Modeling cross-border Energy Communities on Distribution Grid Level

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***Abstract*—This paper investigates the technical and economic benefits of a local cross-border energy community at the German-Dutch border. A cross-border connection of two regions on a medium voltage level is modeled. The underlying model is formulated as a Mixed Integer Problem (MIP). It comprises the electricity loads of two cities, their respective renewable electricity generation plants, a battery storage and an electrolyzer. Our research concludes that the most promising approach to connect the cities is by a switchable "cross-border element". The is a virtual power plant that includes a German and a Dutch wind farm located on both sides of the border. Via a switch the single wind turbines can either be connected to the German or the Dutch electricity distribution grid per quarter hour interval. The German and the Dutch electricity grids are never interconnected directly. By connecting the two regions via the cross border element the annual electric system cost for the region could be reduced by 34%. The are the starting point for the development of legal concepts to enable and realize international cross-border medium voltage electricity transfers.**

***Index Terms*—Citizens energy communities, System Cost, cross-border, model, Smart Energy Region Emmen-Haren (SEREH)**

I. Introduction and Motivation

Historically, cross-border electricity interconnections were only used as additional backup capacities for national electricity markets [1]. Cross-border transmission connections therefore only exist on high voltage level (110 or 380 kV) and are operated by the transmission system operators (TSO).

Article 16 of the recently adopted new European Electricity Market Directive (EU 2019/944) opens the possibility of cross-border citizens energy communities (CEC) [2]. In consequence of the new regulation, new concepts for a medium voltage cross-border energy exchange could arise. This results in the need to analyze the benefits such cross-border electricity exchange concepts on distribution grid level can deliver.

A. SEREH Project

The Smart Energy Region Emmen-Haren (SEREH) project investigates the technical, legal and economic effects of a cross-border exchange of energy (electricity and hydrogen) below the transmission grid level between the dutch municipality of Emmen and the German city of Haren. A possible electricity connection at medium voltage (below 110 kV) would be unique in Europe.

Next to the international medium voltage connection, the project focuses on the integration of battery electricity storage systems and the conversion of electricity into green hydrogen on both sides of the border. Based on this, a concept for a local and decentralized cross-border electricity and energy market is developed.

The initial idea for the SEREH project and an electric cross-border connection on distribution grid level resulted from the complementary properties of the both regions. Emmen has a high electricity demand and Haren local renewable surpluses. A direct electricity transfer between the both regions could help to reduce grid usage, curtailment of renewable electricity and electricity transmission losses on both sides of the border.

B. Options for medium Voltage cross border Connections

Several options for a medium voltage cross-border connection can be considered in theory. Fig. 1 illustrates the three most promising options for a medium voltage cross-border connection.

- **Direct Line** In the "Direct line" scenario, the electric distribution grids of Emmen and Haren are directly interconnected via a cable. For this type of connection it must be ensured, that there never will be a free electricity flow between the both countries to avoid uncontrollable and unpredictable electricity transfers between the German and the Dutch transmission grids. This means, that local produced electricity can be transferred only to the neighboring region for self-consumption within that region, but a further transfer into the corresponding transmission grid has to be avoided. Electricity trades at the foreign exchange are not possible.
- **Microgrid** In the "Microgrid" scenario, the distribution grids of Emmen and Haren are directly connected to each other and form an islanded microgrid. This means that there are no connections to the transmission grid on both sides of the border. The electrical loads have to be fully covered by the local electricity generation. To make such a scenario possible, a further extension of renewable capacities is essential. The concept of an islanded microgrid corresponds to a 100% self-sufficiency scenario.

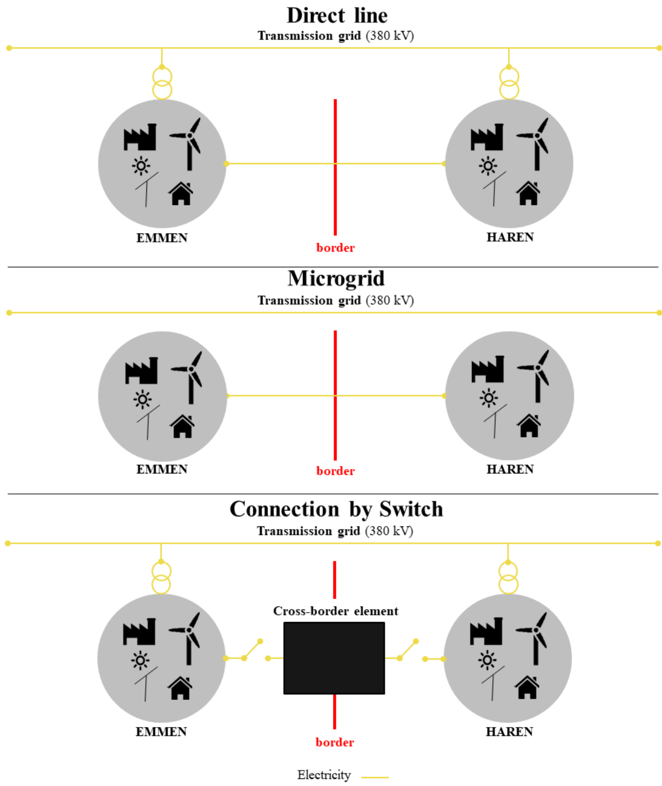

Fig. 1. Medium voltage cross-border connection options.

- **Connection by Switch** In the "Connection by Switch" scenario, the electricity distribution grids of two cities are interconnected via a cross-border element. The cross-border element consists of switchable renewable generation plants which can be connected to one of the both regions per quarter hour interval. The two electric distribution grids are never interconnected directly.

As the "Connection by Switch" scenario has the lowest obstacles for a realization, the benefits of an interconnection via such a cross border element are considered in detail.

II. Model and Input Parameters

To model the technical and economic effects of a cross-border energy community, a mixed-integer programming (MIP) model has been developed. The model is implemented in the programming language Python in combination with the Pyomo modeling library and the CPLEX solver. It runs on an eight core processor with 64 gigabyte of RAM. The model has a quarterly hour resolution and optimizes energy flows for one year.

A. Electricity System Cost

The objective of the model is to minimize the total electric system costs. A possible methodology for calculating electricity system costs is presented in [3]. Our model uses a simplified approach for calculating the system costs that is based on current grid fees and electricity curtailment. The grid fees reflect the costs for the transmission grid utilization. They are directly related to the capital expenditures for grid extensions. The electricity system costs $C_{System}(r)$ for a region r are divided into two cost components:

$$C_{System}(r) = C_{Grid}(r) + C_{Cur}(r). \quad (1)$$

The grid costs $C_{Grid}(r)$ of a region r are determined by the maximum grid usage in one quarter of an hour over the whole year. They are calculated by multiplying the capacity grid usage price $c_{Capacity}(r)$ with the maximum grid demand/grid feed-in $P_{Max}(r)$. This gives:

$$C_{Grid}(r) = c_{Capacity}(r) * P_{Max}(r). \quad (2)$$

The current electricity capacity prices $c_{Capacity}(r)$ from Tennet, which is the TSO on both sides of the border, are used in the model. In our case the German transmission electricity grid capacity price amounts to 113.61 €/kW [4], whereas the Dutch capacity price is 23.58 €/kW [5].

Besides the respective grid usage costs, the model objective function includes an additional revenue for the avoidance of curtailment on TSO level. These costs are calculated as follows:

$$C_{Cur}(r) = c_{Cur}(r) * V_{Cur}(r) * r. \quad (3)$$

The specific transmission network curtailment costs $c_{Cur}(r)$ are calculated from the total annual congestion expenditures of the respective TSO and the annual amount of electricity curtailed. In Germany the specific curtailment cost are 141.23 €/MWh [6] and in the Netherlands 77.76 €/MWh [7]. The avoided curtailment volume $V_{Cur}(r)$ is equal to the local potential increase of renewable electricity self consumption and thus to the reduced transmission grid feed-in volume. However, an increased self consumption does not directly lead to an avoidance of curtailment by the TSO. Only if this self consumption is at times where the TSO has to apply curtailment, costs are avoided. Therefore only a fraction r of the increased self consumption is considered. Based on historical data we estimate that 5% of the total feed-in energy would have been curtailed on national level and thus we choose r = 0.05.

We do not consider congestions on the local electricity distribution grids nor electricity transmission losses.

B. Input Parameter

As a starting point a complete dataset with electricity generation and load for Emmen and Haren for the year 2015 was determined based on different data sources obtained from the project partners [8].

To reflect future development additional investment in renewable capacities were added to the model. Based on plans of the two regions, Table 1 shows the model assumptions for the electrical loads and the total installed renewable capacities made for 2030. Note, that the local electricity production from renewables in Haren already today exceeds its annual electric

TABLE I
MODEL INPUT PARAMETER.

Renewable Capacities	Unit	Emmen	Haren
Electricity Demand	[MWh]	385,688	183,655
Wind farms	[MW]	95.5	137.3
Solar parks	[MWp]	96.07	-
PV rooftop	[MWp]	86.93	27
Biomass	[MW]	-	8
Battery storage Cap.	[MWh]	-	4.9
Battery storage Pow.	[MW]	-	4
Electrolyzer unit	[MW]	-	4

load by more than 23%. Emmen has a large industrial demand and a considerably larger population than Haren.

A battery storage and an electrolyzer are included in the model on the German side. The electrolyzer is used for the conversion of local electricity surpluses into hydrogen.

The cross-border element includes a 67.2 MW wind farm with 16 wind turbines each with 4.2 MW on the German side close to the border. On the Dutch side of the border, there is a wind farm with 24 MW consisting of five wind turbines each with 4.8 MW.

The electric distribution grid of Emmen connects to the 110 kV Dutch transmission grid. The transformers capacity is physically limited to a maximum of 135 MW. Thus, electricity flows to the transmission grid that exceeds this limit have to be curtailed.

The city of Haren neither experiences any local congestion issues on distribution grid level nor on the connection to the transmission grid. Thus, the electricity feed-in is not limited.

C. Reference Scenario

For reference, the energy situation in Emmen and Haren is simulated without a cross-border connection. Each of the two cities can only use its own renewable electricity generation and the national transmission grid for load coverage. Local electricity surpluses have either to be fed into the respective transmission grid or curtailed locally if the flow exceeds the given grid capacity. The battery and the electrolyzer can only be used by Haren.

D. Cross border Connection

The cross-border connection of the regions is realized by a cross-border element, shown in Fig. 2. Each of the 16 wind turbines of the German and the five wind turbines of the Dutch wind farm is equipped with its own single switch. Thus, for each of the wind turbines for each 15-minutes interval the model can be decided if it is connected to the German or the Dutch grid. In case of a connection to Germany, electricity can also be stored in the battery or used in the electrolyzer. Due to this special arrangement of components, it is ensured that the German and the Dutch electric distribution grid are never interconnected directly.

III. RESULTS

Based on the results of the model optimization, electricity flows and electric system cost savings are calculated and analysed.

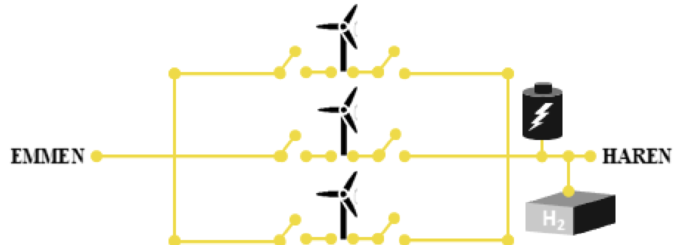

Fig. 2. Schematic overview over the cross-border element.

TABLE II
ELECTRICITY FLOWS MODEL RESULTS.

Scenario	Unit	Reference	Switch	Change
Ren. Gen.	[MWh]	937,506	937,506	0%
Self Con.	[MWh]	468,754	479,174	2.22%
Max. Feed Emmen	[MW]	134.89	123.09	-8.75%
Max. Feed Haren	[MW]	131.20	80.72	-38.48%
Max. Grid Emmen	[MW]	73.70	73.70	0%
Max. Grid Haren	[MW]	24.24	24.24	0%
Grid Vol.	[MWh]	100,589	90,169	-10.36%
Feed Vol.	[MWh]	437,099	429,297	-1.78%
Vol. H2	[MWh]	22,836	26,226	14.84%
Cur. Vol	[MWh]	8,812	2,804	-68.18%
Max. cross-border	[MW]	0	54.60	-
Cross-border Vol.	[MWh]	0	261,069	-
DSS Emmen	[%]	78.75	81.41	2.66%
DSS Haren	[%]	89.86	89.94	0.08%

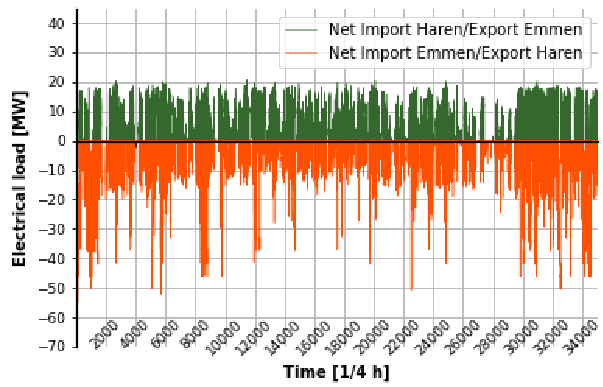

Fig. 3. Electricity import/export for the Switch scenario.

A. Electricity Energy Flows

Table II compares the results for the reference and the cross-border connection scenario. The total electricity generation of the both regions together amounts to 937.5 GWh/a. For both regions, the dimension of the grid connection is determined by the maximum grid feed-in and not by the electricity demand. With a connection on medium voltage level between Emmen and Haren, grid connection capacities to the TSO grid can be reduced as the maximum grid feed-in of Emmen is reduced by 8.75% and the grid connection of Haren is reduced by 38.48%. In contrast the peak load in the do not change and are the same as in the reference scenario.

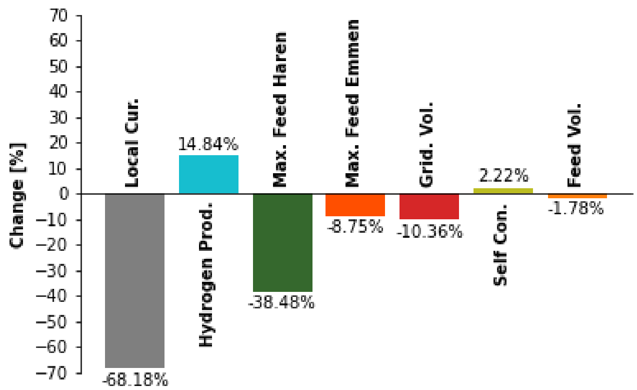

Fig. 4. Percentage changes of Electricity Flows.

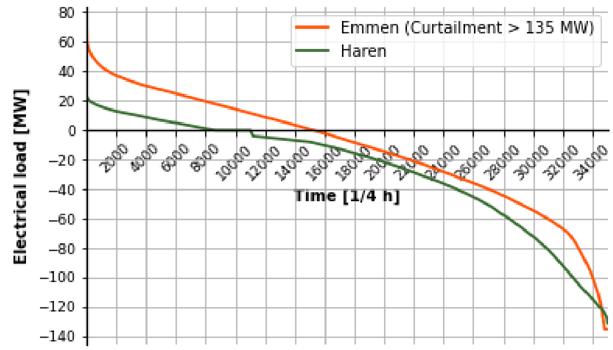

Fig. 5. Annual load duration curves for the Reference Scenario.

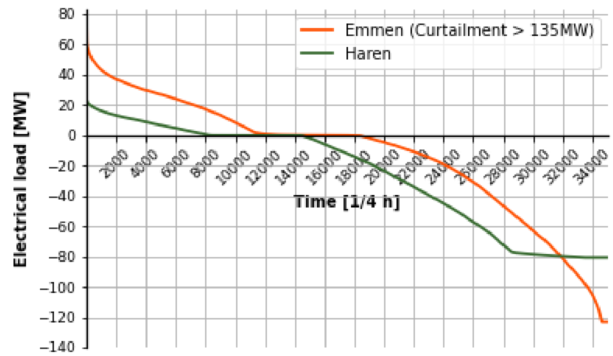

Fig. 6. Annual load duration curves for the Switch scenario.

Fig. 3 shows the optimal quarter hour cross-border net electricity transfers between the two regions in the switch scenario. The maximum net capacity transferred on the German-Dutch cross-border connection is 54.6 MW. The annual transfer volume amounts to 261 GWh. The total volume is subdivided into 122 GWh export from the Netherlands to Germany and 139 GWh export from Germany to the Netherlands. This means that the German export of renewable electricity exceeds the import from the Netherlands by 12%.

Without a cross-border connection, Haren achieves a level of self-sufficiency of 89.84% and Emmen a level of 78.75%. By connecting both regions, the degree of self-sufficiency of Haren remains almost constant and the self-sufficiency of Emmen increases by 2.66% to 81.41%.

With the cross-border connection, the self-sufficiency rates of Emmen and Haren have not deteriorated. This means that only wind turbines are switched to the neighboring region, which are producing surplus electricity.

In Fig. 4 the percentage differences of the most relevant key figures for the two scenarios are given. With the connection scenario, the local electricity self consumption increases by about 2%. This is also reflected in the increase of the self-sufficiency rates. The amount of electricity imported from the grid is reduced by 10.36%. In addition to that, the total surplus feed-in volume into the transmission grid also decreases by 1.78%. Besides the increased renewable electricity self consumption, the amount of electricity used for hydrogen production was increased by 14.84%. With an installed capacity of 4 MW, the electroyser unit operates with a number of 6,557 full load hours per year in the connection scenario. In the reference case, the electrolyzer operates only with 5,709 full load hours.

Due to the physically limited capacity of the transformers of 135 MW on the connection to the 110 kV Dutch transmission grid, in the reference scenario, about 8.8 GWh of local Dutch electricity from renewable production has to be curtailed. By connecting the two cities the curtailed electricity is reduced by 68% to 2.8 GWh.

Fig. 5 shows the annual residual load duration curves for Emmen and Haren without a cross-border connection. The electricity peak demand of Emmen is almost three times higher than Haren ones. The maximum negative residual loads for Emmen and Haren are by coincidence nearly the same and amount to about 135 MW. For Emmen this is due to physical transformers limit of 135 MW (the remaining electricity load is locally curtailed). The transmission grid connection of Haren is not limited. Furthermore, the Fig. 5 shows that in Haren the total number of hours with 100% electricity self-sufficiency amounts to about 6,620 h and is higher than in Emmen with 4,945 h.

Comparing the annual load duration curves of Emmen and Haren in Fig. 5 shows, that the curve of Haren in contrast to that of Emmen shows a flatted part within the range of 8,561 and 11,022 quarter hours. This is due to the additional battery storage and the electrolyzer unit. In the case of a small remaining positive residual load, the storage discharges energy and therefore reduces the grid demand to zero. If the remaining residual load is negative, local surpluses are stored

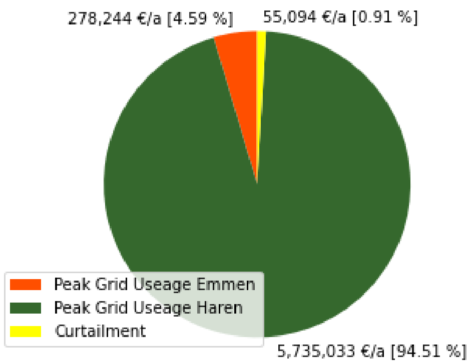

Fig. 7. System Cost Savings.

or converted into hydrogen. Summarizing, this means that in 615 hours of the year Haren has no electricity exchange with the transmission grid.

Fig. 6 shows the annual residual load duration curves of Emmen and Haren after the connection of two electricity systems. In comparison to the reference scenario, in the Switch scenario both curves show large flat areas. This means that by an electricity connection on the border the switchable renewable capacities are allocated better and the electricity systems are completely islanded.

For Haren, the time period without transmission grid electricity exchange is extended to more than 1,480 hours. Emmen now achieves a total number of about 58 hours. The significantly lower number of self-sufficient hours for Emmen is due to the missing of a battery storage and/or an electrolyzer unit. The number of hours with a residual load close to zero is much higher and is nearly the same as the one for Haren.

B. Total Electric System Costs

The total electric system cost in the reference case are 18,086,338 €/a. By the cross-border connection, these costs can be reduced by 33.55% from 12,017,968 €/a to 6,068,370 €/a.

Fig. 7 illustrates the total annual system cost saving achieved with the cross-border scenario subdivided into the main cost components. With a percentage share of 94.51% and a total of 5,735,033 €/a the reduction of peak grid usage of Haren is the main driver for the overall system cost reduction. For Emmen, the peak feed-in reduction leads to additional cost savings of 278,244 €/a. Note, that the cost savings for Harens transmission grid connection are significantly larger than for the one of Emmen. However, as the modeling objective function was to minimize the annual electric system cost this is explainable. As the grid capacity prices of Germany and the Netherlands are very different, the model first reduces the maximum capacity usage in Germany.

Historically only 5% of the electricity fed into the transmission grid would have been curtailed on national level. The avoided curtailment electricity in our model is 0.5 GWh. The reduced costs from avoided curtailment amounts to 55,094 €/a. In comparison to the capacity reduction cost savings, this is relatively low.

IV. Discussion and Conclusions

Due to the special arrangement of the cross-border element, it is ensured that the electricity distribution grids of the two cities are never interconnected directly.

The model shows the benefits from a electricity cross-border connection on a medium voltage level. By connecting two regions, the electric system cost caused by the region can be reduced by 34%. In our simplified approach the main benefit is the reduced peak grid usage.

The presented results form an initial starting point for a comprehensive political debate about the development of new revised legal and regulatory concepts to enable and realize international cross-border electricity transfers on distribution grid level.

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