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Cross-border Energy Communities on a Distribution Grid Level

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***Abstract*—This paper develops an approach to investigate 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. It comprises the electricity loads of two cities, their respective renewable electricity generation plants, a battery storage and an electrolyzer. Our research assumes that a promising approach to connect the cities is by a switchable "cross-border element" which represents a virtual power plant that includes a German and a Dutch wind farm located on either side of the border. The single wind turbines can be connected to either the German or the Dutch electricity distribution grid per quarter hour interval via a switch. The German and the Dutch electricity grids are never interconnected directly. In a simple scenario with constant load and additional renewable investments, connecting the two regions via the cross-border element would lead to a 34 % reduction of the annual electricity system cost caused the region. This is 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 a high voltage level (110 or 380 kV) and are operated by the transmission system operators (TSOs).

Article 16 of the recently adopted new European Electricity Market Directive (EU 2019/944) opens the possibility of cross-border citizens energy communities [2]. As a result 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 can deliver on a distribution grid level.

A. SEREH Project

The Smart Energy Region Emmen-Haren (SEREH) project seeks new concepts for regional cross-border energy systems as well as corresponding law and regulations. In detail, it 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.

In addition 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 both regions. Emmen has a high electricity demand and Haren local renewable surpluses. A direct electricity transfer between the regions could help to reduce grid usage and curtail 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. Figure 1 illustrates the three most promising options for such a connection.

- **Direct Line** With a "Direct line" connection, the electricity distribution grids of Emmen and Haren are directly interconnected via a cable. It must be ensured for this type of connection that there will never be a free electricity flow between both countries to avoid uncontrollable and unpredictable electricity transfers between the German and the Dutch transmission grids. This means that locally 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 must be avoided. Electricity trades on the foreign exchange are not possible.
- **Microgrid** If Emmen and Haren form an islanded electricity "Microgrid", the electricity distribution grids are directly connected to each other. There are no connections to the transmission grid on either side of the border. The electrical loads have to be fully covered by the local electricity generation. A further extension of renewable capacities is essential to enable such a electricity system.

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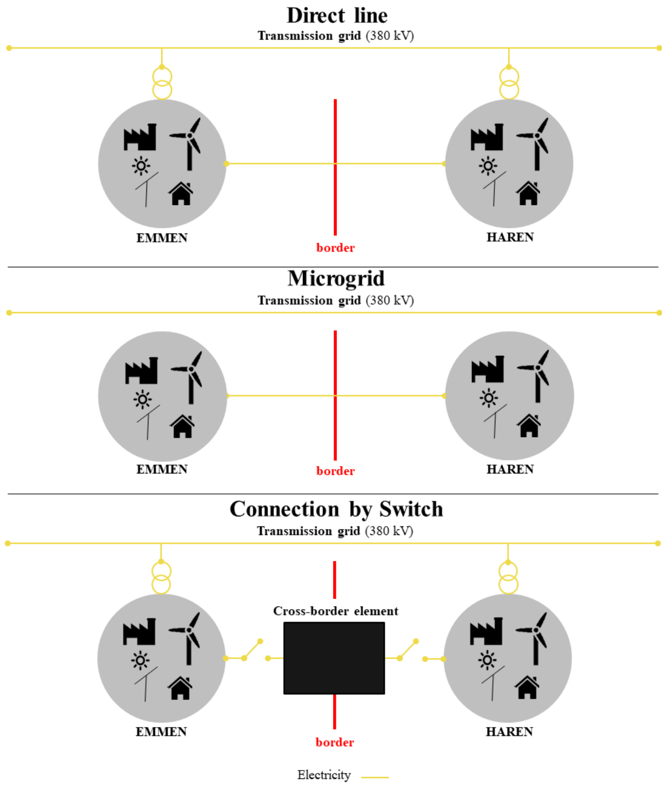

Fig. 1. Medium voltage cross-border connection options.

The concept of an islanded microgrid assumes 100 % of electricity self-sufficiency.

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

As a Switch connection has the fewest obstacles for a realization, the benefits of an interconnection via such a cross-border element are considered in detail.

II. Model and Input Parameters

A mixed-integer programming model has been developed to show the technical and economic effects of a cross-border energy community. 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 electricity system costs caused by the region. Two possible methodologies for calculating electricity system costs are presented in [3], [4]. Our model uses a simplified approach for calculating the system costs based on current grid fees and costs for electricity curtailment. The grid fees reflect the costs of the transmission grid investment and 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:

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

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 $c_{Capacity}(r)$ by the maximum grid demand/grid feed-in $P_{Max}(r)$. This gives:

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

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 [5], whereas the Dutch capacity price is 23.58 €/kW [6].

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

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

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. The specific curtailment costs in Germany are 141.23 €/MWh [7] and in the Netherlands, 77.76 €/MWh [8]. 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. Cost are avoided only if this self-consumption is at times when the TSO has to apply curtailment. 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 a national level and, thus, we chose r = 0.05.

We do not consider congestions on the local electricity distribution grids or electricity transmission losses.

B. Scenario

As a starting point, a complete dataset with realized electricity generation and load for Emmen and Haren for 2015 was determined based on different data sources obtained from the project partners [9].

In a simple scenario to show the principle of the model the load was kept constant. Only additional investment in renewable capacities were added to the model to reflect future development. Based on current plans of the two regions, Table 1 shows the model assumptions for the electrical loads and

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

the total installed renewable capacities made for 2030. Note that the local electricity production from renewables in Haren already today exceeds its annual electric 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 electricity distribution grid of Emmen connects to the 110 kV Dutch transmission grid. The transformer's capacity is physically limited to a maximum of 135 MW. Thus, electricity export to the transmission grid that exceeds this limit has to be curtailed.

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

C. Reference case

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 to be either fed into the respective transmission grid or curtailed locally if the flow exceeds the grid capacity given. 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 Figure 2. Each of the 16 wind turbines of the German and the 5 wind turbines of the Dutch wind farm is equipped with its own single switch. Thus, the model can decide if it is connected to the German or the Dutch grid for each of the wind turbines for each 15-minute interval. In the 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.

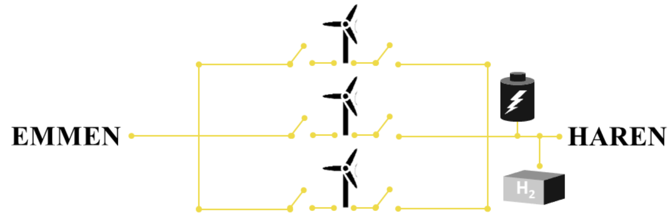

Fig. 2. Schematic overview of the cross-border element.

TABLE II
ELECTRICITY FLOWS MODEL RESULTS.

Key figure	Unit	Reference	Connection	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	65,267	-
DSS Emmen	[%]	78.75	81.41	2.66 %
DSS Haren	[%]	89.86	89.94	0.08 %

III. RESULTS

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

A. Electricity Energy Flows

Table II compares the results for the reference case and the Cross-border Connection. The total electricity generation of both regions together amounts to 937.5 GWh/a. The dimension of the grid connection for both regions is determined by the maximum grid feed-in and not by the electricity demand. With a connection on a 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 %. By contrast, the peak load does not change and is the same as in the Reference case without a connection.

Figure 3 shows the optimal quarter hour cross-border net electricity transfers between the two regions with a connection. The maximum net capacity transferred on the German-Dutch cross-border connection is 54.6 MW. The annual transfer volume amounts to 65.3 GWh. The total volume is subdivided into 30.5 GWh export from the Netherlands to Germany and 34.8 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

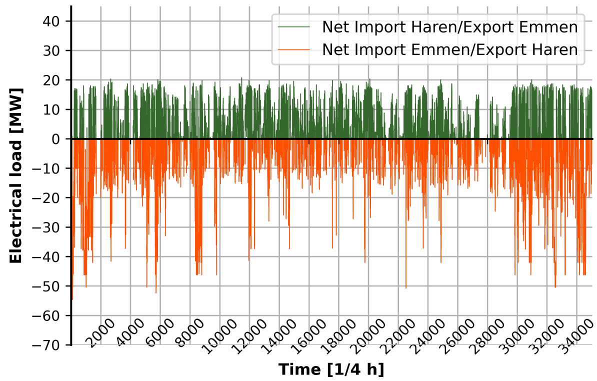

Fig. 3. Electricity import/export for a cross-border connection.

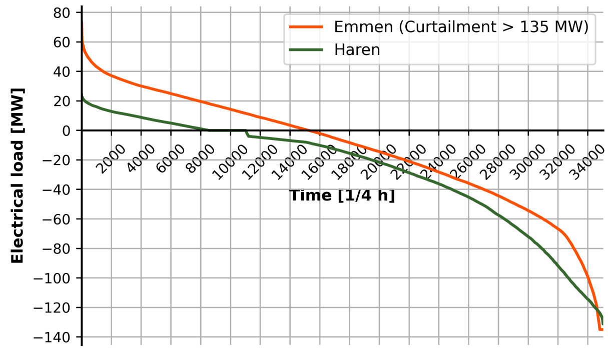

Fig. 5. Annual load duration curves without a cross-border connection.

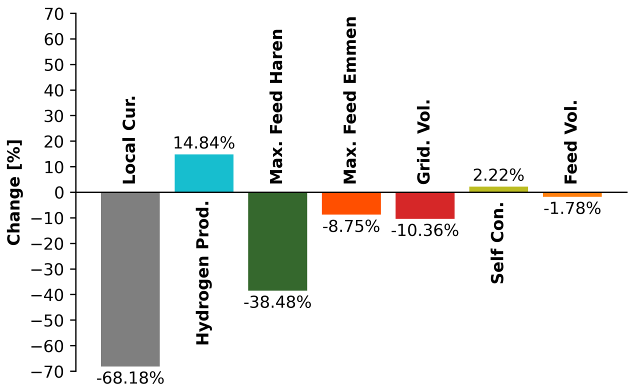

Fig. 4. Percentage changes of electricity flows.

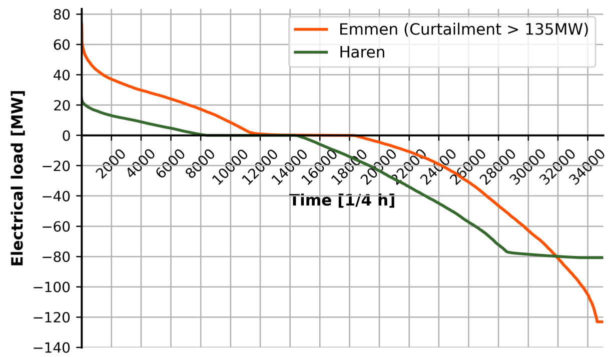

Fig. 6. Annual load duration curves for a cross-border connection.

of Haren remains almost constant and the self-sufficiency of Emmen increases by 2.66 % to 81.41 %.

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

The percentage differences of the most relevant key figures are given in Figure 4. The local electricity self-consumption increases by about 2 % with a cross-border connection. 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, 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 %. The electrolyzer unit, with an installed capacity of 4 MW, operates with 6,557 full load hours per year in the case of a cross-border connection. In the reference case, the electrolyzer operates with only 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, about 8.8 GWh of local Dutch electricity from renewable production has to be curtailed without a connection. By connecting the two cities, the curtailed electricity is reduced by 68 % to 2.8 GWh.

Figure 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. The maximum negative residual loads for Emmen and Haren are, coincidently, nearly the same and amount to about 135 MW. Regarding Emmen, this is due to the physical transformer's limit of 135 MW (the remaining electricity load is locally curtailed). The transmission grid connection of Haren is not limited. Furthermore, Figure 5 shows that the total number of hours with 100 % electricity self-sufficiency in Haren 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 Figure 5 shows that the curve of Haren in contrast to that of Emmen shows a flattened part within the range of 8,561 and 11,022 quarter hours. This is due to the additional

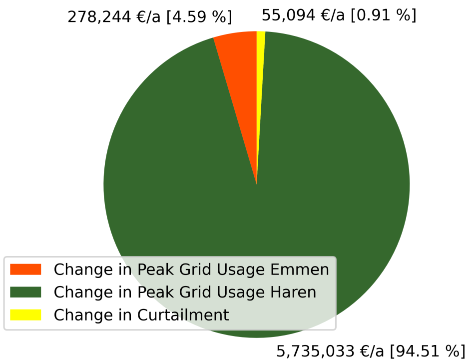

Fig. 7. System cost savings.

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

Figure 6 shows the annual residual load duration curves of Emmen and Haren after the connection of two electricity systems. In comparison to the reference case without a connection, both curves show large flat areas for a cross-border electricity system. This means that the switchable renewable capacities are allocated better by an electricity connection on the border and the electricity systems are completely islanded.

The time period without transmission grid electricity exchange for Haren is extended to more than 1,480 h. Emmen now achieves a total number of about 58 h. The significantly lower number of self-sufficient hours for Emmen is due to the lack 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 electricity system cost in the reference case is 18,086,338 €/a. Utilizing the cross-border connection, these costs can be reduced by 33.55 % from 12,017,968 €/a to 6,068,370 €/a.

Figure 7 illustrates the total annual system cost saving achieved with the Cross-border connection subdivided into the main cost components. The reduction of peak grid usage of Haren, with a percentage share of 94.51 % and a total of 5,735,033 €/a, is the main driver for the overall system cost reduction. The peak feed-in reduction leads to additional cost savings for Emmen of 278,244 €/a. Note that the cost savings for Haren's transmission grid connection are significantly larger than for Emmen. However, as the modeling objective function was to minimize the annual electricity 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 a national level. The curtailment electricity avoided 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 of a cross-border electricity connection on a medium voltage level. The electricity system cost caused by the region can be reduced by 34 % by connecting the two regions. The main benefit of our simplified approach is the reduced peak grid usage.

The results presented 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 a distribution grid level. Next to these aspects, also from the technical site some issues have to be investigated in more detail like e.g. the coordination and realization of the switches.

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