

Incorporation of Flow-Based Grid Modelling in Multinational Transmission Expansion Planning

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Abstract— Multinational transmission expansion planning (TEP), i.e. investments in cross-border electric power exchange capacity, has received increased attention in order to develop adequate models to help decision support for market integration and large-scale integration of renewable energy sources (RES). This paper presents a comparative study quantifying the effects of incorporating different power flow modelling techniques in an optimization model for grid investments. Analyses were conducted by utilizing a mixed integer linear programming (MILP) to quantify the impact of applying the suggested techniques with a North Seas offshore grid (NSOG) case study. The analyses were carried out under the four ENTSO-E 2030 Visions, outlining the future development of the European power system. The results shows that a flow-based (FB) approach stimulates higher investments in interconnector capacity than the suboptimal net transfer capacity (NTC) solutions, shifting Norway's role from provider of power and balancing services to a transportation hub.

Index Terms—Transmission Expansion Planning, North Sea Offshore Grid, Power Flow Modelling, PTFDs, Mixed-Integer Linear Programming.

I. INTRODUCTION

Multinational TEP is an important step towards achieving the ambitious decarbonization targets for the energy sector outlined by the European Commission (EC) [1]. Recent studies conducted by academia and governmental organizations suggest that multinational grid expansion is an absolute necessity to handle the increasing volatility in both electricity prices, and power system balance arising due to the increasing share of intermittent RES in the interconnected European power system resulting from the decarbonization [2]–[5]. In many cases, this can be solved by sufficient transmission capacity and interconnection of market areas [6]. However, the optimal development of an adequate power system represents multiple challenges, as identified by the ENTSO-E [2].

Grid investments are typically highly capital intensive with a long economic lifetime, in addition to being considered as sunk costs. Additionally are some of the wind power plants needed to reach the aforementioned goals located far from shore, requiring long-distance subsea cable connections to the onshore grid [7]. To ensure optimal expansion of the interconnected European power system, it is crucial to coordinate the connection of both future and existing offshore wind power plants with the expansion of cross-border exchange capacity,

possessing the possibility of creating the world's first supergrid as the NSOG are without predefined transmission technology or topology [8], [9]. Thus, TEP can serve the twofold purpose of providing both increased system flexibility and reliability resulting from enhanced dispatch efficiency and greater utilization of RES, and increased trading yielding improved overall market efficiency and socio-economic welfare [10].

A. Previous Work

Due to its importance and priority to the European climate and energy policy, several research projects has been conducted on the NSOG over the past years. These include, among others, the projects of Norwegian Research Center for Offshore Wind Technology (NOWITECH) [11], OffshoreGrid [12], North Sea Transnational Grid [13] and the collaboration between E3G and Imperial College [14]. Despite these, there is still uncertainty as to the optimal design of the grid, and multiple optimization models for multinational TEP have been created [8]. However, most of today's models lack an appropriate representation of the physical grid, precluding the models from calculating realistic power flows and accounting for distributional effects [15]. Models presented by Jaehnert *et al.* utilizing EFIs Multi-area Power-market Simulator (EMPS) [16], Trötcher and Korpås creating Network Optimization Tool (NetOp) [9] (both developed by SINTEF Energy), Akbari *et al.* [17] and Lottfjou *et al.* [18], all use a low degree of detail when modelling the power flows in the system by applying NTC-constraints.

To the author's knowledge, no similar studies regarding the impact of incorporating different power flow modelling techniques in a TEP-context have been conducted, particularly not for joint operational- and investment optimization of multinational offshore applications representing a mix of both HVAC- and HVDC grids. Two relevant contributions from this work will be improvement of AC grid representation in a generic MILP-model for multinational TEP, and quantification of investment- and computational effects of using different power flow modelling techniques. In addition, an indirect contribution of this work includes the possibility of enhanced evaluation of distributional effects of large offshore grid investments resulting from the improved AC grid representation.

II. METHODOLOGY

This section will briefly explain the theoretical background for the two power flow modelling options, namely the transportation model and the flow-based model.

A. Power Transmission Distribution Factors

Modelling of the physical power flows in an optimization model is a difficult task, mainly due to the different laws and characteristics applied to commercial and physical exchange of electricity in an interconnected system [15]. According to Kirchhoff's circuit laws, physical power flows may take multiple paths through a transmission grid [19]. The power transmission distribution factors (PTDFs), or the PTDF-matrix, is a useful way of denoting this interdependency, expressed through a *change* in the approximations of the DC load flow equations, provided in Equation 1, describing a linear relationship between voltage angles δ , nodal power injections P and system susceptance B , also referred to as the bus admittance matrix, Y_{bus} .

$$P = B\delta = Y_{bus}\delta \quad (1)$$

The PTDFs can be viewed as sensitivity factors expressing the percentage of one unit export from a given node, or an area as described later, that will flow on a particular line. In other words, the *change* in power flow on a given line as expressed by Equation 2 where the prime indicates the augmented values with a reference point to account for the singularity of the bus impedance matrix.

$$\Delta P_{ik} = B_{ik}(\Delta\delta_i - \Delta\delta_k) = B_{ik}\Delta P_n(Z'_{bus,ii} - Z'_{bus,ki}) \quad (2)$$

If ΔP_n is set to unity, the effect on power flow on line i-k can be regarded as the PTDF for that line per unit net power injection in node n. This is commonly referred to as the sensitivity factor, or power transmission distribution factor for line i-k arising from the net position (NP) of node n, denoted $PTDF_{ik,n}$.

$$PTDF_{ik,n} = B_{ik}(Z'_{bus,in} - Z'_{bus,kn}) \quad (3)$$

However, as price calculations are done on an area level, corresponding aggregated area PTDFs has to be created. In the market clearing algorithm, only connections between bidding areas, referred to as the critical network elements (CNEs), are taken into account. Area-to-CNE PTDFs indicates how a change in the aggregated net position in an area affects the flow on a given CNE [20]. As the NP of all nodes in an area influence the flow on a given CNE to varying degree, incorrect weighting of a node could yield inaccurate estimates of the actual flows on a CNE. One way to cope with this problem, is the use of Generator Shift Keys (GSKs), describing the effect a change in net position of a node has on its area's net position. Different strategies defines how the node-to-line PTDFs should be weighted in accordance to each other, in order to obtain equivalent area-to-line PTDFs [20]. Gebrekiros

et al. [21] presents three different schemes with varying degree of complexity and information requirement.

A generic formulation of the PTDF of CNE i-k arising from the net position of area A, denoted $PTDF_{ik,A}$, using GSKs can be expressed as shown in Equation 4.

$$PTDF_{ik,A} = \sum_{n \in A} GSK_n \cdot PTDF_{ik,n} \quad (4)$$

Where

$$\sum_{n \in A} GSK_n = 1 \quad (5)$$

One should have in mind that inaccurate GSKs may influence the market extensively, and may be one of the major sources of inaccuracies in FB market clearing (FBMC) [20].

The PTDFs can be used to calculate the flow of any given line in a system, P_{ik} , based on the NP of all nodes according to Equation 6, providing a methodology for power flow calculations.

$$P_{ik} = \sum_{n \in N} PTDF_{ik,n} \cdot NP_n \quad (6)$$

B. NTC Capacity Allocation

The NTC, or rather the available transfer capacity (ATC) obtained when subtracting the already allocated capacity (AAC), is the maximum allowed commercial exchange between two adjacent bidding areas that complies with the security standards of the given synchronous area, and takes into account the technical uncertainties on future grid conditions [22]. These limits are determined by the Transmission System Operators (TSOs) to facilitate the market transactions while safeguarding the grid.

The NTC is defined as total transfer capacity (TTC) less the transmission reliability margin (TRM) [23]. The TRM is a part of the total capacity that is withheld from the market by the TSO in order to manage possible congestions and the physical flows, including transit flows, that will occur in the interconnected system. The transit flows are not taken explicitly into account in the NTC market clearing, also known as coordinated net transfer capacity (CNTC). As a result of this, inefficient allocation of the total capacity might occur if the allocated TRMs are not fully utilized. As transit flows are hard to predict, capacity calculation in an interconnected grid becomes complex and might lead to suboptimal or inefficient capacity allocations, as the transmission constraints in the market clearing algorithm are given as NTCs [20].

C. FB Capacity Allocation

As the entire power system is physically interconnected, an action in one part of the system will in principle affect the entire system, in the form of transit flows. This interdependency can be expressed through the PTDFs described in Section II-A. These parameters is the basis for FBMC, providing the market clearing algorithm with power flow constraints. However, in contrast to NTC capacity allocation is no longer a choice of the TSO that is made in advance, but it is an outcome of the market clearing. Hence the allocation

is market driven, creating a stronger connection between the power markets and the physical system [23]. For this reason, FB market clearing is the preferred approach in the Network Code on Capacity Calculation and Congestion Management (NC CACM) developed by the ENTSO-E [24], stating that a FB approach should be used unless its added value can be disproved compared to an NTC approach [20].

The use of a flow-based model allows for a more precise modelling of the physical flows, as the constraints of the FB optimization problem are simplified grid models, reflecting the impact of changing net positions on the flows in the network [23]. This leads to a more efficient capacity allocation as the market takes all flows in the system into account and no transfer capacity has to be withheld from the market. Transit flows can then be monitored and possible congestions are taken care of in the market clearing algorithm directly [20]. Additionally, the use of PTDFs provide the opportunity of a single allocation mechanism including a mixture of AC and DC elements, often referred to as hybrid coupling [20].

The objective function of the optimization problem remains unchanged with the two methodologies. The only difference is the formulation of power flow constraints. Because there is no need for pre-allocation of capacity in advance of the market clearing, a larger solution domain can be obtained by the algorithm, still containing all possible solutions of the CNTC [20]. This implies that FBMC might contain solutions outside the solution domain of CNTC, providing a greater number of trading opportunities with the same level of security of supply [23]. This is illustrated by Figure 1.

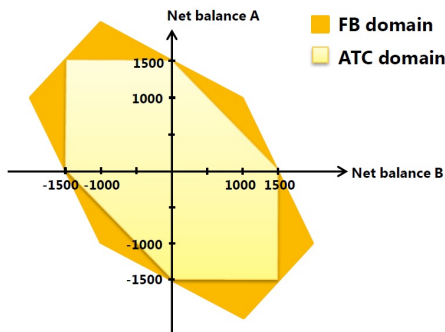


Fig. 1: Illustration of NTC (ATC) compared with FB solution domain [23].

D. The Optimization Model - NetOp

There are numerous ways to model a TEP-problem. One approach is the generic MILP optimization model described by Trötscher and Korpås in [9], NetOp. In the original version a transportation model of the grid was used, simply modelling branches as transmission capacity constraints, expressed as the NTCs described in Section II-B, neglecting the physical nature of electric power flows. However, due to the previously discussed limitations of NTCs, PTDFs deduced in Section II-A, can be utilized to model the interconnected power flows of the entire grid. The NTCs only restrict flow on each connection,

while the PTDFs are used to translate market transactions into physical power flows in the system, creating a stronger coupling between the power market and the physical system. This method provides a better, more realistic description of the grid than using a transportation model, while still maintaining linearity [9].

To account for the flow-based capacity restrictions and the use of PTDFs, the optimization model has to be augmented with the additional constraint given in Equation 7.

$$\sum_{n \in I} PTDF_{ij,n}^s \left(\sum_{g \in G_n} x_g^s - b_n^s \right) \leq x_{ij}^s, \forall i \in I, j \in I_i, s \in S \quad (7)$$

Additionally, the choice was made not to include optimization and expansion of the onshore AC grid in the model due to a severe increase in computation time. Hence, no investment variables involved in onshore AC branches.

III. CASE STUDY

A case study was conducted with a goal of examining the effects of utilizing a FB approach to onshore AC grid modelling, using PTDFs. NetOp was applied to a grid resembling the representation of the Northern European interconnected power system found in the EMPS [16]. The key parameters that were monitored throughout the case study as a foundation for comparison of both model performance and results included; the exchange flows, model computation time, utilization hours and capacity expansion of the interconnectors.

Furthermore, the distributional effects in the PTDFs-represented grid were examined by observing the accumulated flow in that part of the system, and average mean utilizations (AMUs) (average of the mean of the utilization time for all samples) were used as a comparative measure of interconnector utilization. However, the most important parameter for comparison was the power flow, as it is the governing factor of both capacity expansion and utilization.

The load and generation data used in the case study were based on the 2030 Visions outlined by European Network of Transmission System Operators for Electricity (ENTSO-E) [3]. The aggregated winter peak values were distributed among the price areas according to the 2014 total ELSPT volume distribution [25], and divided between the nodes to resemble the situation of the Nordic power system, i.e. high demand and low production in the Oslo-area etc. All other exogenous model parameters, i.e. expansion costs, branch losses and so forth, were used as predefined in NetOp, and used in other research [6], [9].

A. Results

Initially, all branches of the expanded model were optimized. The onshore, PTDF-represented grid is excluded from the figures since it does not consist of any investment variables. Existing capacity on these branches were set high enough so that no constraints were put on these power flows. Capacity on all PTDF-branches were reduced when the NTCs were utilized, compared to PTDFs, representing the TRM discussed in Section II-B.

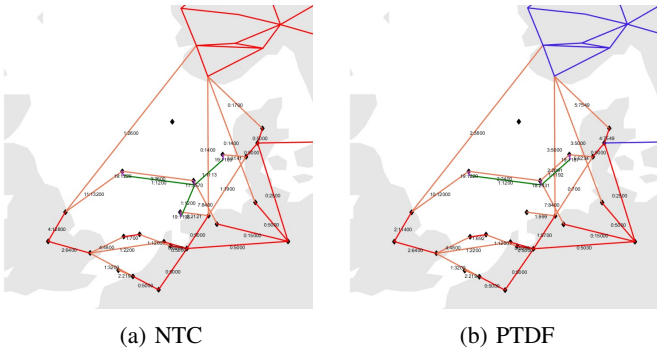


Fig. 2: Optimal grids under Vision 1.

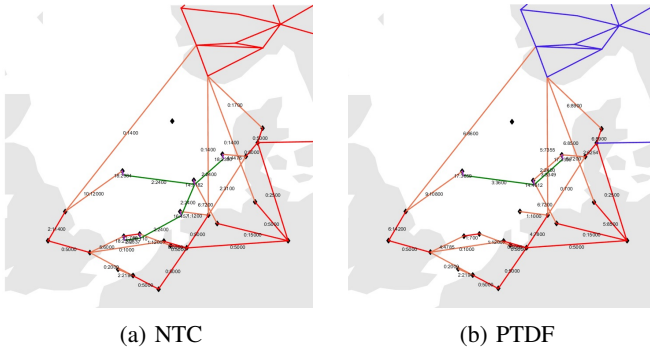


Fig. 3: Optimal grids under Vision 2.

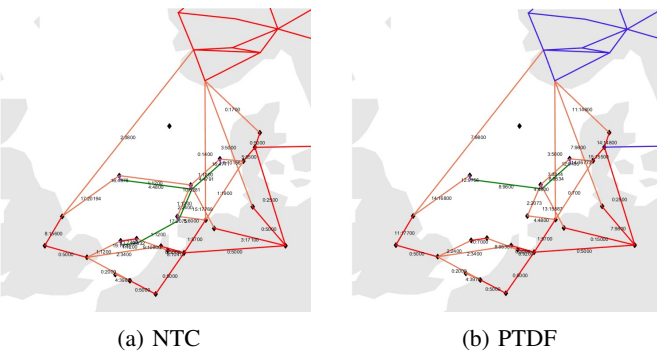


Fig. 4: Optimal grids under Vision 3.

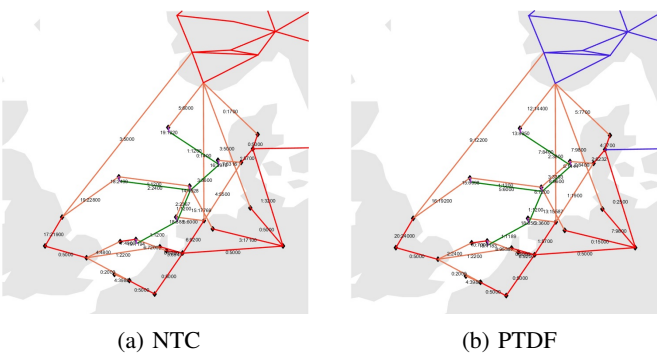


Fig. 5: Optimal grids under Vision 4.

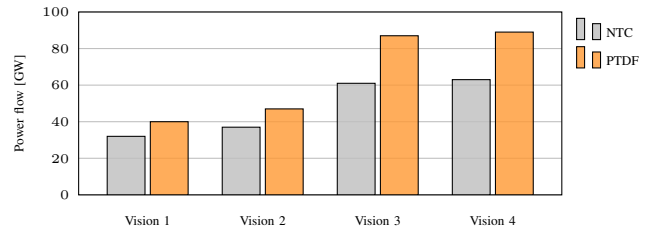


Fig. 6: Graphical comparison of the accumulated interconnector exchange.

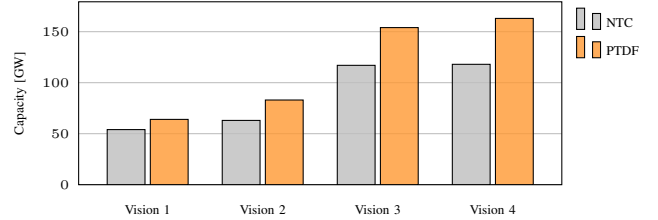


Fig. 7: Graphical comparison of the accumulated interconnector capacity expansion.

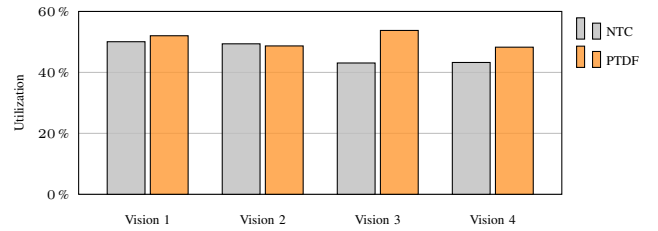


Fig. 8: Graphical comparison of AMUs of all interconnectors.

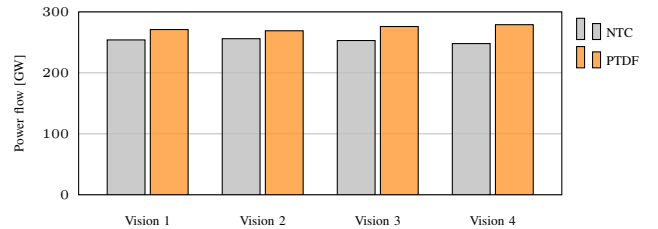


Fig. 9: Graphical comparison of the accumulated active power flows on PTDF branchess.

1) *Discussion of Results:* Considering the data presented, one can clearly observe differences in the results of the two methodologies.

From Figure 6, an increase in optimal interconnector exchange is observed for all Visions, when the flow-based methodology was used. In order to facilitate for these flows, the resulting capacity expansion follows the same trend as indicated by Figure 7. This is in compliance with the theory presented in Section II, stating that the solution domain of a flow based market clearing is greater than, and containing all the solutions of, the solution domain obtained when using NTCs. Furthermore, a stepwise increase in the accumulated

interconnector capacity under the different Visions, for both cases, can clearly be gleaned from Figure 6. This is due to the assumption of an increasing level of pan-European cooperation towards achieving European Union (EU)'s climate goals assumed in the Visions. Increased cross-border exchange capacity facilitates the utilization of the best energy source available at all times, in a greater geographical area. This results in reduced curtailment of wind- and solar power production, thus it has a higher priority in Visions 2 and 4, as they build upon top-down strategies. Furthermore, the larger steps in multiple variables from Vision 2 to Vision 3 than between the others are worth noting. This can be explained by the large increase assumed in both demand and RES penetration between these two scenarios, resulting in a greater need for cross-border exchange and lower production costs.

As indicated by the graph in Figure 9, there is an increasing trend in the difference between the optimal accumulated flow in the onshore PTDF grid in the NTC-case and the FB-case. This is compliant with the theory presented in Section II, stating that an NTC-approach does not account for the distributional effects in an AC system. The PTDFs, however, calculate all transit flows, resulting in a higher accumulated flow in that part of the system. Furthermore, this results in increased production costs in the PTDF-case due to the fact that a higher accumulated flow in the system entails increased losses (assumed linear with power flow) that has to be supplied by a generator.

Another explanation for the increased production costs, is the increased curtailment of RES generation with the flow based modelling under Visions 3 and 4. Curtailment is often a result of inadequate transmission capacity, restricting production dispatch, resulting in demand being supplied by generators of higher marginal costs. Under Visions 1 and 2, the production costs are almost equal in the two methodologies, indicating that the reduction of curtailment covers the increased costs due to losses. Whereas, with the increasing RES penetration under Visions 3 and 4, curtailment increases when using PTDFs, entailing an increased production cost.

B. Power Flow Analysis of the Major Interconnectors of NSOG

Time series of the optimal power flow on the given interconnectors and offshore wind power production in the southern parts of NSOG under Vision 4, are provided in Figures 10 and 11 for the 50 first samples. Figures ?? and ?? provide an illustration of the corresponding wind power production in and power flow between Dogger Bank and the offshore wind power plants off the northern coast of Germany.

1) *Discussion of Results:* When examining the power flow time series, there is an indication of the flow based modelling of the grid resulting in a different utilization strategy of the major NSOG interconnectors, compared with using NTCs.

From Figure 10, there are indications of correlation between some of the time series. Most importantly, there seems to be a positive correlation between offshore wind production in

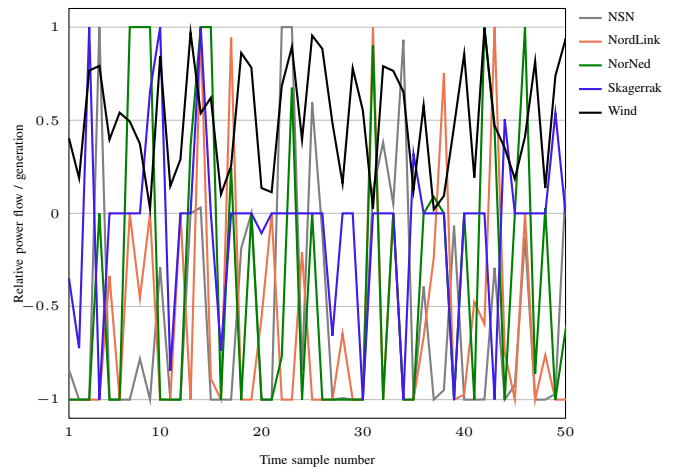


Fig. 10: Power flow time series for some of the major interconnectors under Vision 4 using NTCs with Norway as reference (import +, export ÷, relative to max value).

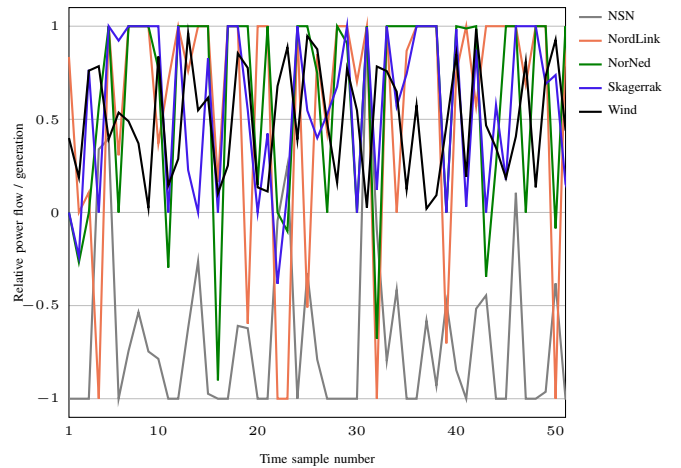


Fig. 11: Power flow time series for some of the major interconnectors under Vision 4 using the PTDFs with Norway as reference (import +, export ÷, relative to max value).

the southern parts of NSOG, and exchange on NSN. Furthermore, there is an indication of a negative correlation between wind production and exchange on NordLink, i.e. import on NordLink increases with decreasing wind production. All these effects, combined with no correlation between the power flows in the different interconnectors, gives ground to say that Norway does not serve as a hub for transportation of power between continental Europe, and the UK. The fact that power is exported in times of high offshore wind production to the feed-in areas indicates that Norway rather serves the role of providing power and balancing services to continental Europe. This is due to the high share of flexibility provided by Norwegian hydro power, exporting balancing power whenever needed.

From Figure 11, one can primarily observe greater variations and magnitudes of power flows when using PTDFs.

This results from, as discussed in Section II, the fact that a flow based grid modelling accounts for all power flows in a system. Furthermore, Figure 11 indicate a decrease in the correlation between offshore wind production and exchange on NSN, while correlation NordLink remains about unchanged. Moreover, the significantly negative correlation between export on NSN and NordLink, together with a clear indication of positive correlation between exchange on NordLink, Skagerrak and NorNed, emphasized by significantly positive correlation coefficients, indicates a different utilization strategy for the interconnectors. It appears that, in the PTDF-model, Norway acts as a hub for transportation of power to and from continental Europe, and the UK. This is also indicated by Figures 2 - 5 where a shift in the interconnector expansion-strategy can be observed, putting more emphasis on the northern cables with the PTDF-approach.

It is important to note that even though there are indications of Norway's role in the European power system shifting away from supplier of balancing power, such services are still provided with PTDF-model. Otherwise, offshore interconnection of Norway would not be necessary as power could be routed through the southern corridor of NSOG, directly from continental Europe to UK, reducing the need for capacity expansion. These results correspond to those obtained by the Twenties project [4], where a shift in utilization strategy is observed when a more detailed flow-based analysis used compared to a more simple NTC-approach.

IV. CONCLUSION

This paper presents a comparative study of different power flow modelling techniques applied to a multinational transmission expansion planning model in order to study the impact on model output. It is shown that a flow-based model yields a greater optimal expansion of the existing capacity than the more commonly used NTC methodology. Moreover, the changes in utilization strategies observed on the major interconnectors of the NSOG is a further indication that the modelling techniques yield significantly different results, and that a more detailed and realistic representation of the grid results in variations in distributional effects in both the onshore and the offshore grid.

The model also assumes one hypothetical TSO in charge of NSOG TEP, disregarding the effects of multinational cooperation and the resulting distribution of both costs and benefits. This might be a major limitation of the model as interconnector investments are conducted bilaterally by the involved TSOs. It is, however, a difficult feature to include in an optimization model due to the conflicting objectives of market participants.

Another limitation is that the PTDF-matrix were used only statically, and not dynamically, implying that the latter is iteratively updated whenever the investment model adds additional transmission capacity. Future research would include investment variables in the onshore AC grid requiring a dynamic PTDF-matrix.

ACKNOWLEDGMENT

The authors would like to extend their gratitude to PhD Candidate Yonas Tesfay Gebrekiros with the Department of Electric Power Engineering at NTNU and SINTEF Energy for his invaluable assistance on flow-based modeling and PTDFs.

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