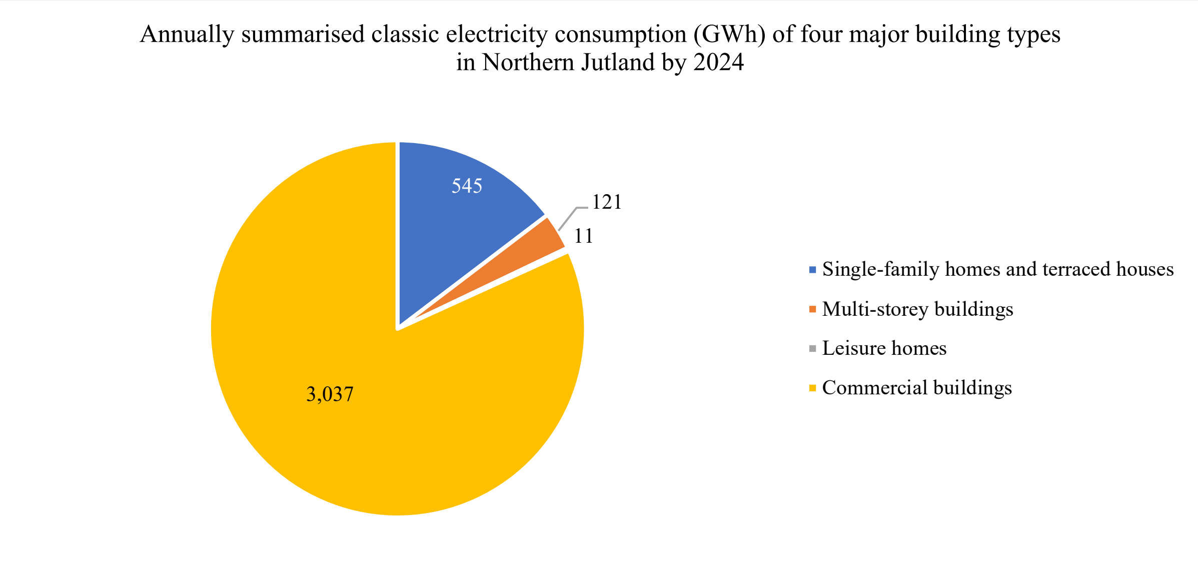

Figure 2: Classic electricity consumption on an annual level by 2024 in the region of Northern Jutland across four major building types.

By assuming that each of the four previously mentioned building types has an identical level of electricity consumption, that is dependent on its indoor floor area, the electricity consumption can be derived for each building in the region of Northern Jutland. By utilising the Danish Building Registry (BBR), which contains the location (centroid of building) of all buildings in Denmark, the summarised indoor floor area to each of the four abovementioned building types is found inside each of the Voronoi polygons to the transmission buses. This allows for determining the annual electricity consumption from the classic electricity consumption across building types to each transmission bus in the electricity transmission grid (*Figure 3*).

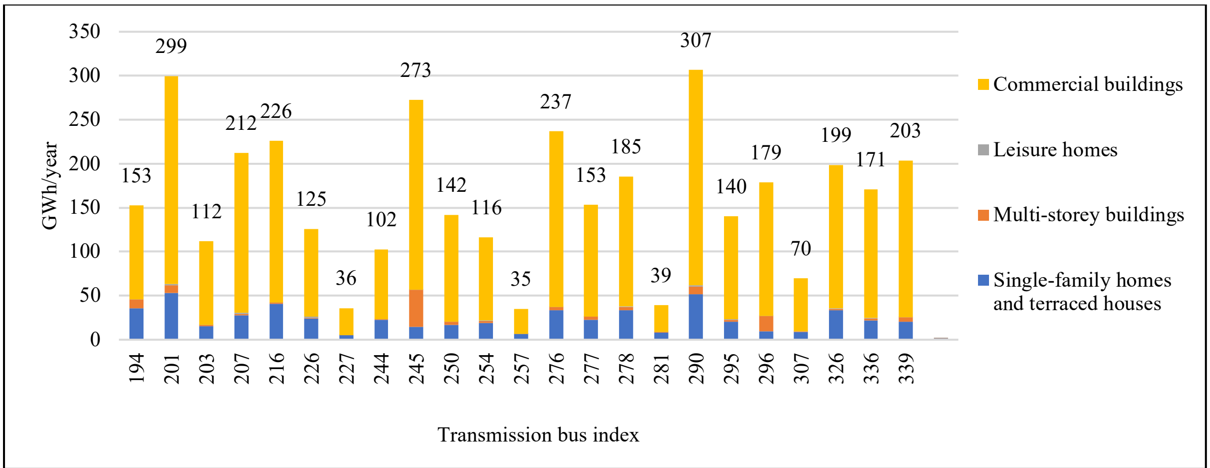

Figure 3: Annual classic electricity consumption per transmission bus in 2024.

The annual level of electricity consumption to each transmission bus is coupled with the respective hourly distributions of electricity consumption as seen in *Figure 4*-*Figure 7*, depending on the building type.

The hourly distributions of the classic electricity consumption displayed in *Figure 4*-*Figure 7* is derived from the same underlying data as that of *Figure 2* and *Figure 3*.

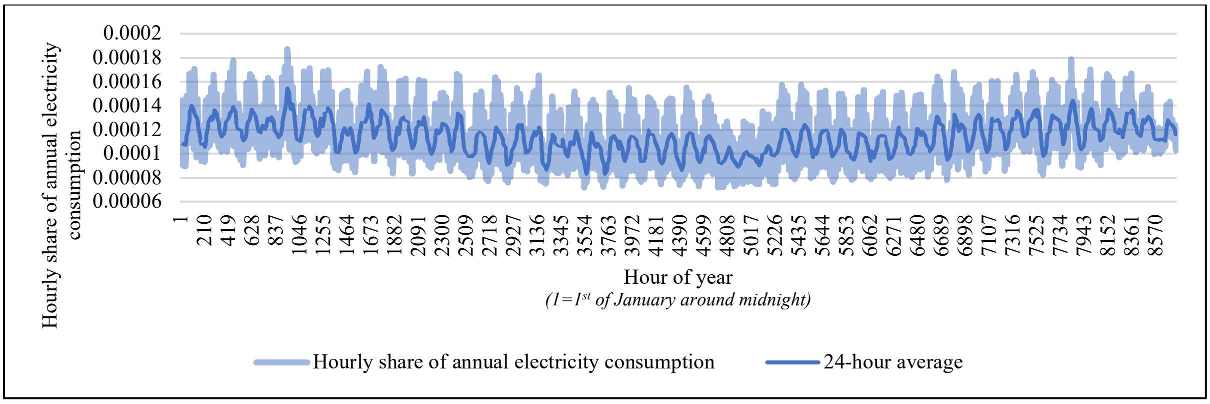

Figure 4: Distribution profile of electricity consumption in commercial buildings to the region of Northern Jutland.

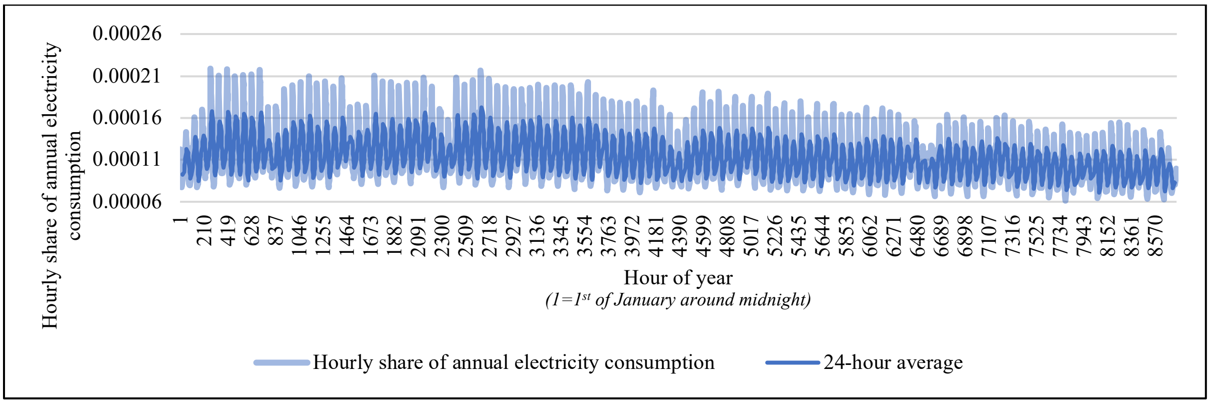

Figure 5: Distribution profile of electricity consumption in single-family homes and terraced houses to the region of Northern Jutland.

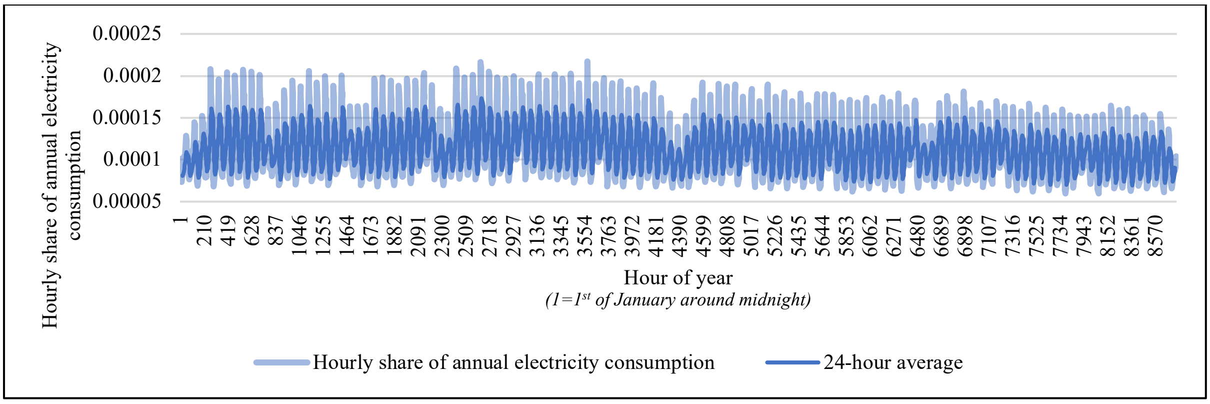

Figure 6: Distribution profile of electricity consumption in multi-storey residential buildings to the region of Northern Jutland.

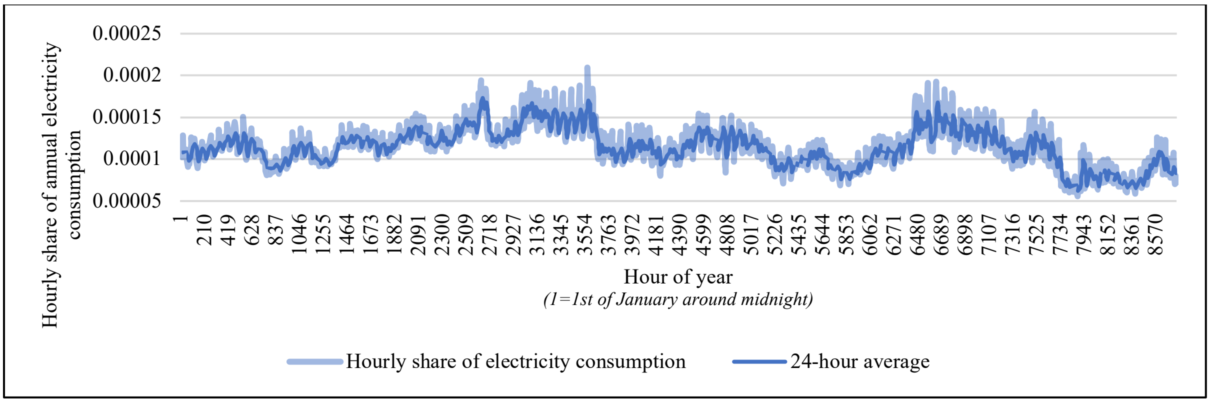

Figure 7: Distribution profile of electricity consumption in leisure homes to the region of Northern Jutland.

3.1.2 Electricity consumption of charging of electric vehicles- and plug-in hybrid vehicles

The charging of electric vehicles is the next type of electricity consumption to be modelled at transmission bus level for this study. To explicitly determine the hourly strain on the transmission grid and the respective transmission buses from the charging of electric vehicles, a summarised battery capacity per transmission bus is coupled with an hourly distribution of a charging pattern for electric vehicles.

To determine the annual electricity consumption from charging of respectively electric vehicles and plug-in hybrid vehicles to each transmission bus, the current (2024) number of electric vehicles and plug-in hybrid vehicles per municipality in Northern Jutland is used as a proxy. Statistics Denmark[1] display the number of electric vehicles and plug-in hybrid vehicles at municipal level in Denmark. Coupled with the Danish Energy Agency's display of the expected annual level of electricity consumption for all electric vehicles- and plug-in hybrid vehicles in 2024, the average electricity consumption for all electrified vehicles – i.e., assuming electric vehicles and plug-in hybrid vehicles have the same annual electricity consumption – is 2.5 MWh/year [26]. However, as a study on the actual charging patterns and annual fuel consumption of plug-in hybrid vehicles showed that just 40% of the annual gross fuel consumption needed to cover the transportation demand was supplied by electricity [27]. Thus, the average annual electricity consumption is assumed to be 3.39 MWh/year and 1.02 MWh/year to respectively the average electric vehicle and the average plug-in hybrid vehicle.

Considering the expected relative increase to the electricity consumption of charging all types of electrified vehicles from 2024 to respectively 2030, 2040, and 2050 as seen in [26], the number of respectively electric vehicles is determined to each of the 11 municipalities in the region of Northern Jutland. The full overview is provided in appendix *7.1 below*.

To allocate the annual electricity consumption from the charging of respectively electric vehicles and plug-in hybrid vehicles at municipal level to each transmission bus of the electricity transmission grid, the interesting areas between *1)* the Voronoi polygons extended by the transmission buses throughout the region and *2)* the physical boundaries of the 11 respective municipalities are found. Land area is assumed to be a proxy of the distribution of electric vehicles- and plug-in hybrid vehicles throughout the municipalities. Thus, the electricity consumption in all the intersecting areas between the municipalities and the Voronoi polygons expanded by the transmission buses can be used to determine the summarised electricity consumption to each transmission bus of the electricity transmission grid. The share of each intersecting area's land mass to the respective municipalities will enact as the proxy of the electricity consumption from charging of electric vehicles and plug-in hybrid vehicles. *Figure 8* shows the intersecting areas between the Voronoi polygons and the respective municipalities.

[1] https://www.dst.dk/en

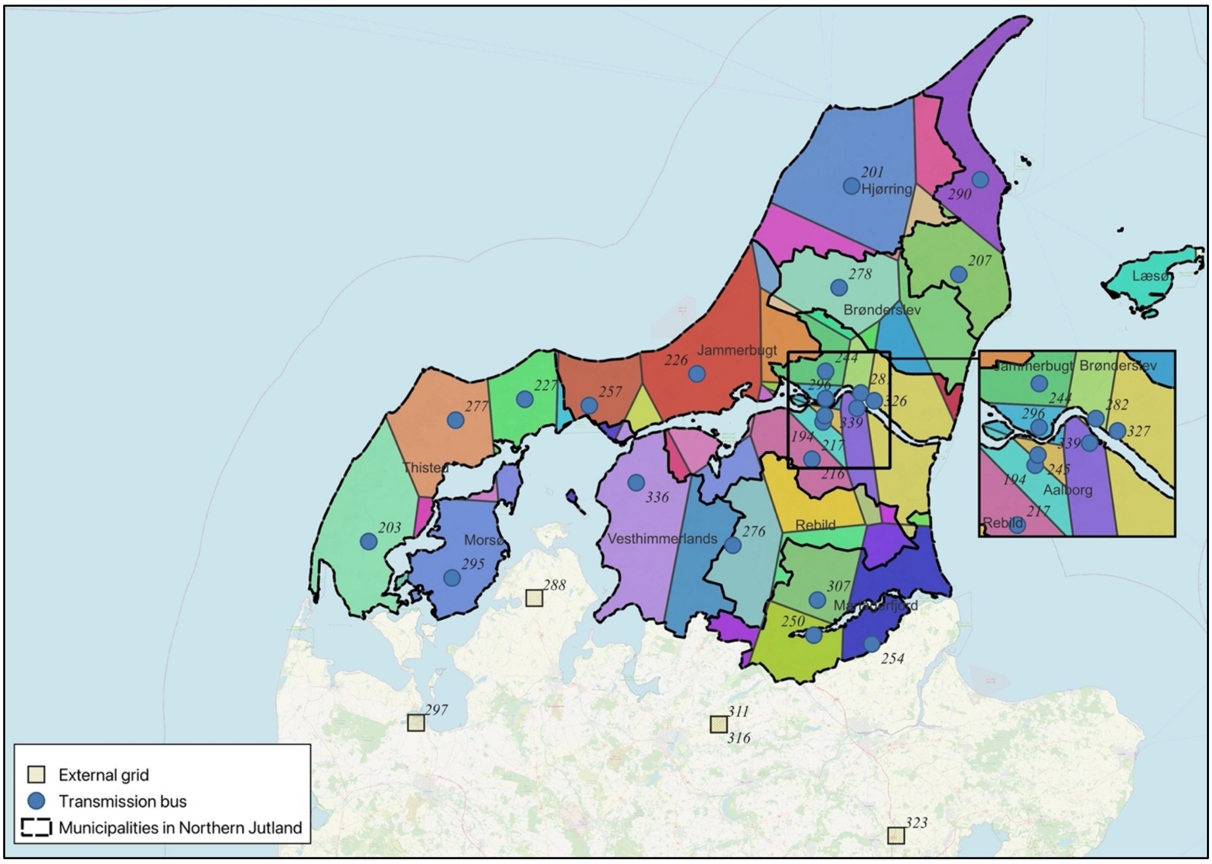

Figure 8: Intersection of areas between Voronoi polygons extended by transmission buses in electricity transmission grid of Northern Jutland and each of the 11 municipalities of Northern Jutland.

By combining the annual electricity consumption from the current (2024) and projected (2030, 2040, and 2050) level of the charging of electric vehicles and plug-in hybrid vehicles, the summarised, annual electricity consumption to each transmission bus of the electricity transmission grid is determined. The summarised electricity consumption of the charging of both electric vehicles and plug-in hybrid vehicles is shown in *Figure 9*.

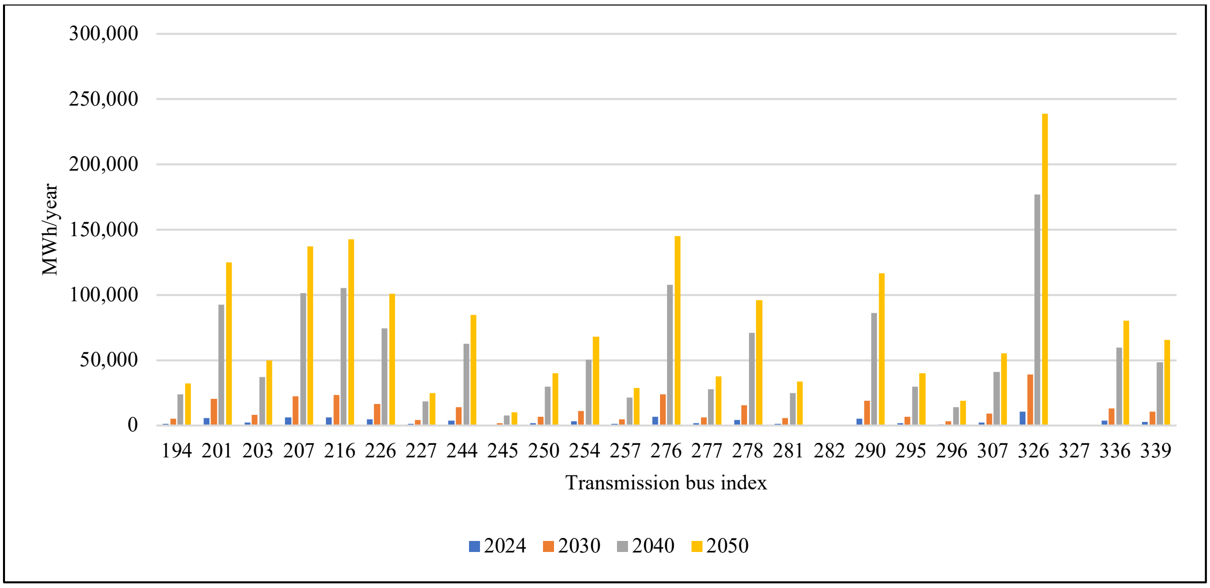

Figure 9: Annual electricity consumption of respectively electric vehicles (EVs) and plug-in hybrid vehicles (PHEV) to each transmission bus, respectively to the years of 2024 and 2040.

To model the strain on the transmission grid in Northern Jutland and its lines, an hourly distribution of the charging pattern throughout a full year is needed. In a 2021-study on different types of residential electricity consumption, the hourly charging pattern of electric vehicles in Danish households amongst other was determined [28]. This hourly distribution of charging is shown in *Figure 10*, and is utilised to distribute the annual electricity consumption to each transmission bus in each of the four modelled years.

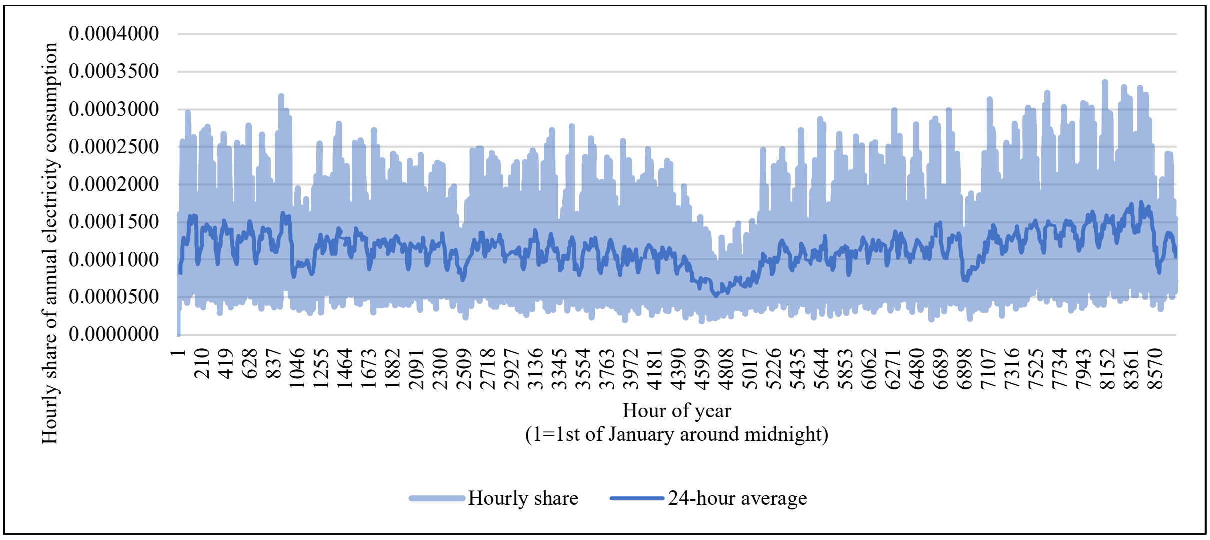

Figure 10: Hourly distribution of charging of electric vehicles and plug-in hybrid vehicles.

3.1.3 Electricity consumption of individual heat pumps

The third type of electricity consumption to be modelled at an hourly level to each transmission bus in the electricity transmission system of Northern Jutland is from individual heat pumps in buildings.

To buildings outside existing district heating areas that are *not* already equipped with an individual heat pump $\left(E_{ij}^{no\_hp}\right)$, the summarised, annual electricity consumption of individual heat pumps to each Voronoi polygon – and thus to the substation of that Voronoi polygon – is the sum of the annual electricity consumption of each

$$E_i^{no\_hp} = \sum_j \left(\frac{H * A_{ij}}{SCOP}\right)$$

Equation I: Annual electricity consumption to buildings outside district heating areas without a heat pump, summarised to each Voronoi polygon.

j denotes the index of buildings inside the *i*'th Voronoi polygon.

Similarly, to buildings outside existing district heating areas that *are* already equipped with an individual heat pump $\left(E_{ij}^{hp}\right)$, the annual electricity consumption of individual heat pumps to each Voronoi polygon – and thus to the substation of that Voronoi polygon – is the sum

$$E_i^{hp} = \sum_k \left(\frac{H * A_{ik}}{SCOP}\right)$$

Equation II: Annual electricity consumption to buildings outside district heating areas already equipped with a heat pump, summarised to each Voronoi polygon.

k denotes the index buildings inside the *i*'th Voronoi polygon.

To both *Equation I* and *Equation II*, *H* is the annual heat consumption depending on the building's primary application and year of construction, *A* is the inside floor area in m^2 to the respective building, and *SCOP* is the annual, average efficiency of the heat pump. According to [29], the *SCOP* of an air-to-water based individual heat pump in a single-family home/terraced house is 3.6. Therefore, the *SCOP* is assumed to be 3.6 to both existing- and future individual heat pumps in the region of Northern Jutland.

Utilising data from the Danish Building Registry (BBR), the location of all buildings in the region Northern Jutland including their primary application, inside floor area, and year of construction. To some buildings, a year of renovation is provided in the data as well. It is assumed that this renovation had led to a (significant) reduction of heat loss. Thus, for buildings marked with a year of renovation, the year of renovation is used as proxy for the respective building's year of construction to determine its expected heat demand rather than the year of its construction. The annual heat consumption (*H*) based on the respective building's primary application and year of construction – or year of renovation if the information is given to the respective building – is seen summarised in appendix *7.2 below*.

Modelling the annual electricity consumption from individual heat pumps in the *PandaPower* model of 2024 to each Voronoi polygon and therefore transmission bus (E_i^{2024}), only buildings already equipped with an individual heat pumps are included (*Equation III*).

$$E_i^{2024} = E_i^{hp}$$

Equation III: Annual electricity consumption from individual heat pumps utilised in PandaPower model of 2024.

As goes for the modelling of the annual electricity consumption from individual heat pumps in the *PandaPower* model to the years after 2024 – 2030, 2040, and 2050, respectively – to each Voronoi polygon and therefore transmission bus ($E_i^{>2024}$), buildings already equipped with an individual heat pumps as well as *all* buildings outside district heating areas without a heat pump are included (*Equation IV*).

$$E_i^{>2024} = E_i^{hp} + E_i^{no\_hp}$$

Equation IV: Annual electricity consumption from individual heat pumps utilised in PandaPower models in years after 2024 i.e., 2030, 2040, and 2050.

While the full calculations can be seen in the external Excel appendices, *Figure 11* shows the annual electricity consumption of respectively buildings outside district heating areas already equipped with an individual heat pump and buildings outside district heating areas that are not equipped with an individual heat pump.

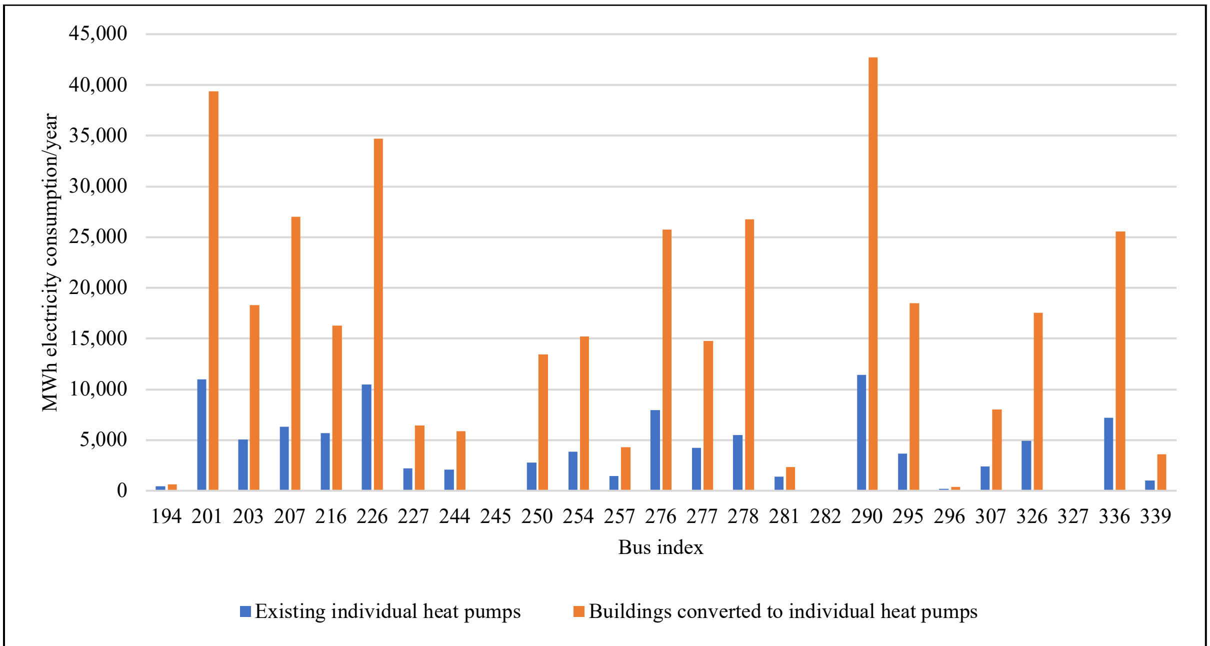

Figure 11: Annual electricity consumption of individual heat pumps, summarised per transmission bus.

As explained above, the level of annual electricity consumption of buildings already equipped with a heat pump are used in the 2024-modelling of the electricity transmission system in Northern Jutland.

To determine the hourly load to each transmission bus, the annual electricity consumption of individual heat pumps is coupled with an hourly distribution, which can be seen in *Figure 12*.

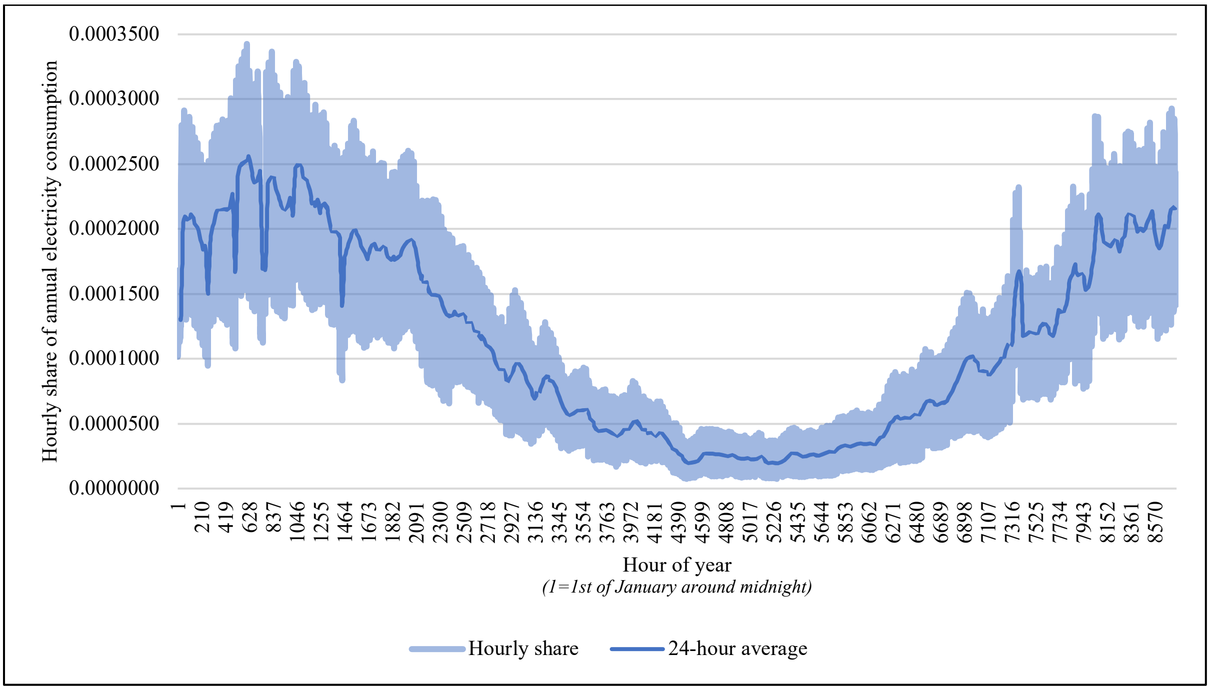

Figure 12: Hourly distribution of electricity consumption to individual heat pumps with ambient air as heat sink.

Unexpectedly, the hourly electricity consumption of individual heat pumps is higher towards the beginning- and end of the year than in the middle of the year. This is due to ambient temperature typically being lower in the hours respectively closer to the beginning- and end of the year. Lower ambient temperatures result in a higher heat loss from buildings which then requires more heating to be supplied from the individual heat pump. Additionally, with ambient air enacting as the heat sink to the individual heat pumps, as they are assumed to be air-to-water heat pumps, lower ambient temperatures in the colder months of the year also lowers their efficiency (coefficient of performance, COP).

3.1.4 Electricity generation from combined heat- and power plants

The first type of electricity generation that is considered for this model in *PandaPower* is the electricity production from combined heat- and power plants.

Acquired via confidential data provided by the Danish Energy Agency, the locations of all combined heat- and power plants, both centralised- and decentralised are known but are aggregated inside the physical extent of the Voronoi polygons which can be seen in *Figure 13*.

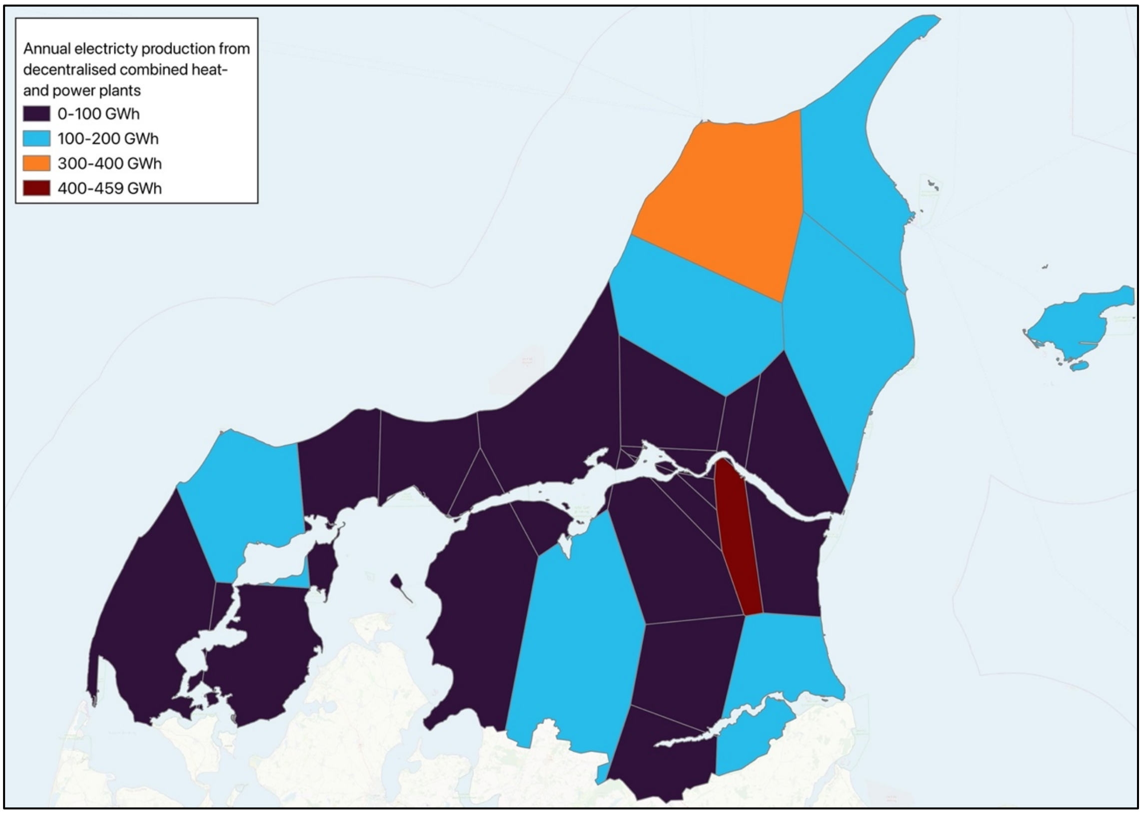

Figure 13: Annual electricity production (2022-data) by decentralised combined heat- and power plants per Voronoi polygon in the region of Northern Jutland. Specific locations of these units are known but are aggregated for purposes of confidentiality.

To determine the hourly electricity production to each transmission bus from all decentralised combined heat- and power plants inside the extent of the respective Voronoi polygons, the summarised annual electricity production to each Voronoi polygon – as seen in – is distributed to an hourly level by the distribution seen in *Figure 14*.

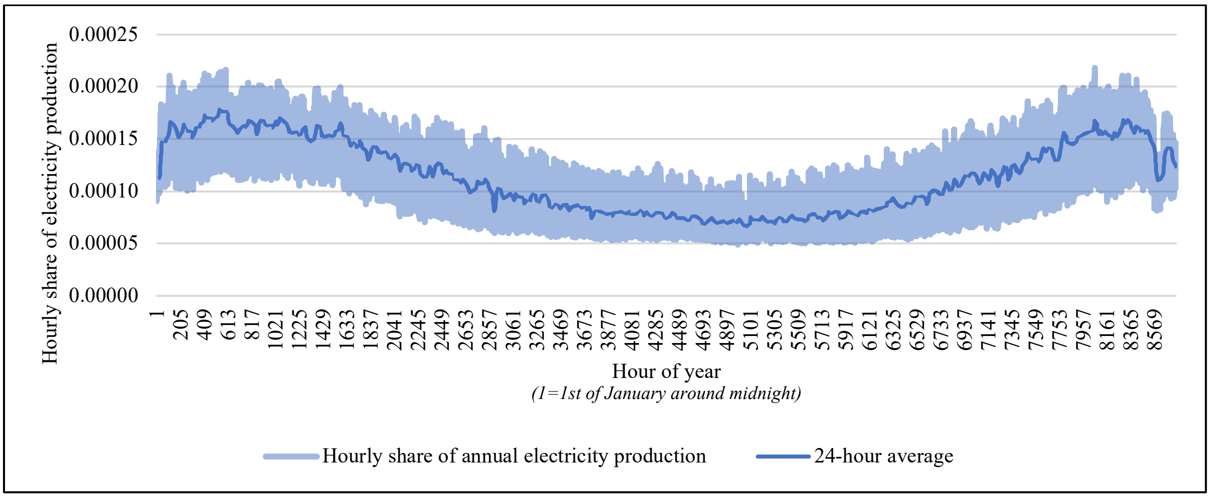

Figure 14: Hourly distribution of electricity production from decentralised combined heat- and power plants.

The hourly distribution of the annual electricity production to the annual electricity production from decentralised combined heat and power plants is derived from [25]. By considering the hourly electricity production from all decentralised combined heat- and power plants in Western Denmark (price zone of DK1) in the years 2005-2024, the hourly distribution of electricity production is considered by the average across these years.

Applying the Danish Energy Agency's expectation to the relative decrease of annual electricity production from decentralised combined heat- and power plants as seen in their *Analyseforudsætninger til Energinet 2023*, the projection of the summarised, annual electricity generation from decentralised combined heat- and power plants can be seen in *Figure 15*.

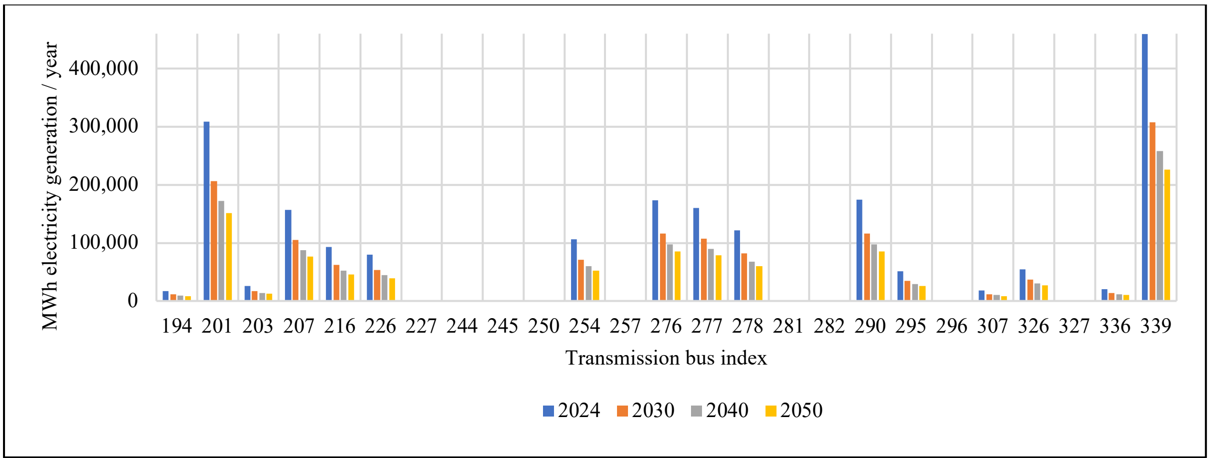

Figure 15: Annual electricity generation from decentralised combined heat- and power plants to each transmission bus by respectively 2024, 2030, 2040, and 2050.

The capacity, annual electricity production, and location of centralised combined heat- and power plants to the region is also provided in the confident data provided bilaterally from the Danish Energy Agency. However, it is allowed to show the summarised, annually aggregated electricity production to the Voronoi polygon extended by the transmission bus, which is shown in *Figure 16*.

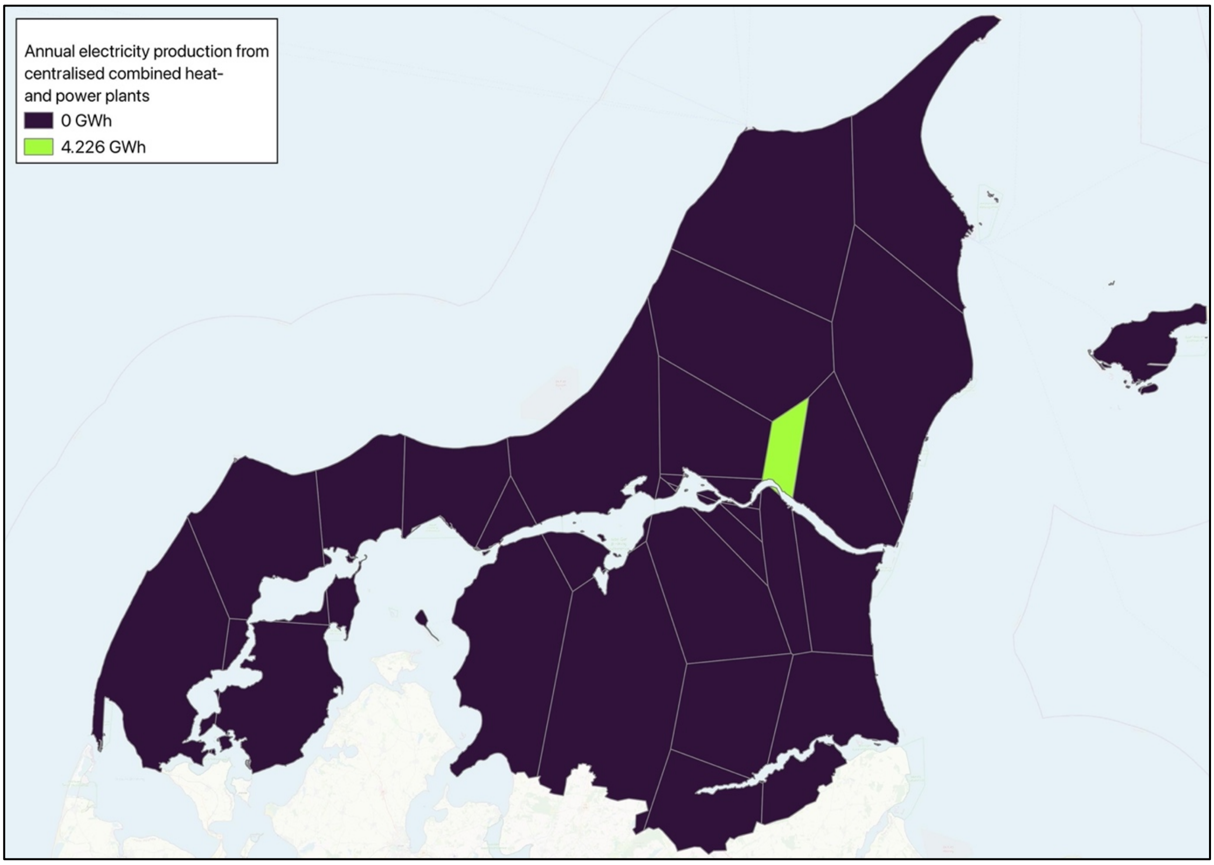

Figure 16: Annual electricity production (2022-data) by centralised combined heat- and power plants per Voronoi polygon in the region of Northern Jutland. Specific locations of these units are known but are aggregated for purposes of confidentiality.

The same principle for projecting the annual deliverance of electricity production from centralised combined heat- and power plants is utilised as was the case for decentralised combined heat- and power plants. I.e., the Danish Energy Agency's expectation to the decrease of annual electricity production as seen in [26] is utilised to project the decrease of the annual electricity generation of centralised combined heat- and power plants.

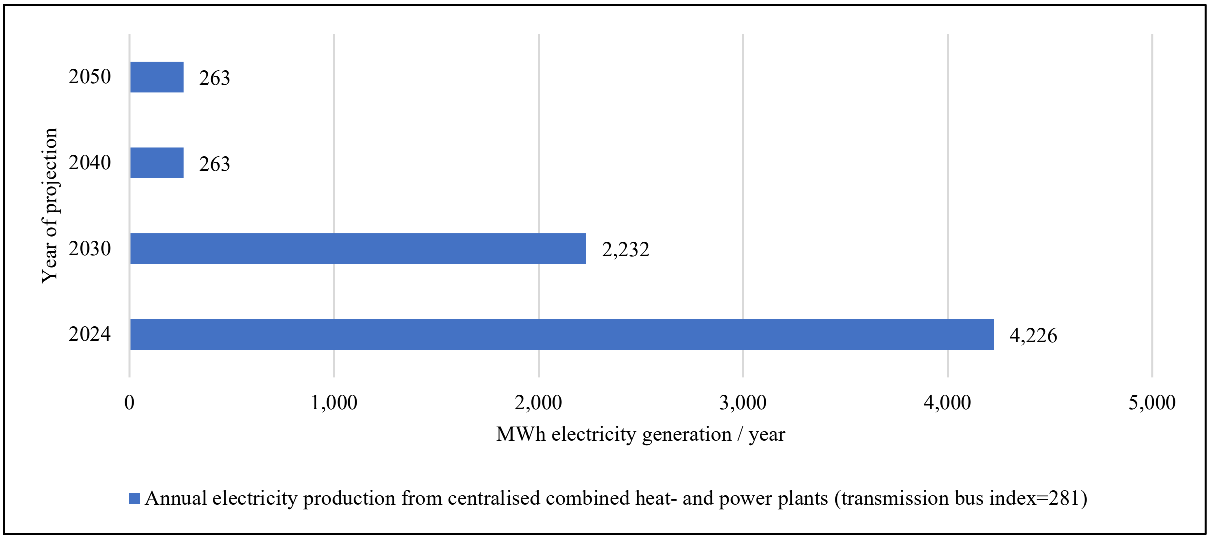

Figure 17: Current (2022-data) level of annual electricity generation from centralised combined heat- and power plants in the region of Northern Jutland including projection of annual generation to 2030, 2040, and 2050.

As can be seen from *Figure 17*, the annual electricity production from centralised combined heat- and power plants decrease by almost 50% from 2024 to 2030, and from 2030 to 2040 the production decreases from ca. 2.2 GWh per year down to 0.3 GWh per year.

The resulting hourly electricity generation to the transmission bus index 281 is found by coupling the annual electricity consumption as seen in *Figure 17* with the distribution of capacity factors as seen in *Figure 18*.

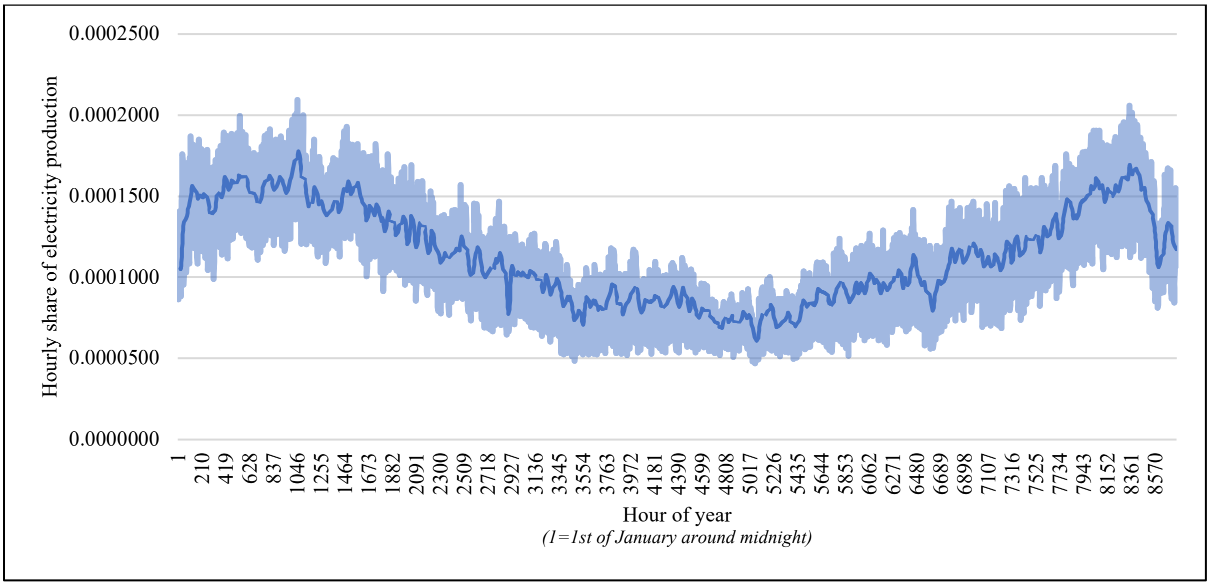

Figure 18: Hourly distribution of electricity production from centralised combined heat- and power plants.

The hourly distribution of the annual electricity production to the annual electricity production from centralised combined heat and power plants is derived from [25]. By considering the hourly electricity production from all centralised combined heat- and power plants in Western Denmark (price zone of DK1) in the years 2005-2024, the hourly distribution of electricity production is considered by the average across these years.

3.1.5 Electricity generation from photovoltaics

To each transmission bus, the existing (2024) capacity of photovoltaics (PVs) are provided in [30]. The capacity of the 2024-levels of PVs to each transmission bus is projected by the factor that the Danish Energy Agency expects in *Analyseforudsætninger til Energinet 2023*, which is shown in [26] (see *Table 2*).

	2030	**2040**	**2050**
Expected increase of existing PV capacity in DK1 (Western Denmark) relative to 2024	+413%	+674%	+916%

Table 2: Relative increase of 2024-capacity of PVs used to project the PV capacity of each Voronoi polygon in the electricity transmission grid to respectively the years of 2030, 2040, and 2050.

This results in increasing PV capacities to all transmission buses in which some level of PV was already existing by 2024.

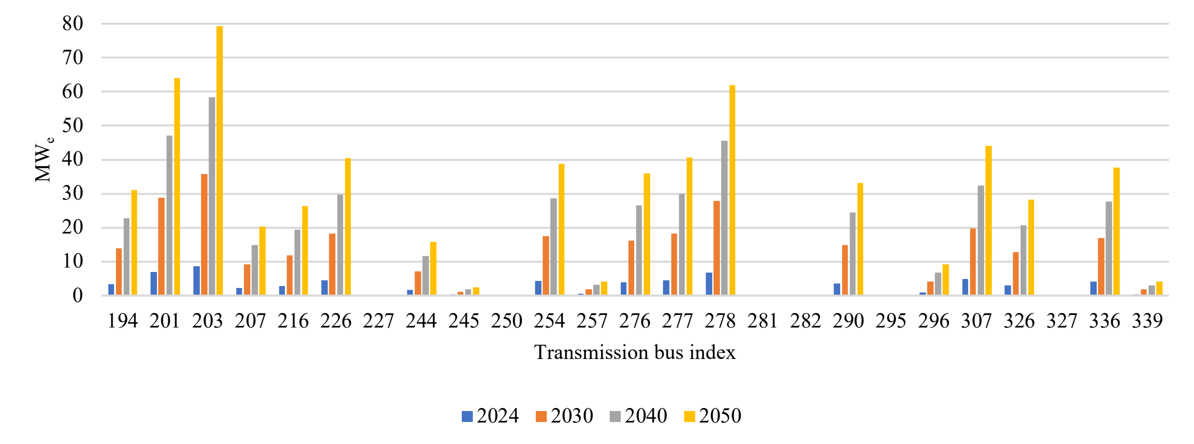

Figure 19: Summarised PV capacity to each transmission bus in the electricity transmission system to respectively the years of 2024, 2030, 2040, and 2050.

The PV capacity to each transmission bus is then coupled with a capacity factor to determine the hourly electricity generation to respectively 2024, 2030, 2040, and 2050. The utilised distribution of capacity factors is seen in *Figure 20*.

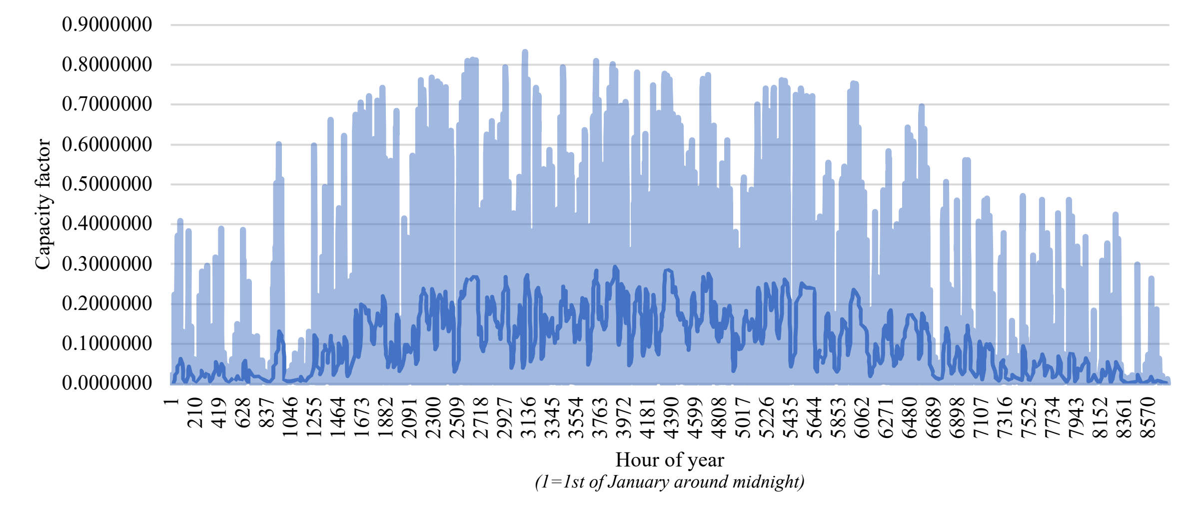

Figure 20: Distribution of capacity factor of photovoltaic electricity production in the region of Northern Jutland.

The distribution of capacity factors to the production of electricity production from PVs seen in *Figure 20* is derived from [31].

3.1.6 *Electricity generation from existing onshore wind*

The location and capacity of all existing onshore wind turbines is displayed in [32], and can be seen visualied to the region of Northern Jutland in *Figure 21*.

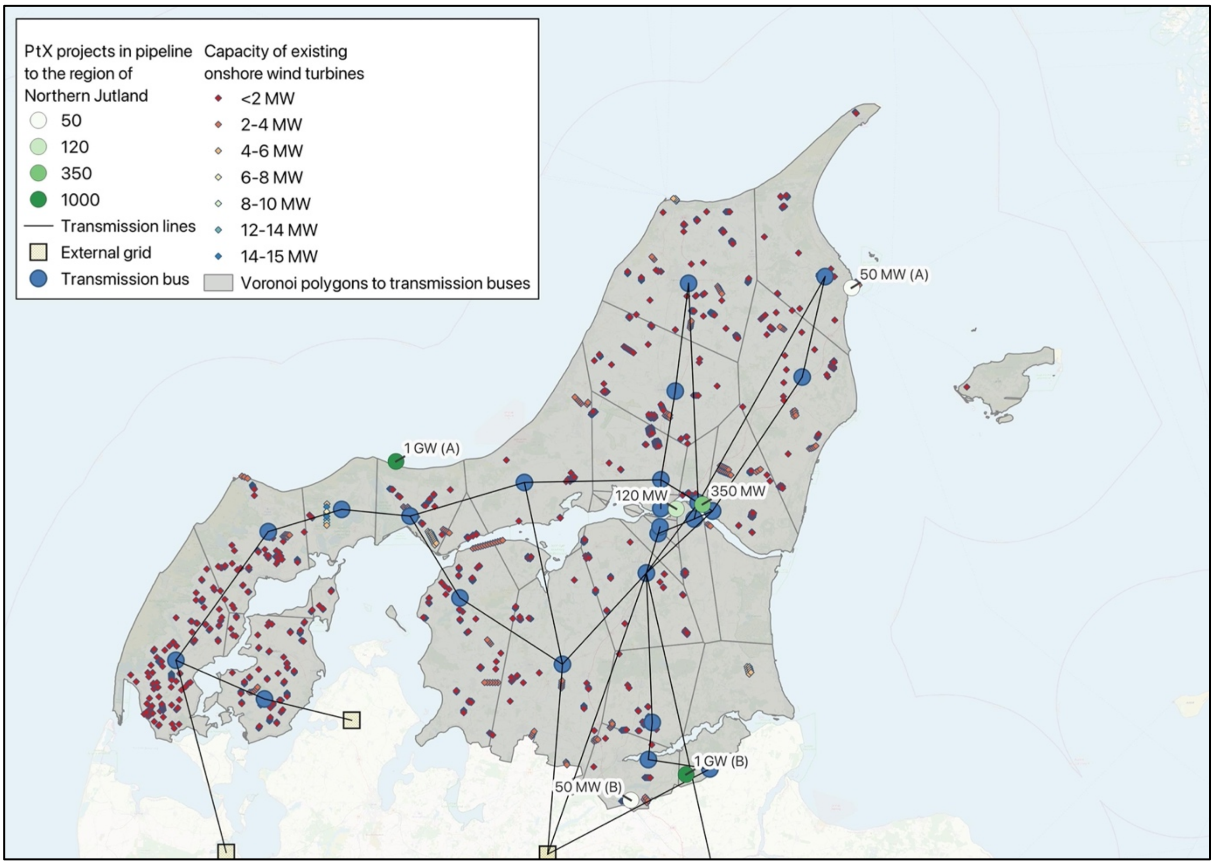

Figure 21: Location and capacity of existing, non-decommissioned onshore wind turbines in the region of Northern Jutland.

Summarising the capacity of existing onshore wind turbines inside each of the Voronoi polygons extended by the transmission buses of the electricity transmission grid in Northern Jutland allows for determining the summarised electricity generating capacity of onshore wind turbines, which is seen in *Figure 22*.

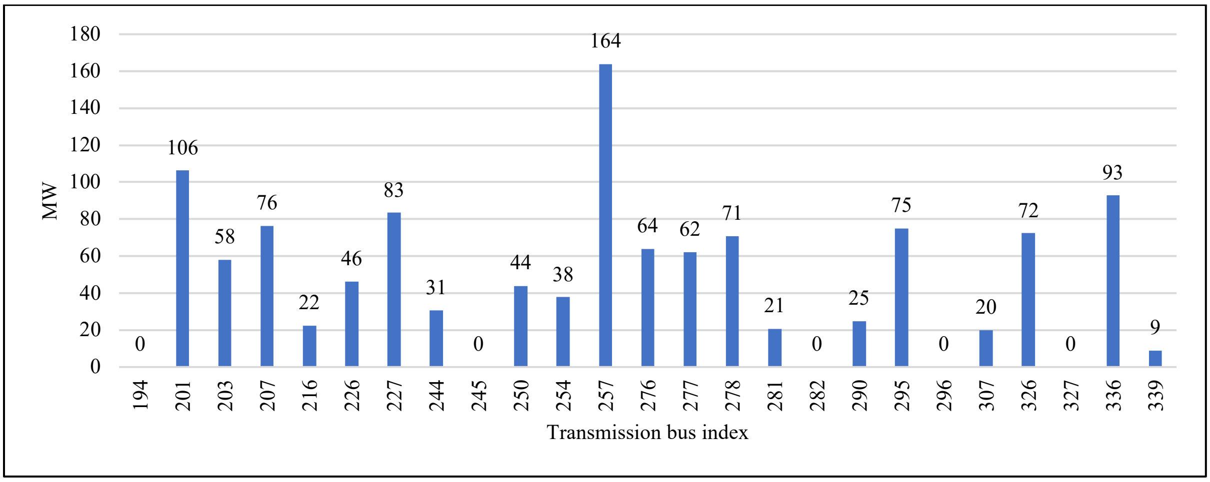

Figure 22: Summarised capacities to transmission buses of existing onshore wind turbines.

The capacities of the existing onshore wind turbines are coupled with the hourly distribution of capacity factors as seen in *Figure 33* to determine the hourly electricity generation utilised in the *PandaPower* models of respectively 2024, 2030, 2040, and 2050.

3.2 *Modelling of PtX facilities in electricity transmission grid*

As was mentioned in the section *Research question and theoretical framework*, the modelling of PtX projects will be that of PtX projects in pipeline to the region. *Table 3* provides the names, summarised electrolyser capacities, and for this study utilised labels of all (six) PtX projects in pipeline to the region of Northern Jutland.

Name in *Hydrogen Denmark* pipeline of PtX projects in region of Northern Jutland, Denmark	**Summarised capacity of electrolysers in PtX project**	**Label used for PtX project in present study**	**Electricity transmission grid modelled in PandaPower used to simulate hourly line loading**
Jyske Banke	1 GW_e	1 GW (A)	Existing grid
Green Hydrogen Hub	1 GW_e	1 GW (B)	Existing grid
Methanol project by Nordjyllandsværket (Aalborg)	350 MW_e	350 MW	Existing grid
Aalborg Havn / European Energy	120 MW_e	120 MW	Existing grid
European Energy / Frederikshavn Havn	50 MW_e	50 MW (A)	Modified grid
Handest	50 MW_e	50 MW (B)	Modified grid

Table 3: Names, capacities, and utilised labels of all six PtX projects in pipeline to the region of Northern Jutland. Names, capacities, and locations are derived from the association 'Hydrogen Denmark'.

Since the time of extracting information of the PtX projects in pipeline to the region, data has been updated.

However, alongside the modelled levels of electricity generation- and consumption to each transmission bus, modelling all six PtX projects to the region of Northern Jutland disenables the convergence of the *PandaPower* model; the electricity load is simply too big for the existing electricity grid. This is regardless of the PtX grid-connection scenario utilised to model the flow of power supply to the respective PtX projects in pipeline. Though no literature is offered on the subject on the cut-off point at which the electricity load becomes too big for *PandaPower* to converge the flow of electricity, this is a clear indication that the existing electricity transmission grid can't support the deployment of either 1 GW PtX projects. Either way, a slightly modified version of the existing electricity transmission grid in the region of Northern Jutland must be modelled if the impact of modelling all six PtX projects in pipeline to the region of Northern Jutland is to be evaluated to the different PtX grid-connection scenarios.

For this reason, the existing electricity transmission grid is extended by a single 400-kilovolts transmission line which enables the convergence of power flow in *PandaPower*. A visualisation of the existing electricity transmission grid alongside the four smaller PtX projects in pipeline to the region of Northern Jutland can be seen in *Figure 23*. The modified – i.e., the existing electricity transmission grid of Northern Jutland with an additional 400-kilovolts transmission line – can be seen in *Figure 24* alongside the locations of all six PtX projects in pipeline to the region of Northern Jutland.

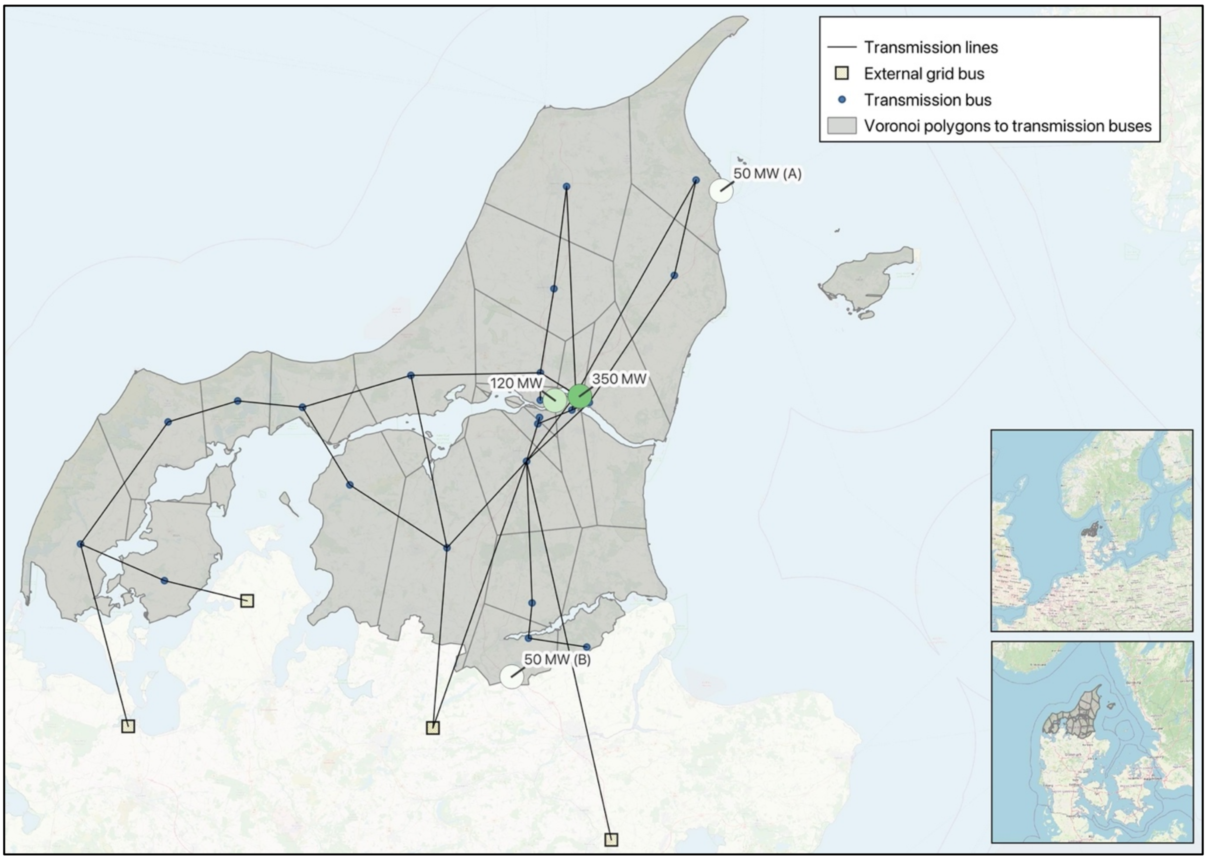

Figure 23: Visualisation of existing electricity transmission network simulated in PandaPower to analyse line loading including preliminary locations of the four smaller PtX projects in pipeline to the region of Northern Jutland.

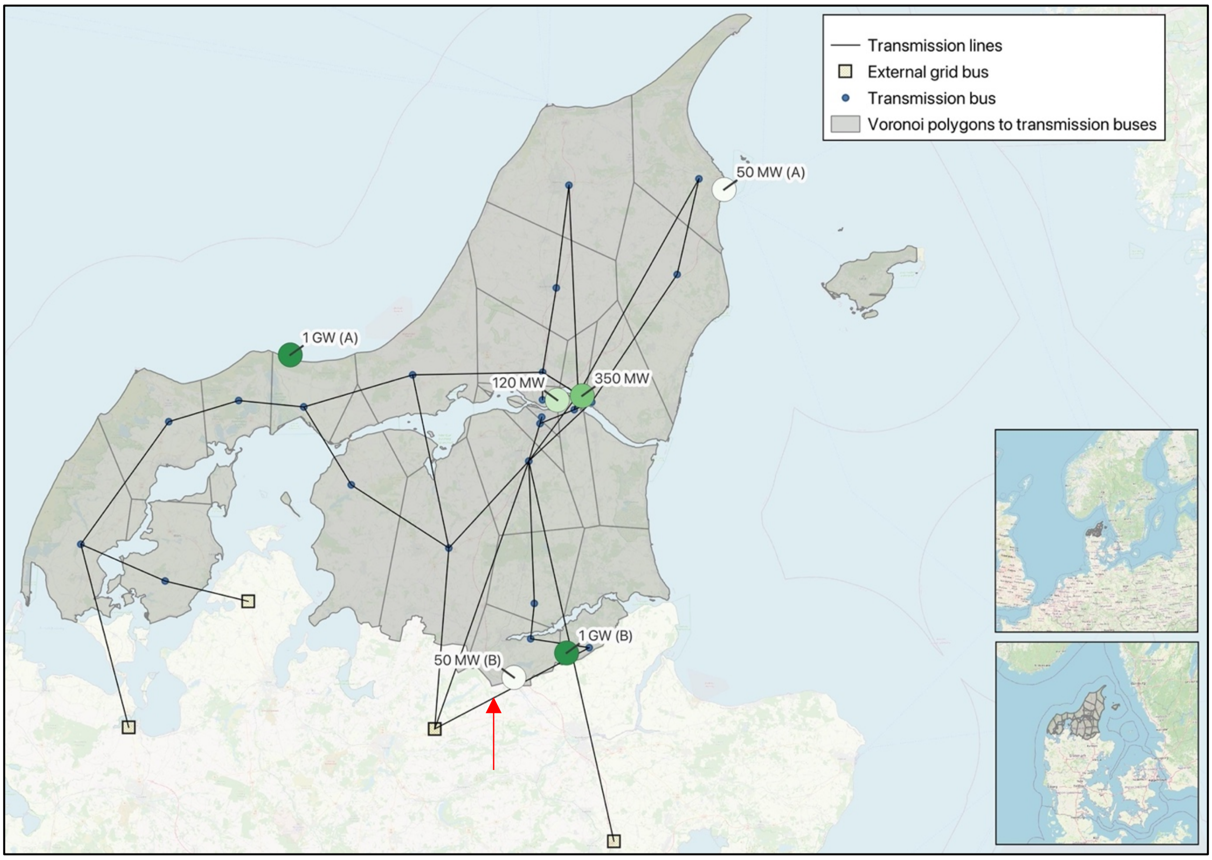

Figure 24: Visualisation of modified electricity transmission network simulated in PandaPower to analyse line loading including preliminary locations of all six PtX projects in pipeline to the region of Northern Jutland.

The four buses just south of the region represents the transmission buses at which the external grid is modelled.

As seen in both *Figure 23* and *Figure 24*, the region of Northern Jutland is divided into polygons. These polygons are *Voronoi polygons*. The process of creating such Voronoi polygons is also called *Voronoi tessellation*. Each of these polygons are by each individual, modelled transmission bus in the electricity transmission grid to the extent of the region Northern Jutland. In previous studies, Voronoi tessellation has been utilised to determine the extent and placement of areas in which any load or generator finds itself the closest to the point utilised to make the Voronoi polygon, i.e. in this case a substation to which the loads and generators must be connected to allow for connecting to the grid [33], [34], [35], [36].

To perform a transmission grid power analysis in *PandaPower*, units are aggregated as to not model the flow of electricity from each individual load – e.g., for every residential building, EV and so forth – and from each individual generator – e.g., for every individual wind turbine, PV etc. In the same manner, each PtX facility in pipeline to the region is assumed connected to the nearest transmission bus. I.e., the preliminary locations of the PtX facilities in pipeline to the region of Northern Jutland also determine the transmission bus to which the respective PtX facilities are modelled to be connected to the electricity transmission grid. As will be explained more in detail in *3.3 below*, the line loading capacity of all transmission lines to the transmission bus connecting the respective PtX projects will determine if hydrogen production can occur in the PtX grid-connection scenarios of *only grid*, *partial grid,* and *partial grid full wind curtailment*. *Figure 25-Figure 30* show the specific transmission lines supplying electricity to each of the six PtX projects in pipeline to the region of Northern Jutland via their respective (closest) transmission buses.

The distribution level of electricity transportation is not modelled in this study. While this would more so reflect the actual flow of power in the region, the absence of modelling the distribution side of the electricity grid is to simplify the analyses. Additionally, the PtX capacities modelled in this study would all other things be connected to medium- or high voltage transmission buses. Thus, the inclusion of the distribution level would be more appropriate for a study on e.g., the modelling of differentiated loading profiles of charging of electric vehicles, individual heat pumps for heating etc.

Figure 25: Transmission lines supplying power to PtX project of 50 MW (A).

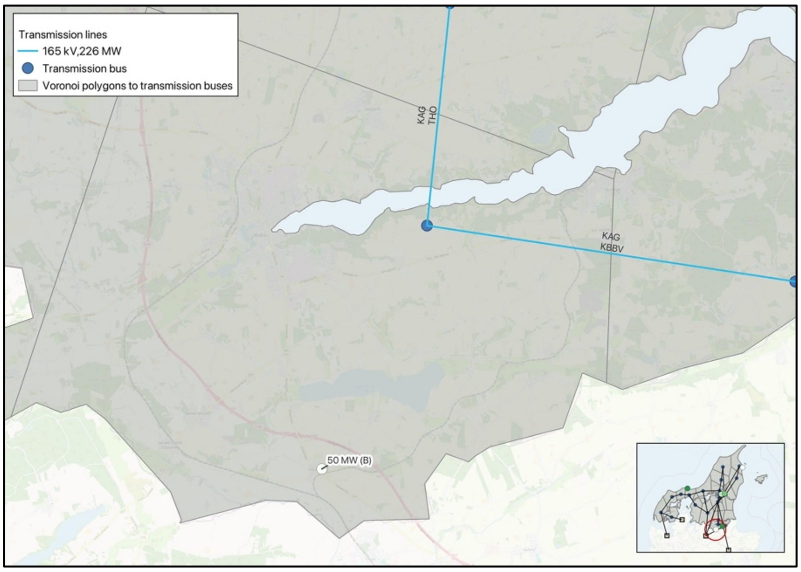

Figure 26: Transmission lines supplying power to PtX project of 50 MW (B).

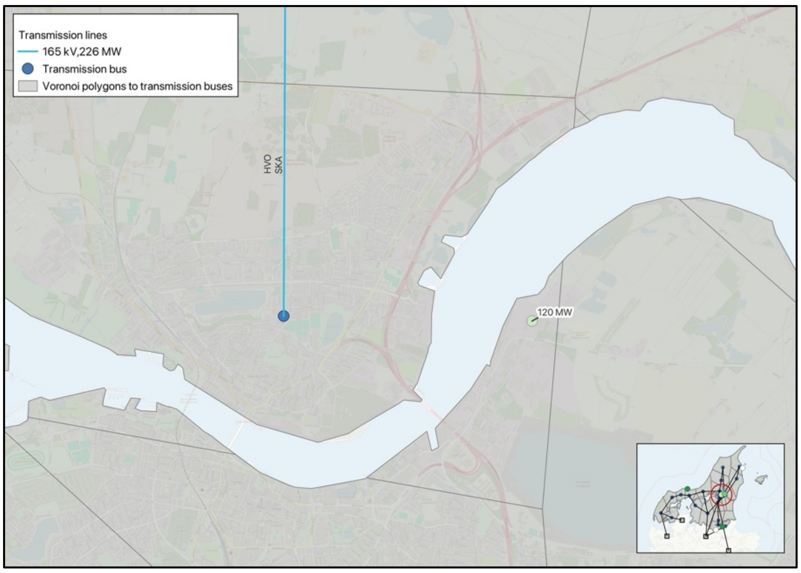

Figure 27: Transmission lines supplying power to PtX project of 120 MW.

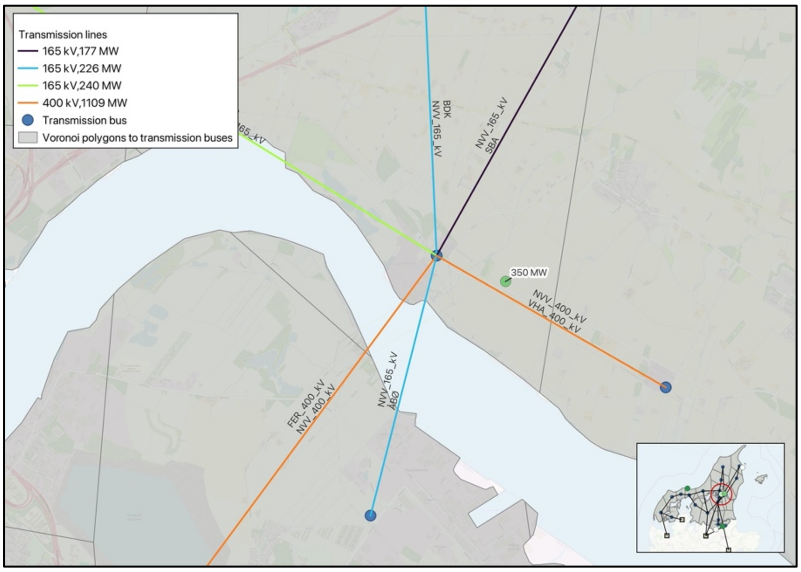

Figure 28: Transmission lines supplying power to PtX project of 350 MW.

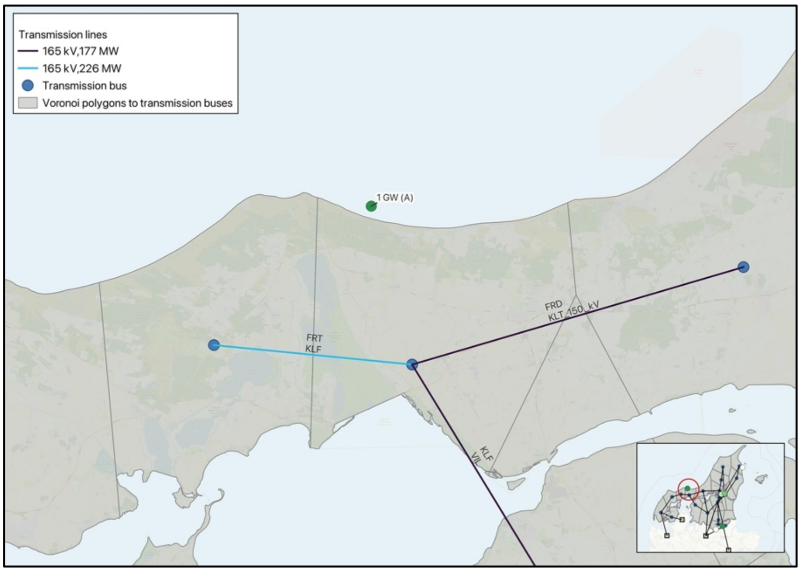

Figure 29: Transmission lines supplying power to PtX project of 1 GW (A).

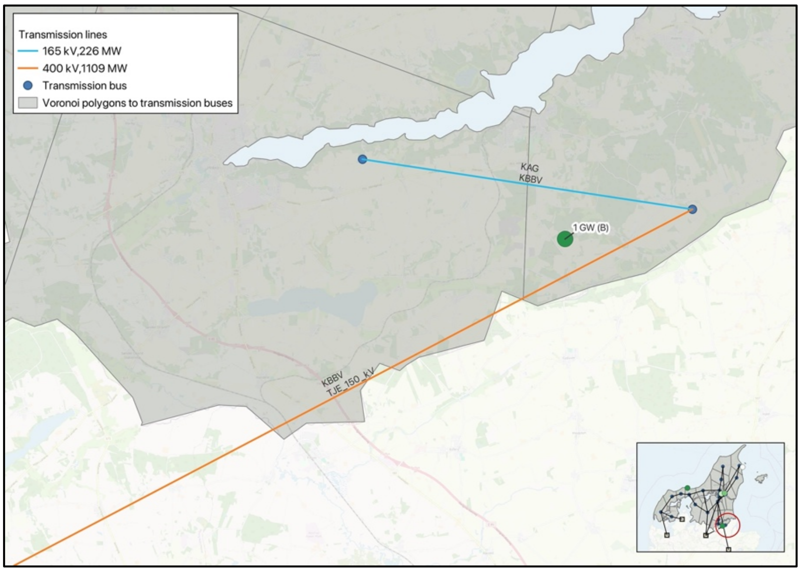

Figure 30: Transmission lines supplying power to PtX project of 1 GW (B).

3.3 PtX grid-connection scenarios – strategies modelled in PandaPower of evaluating the balance between loss of hydrogen production, wind power curtailment, and line loading

For this study, the key metrics to evaluate the impact of different strategic pathways of hydrogen production at PtX facilities is via *1)* loss of annual hydrogen production, and *2)* curtailment of wind power production.

The hourly loss of hydrogen production is across all PtX grid-connection scenarios expressed as the difference between respectively the theoretically highest level of annual hydrogen production and the actual level of annual hydrogen production depending on the PtX grid-connection scenario. *Equation V* shows the calculation of the hourly hydrogen production $\left(H_{2_h}\right)$.

$$H_{2_h} = \frac{AEC * MPC}{24} * \left(\frac{P_h}{MPC}\right)$$

Equation V: Hourly hydrogen production dependent on PtX facility's upper electrolyser capacity and power input.

AEC denotes the maximum, daily output of hydrogen production linearly dependent on the PtX facility's capacity $\left(\frac{\frac{kg\ H_2}{daily\ max}}{MW_e\ input}\right)$, *MPC* (maximum power capacity) denotes the respective PtX facility's capacity (MW_e), and P_h denotes the hourly input of power to the respective PtX facility. The value of AEC is assumed identical to all capacities of PtX facilities in pipeline to the region. Specifically, the value of AEC is acquired from [37] and is constant for all PtX facility capacities at $\frac{\frac{519\ kg\ H_2}{daily\ max}}{MW_e\ input}$.

To acquire the annual hydrogen production $\left(H_{2_{year}}\right)$, the sum of hourly hydrogen production is found in all hours of the year as shown in *Equation VI*.

$$H_{2_{year}} = \sum_{h=1}^{8760} H_{2_h}$$

Equation VI: Calculation of annual hydrogen production.

By assuming full utilisation of capacity in all hours of the year i.e., when $P_h = MPC$ for 8760 hours, the highest possible level of hydrogen production to the respective PtX facility capacities can be derived which is shown in *Figure 31*.

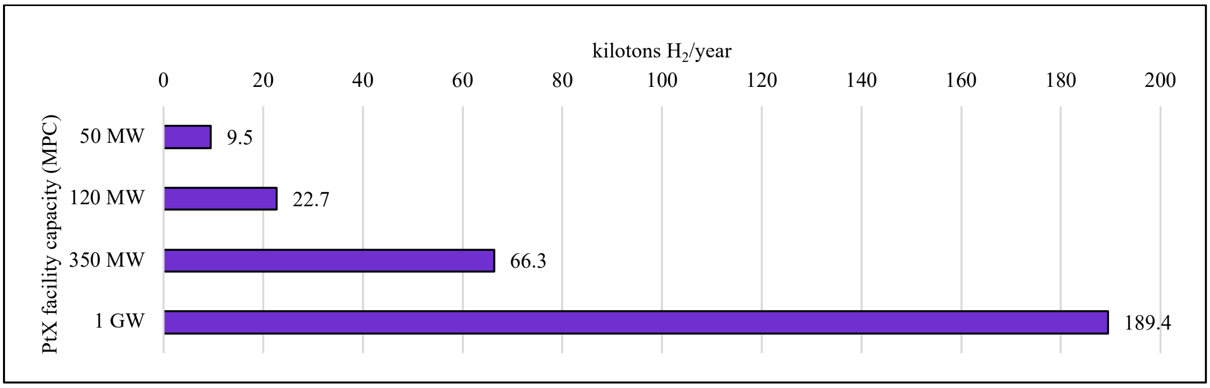

Figure 31: Annual hydrogen production at full capacity utilisation in all hours of year to PtX capacities as seen in pipeline to the region i.e., theoretical maximum.

The annual levels of hydrogen production to the respective PtX capacities seen in *Figure 31*, are used as the reference to determine the annual loss of hydrogen production depending on the PtX grid-connection scenario. Considering the theoretically highest levels of annual hydrogen production to all six PtX projects in pipeline to the region of Northern, the theoretically highest level of annual hydrogen production in the region of Northern

Jutland – if all six PtX projects in pipeline to the region were deployed with full utilisation of capacity in all hours of the year – is 486.8 kilotons H_2/year.

As was mentioned in *Research question and theoretical framework*, four different scenarios of supplying potential PtX facilities in the region of Northern Jutland are investigated in this study:

1. *no grid*
2. *only grid*
3. *partial grid*
4. *partial grid full wind curtailment*

Figure 32 illustrates these four PtX grid-connection scenarios.

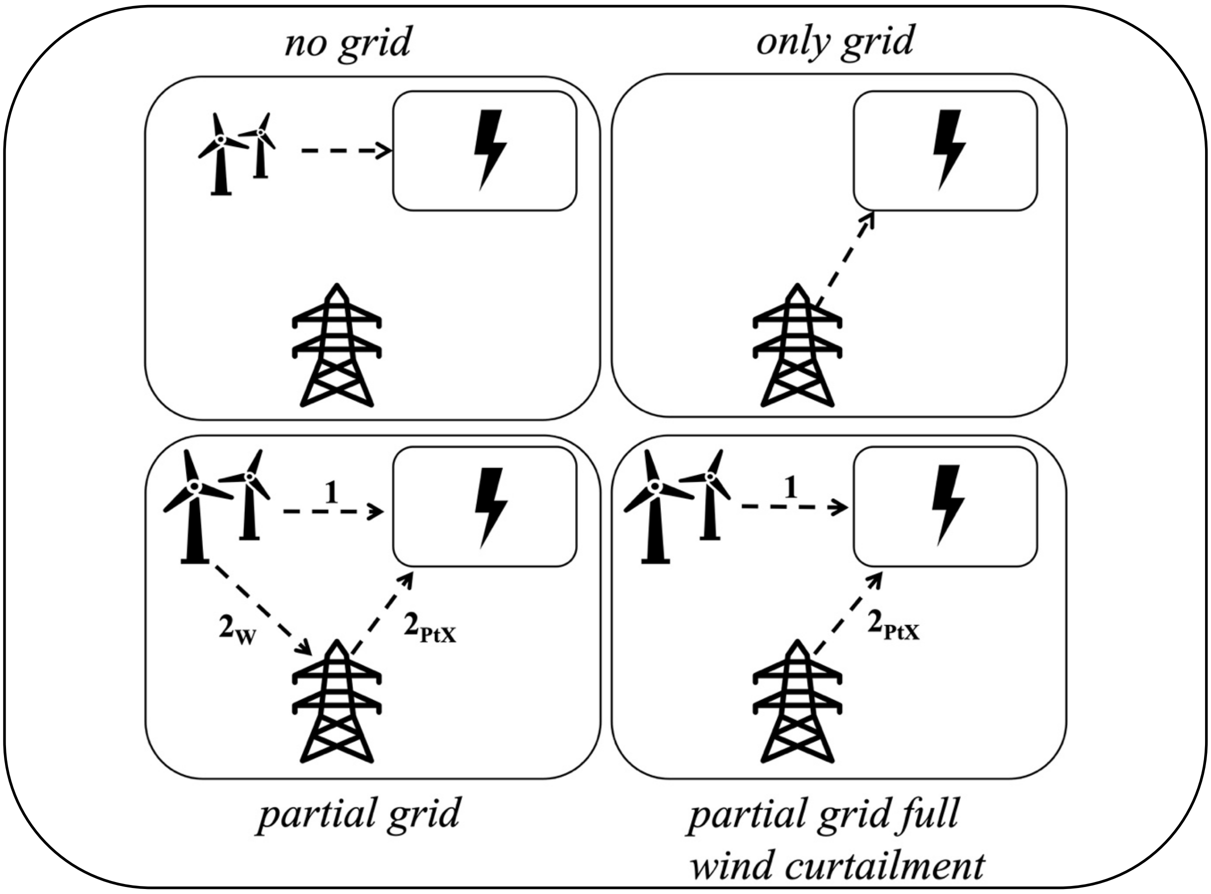

Figure 32: Visualisation of PtX grid-connection scenarios investigated in present study to each separate PtX facility in pipeline to the region of Northern Jutland.

Looking at *Figure 32*, the **1** in the PtX grid-connection scenarios of *partial grid* and *partial grid full wind curtailment* represents that the electricity production from the onshore wind turbines are prioritised to supply power to the respective PtX facilities. The $\mathbf{2_W}$ in the PtX grid-connection scenario of *partial* grid represents that any excess electricity production from the directly connected onshore wind turbines seek to offset this electricity production to the electricity transmission grid via the transmission bus to which the same PtX facility is connected. And lastly, the $\mathbf{2_{PtX}}$ in both the *partial* grid and partial grid full wind curtailment PtX grid-connection scenarios represents that the PtX facilities will only draw power from the electricity transmission grid if the electricity production from the directly connected onshore wind turbines can't deliver power to the full capacity of the PtX facility.

In the PtX grid-connection scenario of *no grid*, any potential PtX facility is modelled to be not connected to the electricity transmission grid at all. The only way for the respective, modelled PtX facilities to acquire a power supply to produce hydrogen is through directly connected onshore wind turbines. To simplify the number of variables and complexity of the study, only 150-metre hub height turbines – which translates into turbines of 7.2 MW_e for each turbine – are assumed deployed to supply power. This holds true in all the PtX grid-connection scenarios in which onshore wind turbines are connected directly to PtX facilities.

In this study, the PtX grid-connection scenario of *no grid* assumes that there can be no curtailment of electricity production from these directly connected onshore wind turbines. Therefore, the capacity of onshore wind turbines directly connected to supply power to the respective PtX facilities is dimensioned as to not exceed the capacity of the respective PtX facility. *Figure 33* shows the utilised distribution of capacity factors to determine the hourly output.

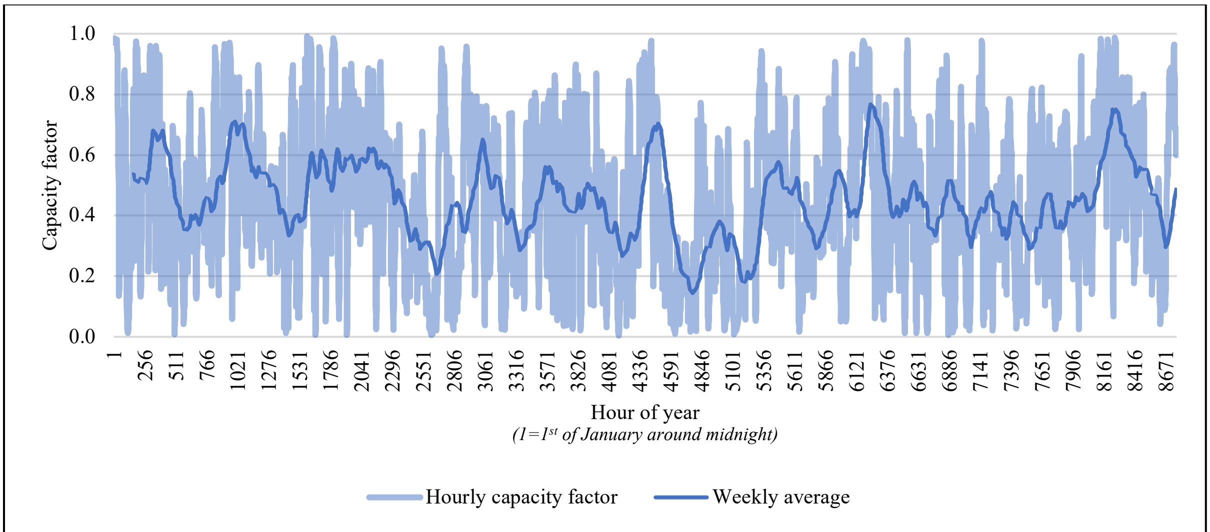

Figure 33: Distribution of capacity factors of 150-metre hub height, 7.2 MW_e onshore wind turbine in the region of Northern Jutland.

The source of data utilised to create the distribution of capacity factors as seen in *Figure 33* is derived from [38].

In the PtX-grid connection scenario of *only grid*, any potential PtX facility is modelled to only draw power from the electricity transmission grid to produce hydrogen. However, the respective PtX facilities can only draw power from the transmission grid if all transmission lines to the transmission bus, at which the respective PtX facilities are connected, do not exceed a certain threshold above their respective line loading capacities. *Table 4* shows the thresholds above line loading capacities utilised in this study to determine the cut-off point at which the respective PtX facilities can't draw power from the electricity transmission grid to produce hydrogen.

	Utilised thresholds above line loading capacities of respective transmission lines in the electricity transmission grid of Northern Jutland						
Utilisation of line loading capacity	>100%	>110%	>120%	>130%	>140%	>150%	>200%

Table 4: Levels of line loading thresholds to respective transmission lines to determine if PtX facilities can draw power to produce hydrogen and offset excess electricity production in the partial grid scenario.

When a line loading threshold of >100% is applied in the PtX grid-connection scenario *only grid* is applied, the respective PtX facilities can't produce hydrogen in a given hour, if the line loading of any transmission line leading to/from the PtX facility's transmission bus is transporting electricity above line loading capacity (i.e., line loading capacity is utilised at >100%).

However, to the PtX grid-connection scenario of *only grid*, there is no curtailment of wind power production, as there are no additional onshore wind turbines connected to the respective PtX facilities.

However, curtailment of wind power arises in the PtX grid-connection scenario of *partial grid*. The capacity of directly connected onshore wind turbines in the PtX grid-connection scenario *no grid* was dimensioned to not produce electricity above the respective PtX facilities' capacity. However, in the PtX grid-connection scenario of *partial grid*, the directly connected onshore wind turbines are dimensioned to annually produce the same level of electricity as the annual level of electricity consumption of the respective PtX facilities, if their respective capacities were fully utilised in all hours of the year. In hours of electricity production from these directly connected onshore wind turbines exceeding the respective PtX project capacity, the model seeks to offset the excess electricity production to the electricity transmission grid. *Figure 34* shows the annual level of this excess electricity production that is available for offsetting to the electricity transmission grid i.e., the sum of electricity production in all hours in which wind power production exceeds the respective PtX facilities' capacity.

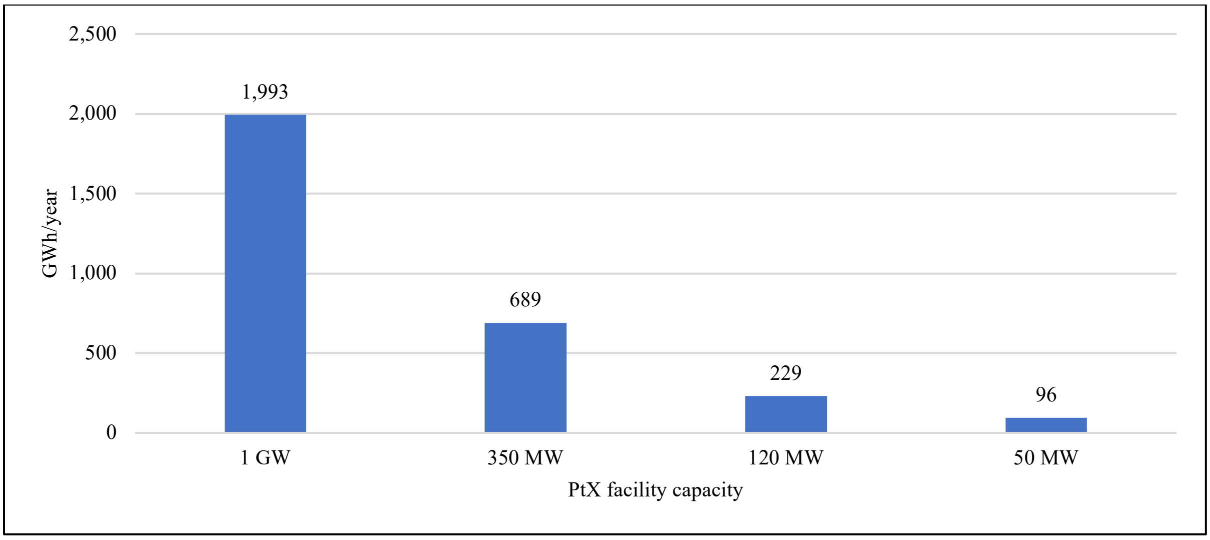

Figure 34: Annual electricity production from offshore wind turbines to be potentially delivered to the electricity transmission grid i.e., excess electricity production from directly connected onshore wind turbines to the respective PtX project capacities. Only applies to the PtX grid connection-scenario of 'partial grid'.

However, any excess electricity production from the directly connected onshore wind turbines can only be offset to the grid, if the line loading of the transmission lines to the respective transmission buses are below a certain threshold – specifically, the same thresholds as seen in *Table 4*. To the same thresholds above line loading capacities as utilised to determine the production of hydrogen in the PtX grid-connection scenario of *partial grid*, the curtailment of excess wind power production occurs when all transmission lines to the transmission bus are exceeded by the different thresholds.

In the PtX grid-connection scenario of *partial grid full wind curtailment*, any excess electricity production from the directly connected onshore wind turbines to the respective PtX facilities is completely curtailed. Thus, the curtailment of electricity production from the directly connected onshore wind turbines will be greater than that of the PtX grid-connection scenario of *partial* grid, as the annual electricity production is the same, as the respective capacities of the onshore wind turbines are not reduced. However, this additional curtailment of wind power production can in turn increase the hydrogen production of the respective PtX facilities, as the strain on the transmission lines all other things considered will be lowered.

To summarise on the PtX grid-connection scenarios utilised in this study to model the impact of different strategic pathways of supplying power for PtX projects, see *Table 5*.

Label of PtX grid-connection scenario	Characteristics of PtX-grid connection scenario
no grid	• PtX facilities can only be supplied with power from directly connected onshore wind turbines. • These directly connected onshore wind turbines have a summarised capacity that – combined with the hourly distribution of capacity factors – in no hour provides electricity production that will exceed the capacity of the respective PtX project. • Loss of hydrogen production arises when electricity production from the directly connected onshore wind turbines are lower than that of the respective PtX project's capacity. • There is no curtailment of electricity production from onshore wind turbines as the capacity is dimensioned to never exceed the capacity of the respective PtX facility's electrolyser capacity.
only grid	• PtX facilities can only be supplied with power from the electricity transmission grid. • The PtX facilities modelled will seek to produce hydrogen at full capacity in all hours of year. • If the line loading capacity of any transmission line that can supply the transmission bus, to which the respective PtX facility is connected, exceeds a given threshold, the PtX facility will produce no hydrogen in that given hour. • There is no curtailment of electricity production from onshore wind turbines as there are no onshore wind turbines modelled (except for existing onshore wind turbines, but these are only connected to the electricity transmission grid).
partial grid	• PtX facilities are initially supplied with power from directly connected onshore wind turbines, *then* by power from the electricity transmission grid via the nearest transmission bus i.e., the transmission bus to which the respective PtX facilities are connected. • Curtailment of wind power production arises when the transmission lines to/from the transmission bus, at which the onshore wind turbines can offset excess electricity production, are overloaded to the line loading threshold levels as seen in *Table 4*.
partial grid full wind curtailment	• This PtX grid-connection scenario is identical to the *partial grid* scenario but with the exception that any excess electricity production from directly connected onshore wind turbines is completely curtailed. • The annual hydrogen production – and thus annual loss of hydrogen production relative to the theoretical maximum of the respective capacities at full utilisation of all hours – may be higher than that of *partial grid* due to possibly lowering the line loading capacities below certain thresholds.

Table 5: Labels- and characteristics of utilised PtX grid-connection scenarios in present study.

			Number of 7.2 MW_e onshore wind turbines directly connected				Summarised capacity of onshore wind turbines directly connected (MW_e)			
Capacity of PtX facility	**Annual electricity production at full capacity utilisation (GWh)**	**Annual hydrogen production at full capacity utilisation (kilo tons)**	*only grid*	*no grid*	*partial grid*	*partial grid full wind curtailment*	*only grid*	*no grid*	*partial grid*	*partial grid full wind curtailment*
1 GW	8,760	189.4	0	140	304	304	0	1,008	2,188.8	2,188.8
350 MW	3,066	66.3	0	49	106	106	0	353.8	763.2	763.2
120 MW	1,051	22.7	0	16	36	36	0	115.2	259.2	259.2
50 MW	438	9.5	0	6	15	15	0	43.2	108	108

Table 6: Summarised capacities of directly connected onshore wind turbines to respective PtX-grid connection scenarios.

4 Results and discussion

In this section, the results obtained in the *PandaPower* model of simulating strain on the electricity transmission grid's lines in the region of Northern Jutland is shown to each of the four different PtX grid-connection scenarios described in *3.3 above*. Utilising the acquired results from the *PandaPower*-models – modified to the PtX grid-connection scenarios and three different years of projection of electricity generation- and consumption (2030, 2040, and 2050) – on the hourly loading of each transmission line, the annual loss of hydrogen production is estimated at different levels of line loading acceptance. The results obtained in the differently configurated *PandaPower* models also show the hourly exchange of power to- and from the region through the external grid buses which will be shown to each PtX grid-connection scenario.

4.1 no grid

The overloading of lines in the PtX grid-connection scenario *no grid* is identical to that of not deploying any PtX facilities in the region, as this PtX grid-connection scenario assumes no connection from PtX facilities to the transmission grid. This PtX-grid-connection scenario also reflects the utilisation of transmission lines in the electricity transmission grid utilisation above line loading capacity of transmission lines when no PtX facilities are deployed in the region, which is seen in *Figure 35*.

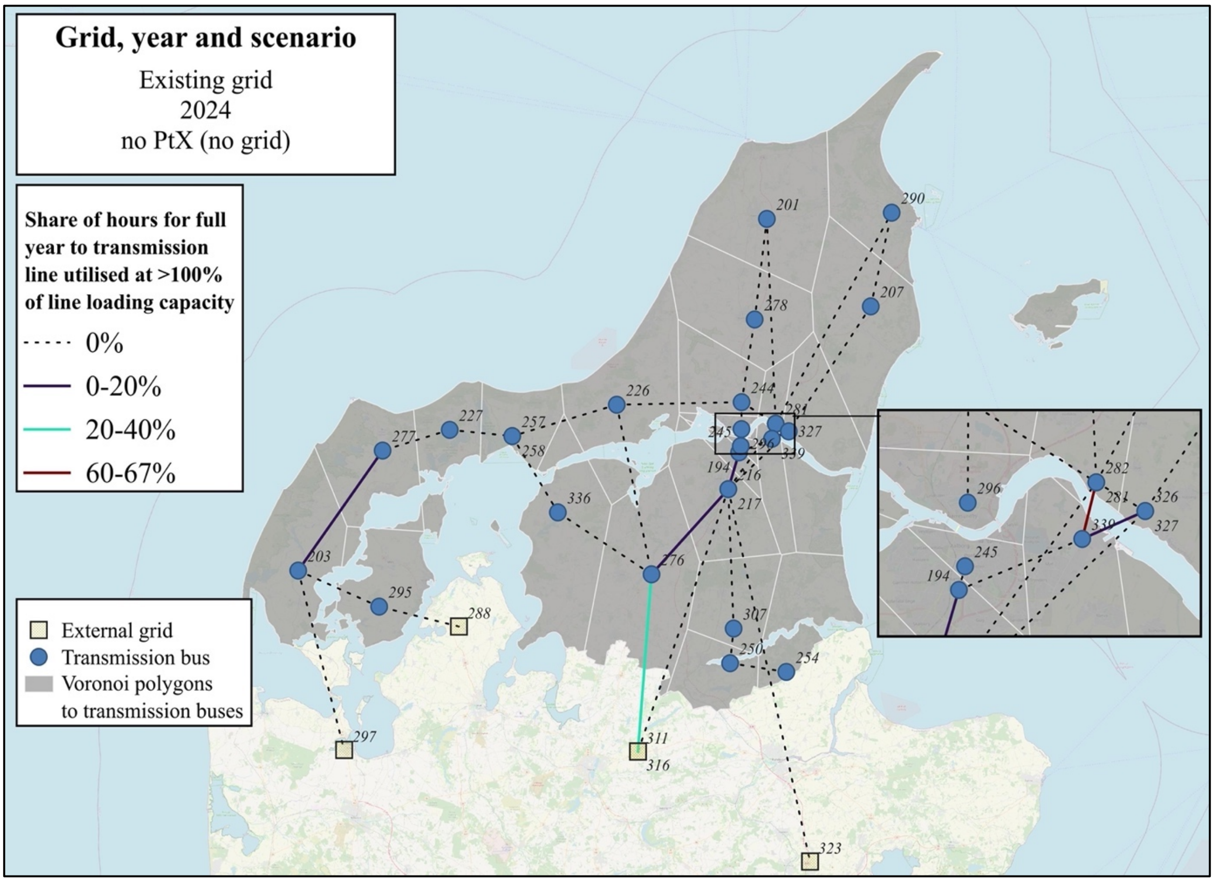

Figure 35: Overloading of transmission lines (utilisation >100% of line loading capacities) in 2024. Existing grid, no PtX facilities are modelled.

As can be seen *Figure 35*, overloading above line loading capacity occurs to four transmission lines of the existing transmission grid; beginning around Aalborg (buses 282/281/330) going south to the external transmission grid busses b311 and b316, transmission lines are utilised above their line loading capacities. This can be a combination of high loads in the populated city centres of Aalborg but more likely is the high level of electricity generation from the centralised combined heat- and power plant. Additionally, the transmission line on the left-hand side of *Figure 35* going from b203 to b277 is utilised in more hours of the year. As it can be seen from *Figure 36* that there's a significantly higher export from the region via the external grid buses b288 and b297 than there is an import via the same external grid buses, it is likely that the overloading of this transmission line stems from the excess electricity production from decentralised combined heat- and power plants in the Western part of the electricity transmission grid.

As to not induce utilisation of these abovementioned transmission lines, it is likely that the combined heat- and power plants would decrease the electricity production hours of excess electricity production. This could entail a curtailment of the annual full-load hours to the electricity production of combined heat- and power plants in the region to account for the overloading of electricity transmission lines.

Line loading utilisation above >100% of the respective line loading capacities decrease (significantly) from 2030 and onwards in the *no grid* scenario. This is due to the decreasing electricity generation from combined heat- and power plants in the model, and in particular the one centralised combined heat- and power plant. As the electricity generation of the combined heat- and power plant decreases (see *Figure 17*), the overloading of electricity transmission lines decreases significantly. By 2030, no transmission lines are utilised at >100% of line loading capacities. This also holds true to the projection of electricity generation- and consumption to the years of 2040 and 2050.

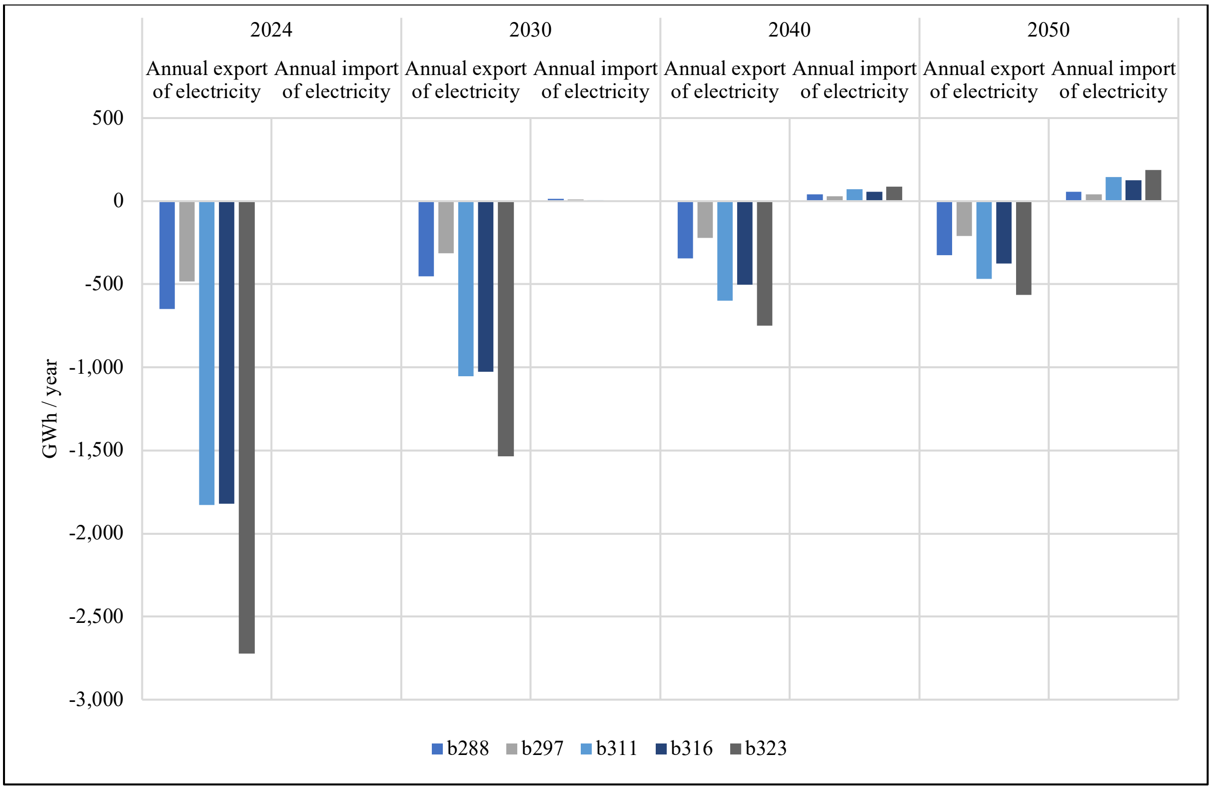

Figure 36: Annual export/import of electricity from/to the region of Northern Jutland in the PtX grid-connection scenario of 'no grid' (all years) via the external grid buses of the transmission model.

From *Figure 36* it can amongst other be deducted that the annual level of electricity exported decreases relatively much more so, than the import of electricity increases. This could indicate that the PtX grid-connection scenario of *no grid* – i.e., no PtX facilities are connected to the electricity transmission grid – have an excess of electricity production that is not sought to be offset for consumption inside of the transmission grid as the load is lower than that of the generation. By 2024, there is hardly any import of electricity to the region via the external grid buses but there is a high level of export of power away from the region. The export of electricity decreases as years progress. As there is an increase of electricity import while there is still an export of electricity, this is likely due to a mismatch in electricity production- and consumption, respectively. By 2024 and 2030, there is a high level of electricity generation from combined heat and power plants, which is gradually substituted by electricity generation from photovoltaics. A better hourly match between the generated electricity and the electricity consumption could possibly minimise the needed export of electricity away from the region via the external grid transmission buses. Such

As goes for the annual loss of hydrogen production in the PtX grid-connection scenario of *no grid*, *Figure 37* compares the annual hydrogen production in the PtX grid-connection scenario of *no grid* to the theoretical maximum (see *Figure 31*).

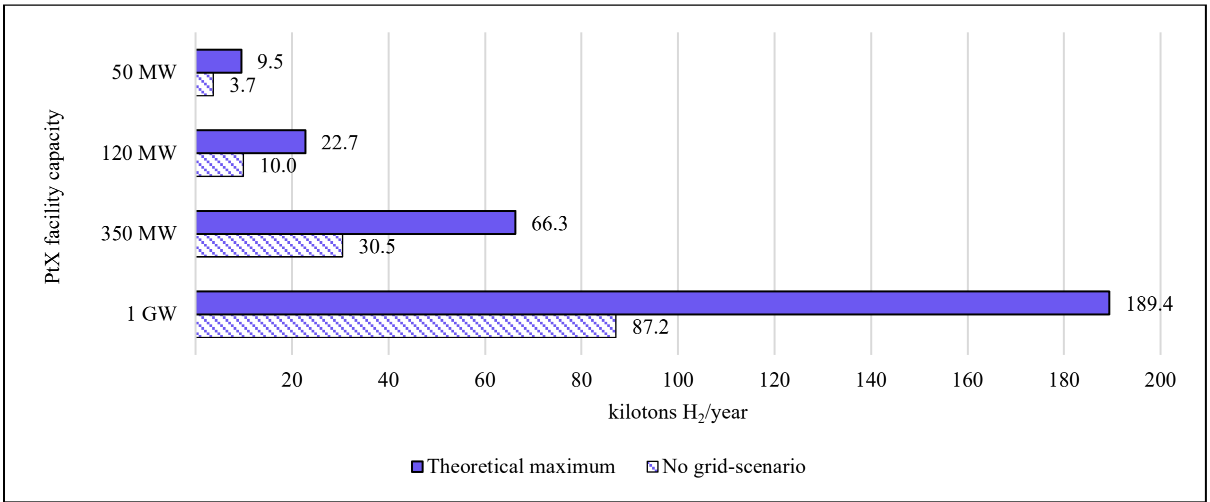

Figure 37: Comparison of theoretically upper level of hydrogen production to the four different sized PtX facilities and annual hydrogen production in the PtX grid-connection scenario of no grid.

Looking at *Figure 37*, the 1 GW PtX projects as well as the 350 MW PtX project will in the PtX grid-connection scenario of *no grid* produce 46% (*curtailment of 54% annually*) of each of their respective theoretical levels of annual hydrogen production. As goes for the 120 MW PtX project, this share of annual hydrogen production in the PtX grid-connection scenario *no grid* decreases by two percentage points to 44% (*curtailment of 56% annually*) of its respective level of the maximum, theoretical annual hydrogen production. For either of the 50 MW PtX projects, this share further decreases by an additional five percentage points to 39% (*curtailment of 61% annually*) of its annual level of maximum, theoretical hydrogen production. The reason for the gradually decreasing share of the annual hydrogen production in the PtX grid-connection scenario of *no grid* with decreasing PtX capacities is that this study assumes only 7.2 MW_e onshore wind turbines deployed as the additional onshore wind turbines to be directly connected to the respective PtX facilities.

Thus, to the PtX grid-connection scenario of *no grid*, the annual curtailment of hydrogen production – regardless of the development in the energy system in which the PtX facilities are embedded, as they are not grid connected – is 54-61%. As the PtX facility's capacity increases, the annual curtailment of hydrogen increases as well, as only 7.2 MW_e turbines in this study are assumed to be the onshore wind turbines that can electricity directly to the PtX facilities (in the PtX grid-connection scenarios to which they apply). If onshore wind turbines of varying capacities were modelled to supply the respective PtX facilities by a direct connection, the annual loss of hydrogen production in the *no grid*-scenario would decrease.

As will be shown in the later scenarios, a higher level of annual hydrogen production can be achieved by the PtX grid-connection scenarios in which grid connection at some level is apparent. Nevertheless, the *no grid* scenario will in the long term show the least necessary curtailment of other components in the energy system. However, if only considering the four smaller PtX projects in pipeline to the region of Northern Jutland, grid connection of the PtX projects in pipeline to the region shows some level of grid balancing by removing overloading of transmission lines. Still, this advantage to the decrease of overloading of electricity transmission lines only holds true in the short term (from 2024 to 2030), and the overloading of transmission lines will be higher than that of applying the *no grid* scenario, even only to the four smaller PtX projects in pipeline to the region.

4.2 *only grid*

In the PtX grid-connection scenario of *only grid*, there is no curtailment of wind power production as this scenario assumes no additional onshore wind turbines that are connected to the respective PtX facilities. Instead, the PtX facilities in pipeline to the region can only be supplied with power from the electricity transmission grid via the nearest transmission bus to which the respective PtX facilities are assumed connected. As such, loss of hydrogen production arises if the transmission lines supplying the respective PtX facilities are utilised at a certain threshold (see *Table 4*) above the respective transmission lines' loading capacities.

Simulating the deployment of the four smaller PtX projects in pipeline to the region of Northern Jutland and not allowing for transmission lines to be utilised above line loading capacities (>100% line loading capacity), there is an annual loss of hydrogen production of around 1% to the 350 MW PtX facility by the year of compared to the theoretical maximum of 66.3 kilotons (see *Figure 37*). By 2030 and 2040, all the four smaller PtX facilities in pipeline can attain full annual hydrogen production. Allowing for transmission lines' capacity to be utilised at 110% of line loading capacities, provides to the 350 MW PtX facility the last percentage point of annual hydrogen production. In summary, this indicates that all PtX facilities in pipeline to the region of Northern Jutland can be supplied solely with electricity from the electricity transmission grid, and these (nearly) all PtX facilities can run at full capacity in all hours of the year; only the 350 MW PtX facility must curtail hydrogen production by one percentage point. However, when modelling all six PtX projects in pipeline to the region of Northern Jutland, the electricity consumption increases dramatically. In turn, as utilisation of transmission lines increase >100% line loading capacities, loss of hydrogen production occurs as the PtX facilities cannot be supplied with power in hours of overload. *Figure 38* shows the annual loss of hydrogen production when modelling all six PtX projects in pipeline in the PtX grid connection-scenario of *only grid* in the modified grid to the years of respectively 2030, 2040, and 2050.

As goes for the biggest difference between the different years of the PtX grid-connection scenario of *only grid* with all 6 PtX projects modelled in the (modified) transmission grid, the 350 MW PtX project will by 2030 only lose about 2% of annual hydrogen production without having to exceed the line loading capacities of any transmission lines to the transmission bus connected to the 350 MW PtX project. However, by 2040 and 2050, the annual loss of hydrogen of the 350 MW PtX facility increases to respectively 43% and 44% at the same threshold of line loading capacity. In 2040 and 2050, the annual loss of hydrogen production of the 350 MW PtX project must allow for exceeding line loading capacities up until 140% of line loading capacity until the annual hydrogen production is about the same as it is by 2030 when not exceeding line loading capacities at all. This shows that a deployment of all six PtX facilities in pipeline the region of Northern Jutland

No hydrogen production can occur at either of the two 1 GW PtX projects in pipeline to the region. It is not until the line loading capacity is allowed to draw power from the transmission lines at <200% utilisation of the transmission lines supplying the 1 GW (B) PtX project with power, that any hydrogen production can occur. This could indicate that transmission lines to/from the transmission buses at which respectively the 1 GW (B) and 50 MW (B) PtX projects are connected needs to be double of that which is modelled in the modified electricity transmission grid. By 2040, the annual loss of hydrogen production at the 1 GW (B) PtX project is 29% compared to the theoretical maximum, but then increases to 38% by 2050.

The same pattern is seen to the 50 MW (B) PtX project. Amongst explanations that both the 1 GW (B) and the 50 MW (B) PtX projects will begin producing hydrogen when allowing the line loading capacity to be <200% of the respective transmission lines supplying these PtX facilities, is the fact that they're both supplied by some of the same lines (see *Figure 26* and *Figure 29*). Thus, the additional strain of line loading that occurs to the transmission lines in the area occurs when deploying the 1 GW (B) PtX project to its assumed transmission bus of connection. Finally, it can be derived from *Figure 38* that both the 120 MW and 50 MW (A) PtX projects can produce hydrogen at their full capacities without having to exceed the line loading capacities of the respective transmission lines that supply these transmission buses with electricity. The specific lines that are overloaded above transmission line capacities i.e., >100% of line loading capacities, can be seen to the years of 2030, 2040, and 2050 in *Figure 39*.

The implication on the level of annual import/export of electricity to/from the region via the external grid buses is shown in *Figure 40* and *Figure 41*. When deploying the four smaller PtX facilities in pipeline to the region, there is still some export of excess electricity production from the region via the external grid buses. This indicates that even though the electricity consumption is increased significantly by connecting the four smaller PtX projects to the grid, there is still an excess of electricity production. However, by 2040, when the electricity generation from combined heat- and power plants in the model decreases even more, the export of electricity decreases. By 2050, the export of electricity is nearly identical to that of 2040. When export of electricity decrease from 2030 to 2040, this indicates that the increase of electricity consumption does not increase at the same ra

In the PtX grid-connection scenario of *only grid* in which the four smaller PtX facilities are modelled, export of electricity still occurs in all three modelled years which was also seen in the PtX grid connection-scenario of *no grid* (see *Figure 36*). This indicates that though the four smaller PtX projects in pipeline to the region of Northern Jutland significantly increase the electricity consumption of the region, there are still hours in which the *PandaPower* model needs to offset excess electricity production. The impact of deploying the two 1 GW PtX facilities in pipeline to the region of Northern Jutland is clearly seen in the difference between *Figure 40* and *Figure 41*: *1)* As the electricity consumption of the region increases significantly with the deployment of the two 1 GW PtX facilities, all electricity production that was previously exported is now absorbed by the increase of electricity load at the respectively connected transmission buses to the respective 1 GW PtX facilities. *2)* The import of electricity through external grid bus b311 increases vastly. This is a direct impact of the deployment of the 1 GW (B) PtX facility, as this is connected by the end of one of the two transmission lines connecting the external grid bus b311 to the modified transmission grid of the region. As goes for the PtX grid-connection scenario of *only grid*, both the 350 MW and 50 MW (B) PtX facilities can produce hydrogen at (nearly) full capacity utilisation in all hours of the year across all three years modelled if both 1 GW PtX facilities are not included in the modelling in *PandaPower*. This indicates that the additional utilisation of transmission lines from the increased electricity consumption of the 1 GW PtX facilities leads to a loss of hydrogen in both the 350 MW and 50 MW (B); a loss of hydrogen that would otherwise have been prevented were the two 1 GW PtX facilities not included. Furthermore, the 1 GW PtX facilities are not able to produce any hydrogen in the PtX grid-connection scenario of *only grid*. It is not until line loading is allowed to exceed 200% of transmission line loading capacity, that the 1 GW (B) PtX facility can attain any hydrogen production. As goes for the 1 GW (B) PtX facility, this would mean that it would have to run at either half capacity, decrease the capacity from 1 GW to 500 MW, or that the transmission lines to/from the area are doubled in electricity transportation capacity.

In summary on the PtX grid-connection scenario of *only grid*: Implementing only the four smaller PtX projects in pipeline to the region of Northern Jutland will achieve full utilisation of their respective capacities, which will lead to an annual production of hydrogen at 108 kilo tons. In the short term (by 2030), no electricity transmission lines will be utilised above their respective line loading capacities. In the medium term (by 2040), one electricity transmission lines is utilised in 1% of hours throughout the year in the 100-150% interval of line loading capacity. Finally, in the long term (by 2050), the same electricity transmission line that was utilised in 1% of hours in the year in the interval of line loading utilisation of 100-150% increases from 1% to 2%. Additionally, in the long term (by 2050), an additional electricity transmission line will be utilised above line loading capacity, specifically in 1% of hours throughout the year in the line loading interval of 100-150% of line loading capacity.

However, several indicators show that applying an *only grid* scenario to the deployment of all six PtX facilities in pipeline to the region shows to be infeasible. Infeasible, as no hydrogen production can occur at either at the two 1 GW PtX facilities. Additionally, deploying the 1 GW PtX projects to the region will undermine the annual hydrogen production of other PtX projects (specifically, the 50 MW (B) PtX project) as some PtX projects are dependent on the same transmission lines to supply power.

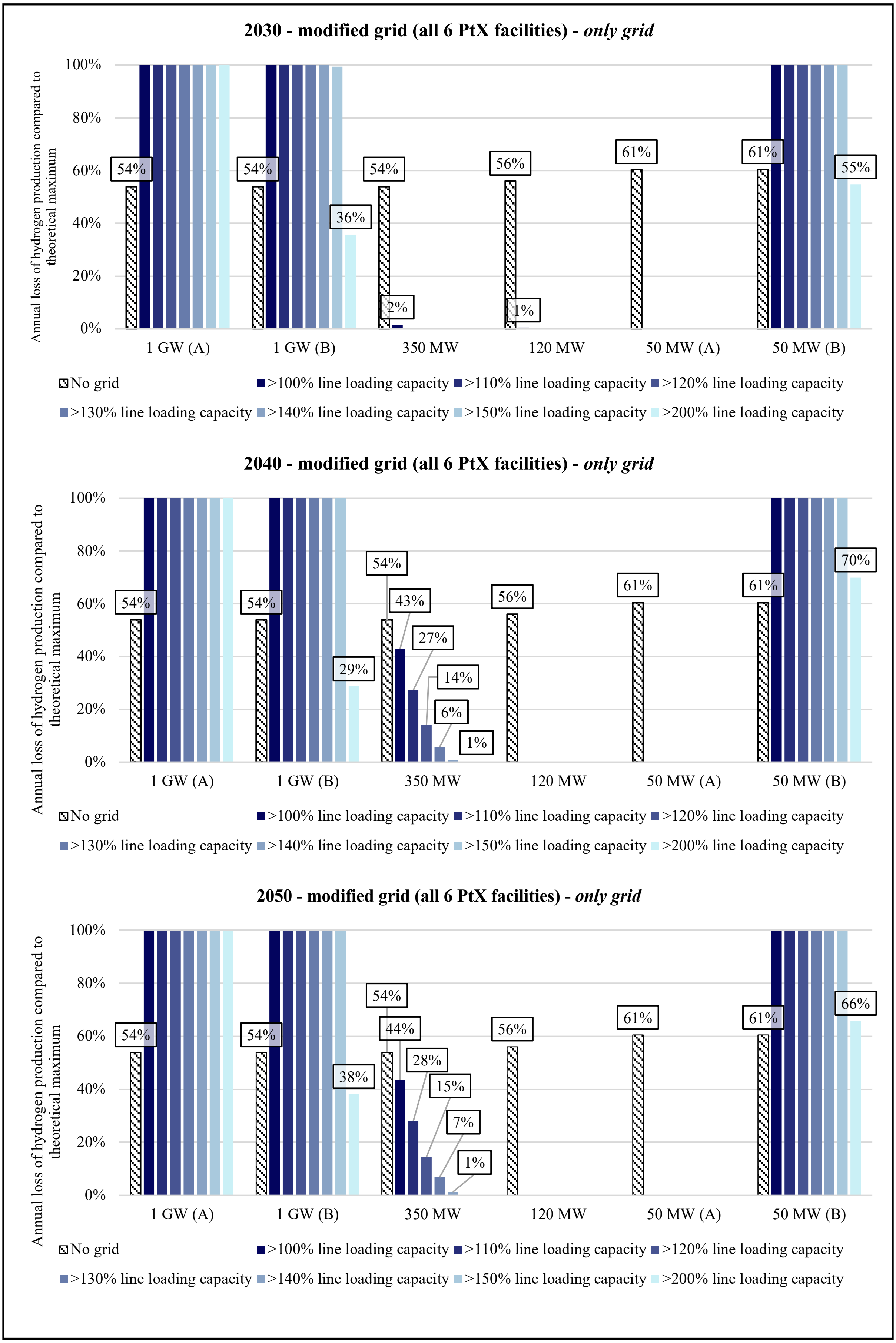

Figure 38: Annual loss of hydrogen production to different thresholds of transmission line overloading in PtX grid connection-scenario only grid to the modified grid (all six PtX facilities are deployed).

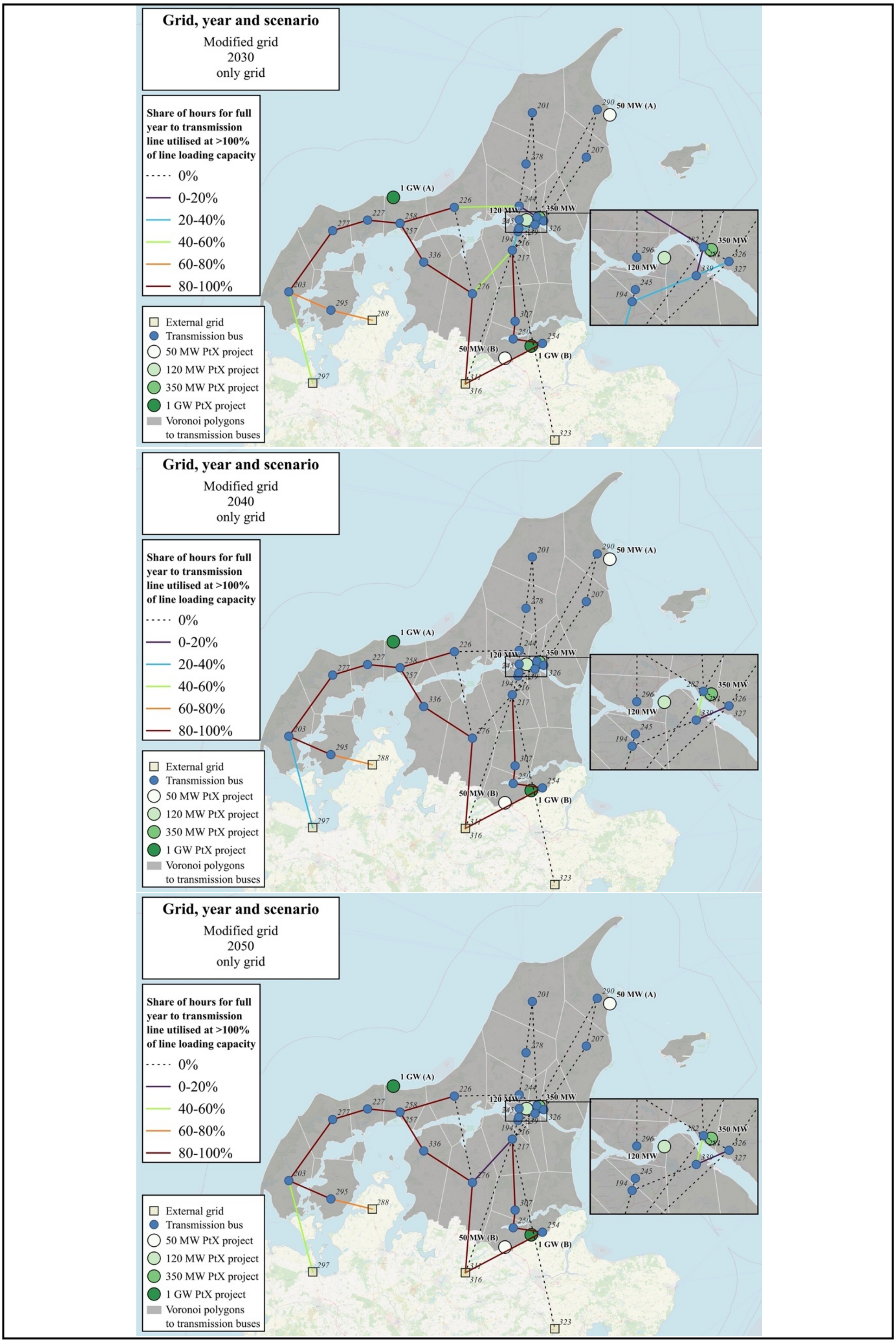

Figure 39: Overloading of transmission lines in PtX grid-connection scenario of only grid with all 6 PtX facilities included.

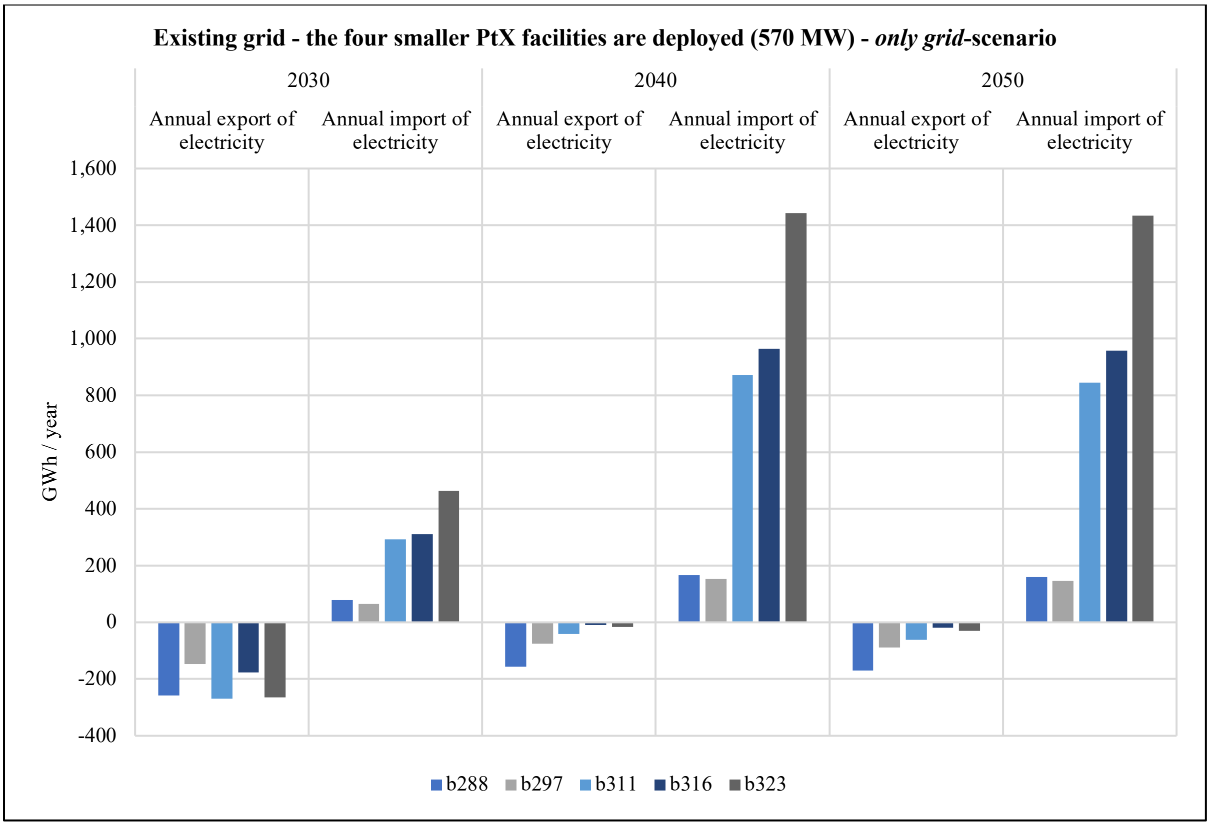

Figure 40: Annual export/import of electricity from/to the region of Northern Jutland in the PtX grid-connection scenario of 'only grid' (all years) via the external grid buses of the existing electricity transmission system.

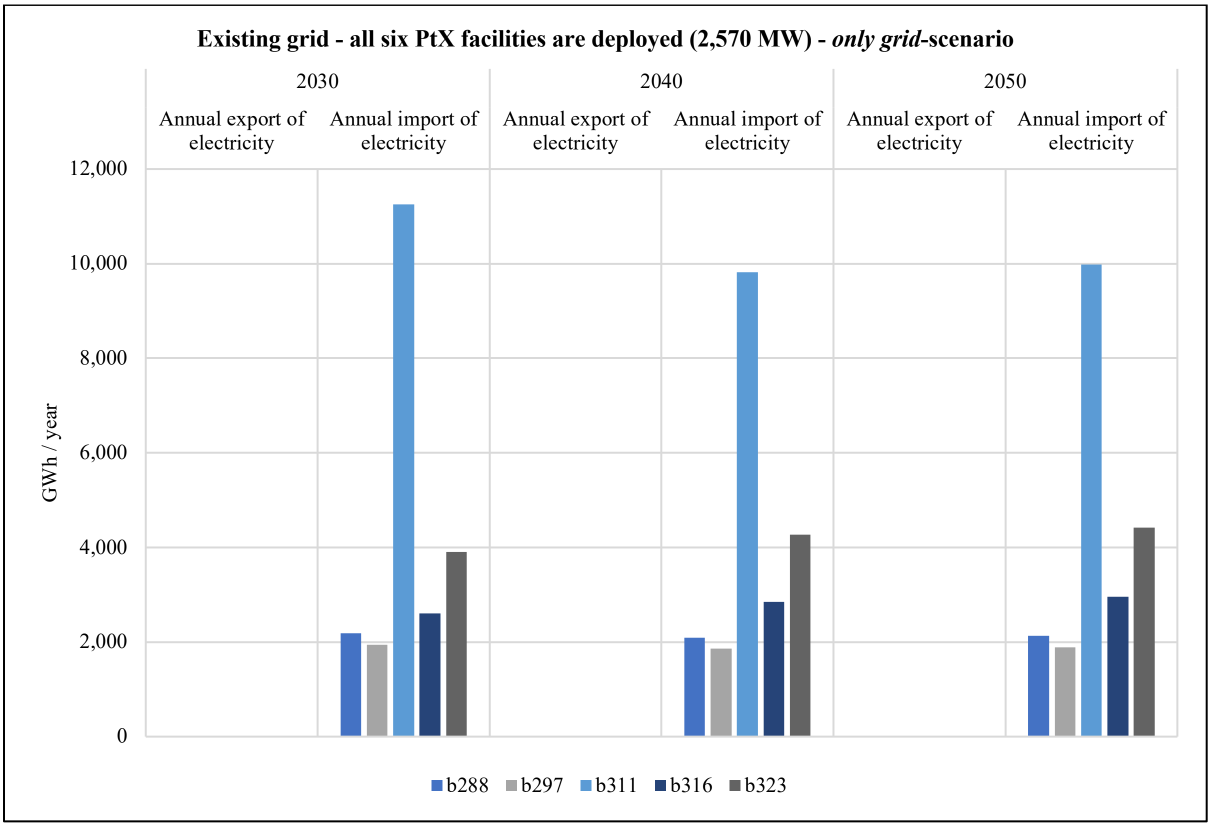

Figure 41: Annual export/import of electricity from/to the region of Northern Jutland in the PtX grid-connection scenario of 'only grid' (all years) via the external grid buses of the modified electricity transmission system.

4.3 *partial grid*

The PtX grid-connection scenario of *partial grid* entails a lesser strain on the transmission lines as PtX facilities are initially supplied with electricity from directly connected onshore wind turbines. This scenario is designed to reflect the strategic development of deploying PtX facilities with directly connected onshore wind at a significantly higher capacity than in the PtX grid-connection scenario of *no grid*. This allows for the offset of any excess electricity production from the directly connected onshore wind turbines in hours of the wind power production being higher than that of the upper capacity of the respective PtX facility's capacity. The lesser import of electricity consumption of PtX facilities lessens the strain on transmission lines, which in turn could increase the production of hydrogen to the respective PtX facilities.

When simulating the deployment of the four smaller PtX projects in pipeline to the region of Northern Jutland, full utilisation of capacity in all hours can be achieved. Additionally, the only instance in which curtailment of excess electricity production occurs is to the 350 MW PtX project: When the transmission line overloading is set at 100% i.e., equal to that of the respective transmission line loading capacities, 8% of the excess electricity production of the directly connected onshore wind turbines must be curtailed. Allowing the transmission lines to/from the transmission bus connecting the 350 MW PtX project to the electricity transmission grid to be utilised at 110% of line loading capacity, 100% of the excess electricity production can be offset to the electricity transmission grid. By deploying the four smaller PtX projects in pipeline to the region in the *partial grid* scenario, 95% of all electricity produced by the directly connected onshore wind turbines are utilised; 17% of which is offset to the grid, and 78% of which is utilised by the respective PtX facilities before any excess electricity production occurs. This indicates that the current state of the electricity transmission grid can for the most part withstand both *1)* the additional electricity consumption required by the respective PtX projects in hours of insufficient electricity production from directly connected onshore wind turbines, and *2)* the excess electricity of the directly connected onshore wind turbines in hours of surplus electricity production, respectively. Additionally, this PtX-grid connection scenario will annually produce a greater amount of hydrogen than the *no grid* scenario.

In conclusion on the *partial grid*-scenario – when only considering the four bigger PtX projects in pipeline to the region of Northern Jutland – the *partial grid*-scenario is from a perspective of maximising annual hydrogen production and integrating a higher level of renewable electricity production in the grid is preferrable to that of both the PtX grid-connection scenarios of respectively *no grid* and *only grid*.

However, as the two bigger PtX facilities in pipeline to the region of Northern Jutland – i.e., the two 1 GW PtX projects – are implemented in the electricity transmission grid alongside the four smaller PtX projects, the increase of electricity consumption induces utilisation above transmission line loading capacities. As a result, loss of hydrogen production arises and wind curtailment increases. *Figure 42* shows the loss of hydrogen production relative to the theoretical maximum for each of the six PtX facilities in pipeline to the region of Northern Jutland.

As goes for the overloading of transmission lines in the entirety of the transmission grid in the region of Northern Jutland, *Figure 43* shows the share of hours for a full year to each transmission line at which they are utilised at >100% line loading capacity.

By deploying all six PtX projects in pipeline to the region of Northern Jutland by the partial grid-scenario, loss of annual hydrogen production from three out of the four smaller PtX facilities occur.

As the two 1 GW PtX projects are deployed in a partial grid-scenario, the electricity transmission lines in the grid are additionally utilised from 1) the increased electricity consumption in hours of insufficient electricity generation from the directly connected onshore wind turbines, and 2) the additional offset of surplus electricity generation from the directly connected onshore wind turbines. In the short term (by 2030), this affects the 50 MW (B) PtX project, as it utilises some of the same electricity transmission lines as the 1 GW (B) PtX project (see figures x-x). When not allowing for electricity transmission lines to be utilised above their respective line loading capacities (>100%), the loss of annual hydrogen production at the 50 MW (B) PtX project is in the short term (by 2030) 14% of the theoretical maximum, and it then decreases in both the medium term (by 2040) and in the long term (by 2050) to 12%. However, the annual hydrogen production at the 50 MW (B) PtX project is still higher than that of the no grid-scenario. Nonetheless, the 50 MW (B) PtX project would show no loss of hydrogen production, if the two 1 GW PtX projects were not deployed.

As goes for the 350 MW PtX project, no loss of hydrogen production arises in the short term (by 2030) when the two 1 GW PtX projects are connected to the grid in the partial grid-scenario. However, in both the medium term (by 2040) and the long term (by 2050), a loss of hydrogen arises due to the additional overloading of transmission lines in the region induced by the deployment of the two 1 GW PtX projects. In the medium term (by 2040) . Thus, the deployment of the two 1 GW PtX projects partially undermine the hydrogen production of the 350 MW PtX project when deploying all six PtX facilities by the partial grid-scenario.

Neither the 120 MW nor the 50 MW (A) PtX projects show any loss of hydrogen production in the partial grid scenario, even with the two 1 GW PtX projects deployed. This indicates that the 120 MW and 50 MW (A) PtX projects are not dependent on the same electricity transmission lines as those being overloaded when the two 1 GW PtX projects are deployed in the region and connected to the grid.

Wind curtailment arises when the electricity transmission lines to/from the transmission buses - at which the PtX facilities and thus their directly connected onshore wind turbines are assumed connected - are utilised above their line loading capacity. Obviously, when surplus electricity arises from the directly connected onshore wind turbines, the re. Thus, wind curtailment from the directly connected onshore wind turbines arise, when the electricity transmission lines transporting the surplus electricity are already (near) overloaded from the transport of power due to the additional production- and generation in the region. Note, that the levels of wind curtailment in the graphs of *Figure 42* reflect that electricity production from the directly connected onshore wind turbines initially supply the respective PtX facilities, and thus the utilisation of wind power directly in the PtX facilities is included in the annual wind curtailment.

The 1 GW (A) PtX project shows the lowest level of wind curtailment. This means that nearly all excess electricity production can be offset to the grid. By utilising electricity transmission lines not higher than their respective line loading capacities (>100%), only 2% of the annual electricity production from the directly connected onshore wind turbines to the 1 GW (A) PtX project must be curtailed in the short term (2030). This necessary curtailment of wind power from the directly connected onshore wind turbines to the 1 GW (A) PtX project increases to 3% in the medium term (by 2040) and stays the same in the long term (by 2050).

The PtX projects in pipeline of 1 GW (B), 350 MW, and 50 MW (B) all need curtailing the electricity production of the onshore wind turbines by 21-22% of the annual electricity production as to not utilise the electricity transmission lines above line loading capacities. Even so, by allowing for transmission lines to be utilised up to 150% of their respective transmission line loading capacities, provides just a bit additional utilisation of wind power from the directly connected onshore wind turbines; just between one and two additional percentage points of wind power utilisation. Considering that there is no curtailment of electricity production from the directly onshore wind turbines to the 350 MW and 50 MW (B) PtX facilities prior to the deployment of the two 1 GW PtX projects, it is clear that the curtailment of wind power of the turbines connected to the 350 MW and 50 MW (B) need to be curtailed as a direct result of the deployment of the two 1 GW PtX projects.

Thus, this could be an indication that any expansion of electricity transmission lines to/from the transmission buses of the PtX projects of 1 GW (B), 350 MW, and 50 MW (B) would need an increase in transmission line capacity of more than 50% in which case wind power curtailment would only slightly decrease. Alternatively, the capacity of the directly connected onshore wind turbines would have to be decreased but as this would increase the number of hours in which the respective PtX facilities would draw power from the grid, it’s not sure as to whether this would show feasible from a transmission line overloading perspective.

As goes for the 50 MW (A) PtX project, there is no necessary curtailment of the onshore wind turbines by 2030 and 2050. As such, all the electricity produced from the directly connected onshore wind turbines can be utilised; initially to provide electricity for the 50 MW (A) PtX facility, secondary offsetting the excess electricity production to the transmission grid. However, by 2040, the electricity transmission lines to/from the transmission bus of the 50 MW (A) PtX project appear to be utilised already by the changing energy system. By 2040, the curtailment of wind power from the onshore wind turbines directly connected to the 50 MW (A) PtX facility needs increased to 21%, and only two percentage points of wind power utilisation can be gained by allowing for the electricity transmission lines to be utilised at 150% of line loading capacity.

To summarise on the partial grid-scenario – when the two 1 GW PtX projects are implemented on top of the already-deployed four smaller PtX facilities – it can be concluded that some of the smaller PtX facilities, that, prior to the deployment of the two 1 GW PtX facilities, show neither any curtailment of directly connected onshore wind turbines due to transmission line overloading nor loss of hydrogen production – which they do, when the two 1 GW PtX facilities are deployed to the grid in the *partial grid*-scenario.

Thus, the deployment of the two 1 GW PtX facilities in the *partial grid*-scenario – if the four smaller PtX facilities are also deployed in the *partial grid*-scenario – could undermine the otherwise achievable annual hydrogen production of the four smaller PtX projects as well as increase curtailment of wind power that would otherwise not have been present.

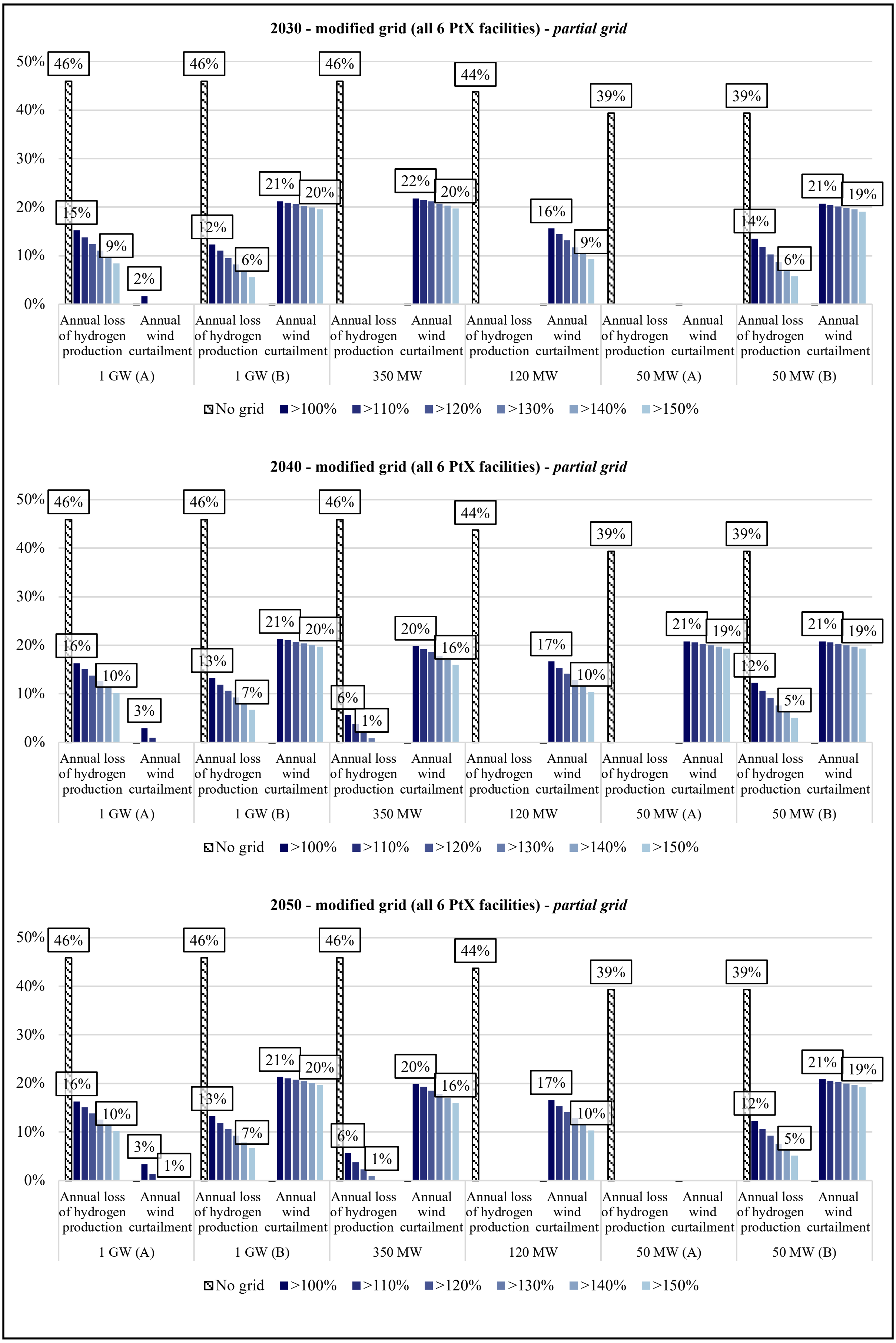

Figure 42: Annual loss of hydrogen production to different thresholds of transmission line overloading in PtX grid connection-scenario partial grid to the modified grid (all six PtX facilities are deployed).

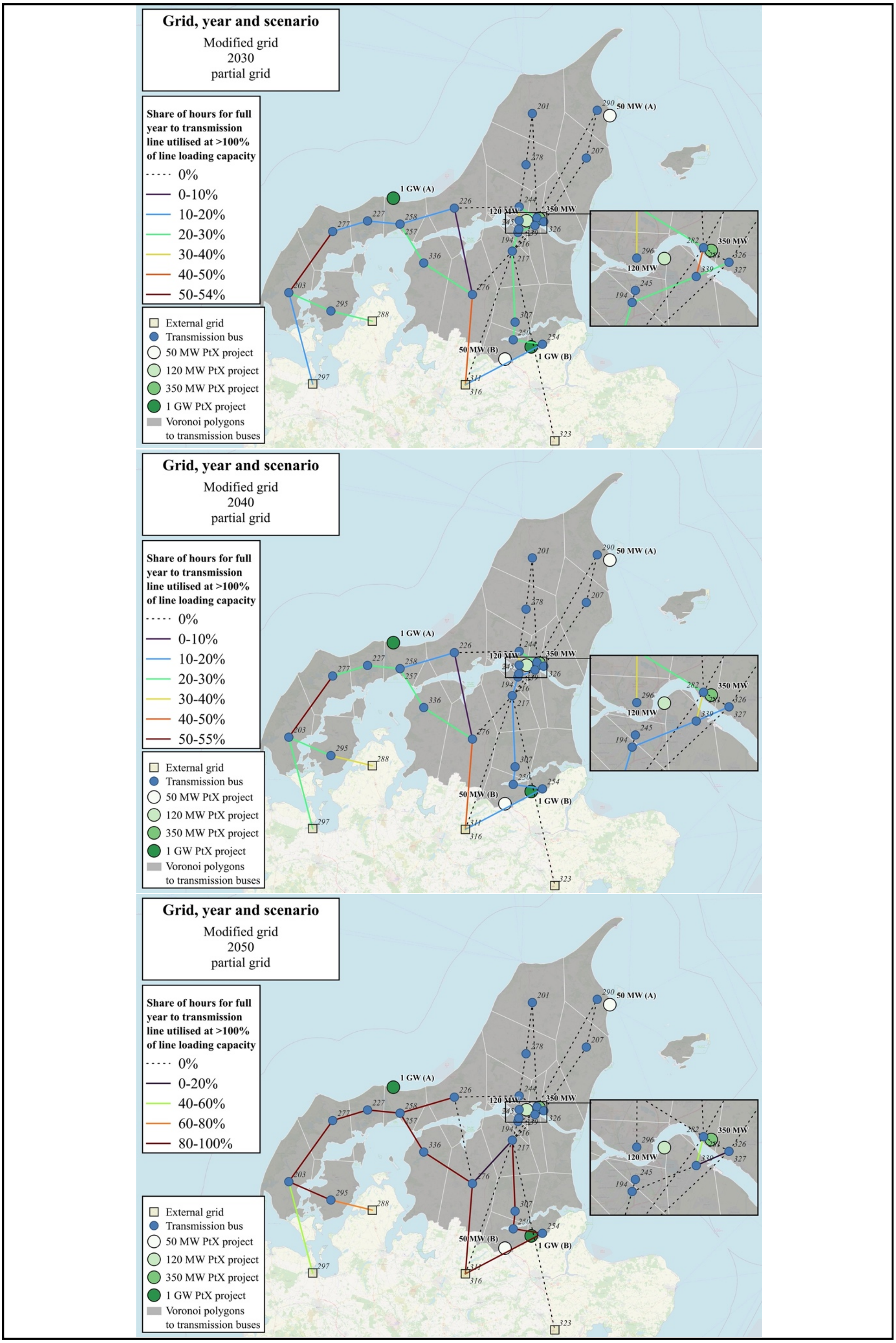

Figure 43: Overloading of transmission lines in PtX grid-connection scenario of partial grid with all 6 PtX facilities included.

The annual export of excess electricity production/import of needed electricity for consumption from/to the electricity transmission grid in the region of Northern Jutland to satisfy the balancing of electricity production and consumption is shown in *Figure 44* and *Figure 45* to respectively the deployment of the four smaller PtX projects and all six PtX projects.

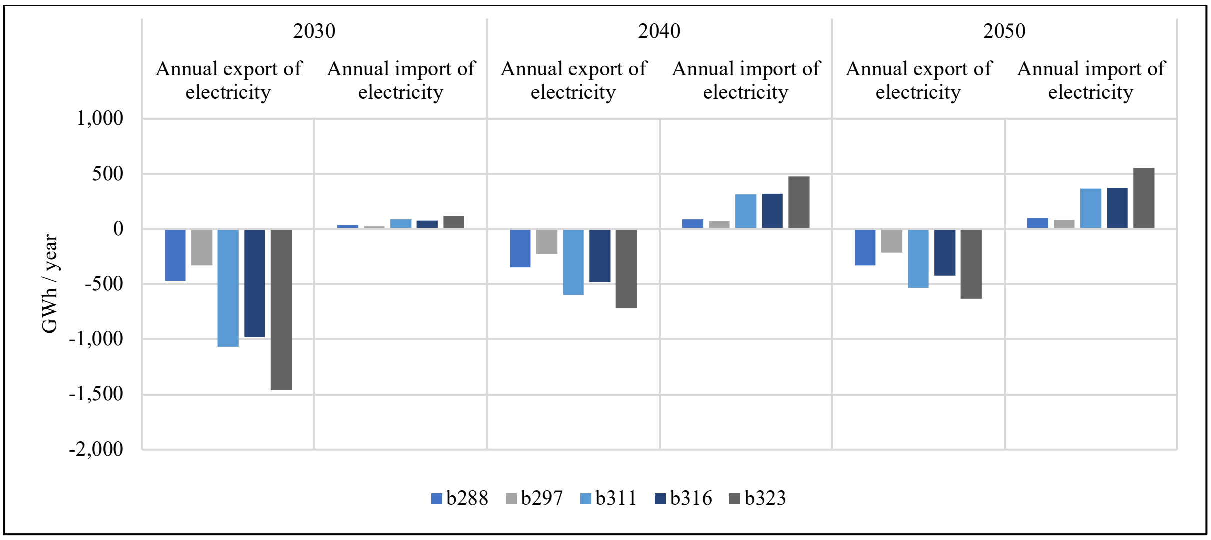

Figure 44: Annual export/import of electricity from/to the region of Northern Jutland in the PtX grid-connection scenario of 'partial grid' (all years) via the external grid buses of the existing electricity transmission system.

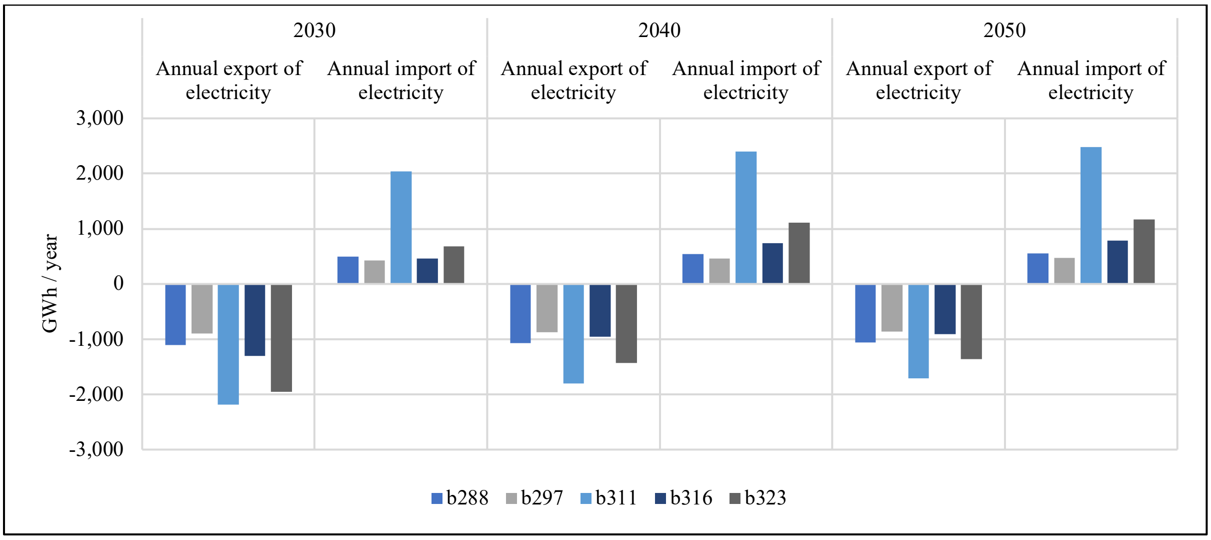

Figure 45: Annual export/import of electricity from/to the region of Northern Jutland in the PtX grid-connection scenario of 'partial grid' (all years) via the external grid buses of the modified electricity transmission system.

4.4 partial grid full wind curtailment

In the above described PtX grid-connection scenario of *partial grid*, the modelling of the PtX projects in pipeline to the region of Northern Jutland and its implications on attainable annual levels of hydrogen production and wind curtailment was seen. The annual need for respectively importing and exporting electricity to/from the region of Northern Jutland to respectively offset excess electricity production and cover all electricity consumption was also shown.

In the final PtX grid-connection scenario of *partial grid full wind curtailment*, the same modelling and approach is utilised as that of the PtX grid-connection scenario of *partial grid*. However, in the *partial grid full wind curtailment* scenario, any excess electricity production from the onshore wind turbines – that are directly connected to the respective PtX facilities in pipeline to the region – is curtailed. This means, that the curtailment of wind will increase to this scenario.

Figure 46 shows the annual loss of hydrogen and the annual wind curtailment in all three years of modelling the energy system (2030, 2040, and 2050) to each of the six PtX facilities in pipeline to the region.

The initial point to be made when comparing the partial grid-scenario and the partial grid full wind curtailment-scenario, is that the loss of annual hydrogen production is practically identical in the two scenarios. This is because the PtX facilities needs electricity to cover the remaining electricity consumption to utilise their full capacities of electrolyses, respectively: That all excess electricity production from the directly connected onshore wind turbines is curtailed, does not change the hours in which the PtX facilities need (additional) electricity to try to fully utilise their respective electrolyser capacities to the full. For the same reason, unexpectedly, the curtailment of wind power increases drastically for some of the PtX projects in pipeline to the region. The PtX projects of 1 GW (A) and 350 MW – in particular – has the curtailment of wind power drastically increased. As goes for the 1 GW (A) PtX project, when utilisation of transmission lines is assumed to be equal to that of the respective transmission line capacities (threshold of >100%), the curtailment of wind increases from 2% to 23% in the short term (by 2030). In the same manner, the curtailment of wind increases from 3% to 23% in both the medium term (by 2040) and the long term (by 2050).

If for any reason the PtX facilities in pipeline to the region of Northern Jutland should be deployed in the partial grid full wind curtailment-scenario, would be to minimise the utilisation of electricity transmission lines above their respective line loading capacities. *Table 7* shows the decrease in number of transmission lines utilised above line loading capacity (>100%) in respectively any hours of the year and in all hours of the year. Additionally, many of the transmission lines that are utilised in any hours of the year above their respective line loading capacities, are sought utilised much higher than that of their line loading capacities. E.g., the transportation of electricity in the electricity transmission line between buses b203 and b277 is >300% of the line loading capacity for 8% of the year i.e., roughly 700 hours of the year. The same holds true to the electricity transmission line between transmission buses b244 and b296 which is utilised in 13% of the hours throughout the year >300% of the line loading capacity i.e., roughly 1,100 hours of the year. As the partial grid full wind curtailment-scenario is utilised to simulate the grid connection of the six PtX projects instead, no single electricity transmission lines are utilised in >250% of line loading capacity. A utilisation of >200% of line loading capacity is still much higher than that of what the current electricity transmission grid can withstand but it underlines an important conclusion to be made in general when comparing the two scenarios: If the electricity consumption of all six PtX facilities in pipeline to the region of Northern Jutland are initially supported by directly connected onshore wind turbines, the majority of problems as goes for over utilisation of electricity transmission lines in the electricity transmission grid of Northern Jutland originate from the excess of electricity production sought offset by the onshore wind turbines in the partial grid- and partial grid full wind curtailment-scenarios - and not the remaining electricity consumption needed of the PtX facilities.

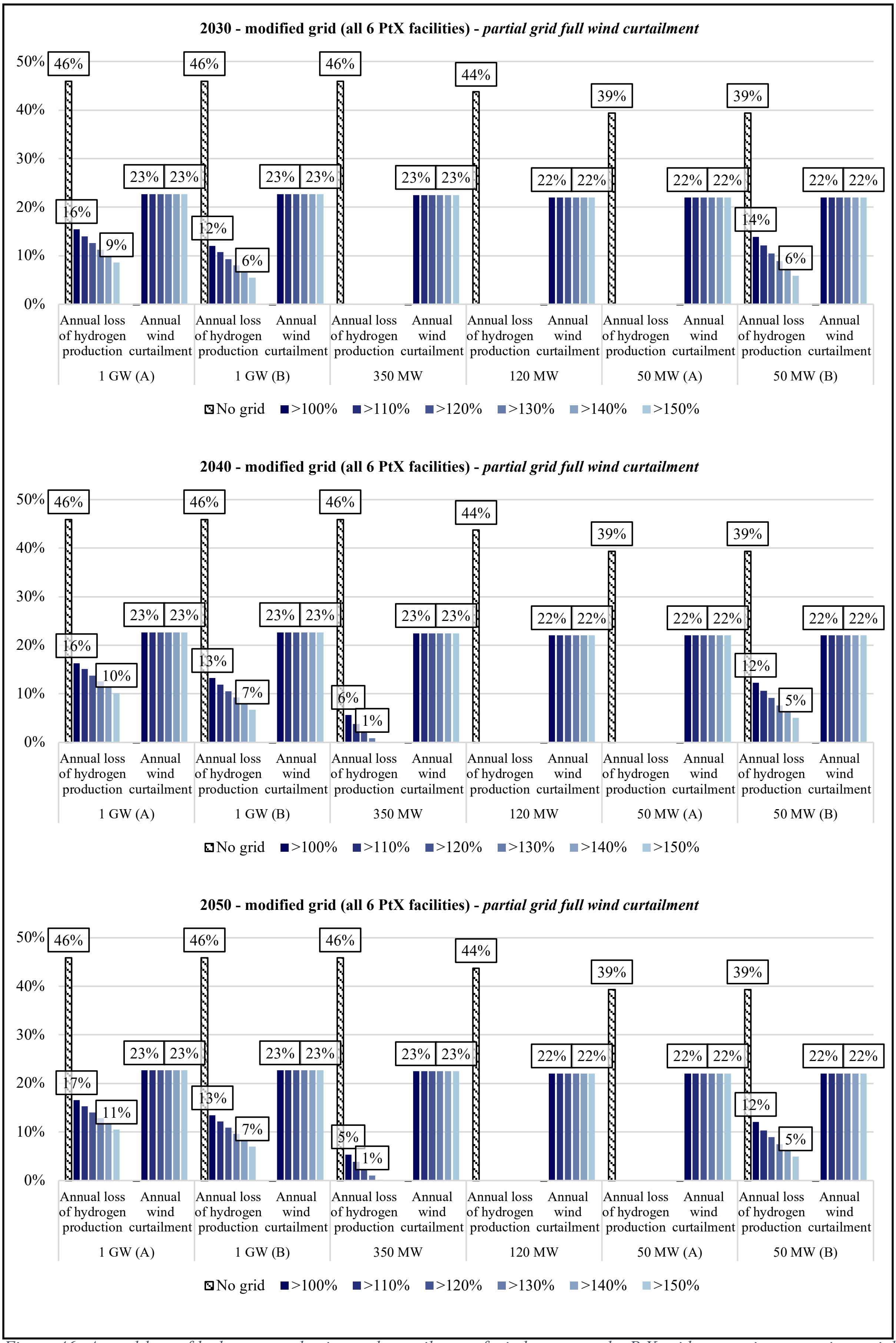

Figure 46: Annual loss of hydrogen production and curtailment of wind power to the PtX grid-connection scenario partial grid full wind curtailment in the modified grid i.e., all 6 PtX facilities are deployed.

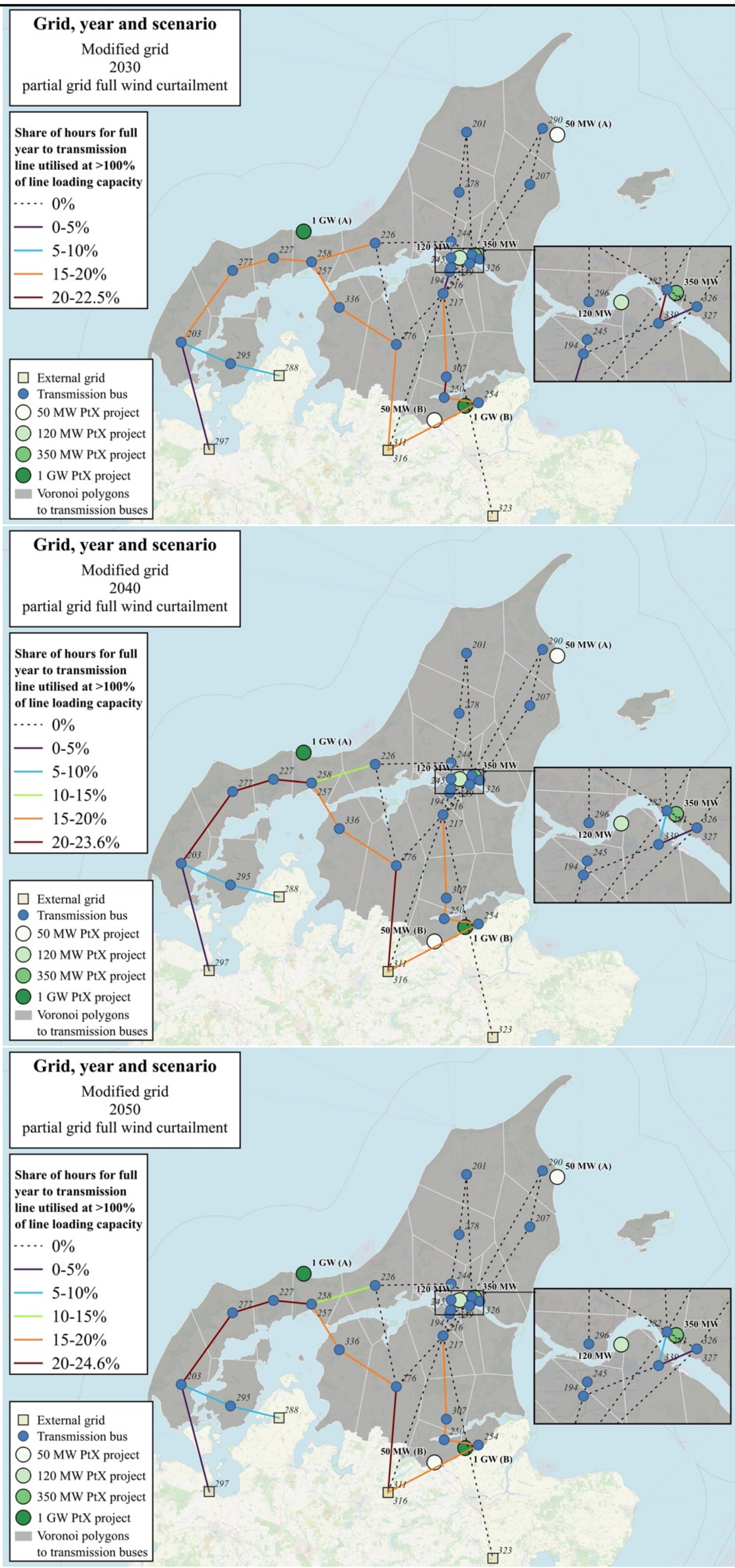

Figure 47: Overloading of transmission lines in PtX grid-connection scenario of partial grid full wind curtailment with all 6 PtX facilities included.

Modified grid: All 6 PtX facilities are included in line loading results	2030		2040		2050	
	partial grid	*partial grid full wind curtailment*	*partial grid*	*partial grid full wind curtailment*	*partial grid*	*partial grid full wind curtailment*
Number of transmission lines utilised above line loading capacity (>100%)	23	17	23	17	17	17
Number of transmission lines utilised in all hours of year above line loading capacity (>100%)	0	0	0	0	12	0

Table 7: Number of transmission lines utilised above line loading capacities in respectively partial grid and partial grid full wind curtailment.

As goes for the import/export of electricity to/from the region of Northern Jutland in the PtX grid-connection scenario of *partial grid full wind curtailment*, *Figure 48* and *Figure 49* show these summarised values on an annual basis to each of the five external grid transmission buses to respectively the existing electricity transmission grid[2] and the modified electricity transmission grid.[3]

[2] In which only the four smaller PtX projects are included.

[3] In which all six PtX projects in pipeline to the region are included.

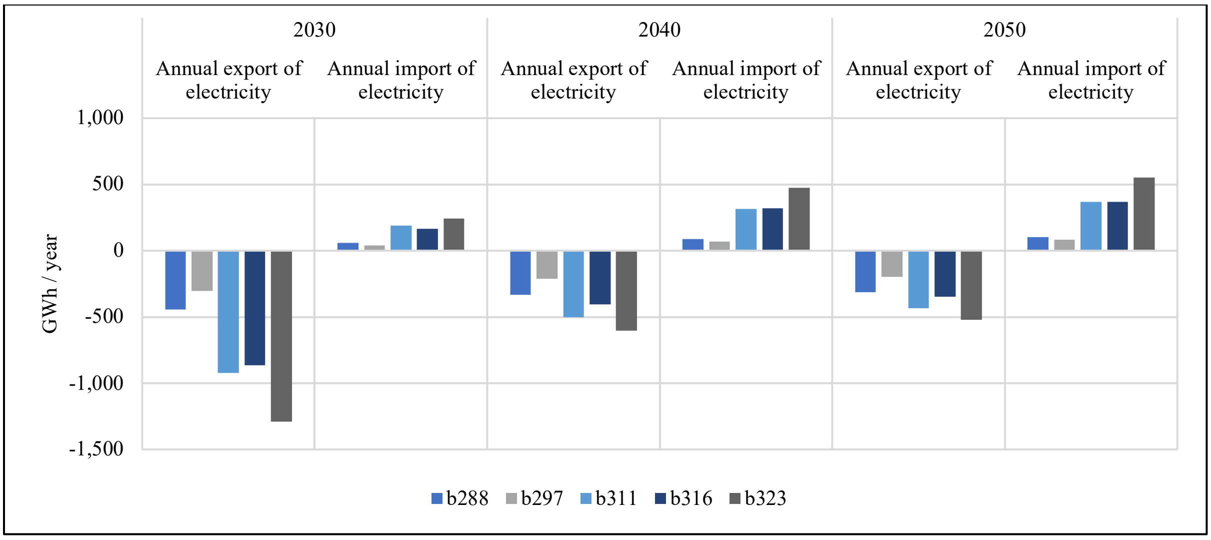

Figure 48: Annual export/import of electricity from/to the region of Northern Jutland in the PtX grid-connection scenario of 'partial grid full wind curtailment' (all years) via the external grid buses of the existing electricity transmission system.

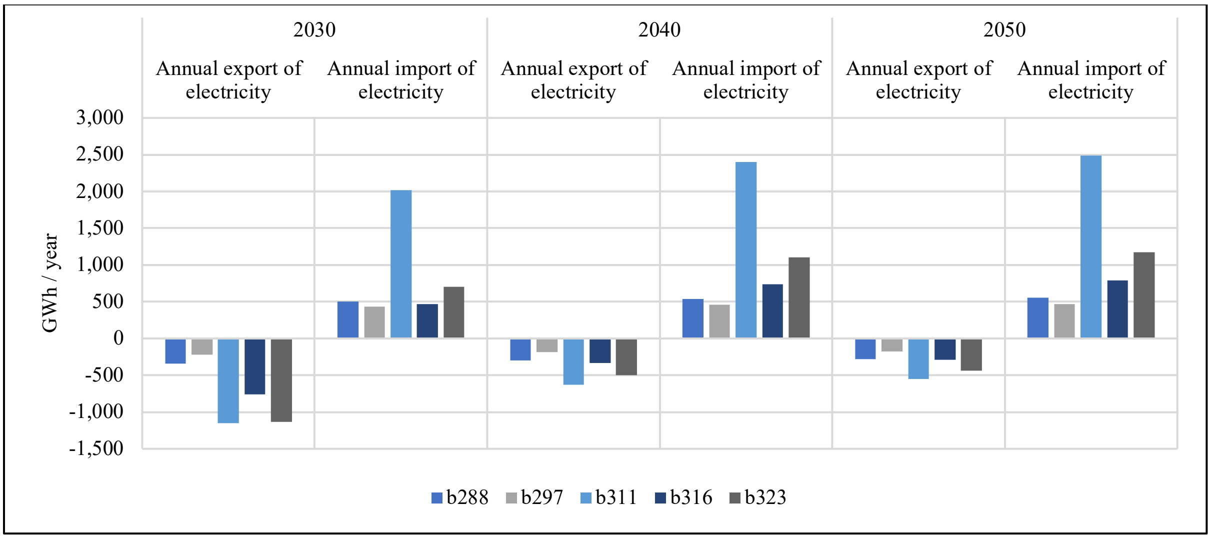

Figure 49: Annual export/import of electricity from/to the region of Northern Jutland in the PtX grid-connection scenario of 'partial grid full wind curtailment' (all years) via the external grid buses of the modified electricity transmission system.

In the PtX grid-connection scenario of *partial grid full wind curtailment*, the deployment of all six PtX projects in pipeline to the region (*Figure 49*) compared to the modelling of only the four smaller PtX projects (*Figure 48*), shows that the additional electricity consumption entails a higher level of export to the region to satisfy the electricity demand from the two 1 GW PtX projects.

By modelling all six PtX projects in pipeline the region of Northern Jutland to the PtX grid-connection scenario of *partial grid full wind curtailment* – compared to the modelling of only the four smaller PtX projects – the export of electricity increases by a total of 3.8 TWh/year by 2030, and by nearly 4 TWh/year in both 2040 and 2050.

4.5 *Across PtX grid-connection scenarios: Annual hydrogen production and number of transmission lines utilised at >100% of line loading capacity*

In the previous subsections of results, the annual loss of hydrogen production was found to each of the four PtX grid-connection scenarios. In this final subsection of results, the annual production of hydrogen, the number of transmission lines utilised above line loading capacities, and the excess electricity production from additional offshore wind turbines offset to the grid are compared amongst the four PtX grid-connection scenarios and years of projecting the energy system (electricity generation- and consumption to each transmission bus not related to PtX facilities nor additional wind power).

Figure 50 shows the summarised, annual hydrogen production when deploying the four smaller PtX facilities in pipeline to the region of Northern Jutland to the three modelled years (2030, 2040, and 2050) across the four PtX grid-connection scenarios.

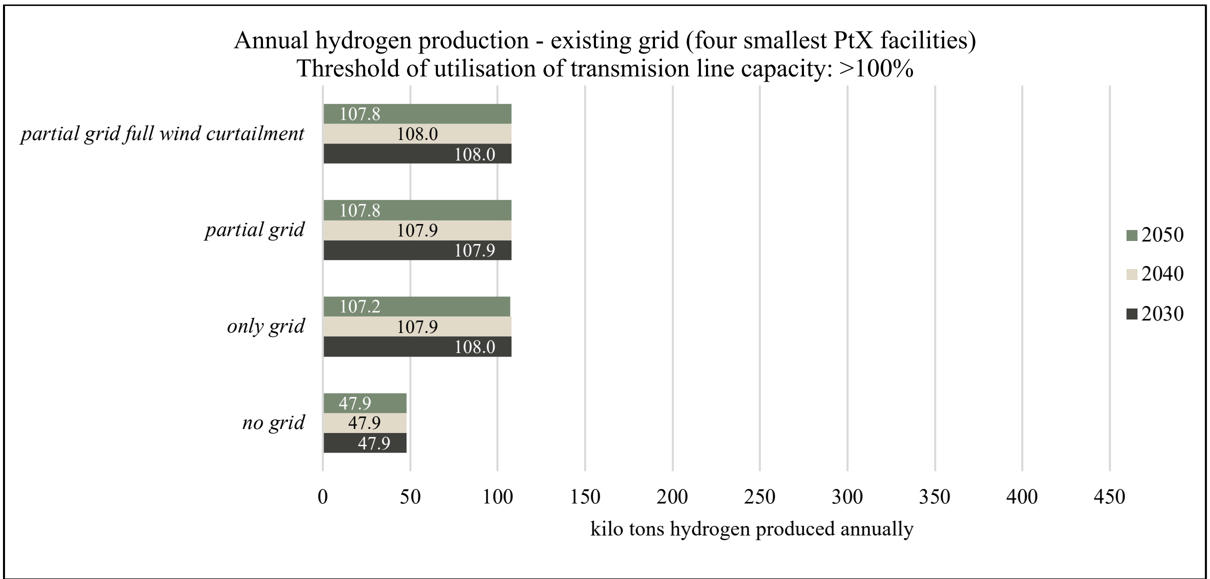

Figure 50: Annual, summarised hydrogen production in kilo tons across the three years of modelling to each of the four PtX grid-connection scenarios when deploying the four smaller PtX facilities (570 MW) in pipeline to the region.

When simulating the deployment of the four smaller PtX projects in pipeline to the region of Northern Jutland (50 MW (A), 50 MW (B), 120 MW, and 350 MW) in the existing electricity transmission grid of the region, the summarised annual hydrogen production is at its lowest in the *no grid* scenario at 47.9 kilo tons. To all three of the remaining scenarios, the annual hydrogen production is nearly identical: In 2030, the four deployed PtX facilities annually produce 108 kilotons H2. By 2040, the summarised annual hydrogen production is nearly identical across the three PtX grid-connection scenarios as it was in 2030. By the year of 2050, the annual hydrogen production decreases in the *only grid* scenario from 107.9 kilo tons to 107.2 kilo tons (*-0.6%*).

When the annual hydrogen production is (nearly) identical in all PtX grid-connection scenarios in which the four smaller PtX facilities in pipeline to the region of Northern Jutland are grid connected, this can be explained through the fact that the additional electricity consumption from deploying the PtX facilities do not entail overloading of transmission lines in the existing electricity transmission system. In fact, the deployment of the four smaller PtX projects help decrease overloading of electricity transmission lines in the *only grid* scenario in which the electricity to supply the grid connected PtX facilities are at its highest (compared to the PtX grid-connection scenarios of *partial grid* and *partial rid full wind curtailment*). *Table 8* shows that the number of transmission lines in the electricity transmission grid by 2030 drops from 2 to 0 by 2030. As has been mentioned earlier, the overloading of transmission lines in the electricity transmission grid without any PtX facilities being grid connected is by 2030 due to the high level of electricity generation from the centralised combined heat- and power plant. As the annual electricity production of the centralised combined heat- and power plant is set to significantly decrease towards 2040 and 2050 (see *Figure 17*), the overloading of transmission lines in the *no grid* scenario also decreases. In summary, the deployment of the four smaller PtX projects show no significant problems as goes for the overloading of electricity transmission lines in the electricity transmission lines of Northern Jutland

In the PtX grid-connection scenario of *partial grid*, the number of transmission lines being overloaded – i.e., the line is utilised at >100% of its capacity – increase compared to that of the *only grid* scenario. This increase occurs as the excess electricity production from the directly PtX-connected onshore wind turbines is offset to the electricity transmission grid.

Existing grid: The four smaller PtX projects in pipeline are deployed	2030		2040		2050	
	Number of transmission lines utilised in *any* hours above line loading capacity (>100%)	Number of transmission lines utilised in *all* hours above line loading capacity (>100%)	Number of transmission lines utilised in *any* hours above line loading capacity (>100%)	Number of transmission lines utilised in *all* hours above line loading capacity (>100%)	Number of transmission lines utilised in *any* hours above line loading capacity (>100%)	Number of transmission lines utilised in *all* hours above line loading capacity (>100%)
no grid	2	0	0	0	0	0
only grid	0	0	1	0	2	0
partial grid	3	0	1	0	1	0
partial grid full wind curtailment	2	0	0	0	1	0

Table 8: Number of transmission lines utilised above line loading capacity (>100%), respectively in some hours of the year and in all hours of the year.

When simulating the deployment of all six PtX projects in the region utilising the modified electricity transmission grid (see *Figure 24*), the production of annual hydrogen increases compared to the deployment of only the four smaller PtX projects.

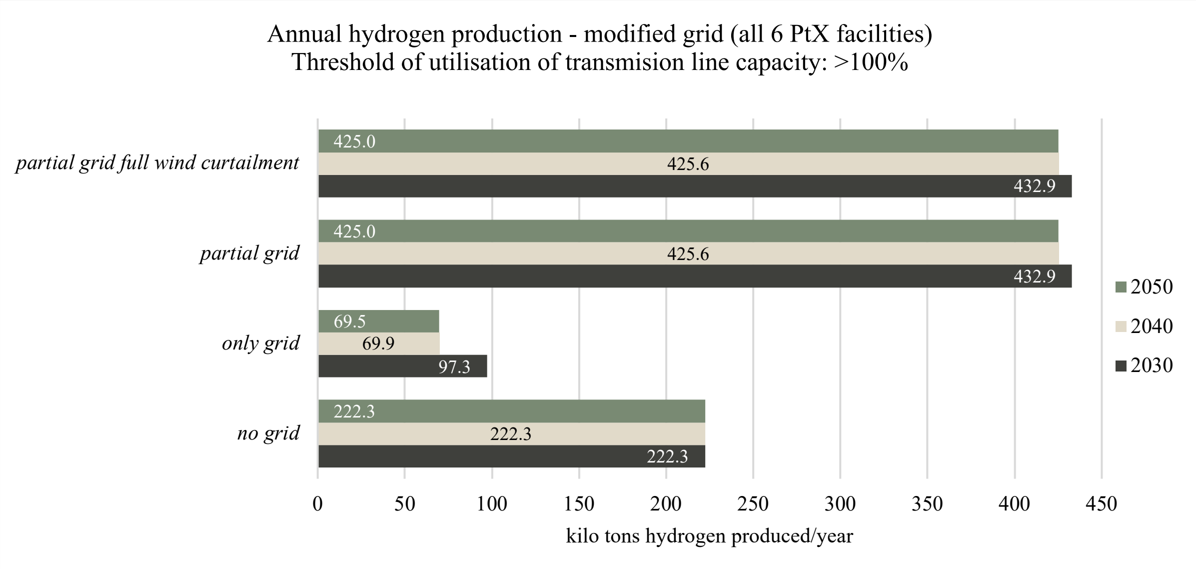

Figure 51: Annual, summarised hydrogen production in kilo tons across the three years of modelling to each of the four PtX grid-connection scenarios when deploying all six PtX facilities (2,570 MW) in pipeline to the region.

In the *no grid* scenario, the annual hydrogen production increases from 47.9 kilo tons hydrogen annually to 222.3 kilo tons (*+364%*), as the summarised PtX capacity increases from 570 MW to 2,570 MW (*+351%*).

In the *only grid*-scenario, the annual hydrogen production from all six PtX facilities decreases to 69.5-97.3 kilo tons hydrogen annually compared to that of deploying the four smaller PtX facilities in the *only grid*-scenario at 107.2-108 kilo tons H2, which is a relative decrease of 9-36% (depending on the year of projection of the energy system). This is due to the high level of electricity consumption required by deploying all six PtX facilities which induces overloading of transmission lines that also affect the four smaller PtX projects. Thus, in the *only grid*-scenario, the summarised, annual hydrogen production in the region of Northern Jutland is higher when only deploying the four smaller PtX projects in pipeline to the region. A proxy of the increase in overloading of transmission lines can be seen when comparing *Table 8* to *Table 9*: The number of transmission lines being utilised above their respective line loading capacities increase compared to that of deploying only the four smaller PtX projects in pipeline to the region. Additionally, no electricity transmission lines are utilised in *all* hours of the year above their respective line loading capacities (>100%) when deploying only the four smaller PtX projects in pipeline to the region. However, this number increases from 0 to 11 or 12 (depending on the year of projection of the underlying energy system).

When simulating the PtX grid-connection scenario of *partial grid* deploying all six PtX projects compared to that of the four smaller PtX projects, the annual hydrogen production increases from 107.8-107.9 kilotons to 425-432.9 kilotons, which is a relative increase of 294-302% (depending on the year of projection of the energy system). However, as was also the case in the *only grid*-scenario, the number of electricity transmission lines in the region utilised above their respective line loading capacities increase when deploying all six PtX facilities. In the short term (by 2030) and in the medium term (by 2040), no electricity transmission lines are utilised above line loading capacity in *all* hours of the year. Nonetheless, in the long term (by 2050), several transmission lines are utilised above their respective line loading capacities in *all* hours of the year, when deploying the two 1 GW PtX projects in the *partial grid*-scenario.

In the final PtX grid-connection scenario of *partial grid full wind curtailment*, the increase in annual hydrogen production is identical to that of *partial grid*.

Modified grid: All six PtX projects are deployed	2030		2040		2050	
	Number of transmission lines utilised in *any* hours above line loading capacity (>100%)	Number of transmission lines utilised in *all* hours above line loading capacity (>100%)	Number of transmission lines utilised in *any* hours above line loading capacity (>100%)	Number of transmission lines utilised in *all* hours above line loading capacity (>100%)	Number of transmission lines utilised in *any* hours above line loading capacity (>100%)	Number of transmission lines utilised in *all* hours above line loading capacity (>100%)
only grid	21	11	17	12	17	12
partial grid	23	0	23	0	17	12
partial grid full wind curtailment	17	0	17	0	17	0

Table 9: Number of transmission lines utilised above line loading capacity (>100%) in the , respectively in some hours of the year and in all hours of the year.

5 Conclusion

This study set out to determine the annual loss of hydrogen production from PtX facilities of varying capacities in the region of Northern Jutland. According to Hydrogen Denmark, six PtX facilities are in pipeline to the region of Northern Jutland: Two facilities of each 50 MW, one PtX facility of 120 MW, one PtX facility of 350 MW, and two PtX facilities of each 1 GW. All capacities refer to the electrolyser capacity. Assuming the geographically nearest transmission bus (165- or 400 kilo volt transformer) in the electricity transmission grid of Northern Jutland to be to the points of connection to each respective PtX facility, four different scenarios of PtX grid-connection were investigated. The hourly flow of power in the electricity transmission grid to each of these four PtX grid-connection scenarios were modelled in the power flow tool of *PandaPower*, utilising the existing model and code as seen in [21]. The hourly electricity generation- and consumption, that is also an inherent part of the electricity transmission grid and thus potential contribution towards overloading of transmission lines, is projected to the years of 2030, 2040, and 2050 respectively, to reflect changes in the energy system that may also potentially contribute to the overloading of electricity transmission lines.

When all six PtX facilities in pipeline to the region of Northern Jutland i.e., 2,570 MW is deployed without any electricity transmission grid connection – the PtX grid-connection scenario of *no grid* – it would require a summarised onshore wind turbine capacity of 2.57 GW directly connected to the PtX facilities. This would enable an annual hydrogen production of 222.3 kilo tons of hydrogen annually. The theoretically highest level of these 2,570 MW of PtX facilities is in this study determined at 487.8 kilo tons of hydrogen annually i.e., if all PtX facilities utilise the full extent of their respective capacities in all hours of the year. Thus, by supplying the PtX facilities in pipeline to the region of Northern Jutland only from directly connected onshore wind turbines – whose electricity production never exceeds the capacity of the respective PtX facilities when applying a distribution of capacity factors from [38] – the annual hydrogen output is ca. 45% of the theoretically highest level. In other words: the summarised 2,570 MW of electrolysers to the six PtX facilities in the region would operate with just shy of 4,000 full-load hours.

By allowing the four smaller PtX facilities with a summarised electrolyser capacity of 570 MW to only be supplied with electricity from the transmission grid, seeking to utilise full capacity in all hours of the year, the annual hydrogen production of the initial 570 MW is increased by 124-125% from 47.9 kilo tons to 107.2-108 kilo tons (depending on the year of projection of the underlying energy system). Thus, in this PtX grid-connection scenario, the four smaller PtX projects in pipeline to the region of Northern Jutland can fully utilise their respective capacities and produce the theoretically highest level of hydrogen annually. Additionally, the electricity transmission lines in the existing electricity transmission grid of Northern Jutland undergoes hardly any overloading of line loading capacities.

However, if the two 1 GW PtX facilities also in pipeline to the region are also deployed, and they are only able to draw power from the grid to supply their electrolysers for hydrogen production as well, several electricity transmission lines in the grid of Northern Jutland would be used above line loading capacity in all hours of the year, and even more would be used in some hours of the year – transmission lines that prior to the deployment of the two bigger PtX facilities were not utilised above line loading capacity in any hours of the year. The power needed to supply the two 1 GW PtX facilities would increase the utilisation of transmission lines in the region to a degree that it would partially undermine the hydrogen production of the other, smaller PtX facilities. In fact, the annual hydrogen production of the region would decrease by 9-36% from 107.2-108 kilo tons hydrogen annually to 69.5-97.3 kilo tons, depending on the year of the underlying energy system's projection. Additionally, the electricity transmission grid as whole would be utilised much higher than many electricity transmission lines' capacities. Thus, in a PtX grid-connection scenario in which the PtX facilities in pipeline to the region of Northern Jutland can only be supplied with power from the electricity transmission grid, it would not be viable to install all six PtX projects in the pipeline. Many electricity transmission lines in the system would be utilised above their line loading capacities, and several of those same transmission lines would be utilised above their respective line loading capacities in *all* hours of the year.

Considering a PtX grid-connection scenario of directly connecting onshore wind turbines that can initially supply the PtX projects with electricity, and assuming all excess electricity production of those same onshore wind turbines to be offset to the electricity transmission grid via the same transmission buses as the respective PtX buses are connected – the *partial grid*-scenario – the dynamics change: By applying this PtX grid-connection scenario to only the four smaller PtX projects in pipeline to the region of Northern Jutland, the full extent of the theoretically highest level of annual hydrogen production is still achieved. However, to this scenario, there is also effectively an offset of 188.6 GWh of excess electricity production from the onshore wind turbines to the electricity transmission grid. By applying this scenario to all six PtX facilities in the pipeline of the region, several electricity transmission lines in the grid would be utilised above their respective line loading capacities, but no electricity transmission lines would be utilised above their line loading capacities in *all* hours of the year.

At the same time, the deployment of all six PtX facilities in pipeline to the region in the *partial grid*-scenario incurs an overloading of transmission lines that enforce some of the four smaller PtX projects to decrease the annual hydrogen production. This results from the fact that some of smaller PtX facilities are supplied with power from the same electricity transmission lines as the 1 GW PtX facilities, thus undermining the hydrogen production of some of the other PtX projects in some hours of the year.

The final PtX grid-connection scenario that was considered for this study was the *partial grid full wind curtailment*. This scenario shows the same mechanics and dynamics as in *partial grid* but any excess/surplus electricity production from the directly connected onshore wind turbines is curtailed. This was done as to investigate the lessened strain on the electricity transmission lines of the grid in the region.

By applying this PtX grid-connection scenario to the four smaller PtX projects, the same level of annual hydrogen production is achieved as in both the *only grid*-scenario and the *partial grid*-scenario. The impact of lessened strain on electricity transmission lines by applying this PtX grid-connection scenario to the four smaller PtX projects is near negligible. The only achieved outcome to the *partial grid full wind curtailment*-scenario applied to the deployment of the four smaller PtX projects in pipeline is that the otherwise 188.6 GWh of excess electricity production is curtailed.

However, when applying this PtX grid-connection scenario to all six PtX projects in pipeline to the region, the potential hydrogen production to be achieved from the deployment of all 2,570 MW in the region is nearly the same as in the *partial grid*-scenario but with fewer electricity transmission lines being utilised above their line loading capacities. In both the short term (2030) and medium term (2040), the number of electricity transmission lines utilised in any hours of the year above their respective line loading capacities is reduced from 23 to 17, indicating the overloading of transmission lines to decrease. Additionally, in the long term (2050), no electricity transmission lines are utilised in *all* hours of the year, which is otherwise the case in the *partial grid*-scenario to 12 electricity transmission lines. Thus, if the deployment of all six PtX projects in pipeline to the region of Northern Jutland is to achieve a higher level of hydrogen production annually than that of the *no grid*-scenario, a lesser reinforcement/expansion of the electricity transmission grid in the region of Northern Jutland would be required, compared to that of the *partial grid*-scenario. Though this comes at a cost of curtailing ca. 2 TWh of excess electricity production from onshore wind turbines in the region. However, to effectively offset these ca. 2 TWh of excess electricity production from the directly connected onshore wind turbines to the PtX facilities would still require a substantial expansion or reinforcement of the electricity transmission grid.

In short, it is infeasible to apply any PtX grid-connection scenario in which the 1 GW PtX facilities in pipeline to the region of Northern Jutland are in fact connected to the electricity transmission grid.

As to conclude on the deployment of PtX facilities in the region of Northern Jutland: The existing electricity transmission can withstand the increased electricity consumption that is from deploying the four smaller PtX projects in pipeline to the region, a total of 570 MW electrolyser capacity. This is regardless of the PtX grid-connection scenario, and therefore the scenario of *partial grid* is preferable over the other investigated scenarios. However, if the two 1 GW PtX projects in pipeline to the region are to be deployed as well, the existing electricity transmission grid can't withstand the additional electricity consumption from the two 1 GW PtX projects. This would lead to several electricity transmission lines being utilised above their line loading capacities: many in all hours of the year. Additionally, the hydrogen production from one of the two 50 MW PtX facilities in pipeline to the region would effectively be undermined, as one of the two 1 GW PtX projects are assumed to utilise some of the same electricity transmission lines. If all PtX projects in pipeline to the region of Northern Jutland were in fact to be deployed, it is determined that the best mix of options – as to not induce overloading of electricity transmission lines higher than their respective line loading capacities – would be to install the four smaller PtX facilities in the pipeline by the *partial grid*-scenario, and to install both 1 GW PtX projects without any connection to the electricity transmission grid but instead to be supplied only with directly connected onshore wind turbines.

On a more general notice, it can be concluded from this case study of simulating different PtX grid-connection scenarios to PtX facilities of varying capacities, that the deployment of future PtX facilities being connected to electricity transmission grids must consider potential curtailment of hydrogen production from potential overloading of electricity transmission lines. Additionally, no PtX facility being grid connected nor the transmission lines leading to/away from the point of connection is an island – changes elsewhere in the system may affect the balance of the electricity transmission grid in a greater area, thus leading to e.g., possible curtailment of hydrogen production and/or curtailment of onshore wind turbines that could otherwise offset excess wind power to the grid. Considerations to the future balance in the electricity transmission system – in which a potential, future PtX facility is embedded – alongside other projects at regional scale must be considered as this may determine if one or another operational strategy of power supply will show the greatest annual yield of hydrogen production.

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7 Appendices

7.1 Number of electric vehicles and plug-in hybrid vehicles to each of the 11 municipalities in the region of Northern Jutland in 2024, 2030, 2040, and 2050

	2024					2030			2040			2050		
	Number of …		Annual electricity consumption (MWh) of …			Annual electricity consumption (MWh) of …			Annual electricity consumption (MWh) of …			Annual electricity consumption (MWh) of …		
Municipality	Electric vehicles	Plug-in hybrid vehicles	Electric vehicles	Plug-in hybrid vehicles	*sum*	Electric vehicles	Plug-in hybrid vehicles	*sum*	Electric vehicles	Plug-in hybrid vehicles	*sum*	Electric vehicles	Plug-in hybrid vehicles	*sum*
Brønderslev	1,203	720	4,077	733	4,810	14,843	2,669	17,512	67,056	12,057	79,113	90,573	16,285	106,858
Frederikshavn	1,780	1,441	6,032	1,467	7,500	21,962	5,341	27,304	99,219	24,131	123,350	134,014	32,593	166,608
Hjørring	2,077	1,352	7,039	1,377	8,415	25,627	5,011	30,638	115,774	22,640	138,414	156,375	30,580	186,955
Jammerbugt	1,322	718	4,480	731	5,211	16,311	2,661	18,973	73,690	12,024	85,713	99,532	16,240	115,772
Læsø	55	39	186	40	226	679	145	823	3,066	653	3,719	4,141	882	5,023
Mariagerfjord	1,660	851	5,626	866	6,492	20,482	3,154	23,636	92,530	14,251	106,781	124,980	19,248	144,228
Morsø	462	434	1,566	442	2,008	5,700	1,609	7,309	25,752	7,268	33,020	34,784	9,816	44,600
Rebild	1,416	714	4,799	727	5,526	17,471	2,647	20,118	78,929	11,957	90,886	106,609	16,150	122,759
Thisted	1,205	852	4,084	867	4,951	14,868	3,158	18,026	67,168	14,267	81,435	90,723	19,271	109,994
Vesthimmerland	1,030	707	3,491	720	4,210	12,708	2,621	15,329	57,413	11,839	69,252	77,548	15,991	93,539
Aalborg	7,664	4,477	25,973	4,558	30,531	94,561	16,595	111,156	427,199	74,971	502,170	577,015	101,263	678,278

7.2 *Annual heat consumption of buildings based on year of construction/renovation and primary application*

The very left-hand side of the table shows the application code the buildings as registered in the Danish Building Registry (BBR). See *7.3 below* for explanation of each application code of buildings.

All values in the table below shows the annual heat demand per square meter of indoor floor area per year $\left(\frac{\frac{kWh\ heat\ consumption}{m^2\ indoor\ floor\ area}}{year}\right)$.

	Before 1850	1850-1930	1931-1950	1951-1960	1961-1972	1973-1978	1979-1998	1999-2006	≥2007
110	137	156	173	179	138	126	115	106	82
120	152	185	197	163	123	110	97	82	65
121	152	185	197	163	123	110	97	82	65
122	152	185	197	163	123	110	97	82	65
130	170	180	192	172	130	112	80	69	67
131	170	180	192	172	130	112	80	69	67
132	170	180	192	172	130	112	80	69	67
140	143	139	144	148	117	116	84	76	68
150	182	177	164	141	128	180	122	111	86
160	249	206	171	186	153	143	125	112	82
185	142	172	196	155	151	131	106	74	83
190	142	172	196	155	151	131	106	74	83
210	215	244	235	190	198	192	157	166	148
211	0	0	0	0	0	0	0	0	0
212	0	0	0	0	0	0	0	0	0
213	0	0	0	0	0	0	0	0	0
214	0	0	0	0	0	0	0	0	0
215	0	0	0	0	0	0	0	0	0
216	0	0	0	0	0	0	0	0	0
217	0	0	0	0	0	0	0	0	0
218	0	0	0	0	0	0	0	0	0
219	215	244	235	190	198	192	157	166	148
220	183	171	163	151	142	141	107	103	94
221	183	171	163	151	142	141	107	103	94
222	183	171	163	151	142	141	107	103	94
223	183	171	163	151	142	141	107	103	94
229	183	171	163	151	142	141	107	103	94
230	195	195	104	104	171	184	145	227	164
231	195	195	104	104	171	184	145	227	164
232	195	195	104	104	171	184	145	227	164
233	195	195	104	104	171	184	145	227	164
234	195	195	104	104	171	184	145	227	164
239	195	195	104	104	171	184	145	227	164
290	211	185	184	161	138	183	105	132	72
310	200	178	211	204	176	121	112	119	101
311	200	178	211	204	176	121	112	119	101
312	200	178	211	204	176	121	112	119	101
313	200	178	211	204	176	121	112	119	101

314	200	178	211	204	176	121	112	119	101
315	200	178	211	204	176	121	112	119	101
319	200	178	211	204	176	121	112	119	101
320	124	125	153	144	125	114	95	75	55
321	124	125	153	144	125	114	95	75	55
322	124	125	153	144	125	114	95	75	55
323	124	125	153	144	125	114	95	75	55
324	124	125	153	144	125	114	95	75	55
325	124	125	153	144	125	114	95	75	55
329	124	125	153	144	125	114	95	75	55
330	215	175	170	152	182	149	135	146	117
331	215	175	170	152	182	149	135	146	117
332	215	175	170	152	182	149	135	146	117
333	215	175	170	152	182	149	135	146	117
334	215	175	170	152	182	149	135	146	117
339	215	175	170	152	182	149	135	146	117
390	102	121	140	162	113	197	128	99	134
410	182	162	163	156	150	138	121	116	123
411	182	162	163	156	150	138	121	116	123
412	182	162	163	156	150	138	121	116	123
413	182	162	163	156	150	138	121	116	123
414	182	162	163	156	150	138	121	116	123
415	182	162	163	156	150	138	121	116	123
416	182	162	163	156	150	138	121	116	123
419	182	162	163	156	150	138	121	116	123
420	253	231	233	244	173	163	130	114	102
421	253	231	233	244	173	163	130	114	102
422	253	231	233	244	173	163	130	114	102
429	253	231	233	244	173	163	130	114	102
430	363	237	220	249	161	152	133	148	130
431	363	237	220	249	161	152	133	148	130
432	363	237	220	249	161	152	133	148	130
433	363	237	220	249	161	152	133	148	130
439	363	237	220	249	161	152	133	148	130
440	256	243	233	216	168	157	125	116	96
441	256	243	233	216	168	157	125	116	96
442	256	243	233	216	168	157	125	116	96
443	256	243	233	216	168	157	125	116	96
444	256	243	233	216	168	157	125	116	96
449	256	243	233	216	168	157	125	116	96
490	167	177	201	158	187	155	113	136	78
510	94	107	106	98	101	100	71	73	69
520	167	200	211	164	153	135	131	106	174
521	167	200	211	164	153	135	131	106	174
522	167	200	211	164	153	135	131	106	174
523	167	200	211	164	153	135	131	106	174
529	167	200	211	164	153	135	131	106	174
530	163	141	127	142	133	131	115	130	124

531	163	141	127	142	133	131	115	130	124
532	163	141	127	142	133	131	115	130	124
533	163	141	127	142	133	131	115	130	124
534	163	141	127	142	133	131	115	130	124
535	163	141	127	142	133	131	115	130	124
539	163	141	127	142	133	131	115	130	124
540	0	0	0	0	0	0	0	0	0
585	0	0	0	0	0	0	0	0	0
590	116	107	99	104	97	108	69	68	58
910	0	0	0	0	0	0	0	0	0
920	0	0	0	0	0	0	0	0	0
930	0	0	0	0	0	0	0	0	0
940	0	0	0	0	0	0	0	0	0
950	0	0	0	0	0	0	0	0	0
960	0	0	0	0	0	0	0	0	0
970	0	0	0	0	0	0	0	0	0
990	0	0	0	0	0	0	0	0	0
999	0	0	0	0	0	0	0	0	0

7.3 Explanation of application codes of buildings as seen in the Danish Building Registry

110 - Farmhouse for agricultural property

120 - Detached single-family house

121 - Semi-detached single-family house

122 - Detached single-family house in dense low-rise buildings

130 - (PHASE OUT) Terraced, semi-detached or semi-detached house (vertical separation between the units).

131 - Row, chain and cluster house

132 - Semi-detached house

140 - Apartment building, multi-family house or two-family house

150 - College

160 - Residential building for a residential institution

185 - Annex in connection with year-round housing.

190 - Second building for year-round residence

210 - (OUT-PHASE) Building for commercial production relating to agriculture, horticulture, raw material extraction, etc.

211 - Barn for pigs

212 - Barn for cattle, sheep etc.

213 - Barn for poultry

214 - Minkhal

215 - Greenhouse

216 - Barn for feed, crops, etc.

217 - Machine house, garage, etc.

218 - Barn for straw, hay, etc.

219 - Other building for agriculture etc.

220 - (OUT-OF-PHASE) Building for commercial production relating to industry, crafts, etc. (factory, workshop, etc.)

221 - Building for industry with integrated production equipment

222 - Building for industry without integrated production equipment
223 - Workshop
229 - Second building for production
230 - (PHASE OUT) Electricity, gas, water or heating plant, incineration plant, etc.
231 - Building for energy production
232 - Building for energy distribution
233 - Building for water supply
234 - Building for handling waste and waste water
239 - Other building for energy production and supply
290 - (PHASE OUT) Other building for agriculture, industry etc.
310 - (UPDATED) Transport and garage facilities (freighter's hall, airport building, railway station building, car park). Garage with space for one or two vehicles is registered with use code 910
311 - Building for railway and bus operations
312 - Building for aviation
313 - Building for parking and transport facilities
314 - Building for parking more than two vehicles in connection with housing
315 - Port facilities
319 - Other transport facility
320 - (OUT-OF-PHASE) Building for office, trade, warehouse, including public administration
321 - Office building
322 - Building for retail trade
323 - Building for storage
324 - Shopping centre
325 - Gas station
329 - Second building for office, trade and storage
330 - (OUT-OF-PHASE) Building for hotel, restaurant, laundry, hairdresser and other service business
331 - Hotel, inn or conference center with accommodation
332 - Bed & breakfast etc.
333 - Restaurant, café and conference center without accommodation
334 - Private service business such as hairdresser, laundromat, internet cafe, etc.
339 - Second building for service businesses
390 - (PHASE OUT) Other building for transport, trade etc
410 - (OUT-OF-PHASE) Building for cinema, theatre, commercial exhibition, library, museum, church etc.
411 - Cinema, theatre, concert venue, etc.
412 - Museum
413 - Library
414 - Church or other building for religious practice for state-recognised religious communities
415 - Assembly hall
416 - Amusement park
419 - Other building for cultural purposes
420 - (OUT-PHASE) Building for teaching and research (school, gymnasium, research laboratory etc.).
421 - Elementary school
422 - University
429 - Second building for teaching and research
430 - (PHASE OUT) Building for hospital, nursing home, maternity clinic etc.
431 - Hospital and hospital

432 - Hospice, treatment home, etc.
433 - Health center, doctor's office, maternity clinic, etc.
439 - Other building for health purposes
440 - (PHASING OUT) Building for daycare
441 - Daycare
442 - Service function at an inpatient institution
443 - The barracks
444 - Prison, detention center, etc.
449 - Other building for institutional purposes
451 - Shelter
490 - (PHASE OUT) Building for another institution, including barracks, prison etc.
510 - Summer house
520 - (PHASING OUT) Building for holiday colony, hostel etc. except for summer house
521 - Holiday centre, center for campsites etc.
522 - Building with holiday apartments for commercial letting
523 - Building with holiday apartments for own use
529 - Other building for holiday purposes
530 - (PHASE OUT) Building in connection with sports (club house, sports hall, swimming pool, etc.)
531 - Club house in connection with leisure and sports
532 - Swimming pool
533 - Sports hall
534 - Tribune in connection with the stadium
535 - Building for training and housing horses
539 - Other building for sports purposes
540 - Colony garden house
585 - Annex in connection with leisure and summer house
590 - Other building for leisure purposes
910 - Garage
920 - Carport
930 - Outbuilding
940 - Greenhouse
950 - Detached roof covering
960 - Detached conservatory
970 - Remaining agricultural building
990 - Dilapidated building
999 - Unknown building