Study – System balancing solutions with detailed grid data

Statnett

Phase 2 – Core Analysis

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Disclaimer

This report was prepared by N-SIDE and NHH for Statnett SF. Views, opinions and conclusions are of a general character and cannot be taken to represent specific Statnett positions on any of the topics treated in the report.

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0 Executive summary

0.1 Objectives and methodology of the study

The problem faced by Statnett is the fact that European balancing platforms such as MARI are executed at zonal resolution. This may cause congestion problems within the Norwegian (or also Nordic) network, when MARI platform is activating resources.

Therefore, three approaches have been selected as promising methodologies to solve this problematic and have been investigated in this report:

- ***Approach A1: BSPs represented individually within MARI***. Individual BSPs are bid directly into MARI. In case the activation causes a network violation, Statnett restores the network feasibility with post-MARI corrective actions.
- ***Approach A2: BSPs aggregated in MARI***. Norwegian BSPs are aggregated by Statnett into a system-wide residual supply function, which is bid as a single aggregate BSP in MARI (so implicitly considering network constraints).
- ***Approach A8: Nodal Norway in MARI***. MARI platform uses a representation of the Norwegian system with a nodal resolution.

All these approaches suffer from a **certain level of uncertainty** as they will rely on certain assumptions (including foreign network flows, imbalance location, etc.). This means that, in any case, **some corrective actions might be needed after the MARI clearing results are revealed**. **But, while approach A1 fully relies on these corrective actions, approaches A2 and A8 attempt to precede them with some preventive actions which attempt to mitigate the corrections that are required afterwards**. Let us also stress that this re-dispatch might not be needed, depending on the feasibility of the dispatch of MARI. In this sense, approach A2 substantially differs from A1 and A8 as A2 inherently implies some necessary actions after MARI, while the others only include an "optional" step of re-dispatch after MARI.

These three approaches have been studied and compared towards several "dimensions" as illustrated on the following figure:

- ***Settlement rules & pricing***: this dimension discusses the pros and cons of the different pricing rules that can be implemented for each approach and puts forward the most appropriate one.
- ***Economic efficiency***: the discussion here focuses on welfare. In order to establish a consistent basis for comparison, we will consider the efficiency of the entire system, without limiting our attention to the Norwegian zone. Cases where the final outcome violates constraints out of the Norwegian zone are pointed out.
- ***Payments for TSO***: this dimension analyzes the financial exposure of the TSO. Concretely, we are interested in the payments of the TSO to (i) the MARI platform, and (ii) any side payments associated with corrective actions *after* the clearing of MARI.
- ***Uncertainty***: this dimension discusses the exposure of each approach to parameters that need to be forecast by TSOs.
- ***Complexity***: this dimension analyzes the procedural complexity of each approach.
- ***Assessment of ICT issues***: this dimension discusses computational, algorithmic, and other ICT related issues.

- ***Gaming opportunities***: this dimension discusses the vulnerability of the different approaches to gaming.
- ***Political, regulatory and legal***: this dimension evaluates the political, regulatory and legal issues linked to the different approaches. Indeed, the disruptiveness of an approach, while being very efficient economically, could also raise political or legal concerns. This dimension includes the analysis of the characteristics of each approach against the main requirements in the market network codes (compatibility of each proposed approach against the EU guidelines).

In order to bring a valuable insight, this comparison and analysis has been supported by an illustration of the three approaches on two corner cases which are assumed to be representative of the kind of issue that can result from MARI zonal model. These corner cases rely on a model where multiple bids are located in 6 nodes aggregated in MARI into 3 zones (and therefore neglecting intra-zonal network constraints) : a North zone - assumed to be Norway, and two South zones). The two corner cases are:

- **Commercially congested exporting scenario**: in DA, there is an export of power from the North zone to the Southern zones such that there is a congested North-to-South ATCs line. This is followed by an **imbalance in the Northern zone**, resulting in activation in MARI creating internal congestion in the Northern zone.
- **Commercially uncongested exporting scenario**: in DA, there is an export of power from the North zone to the Southern zones but such that there is space left available on the North-to-South ATCs. This is followed by an **imbalance in the Southern zones**, resulting in activation in MARI creating internal congestion in the Northern zone.

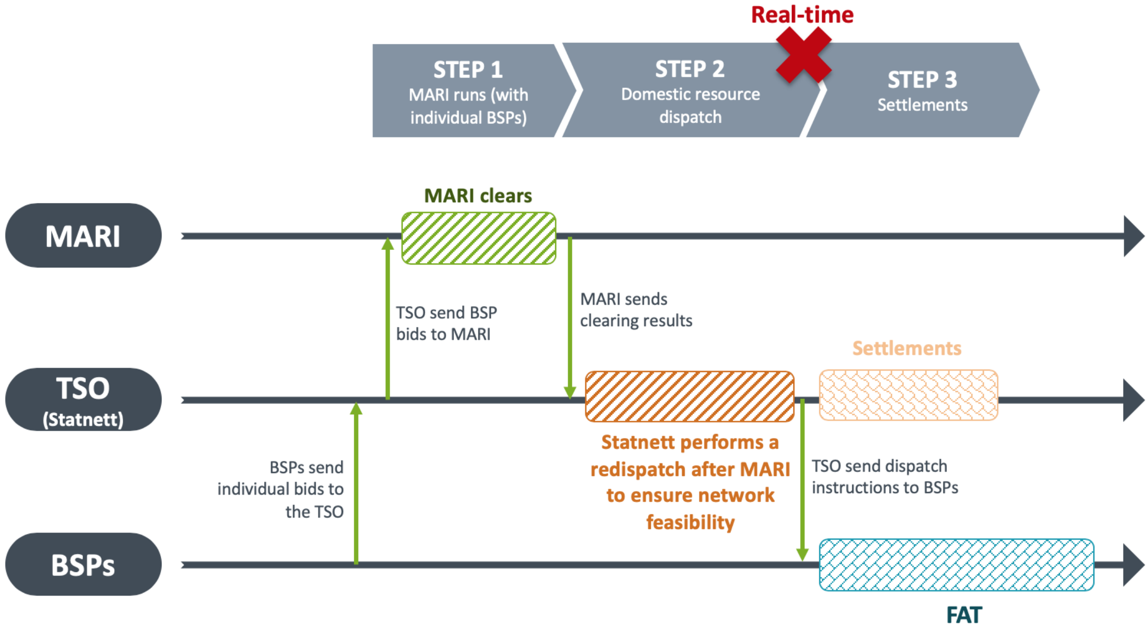
The analysis and results of the approaches on these corner cases are elaborated in the report. We don't detail them in this executive summary which is focused on presenting the conclusions that has been generated, among other from these corner cases.

0.2 Approach A1 – BSPs represented individually in MARI

0.2.1 Timeline & outline of the approach

According to approach A1, Norwegian BSP bids are represented within the MARI platform. The timeline of approach A1 is outlined in the following figure.

The assumption in this approach, which has been confirmed by Statnett, is that there probably will be sufficient time to execute an optimal power flow after the clearing of the MARI platform, since a run time for an optimal power flow lasts for 2 seconds, not including the time that is required for data exchange with the control center. Thus, we assume in what follows that we have enough time after MARI to perform a re-dispatch, with the same bids that are available in MARI.



Step 1: MARI execution

In this step, the MARI platform is executed with the BSP resources of the Northern zone being represented individually within the platform (i.e. standard MARI use). The platform produces a market clearing quantity for each BSP, as well as a clearing price (pay-as-cleared) to which each BSP is entitled.

Step 2: domestic resource dispatch (after MARI, before real time, in case of constraint violation)

Come real time, the TSO can execute an optimal power flow in order to respect its internal and inter-zonal constraints. Note that the execution of this step is not strictly required if the execution of MARI results in a feasible dispatch within the Northern zone. The dispatch instructions may deviate from those of MARI, and settlements will be handled in step 3. Note that, although individual BSPs may be asked to deviate from the results of MARI, the zone as a whole maintains the balance that is dictated by the MARI platform, and since the MARI platform settles on a uniform price, there should be no net payments towards the platform as a result of the override instructions. The OPF that is solved is based on the gross MARI request, and finds the optimal solution to the resulting imbalance problem while respecting all the cross-border flows into and out of Norway (but possibly changing the position of individual Norwegian bidding zones).

The solution is optimal in the sense of aiming at **minimizing deviations from MARI positions**. An alternative objective for the Northern TSO could have been to maximize economic surplus. The role of the TSO in real time (maximizing benefits from economic trade versus minimizing deviations from BSP setpoints) has been the subject of debate also in the MARI design (in particular the role of counter-activations in the platform) and is a recurrent question in European balancing market design. Whereas the concept of merit order activation in balancing is conformant to the goal of maximizing economic efficiency in real time, the idea in our present analysis is that this goal will be handled by the MARI platform. Instead, the role of Statnett in the post-MARI stage will be assumed to **restore feasibility in the network flows while minimizing deviations from the MARI** outcome. In this sense, the post-MARI stage of approach A1 resembles an **out-of-market correctio**n. We discuss the connection with out-of-market corrections, and how this argument influences our settlement logic, further in the later sections of the report.

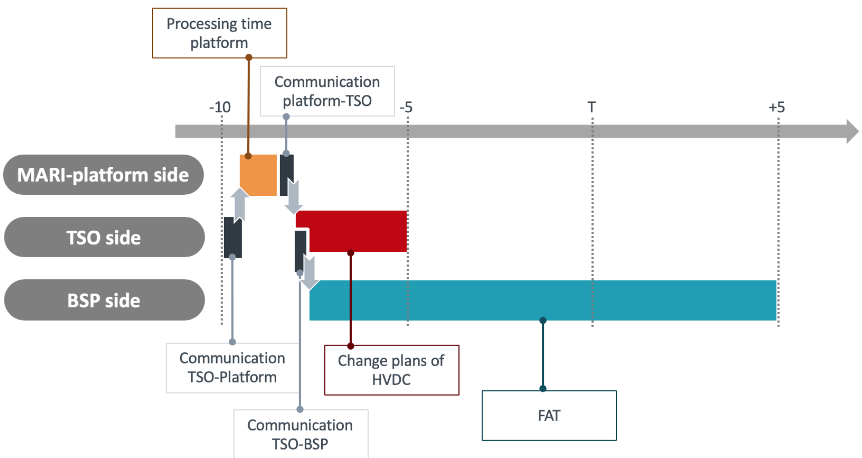
Step 3: settlements of instructed deviations (after real time)

At this step, the TSO settles instructed deviations using side payments (pay-as-bid). We consider this step as an-out-of-market correction, and discuss the pay-as-bid logic of this step subsequently. However, we also note that these side payments may create INC-DEC gaming opportunities.

0.2.2 Fast products

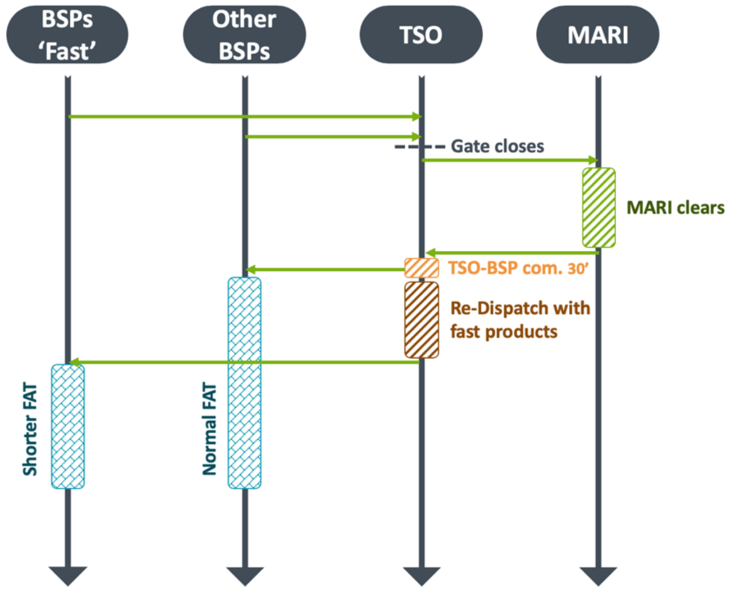
The discussions on approach A1 also triggered more thoughts on the usage of fast-product. The complete presentation is available in the appendix B of this report, but the main highlights are reported below.

Approach A1 assumes that the time left after MARI is sufficient to resort to a re-dispatch (understood as an out-of-market correction after MARI, relying on the resolution of an OPF and assuming a pay-as-bid scheme) of the bids submitted to MARI as such. Somehow, it was neglecting the timing constraint or the heterogeneous flexibility of the various BSPs towards this constraint. The timing of MARI is nevertheless extremely constrained as illustrated on the next figure.



In case the post-MARI step cannot be made in this short timing, one could rely on faster product. Indeed, most of the flexibility in Norway comes from hydropower which is not significantly ramp-constrained. This means that many BSPs in Norway have a faster response time than what is currently proposed in MARI. Such flexibility could be exploited to allow more time for re-dispatching. One way to exploit this flexibility is to design a specific product, available for these “fast-ramp BSPs”, with a shorter FAT, e.g. 5 minutes, which could be introduced for re-dispatch purposes. This product could be leveraged in order to solve undesired effects of MARI activations with a subset of the bids that can react faster.

One way of implementing these "fast products" is to rely on the mFRR product of MARI in which we introduce a slight variation allowing the Norwegian BSPs to somehow check a box "also available for fast activation". In this way, after MARI returns the activated bids, a redispatch is performed by Statnett with the subset of the bids marked as "fast".



The BSPs are split in two groups : (1) the "normal" BSPs which face the standard FAT of MARI and (2) the "fast" BSPs which allow the TSO to re-dispatch them in a timeframe that extends beyond 30 seconds after MARI clears and therefore face smaller FAT. It is therefore the assumption that the BSPs of Norway are split into two groups and that a subset of the BSPs (the BSPs "fast") are used to perform a re-dispatch.

All the BSPs send their bids to Statnett before the gate closes. These bids are transmitted by the TSO to MARI which clears and publishes the market results. Afterwards, Statnett has the standard 30 second timeframe to communicate the results to the "normal" BSPs while, in parallel, the redispatch is conducted with the Fast BSPs. The final results of both MARI and the redispatch are then published to the fast BSPs which therefore face a shorter FAT.

Let us notice that there is no interference with MARI in this procedure, except for the MARI direct activation (MARI-DA). Indeed, the MARI protocol foresees, in case of contingencies (i.e. generator contingencies) happening after the MARI auction, a "direct activation" procedure which corresponds to on-the-spot activation of units through MARI. The redispatch performed by Statnett with the "fast BSP" would therefore interfere with this MARI-DA procedure.

The analysis conducted on this fast product ("Approach A1 bis") highlighted the following **upward**: it enables having faster reaction, which can be advantageous in certain cases.

The analysis highlighted the following **downward**:

- Tension between MARI and the fast product price: The fast product auction produces price discrepancies which will tend to push BSPs at high-price locations to wait for the second stage, and vice versa.
- The fewer the BSPs that can participate in the fast product auction, the stronger this effect becomes.
- Certain BSPs can collect windfall profits by being activated upward in MARI at a higher price and activated downward by the fast product auction at a lower price (considering that the activations in MARI are to be paid in any case - see legal discussion). This does not differ from A1.
- Compared to approach A1, the fast auction produces a slightly higher financial deficit for the TSO

The analysis also triggered a discussion on the **Direct Activation procedure**, which is not specific to the fast product and is valid for all cases. One important conclusion is that the direct activation procedure could in theory create congestion on the Statnett network as well. So in principle, congestion checks and mitigation procedures should be performed one more time after each DA procedure. This is not further studied here but could be a subject of further work.

0.2.3 Main conclusions

One advantage of the approach A1 is that it has straightforward interaction with MARI: all BSPs are represented in MARI, and net settlements are in accordance with MARI, i.e. there are no net payments to MARI from after MARI deviations. The deviations from MARI are considered to be out-of-market corrections and are settled pay-as-bid

With that respect, the fact that the approach makes the corrections after MARI clearing step resolves a significant amount of uncertainty in the system, especially related to unknown platform requests. Insofar as the next imbalance interval is concerned, demand and renewable supply are largely foreseeable. The most uncertain aspect is the flow across the border. There could also be uncertainty related to the change of BRP/BSP positions.

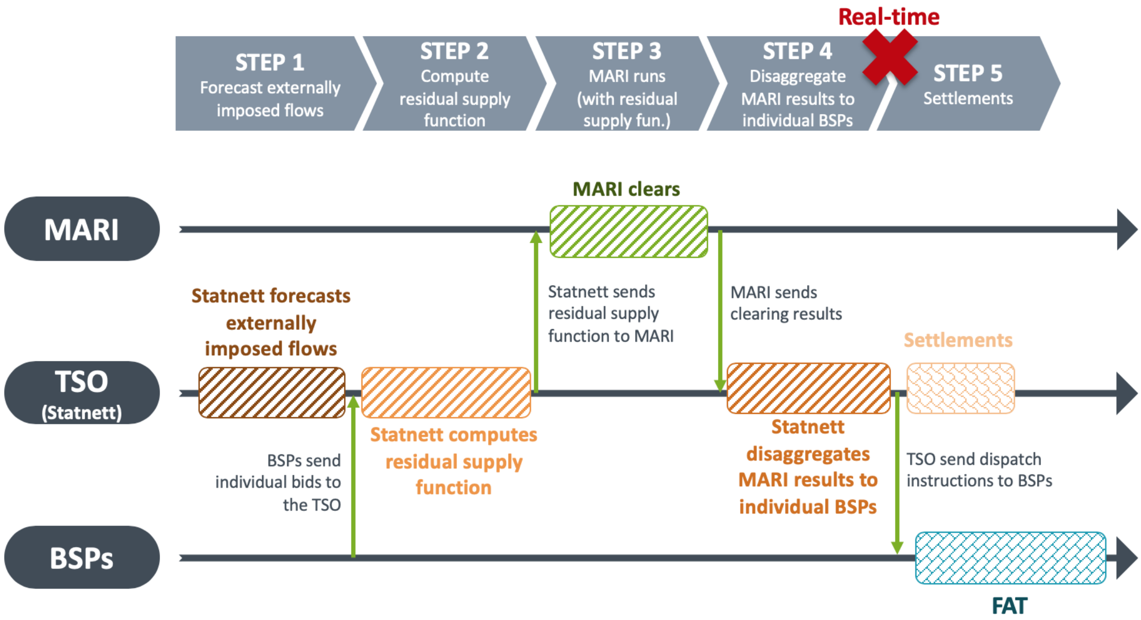
Nevertheless, let's stress that as approach A1 doesn't do anything beforehand to solve possible upcoming issues, it somehow assumes that all possible issues arising from MARI could in theory be solved afterwards. This might not be the case and solving all the issues afterwards might turn out to be infeasible at the end, which can be viewed as a major source of uncertainty.

0.3 Approach A2 – BSPs aggregated in MARI

0.3.1 Timeline & outline of the approach

Approach A2 is a "hierarchical approach" where the idea is to design a **residual supply function**, which is submitted to the MARI platform, instead of submitting the BSP bids individually. Suppose that the dispatch of other TSOs does not change from the most recently metered value. We can then fix their net injections, and pose the question of what is the cheapest way in which we can export a given amount of power from our zone. The answer to this question is given by the residual supply function which is transferred to MARI.

The sequence of steps implied by the approach is depicted at a high level in the following figure.



Note that the TSO has to relate to the aggregate bid curve and not the individual BSPs behind it. Thus, the only bid that the Northern TSO can buy is from the "aggregate Northern BSP". This will become part of the total export target that the Northern TSO needs to meet, and it will be sourced from the optimization of step 4.

Step 1: forecast externally imposed flows (before MARI)

The idea of step 1 is to 'filter out' the impact of the resources that cannot be controlled by Statnett. Essentially, this implies assigning values to the flow coming from the other regions, which is a straightforward calculation for Statnett based on its locally observable information: Statnett subtracts from the measured flows on its lines the impact of the dispatch of the resources on his grid in the previous imbalance interval. If steps 2 - 4 of approach A2 can be executed fast enough, then this calculation can be performed after the activation of non-Noway MARI resources (i.e. within the new imbalance interval). If this is not possible, it is still acceptable to use a reasonable approximation of the non-Norway induced flows, since the residual supply function does not have to be estimated perfectly in order for approach A2 to perform effectively.

Step 2: Compute residual supply function for submission to MARI

In this stage, Statnett estimates the residual supply function that it plans to submit to MARI. The estimation of the residual supply function requires the resolution of as many OPFs as the points around which we wish to approximate the residual supply function. As correctly pointed out by Statnett, the sum of the ATC capacities defines the outer boundary of this calculation, meaning that the total cost function does not need to be approximated beyond this boundary.

A possible implementation of this calculation is that Norway has access to the day-ahead nominations of generators, in order to be able to compute the *incremental* cost relative to the day-ahead nominations, and thereby the residual supply curve. In effect, this means that the bids should be locational. This is how our simulations have been run.

Step 3: Clear MARI with Northern residual supply function

In this stage, the residual supply function that is computed in step 2 is converted into synthetic BSP bids (i.e. the function is discretized, each piece being considered as a bid for MARI) and inserted in the MARI market clearing platform. The idea is that Statnett zone will export its scheduled volume, and any imbalances will be dealt with via a delta on the net position (relative to a day-ahead or intraday schedule), the marginal cost of which is computed from the residual supply function of the previous step.

Step 4: Disaggregate the results of MARI in the Northern zone

In this step, Norway needs to allocate the activation decided by MARI to the BSPs within its zone. The idea will be for Norway to run an optimal power flow limited to its own zone. This implies that the dispatch actions of Statnett may cause problems outside of Norway. Note, however, that if the entire zone is bid as a single 'BSP' by Statnett, then there is nothing inconsistent with the actions of the Norway (even if Statnett causes congestion outside Norway through its actions). The platform instructions are followed, and there is no net payment due to the platform.

One important difference between step 4 of approach A2 and the post-MARI step of the other approaches is that in the other approaches the post-MARI part is optional if the system is feasible after MARI clears. In A2, the post-MARI process in step 4 is necessary in order to have a well-defined set of dispatch instructions.

Step 5: Settlements

Statnett implements a nodal system within its own zone when disaggregating resources. Statnett thus collects a payment as an aggregate BSP (step 3, MARI), and then uses these funds to procure balancing power in the disaggregation phase (step 4). The approach does not involve gaming opportunities between the MARI and post-MARI steps (even if there are still gaming opportunities between the day-ahead market clearing and real time).

0.3.2 Main conclusions

Generally, approach A2 seems quite promising: it is economically efficient and unlike approach A1, it manages to "model implicitly" the network within MARI to better ensure feasibility without having to implement disruptive changes as in approach A8.
One observation is that while MARI quantities and settlements are respected, the revenue that the TSO can collect based on the MARI prices does not necessarily cover exactly the payments that the TSO has to make, i.e. the TSO may have a surplus or a deficit.

Nevertheless, let's notice that the approach is also complex and represents more a "family" of approaches than a unique well-define approach. In other words, there are various design choices which are still open (i.e. these open points are listed in section 6).
In particular, an unresolved question is how the approach can be adapted to multiple price zones within the area of one TSO. Indeed, an important observation is that the residual supply function is one-dimensional as long as we are focusing on a single dispatch interval, even if we have multiple zones to which the zone in question is connected. The fact that there may be multiple zones to which Norway zone is connected does not mean that the total cost function is multi-dimensional. This may not be true if the interzonal connectors are HVDC lines (and therefore have a controllable flow), or if we are considering total cost over multiple periods.

Finally, let's notice that a potential challenge is whether Statnett can use the rules of a central dispatch system.

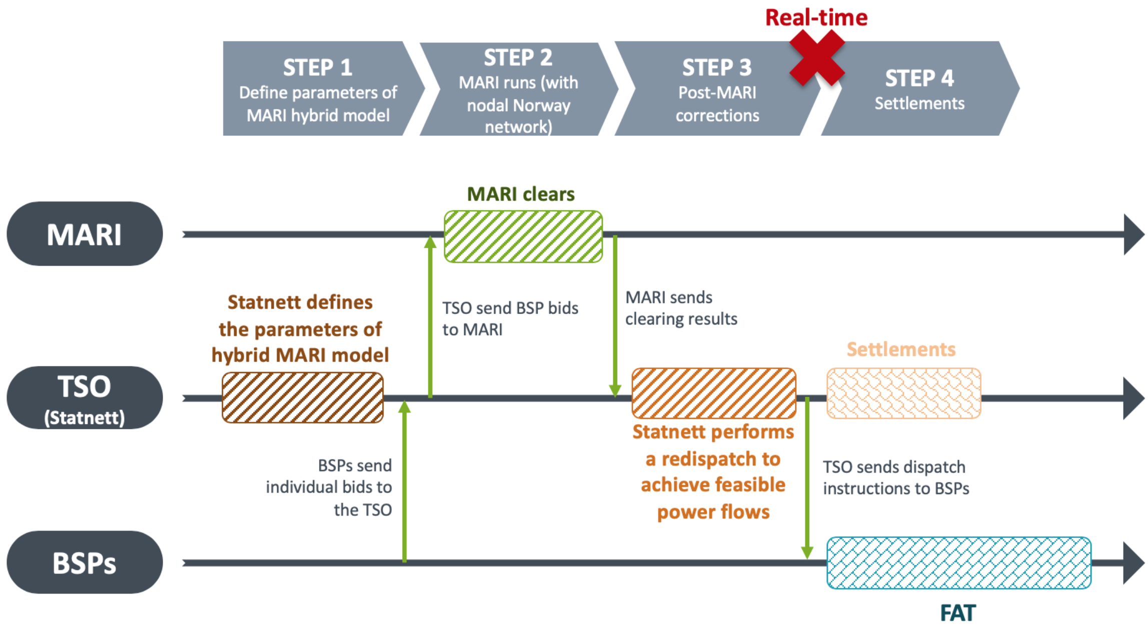
0.4 Approach A8 – Nodal Norway in MARI

0.4.1 Timeline & outline of the approach

Approach A8 is based on the idea that the Norway is represented in full detail as a nodal network in the MARI platform directly. The timeline of approach A8 is outlined in the following figure.

It is worth noting that this is a simpler timeline than that of approach A2. Note, in particular, that steps 3 and 4 are optional in the examples that we demonstrate below, meaning that the dispatch is already feasible from step 2. Instead, approach A2 involves post-MARI operations which also necessitates certain settlements out of the MARI platform in approach A2.

The general idea of the approach is to (i) use a transportation / ATC model for non-Norway links, (ii) represent intra-zonal lines linking the Norway zone to the remainder of the system essentially as HVDC links with controllable flow (we discuss later how the capacity of these links should be decided), and (iii) represent the interior of the Norway zone using linearized power flow equations (note that this latter representation is not yet foreseen in the MARI requirements).



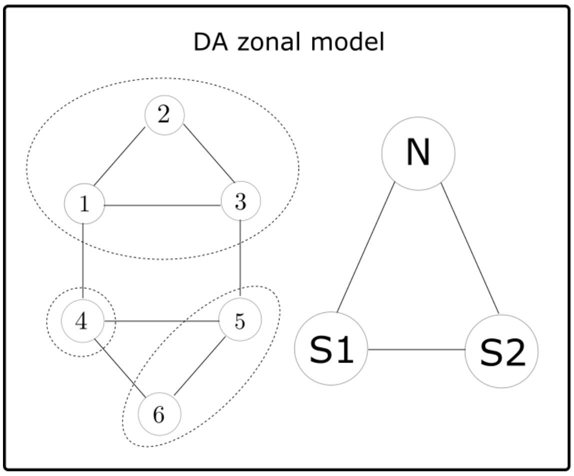
Step 1: Define parameters of MARI hybrid model

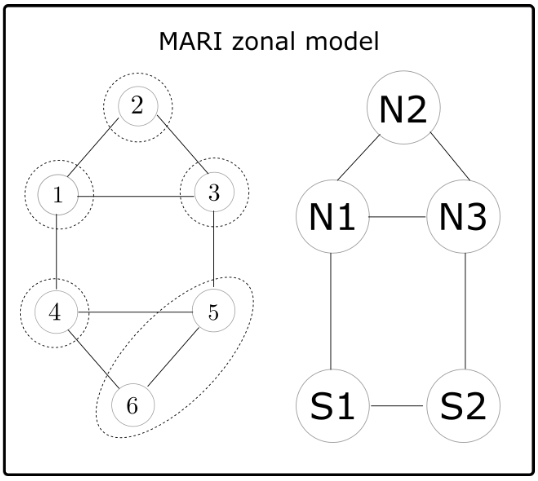
One notable aspect of approach A8 is the need to define the zonal capacities that are used in the MARI model. When disaggregating a zonal model (day-ahead) to a more granular hybrid model (MARI), three types of links may emerge in the MARI model:

- *Type 1 links*: the DA zonal links are unaffected.
- *Type 2 links*: the MARI zonal links correspond to physical lines. Note that type 2 links can be inter-zonal, or intra-zonal.
- *Type 3 links*: neither the first nor the second possibility, i.e. the MARI zonal links correspond to neither day-ahead zonal links nor physical lines, i.e. they are still aggregations of physical lines, but finer aggregations than those of the day-ahead zonal model.

In order to illustrate these definitions, let us consider the following figure. In the left box of the figure below, we present the aggregation of the nodal system into the day-ahead zonal market clearing model. In the right box of the figure, we present the aggregation of the nodal system into the MARI zonal model. We can classify the MARI zonal model links as follows:

- **Type 1 links**: S1-S2: the S1-S2 link exists already in the day-ahead zonal model, and is replicated identically in the MARI zonal model.
- **Type 2 intra-zonal links**: N1-N2, N2-N3 and N1-N3: these links are type 2, because they correspond to physical lines (lines 1-2, 2-3 and 1-3 of the nodal model respectively). They are intra-zonal because they are subsumed in the Northern zone in the day-ahead zonal market clearing model.
- **Type 2 inter-zonal links**: N1-S1, and N3-S2: these links are type 2, because they correspond to physical lines (lines 1-4 and 3-5 of the nodal model respectively). They are inter-zonal because they are connecting the Northern zone of the day-ahead zonal market clearing model to other zones of the day-ahead market clearing model.
- **Type 3 links:** no such links exist for this example.





It is natural to assign capacities for type 1 links as being equal to those of the DA model. For type 2 intra-zonal lines, these can be assigned to their physical capacity. For type 2 inter-zonal lines, two possible choices of capacities are the physical capacities, or the DA capacities. We will refer to the former as "**aggressive capacity assignment**", and the latter as "**conservative capacity assignment**".

Step 2: MARI market clearing

In the MARI market clearing, we assume that the imbalance that will occur in the system has already been revealed through a TSO need on the MARI platform.

Step 3: Post-MARI corrections (optional)

If step 2 turns out to cause infeasible flows for Statnett network, a post-MARI correction is executed, where Statnett adjusts the dispatch of BSPs in order to achieve feasible power flows, while aiming at minimizing deviations from the MARI clearing result. Note that an alternative objective for Statnett could have been to maximize economic benefits of trade in step 3. However, this is deemed inappropriate in practice because (i) it can be shown to cause 'oscillations' between step 2 and step 3 (with BSPs being activated upwards in step 2, only to be activated downwards in step 3, and vice versa), and (ii) such an objective would encounter challenges in being accepted in practice by stakeholders.

Step 4: Settlement (optional)

If step 3 is needed in order to prevent a violation of flows in Statnett network, then this is considered as an out-of-market (OOM) correction. Step 4 settles these OOM corrections on a pay-as-bid basis, as in the case of the post-MARI corrections in approach A1.

0.4.2 Main conclusions

An important issue of the approach is how to **set the commercial capacity limits**: an outstanding challenge of this approach is how to set the capacities of the interconnections between the nodal and the zonal bidding zones. Let's however notice that, in the (hypothetical) situation that the whole Nordic synchronous area would go for this solution, all interconnectors would be HVDC, in which case the setting of the capacities would be straightforward, and this would therefore increase the economic efficiency, probably significantly. Another option is the case where Norway and Sweden together go for this approach, which would already largely reduce the interconnectors to HVDC only, with the exception of two "semi radial" interconnectors to Finland and East Denmark.

Furthermore, the aggregated commercial links introduce some uncertainty in the system, since the actual ex-post flows may not be exactly as in the market clearing model

Let’s also notice that when the network model changes from a zonal pricing model in the day-ahead market to a hybrid nodal and zonal model in the balancing market, large redispatches may result only because of the change in the network model. There may also be large redistributions in post-MARI corrections if the objective is to maximize welfare or minimize cost. Post-MARI corrections may be small or not even needed if the objective is to minimize deviations from the MARI schedules

Of course, one outstanding issue of this approach is simply that the MARI platform may not be ready to clear the market with a nodal pricing area.

0.5 Cross-comparison of the approaches

This section provides a summary of the cross-comparison of the three approaches detailed in section 5 of this report.

0.5.1 Economic efficiency

In terms of economic efficiency, we focus on reporting two performance indicators: (i) cost throughout the system, and (ii) cost in the Northern zone (corresponding to Norway in the corner cases). We report the profits of different agents, including BSPs, BRPs and the TSO, in the welfare breakdown tables of sections 2-4.
We present the cost results in the following table. Nodal refers to the fully nodal resolution as presented in section 1. “Business as Usual” approach (BAU) refers to the approach where MARI design remains unchanged, all bids are transmitted to MARI and no post-correction takes place.

	Commercially congested	**Feasible in RT**	**Commercially uncongested**	**Feasible in RT**
Nodal	System: 24,110 (-10.2%) North: 13,684 (+32.6%)	Y	System: 9,527 (-64.5%) North: 9,527 (+2.9%)	Y
BAU	System: 26,781 (-0.3%) North: 10,250 (-0.7%)	N	System: 9,675 (-0.1%) North: 9,250 (-0.1%)	N
A1	System: 26,854 (0%) North: 10,323 (0%)	Y	System: 9,681 (0%) North: 9,256 (0%)	Y

A2	System: 26,854 (0%) North: 10,323 (0%)	Y	System: 9,681 (0%) North: 9,256 (0%)	Y
A8	System: 27,170 (+3.1%) North: 10,639 (+1.2%)	Y*	System: 9,938 (+2.8%) North: 9,513 (+2.7%)	Y*

The table indicates the cost of each approach, as well as its relative performance compared to approaches A1 and A2, which we consider the benchmark for our analysis, since these are the most efficient dispatch options under the constraint of zonal pricing. We point out the following observations:

- Nodal pricing achieves a superior welfare.
- The BAU approach performs seemingly better in terms of cost, both for the overall system as well as for the Northern zone. However, this is an artefact of the fact that the BAU dispatch is actually not feasible for the network.
- Approaches A1 and A2 attain identical performance. Indeed, it turns out that the final dispatch of resources is identical in both approaches. This is driven by the fact that the MARI clearing step in both approaches is fixing southern resources to identical schedules. Both approaches will arrive at an efficient dispatch of Northern resources given day-ahead commitment of inflexible resources and given southern schedules, and therefore the efficiency of both approaches is also identical. **This is specific to our illustrative examples, and cannot be generalized as an observation**.
- Let's notice that, despite what is concluded by the analysis of the toy example, **in theory, A2 would be expected to be more efficient than A1**, as the MARI bids in A2 already contain implicit information on congestion while in A1, the congestion are fully solved in the post-MARI corrections which could intuitively lead to costlier actions. The reason is that there is an irrevocable decision of net position that is made in MARI. For example, we can imagine a case where MARI would activate a bid at 20€ (located in the North) and then would need to correct it afterwards with a bid of 80€ (located in the North), while if it would have known it in advance, it would have activated a bid at 40€ (located in the South) in the first place. This is not shown in our toy examples, but would in practice happen and would likely be more visible on a broader test set.
- Approach A8 exhibits notable efficiency losses, both from a system level, as well as for the North in particular. This observation is consistent for both stress tests.

We note that the efficiency results based on truthful bidding cannot be conclusive, and instead **it is important to examine the influence of the different designs on gaming behavior of agents. Under strategic behavior, the efficiency results can be substantially different**.

0.5.2 TSO payments and revenues

We summarize the TSO cash flows (a positive number means a revenue, a negative number means a payment) in the following table. For the "Nodal" entries, the "MARI" column corresponds to a real-time dispatch with a nodal model, as shown in section 1 of the present report. The "Business as usual" entry corresponds to application of MARI market clearing, without post-MARI corrections. This is what would effectively occur if neither of the approaches would be implemented. This entry effectively amounts to the MARI congestion revenues that are collected in approach A1. Since the BAU approach is in fact not feasible for the network, there will be additional redispatch costs involved in the BAU approach that we do not quantify in this analysis.

	Commercially congested DA			**Commercially uncongested DA**		
	MARI	**Post-MARI**	**Total**	**MARI**	**Post-MARI**	**Total**
Nodal	1,070	N/A	1,070	94	N/A	94
Business as usual	0	N/A	0	438	N/A	438
Approach A1	0	-73	-73	438	-6	432
Approach A2	1,080 ('BSP-N')	-1,073	7	1,350 ('BSP-N') + 388 (cong rev)	-1,261	477
Approach A8	-475	0	-475	61	0	61

We note that approach A2 results in the highest TSO revenues in the commercially congested case, whereas the contrary is the case in the commercially uncongested case. On the one hand, the net of the 'BSP North' activation and the nodal uniform payments after disaggregation generate a slight surplus for the Northern TSO, i.e. the TSO collects slightly more in MARI as an 'aggregate North BSP' than it pays out to its domestic BSPs for disaggregation. On the other hand, the congestion revenues collected by the Northern TSO are slightly higher in A1 than in A2 in the commercially uncongested case, and identically equal to zero in the commercially congested case.

In approach A1, the Northern TSO has a slight financial exposure at the post-MARI phase, since post-MARI settlements are typically towards more expensive BSPs being dispatched up and paid as bid, while cheaper BSPs are being dispatched down and pay the TSO as bid. This creates a slight financial deficit for the TSO, which is added to its congestion surplus from the MARI clearing stage.

Approach A8 is the least favorable towards TSO revenues. In the commercially congested case, the payment at the MARI stage is dominated by payments to BSP G3, which are due to the change in network model. In fact, there is no congestion rent associated with the inter-zonal links in the commercially congested case: the negative congestion rent originates from the fact that more expensive BSPs are activated upwards, whereas cheaper BSPs are activated downwards. Similarly, for the commercially uncongested case the performance of approach A8 is lower than the competing methods.

0.5.3 Gaming Opportunities

All the models presented above ultimately rely on a nodal representation of the grid, which is conceptually appropriate given the intra-zonal congestions that need to be solved before real-time. Though, a zonal model is used for all the preceding timeframes (i.e. day-ahead, intraday and cross-border balancing).

This discrepancy in pricing zone definitions undeniably induces challenges in terms of INC-DEC possibilities. This issue has been well-documented by Hirth (2019)[1], although in a slightly different context. We undoubtedly consider this paper as a must read.
In a nutshell, the paper explains, in case an asset can be traded on different markets with different price delineations, the consequences of the natural incentive to exploit the price differences between these markets, especially when congestions are highly predictable. Consequently, and even in the full absence of market power, inc-dec gaming may easily occur and actors can in effect exacerbate the congestions and increase asset revenues through windfall profits (which are typically paid by the grid users through the tariffs): in regions of scarcity, the bidders will have incentives for underbidding and so to withhold capacity; while in regions of oversupply, the market parties will have incentive for overbidding and so to overproduce - these two behaviours aggravating the congestion.

It is important to realize that it is the discrepancy between the zonal DA spot market and the nodal balancing/redispatch mechanism which is the cause of the phenomenon, and that consequently, INC-DEC is thus generally unavoidable as long as such a discrepancy exists. As such, the opportunity is already currently existing in the internally congested Norwegian areas. Nevertheless, in what follows, we focus on the differences of the different proposed approaches in order to identify whether some approaches are more prone to abuse than others.
Note that Hirth paper [6] suggests two plausible ways forward for addressing the concern: either implementing full-fledged nodal pricing in all time frames, or relieving intra-zonal congestion through regulatory redispatch with cost compensation.

In what follows, we highlight the differences in the way each of the approaches is vulnerable to gaming.

Approach A1

In approach A1, the first step consists of a "normal" MARI execution, where marginal cost bidding is the theoretically optimal bidding strategy and where intra-zonal congestion is not considered whatsoever. The same bids are then used in step 2 to correct the dispatch and make it feasible.
Because the settlement of step 1 completely ignores the possible upcoming congestion patterns (while they can often be anticipated by the asset owners), and because there are effectively **two distinct settlements** for step 1 and step 2, INC-DEC between MARI and post-MARI stages is in principle possible under approach A1. One may indeed "force" an activation in step 1 (paid-as-cleared) by submitting an overly optimistic price, while anticipating to be deactivated in step 2 (paid-as-bid) because of a local congestion. The windfall profit will in this case be the infra-marginal rent acquired in step 1. This is further illustrated on an example below.

[1] https://ideas.repec.org/p/zbw/esprep/194292.html

Let's notice that such windfall profits are prevented, or largely mitigated, in approaches A2 and A8 as by design the network constraints are taken into account before MARI and because there is a unique settlement.

However, despite approach A1 is vulnerable to such types of gaming, let's notice that using the same bids in the two steps makes it somewhat harder to play INC-DEC: a bidder who oversells in MARI and is bought back in the redispatch step can only make a windfall profit in case he has obtained an infra-marginal profit in the step 1. This implies that the marginal price of his price zone is set by another bid further down in the merit order.
If we assume that the grid is uncongested prior to the MARI process, and that MARI activation volume is typically thin, an INC-DEC strategy might be risky compared to the small expected gains.

If the grid suffers from congestion prior to MARI, INC-DEC is definitely possible against the day-ahead market. This latter point can not be resolved with any approach focusing only on MARI-related processes.

Approach A2

Approach A2 probably creates better incentives than paying the disaggregated instructions at the MARI price and using pay-as-bid settlements for any deviations between disaggregated dispatch and the MARI price signal, as was the case in A1. This is because the **A2 approach already largely takes into account the likely congestions** when computing the residual supply function. For example, a bid that has no chance to remain activated at the end will simply not be included in the residual supply function, and therefore can not be activated in MARI. The volumes of corrections required after the MARI process are therefore more limited.
In particular, if the grid is uncongested prior to MARI, and if imbalances are generally speaking unforeseeable (at least for those out of the control of the asset owner, e.g. imbalances in another country), INC-DEC gaming becomes very challenging and risky: not only is it visible
As for any other approaches, if the grid is congested prior to the MARI process, INC-DEC gaming opportunities with the spot market exist and can hardly be resolved.

Approach A8

An important property that mitigates gaming the MARI / post-MARI step in approach A8 is the fact that the approach produces nodal prices at the MARI clearing stage. However, we note that both approach A8 as well as A2 effectively produce a different price for the same location when moving from day ahead to real time (due to the *explicit* change in network model in A8, and the *implicit* change in network model in A2), and this may have undesirable effects in terms of extracting liquidity from the day-ahead market in case asset owners believe that their assets are better valued in real time.

0.5.4 Settlement rules & pricing

The following table summarizes the settlement rules that has been implemented in this report for the different steps of each approach:

	MARI step	Post-MARI step
Approach A1	Zonal pay-as-cleared	Pay-as-bid (out of market correction, same bid as in MARI)
Approach A2	Zonal pay-as-cleared (on the aggregated residual supply curve)	Pay-as-bid (desegregating the residual supply curve)
Approach A8	Nodal (for Norway) pay-as-cleared	Pay-as-bid (same bid as in MARI)

0.5.5 Legal aspects and political acceptability

The following discussion on legal aspects is based on the examination of regulation 2017/2195 (the electricity balancing guideline / EBGL), and how it interacts with each of the approaches. There are consistent statements in the EBGL which raise encouraging signals but also potential challenges with each of the approaches.

ALL

1. Compatibility with operational security and network constraints. The way in which zonal modeling is implemented in MARI and PICASSO may contradict the requirement of the EBGL for ensuring operational security and satisfaction of network constraints through the balancing procedures. This requirement for operational security is expressed in articles 0(14), 0(18), 3(1c), 3(2d), 3(2f), 31(1b), 58(4a), 58(4b).

Approach A1

Approach A1 relies on out of market (OOM) corrections to the MARI result. These OOM corrections rely on side payments which are typically paid as bid. <u>The question is whether such side payments are acceptable according to the EBGL</u>.

1. Economic efficiency objective. There are articles in the EBGL which emphasize the fact that balancing should promote economic efficiency. This may challenge the objective of minimizing deviations in the post-MARI step. This is reflected in articles 0(6), 2(1), 3(1e), 3(2c).

2. Transfer of balancing capacity. The post-MARI process whereby one BSP activation is excluded and counteracted with the activation of another one could be interpreted (loosely) as a transfer of balancing capacity. Transfer of balancing capacity is defined in articles 2(26), 34(1). However, it is not clear whether the interpretation of this transfer of balancing capacity is compatible with the timelines envisioned for transfer of balancing capacity, as explained in article 34(2).

3. Level playing field. We have explained in the report why the post-MARI step may be susceptible to INC-DEC gaming. By contrast, the EBGL stipulates rules that lead to a level playing field, see article 3(1f).

4. Deviations from merit order. Deviation from the common merit order list activation is foreseen through fallback procedures. These are discussed in articles 28(3), 29(5), 31(11). It is clarified in article 30(1b) that out of merit actions shall not set the marginal price, which justifies the side payments proposed under this approach.

Approach A2

Approach A2 relies on the Norwegian TSO representing its BSP bids as an aggregate BSP in MARI, and then disaggregating the MARI results to its domestic BSPs. The question is whether this aggregation / disaggregation procedure is compatible with the EBGL. It is possible that a similar approach has been adopted in Poland, it may eventually be worth for Statnett to exchange views with the Polish TSO.

1. Merit order. The fact that approach A2 produces a merit order list for MARI is consistent with EBGL requirements on submitting merit order lists in order to ensure cost-efficient activation of bids. Relevant articles are 0(11), 21(3k).

2. Compatibility with TSO-TSO model. The definition of a TSO-TSO model is one in which the BSPs interact with non-domestic TSOs through their domestic TSO (as opposed to directly). This seems compatible with what is being proposed in A2. Relevant article is 2(21).

3. Forwarding BSP bids to the platform. There are certain provisions in EBGL which suggest that the TSO is required to forward its domestic bids directly to the platform. These provisions may be at odds with the aggregation that is being proposed in the pre-MARI step of approach A2. Relevant articles are 2(38), 12(b), 16(2), 21(6a), 29(9), 33(3). Limitations on this practice are foreseen, subject to regulatory approval, in article 5(4e).

4. Integrated scheduling process in central dispatching. There are explicit provisions in the EBGL regarding the conversion of bids, by TSOs operating an integrated scheduling process within a central dispatching context. The conversion of bids from an integrated scheduling process is discussed explicitly in articles 12(3c), 12(3d), 18(8d), 27(3). TSOs that wish to apply a central dispatching model need to notify the relevant regulatory authority, as foreseen in article 14(2).

Focusing on article 27(3), the text reads as follows:

Each TSO applying a central dispatching model shall convert as far as possible the integrated scheduling process bids pursuant to paragraph 2 into standard products taking into account operational security. The rules for converting
the integrated scheduling process bids into standard products shall:
(a) be fair, transparent and non-discriminatory;
(b) not create barriers for the exchange of balancing services;
(c) ensure the financial neutrality of TSOs.

One concern about this interpretation is that the spirit of these provisions is to allow the mapping of bids submitted in a unit commitment tool to bids that are submitted to an exchange. Concretely, the integrated scheduling process receives information about startup cost, min up/down times, ramp rates, technical minima, min load cost, etc., whereas the balancing platforms will require much simpler bids which internalize many of these factors. Therefore, the interpretation of the integrated scheduling process articles as a means of avoiding congestion could be challenged.

Approach A8

Approach A8 relies on defining a finer resolution for the MARI model, and then possibly resorting to out of market corrections with side payments in order to settle congestion problems. The question is whether the post-MARI settlements are compatible with legislation, and whether a different zonal model can be used in MARI.

1. Consistency between zonal day-ahead model versus zonal MARI model. The EBGL requires consistency between zonal models in the day-ahead, intraday and balancing timeframe. This is reflected in articles 0(5), 3(1d), 30(1e). In this perspective, A8 could be in contradiction with EGBL unless DA and ID are also modelled through a nodal representation.

2. Economic efficiency objective. There are articles in the EBGL which emphasize the fact that balancing should promote economic efficiency. This may challenge the objective of minimizing deviations in the post-MARI step. This is reflected in articles 0(6), 2(1), 3(1e), 3(2c).

3. Transfer of balancing capacity. The post-MARI process whereby one BSP activation is excluded and counteracted with the activation of another one could be interpreted (loosely) as a transfer of balancing capacity. Transfer of balancing capacity is defined in articles 2(26), 34(1). However, it is not clear whether the interpretation of this transfer of balancing capacity is compatible with the timelines envisioned for transfer of balancing capacity, as explained in article 34(2).

4. Level playing field. We have explained in the report why the post-MARI step may be susceptible to INC-DEC gaming. By contrast, the EBGL stipulates rules that lead to a level playing field, see article 3(1f).

5. Multiple common merit order lists. The separation of the MARI model into more granular zones introduces additional common merit order lists. Multiple common merit order lists are foreseen in the regulation in article 25(3b).

6. Deviations from merit order. Deviation from the common merit order list activation is foreseen through fallback procedures. These are discussed in articles 28(3), 29(5), 31(11). It is clarified in article 30(1b) that out of merit actions shall not set the marginal price, which justifies the side payments proposed under this approach.

0.5.6 Uncertainty

There is a generic aspect of uncertainty, which relates to all approaches. (i) We do not know the details of the neighboring networks (i.e. where the MARI requests and activations take place). (ii) In general, we also do not have access to imbalance measurements at a nodal resolution.

Regarding the first aspect, we assumed that the Northern TSO can measure left-over capacity in its lines before resorting to post-MARI corrections. This assumption is clearly optimistic. Regarding the second aspect, Statnett has explained their disaggregation procedure and considers the assumption of observable nodal imbalances to be acceptable even if not perfectly precise in practice.

Approach A1

Step 2 of A1 benefits from perfect hindsight regarding the results of the MARI platform, as well as the upcoming imbalances. Therefore, A1 can be seen as robust towards uncertainty, since the optimal power flow that is being solved in step 2 (post-MARI) has all information available for selecting an optimal dispatch from the point of view of Statnett. Nevertheless, as approach A1 doesn't do anything beforehand to solve possible upcoming issues, it somehow assumes that all possible issues arising from MARI could in theory be solved afterwards. This might not be the case and solving all the issues afterwards might turn out to be infeasible at the end.

Approach A2

The flows induced by non-Norwegian injections can be estimated based on information that is monitored locally by the Norwegian TSO. Therefore, Statnett can estimate the input that is required for the execution of the residual supply function estimation without the need for explicit communication with other TSOs.

Approach A8

Step 1 of A8 involves the estimation of zonal network parameters. The uncertainty that the system operator faces regarding real-time demand across the network implies that the zonal network parameters of MARI may be chosen such that the clearing of MARI could cause congestion to the Norwegian network.

0.5.7 Complexity

By complexity, we mean here the complexity of implementing the whole process implied by the approach.

Approach A1

Three main appealing attributes of approach A1 are the fact that (i) the zonal network of MARI is consistent with that of the day-ahead market, (ii) there are relatively minor changes (if any) in the post-MARI dispatch, and (iii) the net position of the Northern zone is unchanged in the post-MARI step. On the other hand, the post-MARI step actively overrides the MARI results. Therefore, we assign a high, but not perfect, score to approach A1 in terms of implementation complexity.

Approach A2

Intuition suggests, and numerical experiments confirm, that approach A2 can perform well even if there are inaccuracies in the estimation of the residual supply function. The intuition for this behavior is that, as long as the marginal cost of the aggregate Norwegian network is estimated reasonably at the optimal point of dispatch, then the post-MARI disaggregation ensures that this aggregate net position is sourced optimally within the Norwegian network without violating its local constraints.

Approach A8

A significant element of complexity in A8 relates to the definition of the zonal network in MARI, which is far from obvious. Certain links in the ATC model of MARI may be associated with physical lines (within Norway or inter-zonal), and may therefore admit relatively obvious values. For other links (inter-zonal MARI links which correspond to physical lines), the capacity that should be assigned is not obvious, and this will in general impact the pricing results of

MARI. The same general observation applies to the model that is used for representing linearized power flows in the Northern network. Two possible choices here are based on GSKs and susceptances, and in general both may result in a market clearing within MARI which would not allow the Northern TSO to restore feasibility after MARI.
Another significant element of complexity in A8 relates to the fact that the activations within MARI may exceed significantly the actual level of imbalances that is occurring in the system. Effectively, MARI reacts to the fact that the MARI zonal network model appears to be different from the day-ahead zonal network model. Thus, it may turn out that resources are being activated more in response to the different network model and less for the sake of relieving imbalances in the system.

0.5.8 Assessment of ICT issues

The following table summarizes the ICT requirements of each approach.

Approach A1	Step 2: Solution of a nodal optimal power flow restricted to the Norwegian zone *after* MARI (time critical).
Approach A2	Step 1: Estimation of non-Statnett injections based on previous Norwegian line flow measurements and Norwegian net injections (e.g. day-ahead or previous imbalance interval) Step 2: Estimation of residual supply function based on repeated solution of multiple OPFs, using results of step 1 as input. Can be computationally challenging in case of multi-dimensional residual supply functions. Step 4: Estimation of non-Statnett injections based on previous Norwegian line flow measurements and Norwegian net injections, in **real time, <u>after</u> MARI activation**
Approach A8	Step 1: One significant issue is the ICT complexity of transferring more or less on line Scada data to the MARI platform. Indeed, this implies a technical issue, but also an ICT security issue, as these are highly confidential data, which means getting the approval for that might be difficult. Step 4: Solution of one nodal optimal power flow problem restricted to the Norwegian zone *after* MARI (time critical). In a GSK approach, the results of the previous imbalance interval dispatch may need to be communicated to the MARI platform in order to compute the GSKs for the upcoming interval.

0.6 Main conclusions

The following table summarizes the comparison of the different approaches. The table assigns a score to each approach along each dimension of analysis. The scores range from '- -' (lowest possible ranking) to '+ +' (highest possible ranking). A score of '0' indicates the medium ranking.

Of course, let's bear in mind when reading the table that the different dimensions should not have the same weight. Furthermore, two additional criteria, not investigated in this report but which might bring some valuable insight have been added at the end of the table.

	Approach A1	Approach A2	Approach A8
Economic efficiency	0	+	0
Robust to **Gaming**	--	+	+
Financial neutrality of the **TSO**	+	+	-
Compatibility **with MARI processes**	+ +	+ +	- -
Political acceptability	+ +	+	-
Compatibility with **EU legislation**	+	-	- -
Robust to **Uncertainty**	-	+	+
Keep **Complexity** manageable	+	0	+
Manageable **ICT issues**	+	0	-
Compatible to **TSO / DSO coordination**	0	++	0
Generate proper **grid investment** incentives	-	+	+

0.7 Further work

In this report, we developed, analyzed and compared three approaches to mitigate and solve the possible congestions that could result from activations in MARI. Nevertheless, it should be noted that these "three approaches" should in fact be understood as "three families of approaches" for which one instance has been implemented in this report. It means that within each of these families, multiple variations are possible and therefore, if the main differences between these families have been correctly highlighted in the report, some more nuances remain to be explored within each family and could therefore lead to further work.

In particular, there are outstanding open questions that remain on some of these approaches and more specifically on approach A2 which, based on the analysis, seems to be really attractive but is also conceptually complex and is a broad topic in itself. Furthermore, there are overall some *quantitative* insights which are missing in the analysis, as it relies on a 6-node example. This is further detailed in the section 6 of this report.

1 Introduction

1.1 Outline of the analysis

In the first phase of the project, we proposed various designs that were short-listed by Statnett. The approaches that were short-listed by Statnett are the following:

- *Approach A1: BSPs represented individually within MARI*. According to this approach, individual BSPs are bid directly into the MARI platform. Since the activation that takes place in the platform may cause violations in the Norwegian network, Statnett may need to resort to corrective actions after MARI clears, in order to restore feasibility within its network.
- *Approach A2: BSPs aggregated in MARI*. According to this approach, Norwegian BSPs are aggregated by Statnett into a system-wide residual supply function, which is bid as a single aggregate BSP in the MARI platform. The MARI platform then determines activation of the "virtual" bids as well as a net position for the Statnett zones, which is disaggregated by the Norwegian operator to individual BSPs within the Norwegian network, such that the network constraints of Statnett are respected.
- *Approach A8: Nodal Norway in MARI*. According to this approach, the MARI platform uses a representation of the Norwegian system with a nodal resolution. Post-MARI corrections relative to the MARI dispatch may be required.

Let us notice that somehow all these approaches suffer from a **certain level of uncertainty** (cf. “uncertainty” dimension below) as they will rely on certain assumptions (including foreign network flows, imbalance location, etc.). This means that, in any case, **some corrective actions might be needed after the MARI clearing results are revealed**. **But, while approach A1 fully relies on these corrective actions, approaches A2 and A8 attempt to precede them with some preventive actions which attempt to mitigate the corrections that are required afterwards**. Let us also stress that this re-dispatch might not be needed, depending on the feasibility of the dispatch of MARI. In this sense, approach A2 substantially differs from A1 and A8 as A2 inherently implies some necessary actions after MARI, while the others only include an “optional” step of re-dispatch after MARI.

In this phase, we first provide a detailed description of each design and its timeline, as well as a discussion of the interaction of each approach with MARI. This comes together with an illustration of each approach on the stress test examples. This assumes truthful bidding as gaming is discussed in a dedicated section.
We then analyze and compare each of the three short-listed approaches along the following dimensions:

- *Settlement rules & pricing*: this dimension discusses the pros and cons of the different pricing rules that can be implemented for each approach and puts forward the most appropriate one.
- *Economic efficiency*: the discussion here focuses on welfare. In order to establish a consistent basis for comparison, we will consider the efficiency of the entire system, without limiting our attention to the Norwegian zone. Cases where the final outcome violates constraints out of the Norwegian zone are pointed out.

- *Payments for TSO*: this dimension analyzes the financial exposure of the TSO. Concretely, we are interested in the payments of the TSO to (i) the MARI platform, and (ii) any side payments associated with corrective actions *after* the clearing of MARI.
- *Uncertainty*: this dimension discusses the exposure of each approach to parameters that need to be forecast by TSOs.
- *Complexity*: this dimension analyzes the procedural complexity of each approach.
- *Assessment of ICT issues*: this dimension discusses computational, algorithmic, and other ICT related issues.
- *Gaming opportunities*: this dimension discusses the vulnerability of the different approaches to gaming.
- *Political, regulatory and legal*: this dimension evaluates the political, regulatory and legal issues linked to the different approaches. Indeed, the disruptiveness of an approach, while being very efficient economically, could also raise political or legal concerns. This dimension includes the analysis of the characteristics of each approach against the main requirements in the market network codes (compatibility of each proposed approach against the EU guidelines).

1.2 Recalling the Chao-Peck example

In this section we recall the Chao-Peck example that has been used in phase 1. We will use this example to illustrate how the activation of reserves within MARI may cause congestion in real time, and how a nodal dispatch can avoid such an outcome. We consider two stress tests, (i) a ***commercially congested stress test*** in which the North-South capacities are congested in the day-ahead time stage, and an imbalance occurs in the North, and (ii) a ***commercially uncongested stress test*** in which the North-South link has available capacity, and an imbalance occurs in the South. In this simplified example, the **Norwegian system corresponds to the Northern zone**, whereas the rest of the system corresponds to the Southern zones.

1.2.1 Resources

On the generation side, the supply functions are shown in the following figure.

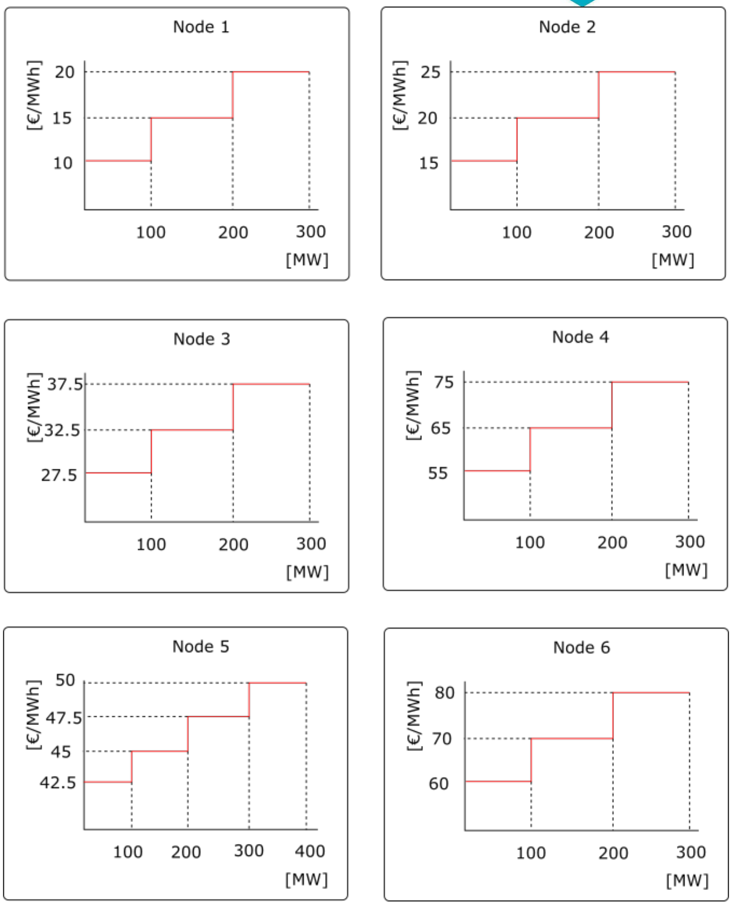


Figure 1: The marginal cost curves used in the Chao-Peck example.

The Chao Peck example has demand in nodes 3, 4, and 6. We will assume that consumers behave as price takers (VOLL of 1000 €/MWh) in our analysis. On the demand side, we will consider two possible scenarios, based on the input that we have received from Statnett.

In the **commercially congested exporting scenario**, the demand in the Northern zone, South-1 zone and South-2 zone is 300 MW each. This will result in an export of power from the North zone to the Southern zones. We will then introduce an imbalance in the Northern zone, and we will show how a MARI activation can result in internal congestion in the Northern zone.

In the **commercially uncongested exporting scenario**, the demand in the Northern zone remains equal to 300 MW, while in the South-1 zone and South-2 zone the demand is reduced to 100 MW each. This will still result in an export of power from the Northern zone to the Southern zones, but with space left available on the North-to-South ATCs. We will then introduce an imbalance in the Southern zones, and we will show how a MARI activation can again result in internal congestion in the Northern zone.

1.2.2 Nodal model

We use the following line limits and PTDF matrix in our model.

			PTDF					
Line	**Limit (MW)**	**Susceptance**	**1**	**2**	**3**	**4**	**5**	**6**
1-2	125	1	0.088	-0.530	-0.105	0.030	-0.020	0
1-3	180	1.5	0.279	-0.011	-0.332	0.094	-0.064	0
1-4	300	1.6	0.634	0.540	0.437	-0.124	0.084	0
2-3	170	0.9	0.088	0.470	-0.105	0.030	-0.020	0
3-5	200	1.1	0.366	0.460	0.563	0.124	-0.084	0
4-5	125	1.3	0.160	0.095	0.023	0.329	-0.223	0
4-6	125	0.95	0.474	0.446	0.414	0.547	0.307	0
5-6	270	1.4	0.526	0.554	0.586	0.453	0.693	0

Table 1: Network data of the Chao-Peck example.

1.2.3 Zonal model

The six-node network is partitioned into a north zone that has cheap generation and two south zones which have more expensive generation. We impose an ATC limit for the zonal model with **conservative** choices for capacity values. Concretely, the capacities of the ATC links are chosen as follows[2]: 150 MW for link N-S1, 100 MW for link N-S2, and 62.5 MW for link S1-S2.

[2] Note that, if we were to select the minimum of any inter-zonal link between adjacent zones, we would have to choose 300 MW for link N-S1, 200 MW for link N-S2, and 125 MW for link S1-S2. Interestingly, this choice of capacity values results in congestion, when the physical flows implied by the zonal day-ahead solution are computed. Therefore, we derate these capacities even further (to one half of the above capacities), until we arrive at a physically implementable day-ahead zonal solution.

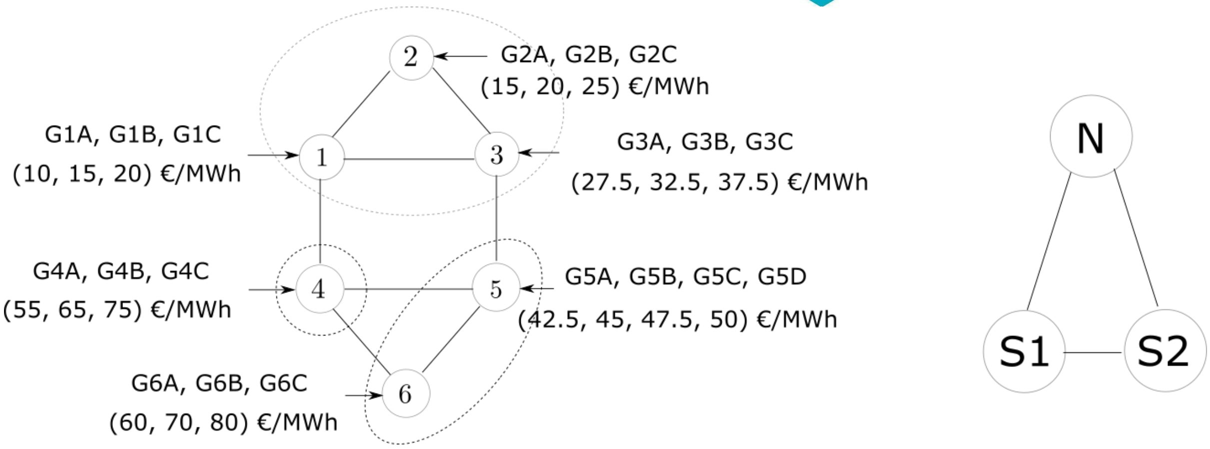


Figure 2: A modified version of the Chao-Peck 6-node example.

1.3 The stress tests

We will consider a variation of the model where we have the following sequence of events:

- A day-ahead zonal market clears
- The schedules of *individual resources* (as opposed to the zonal positions) are fixed to the day-ahead outcome for the balancing stage

In the balancing stage, a *subset* of the resources are activated. Note that, for the sake of the numerical illustrations, we will assume that we can observe imbalances at a nodal level. This assumption is somewhat optimistic but adequate for the need of this analysis. In practice, Statnett disaggregates zonal imbalances to forecasts of nodal imbalance. Concretely, the zonal imbalance is translated to an imbalance in demand and in renewable generation. This aggregate demand / renewable imbalance is then distributed to nodes in proportion to the installed capacity of load and renewable resources.

1.3.1 Zonal market clearing: commercially congested exporting scenario

The zonal market outcome is producing a northern zonal price of 25 €/MWh, a price of 55 €/MWh for Southern zone 1, and a price of 47.5 €/MWh for Southern zone 2. Both ATC links from north to south are fully congested, which is why we refer to this scenario as the commercially congested exporting scenario. The dispatch is shown in the following figure.

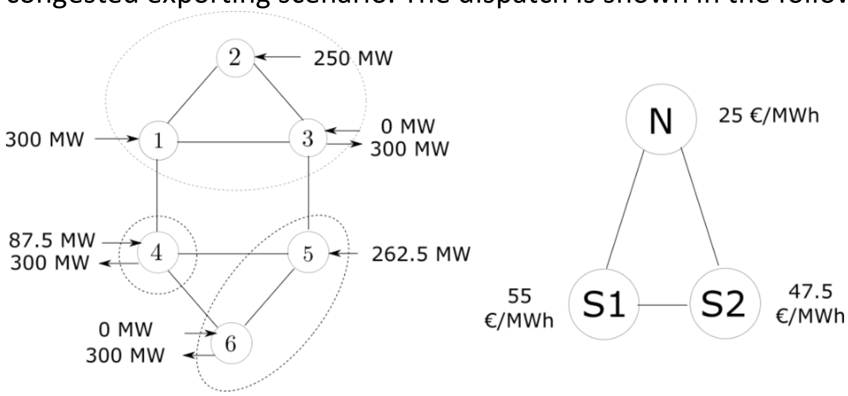


Figure 3: The zonal day-ahead market clearing dispatch and prices for the commercially congested export scenario.

The day-ahead positions imply a certain physical flow, which we compute by using the DC (linearized) power flow equations. Note that it is perfectly possible that we get price separation in the zonal model due to the fact that the ATC-based link is used at its full capacity, even if the actual network has no inter-zonal or intra-zonal congestion[3]. To see this trivially, note that we could set the capacity of the north-south link to 0 MW.

Suppose now that an imbalance of -40 MW occurs in the Northern zone (the convention is that negative imbalance implies additional demand which appears in real time). We assume that imbalance is due to unpredictable changes in demand, therefore the imbalance is distributed uniformly across all nodes of a zone which have demand (in the case of this example, the imbalance is fully located in node 3). We will assume that all loads are fixed in real time, and that only the generators can change their production in response to imbalances.

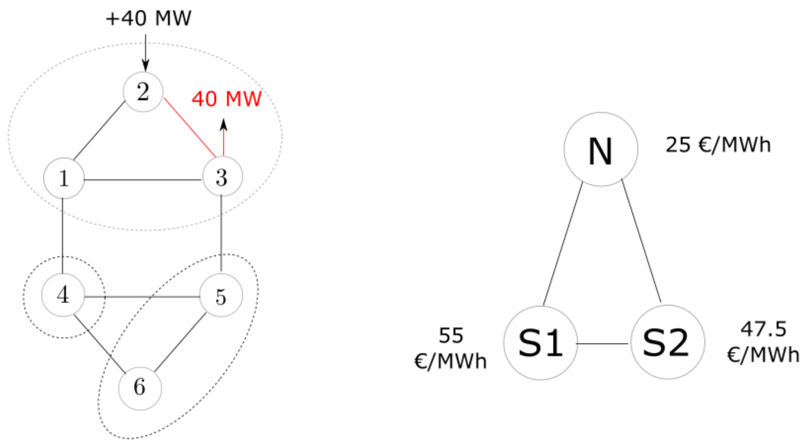


Figure 4: Balancing with a zonal model in the North-South commercially congested scenario. Violated line constraints are indicated with red in the left.

The zonal solution responds to this imbalance by activating +40 MW of production from location 2, which results in a physical overloading of line L23. The solution is shown in the figure above.

The welfare maximizing nodal balancing solution is presented in the following figure. Note that the flow on line L23 is 170 MW, which is exactly the flow limit of the line.

[3] This phenomenon is strongly related to N-1 assumptions. There might also be N-1 violations within the detailed grids, which are indeed one of the major challenges of Statnett at the moment.

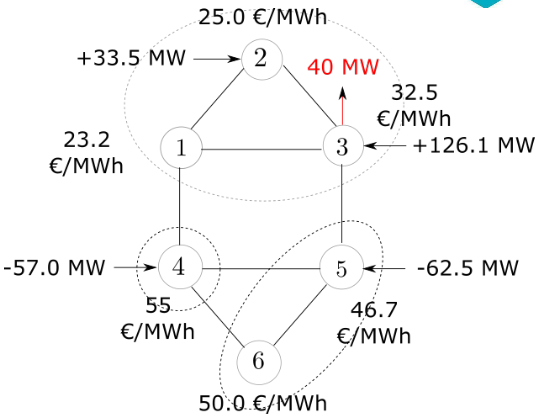


Figure 5: Balancing with a nodal model in the commercially congested scenario.

Settlements and the financial exposure of the Northern TSO are an important part of our analysis. As a benchmark, we present in the following table the settlements of the producers (which we consider as equivalent to balancing service providers), loads (which we consider as equivalent to balancing responsible parties) and transmission system operators. There are two assumptions that we adopt in order to develop the following settlement tables:

- Balancing responsible parties are exposed to an imbalance charge which is equal to the balancing price that the balancing platform pays out to balancing service providers. (NB: In a nodal system, the LMP price is also the imbalance price for that node).
- The total congestion surplus in the day ahead and balancing time frame is shared equally (50-50) between the Northern TSO and the Southern TSOs. An alternative could be to split the congestion surplus of each link evenly between the adjacent TSOs. This more realistic simulation can be considered in a possible extension of the analysis to a 44-node system (this is further detailed in section 6 where some suggestions for further work are highlighted, among which a more extensive simulation with a 44 nodes system).

Based on these assumptions, we record the following settlements for the case of the commercially congested stress test.

	Day-ahead	**Balancing**	**Total**
G1 (BSP)	7500	0	7500
G2 (BSP)	6250	838	7088
G3 (BSP)	0	4098	4098
L3 (BRP)	-7500	-1300	-8800
South BSP	17281	-6054	11228
South BRP	-30750	0	-30750
North TSO	3375	1070	4445
South TSO	3844	1350	5194

Total	0	3	3

Table 2: Settlements under nodal balancing in the commercially congested scenario.

Note that the sum of settlements across all agents sums up to zero. This is due to the fact that any congestion surplus generated by the day-ahead and balancing auctions is collected and split between the system operators. The day-ahead zonal auction generates a non-zero congestion surplus since the North-South zonal links are commercially congested, and price separation occurs. The same is true for the nodal balancing model: physical congestion occurs in the system, and the TSOs split congestion revenues at the balancing stage. Any non-zero entry in the last row is due to rounding error, since we only consider prices up to one significant digit when computing congestion rents for TSOs.

The welfare breakdown of the nodal solution is presented in the following table. Identical tables are produced for all the approaches throughout the report. The computations assume that all demand, including the imbalance in real time, is valued at VOLL (Value of Lost Load), which we have assumed to be equal to 1000 €/MWh. Note that, insofar as the last row of the table is concerned, the only entry that changes between the different approaches that are analyzed in the report is the second column (BSP cost), since all demand is satisfied under all approaches, and also the payments net out to zero under all approaches. Thus, when comparing welfare between the different approaches, we may as well focus our attention on producer cost. Note also the dual interpretation of welfare which is evident in this table as sum of BSP/BRP/TSO profits or difference between consumer value and producer cost.

	Producer (BSP) cost	**Consumer (BRP) value**	**Total revenue / Cost**	**Surplus**
G1 (BSP)	4500	N/A	7500	3000
G2 (BSP)	5586	N/A	7088	1501
G3 (BSP)	3597	N/A	4098	501
L3 (BRP)	N/A	340000	-8800	331200
South BSP	10426	N/A	11228	801
South BRP	N/A	600000	-30750	569250
North TSO	N/A	N/A	4445	4445
South TSO	N/A	N/A	5194	5194
Total	24110	940000	3	915893

Table 3: Welfare breakdown under nodal balancing in the commercially congested scenario.

1.3.2 Zonal market clearing: commercially uncongested exporting scenario

In order to capture additional concerns brought up by Statnett, we now consider the case where the North-South link is not congested before balancing, and an imbalance occurs in the South. The dispatch is shown in the following figure.

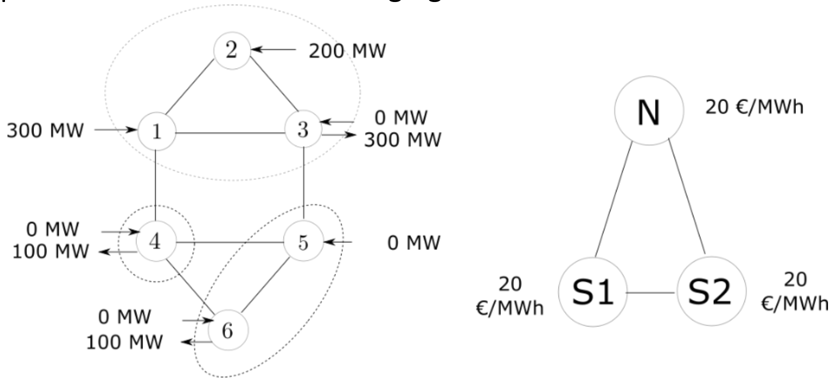


Figure 6: The zonal day-ahead market clearing dispatch and prices for the commercially uncongested export scenario.

The day-ahead positions imply a physical flow based on the DC (linearized) power flow equations. The flows resulting from the physics obey the limits of the transmission lines. Moreover, the zonal model yields a flow of 100 MW on each of the links N-S1 and N-S2, so the N-S1 ATC link remains uncongested (recall that the ATC capacity of the N-S1 link equals 150 MW), and there is a way to route more power to the South (according to the zonal model).

Suppose now that an imbalance of -60 MW occurs in the South, which is assumed to be split equally between the load in S1 and the load in S2. The zonal solution responds to this imbalance by activating +50 MW of production from location 2 (which is the cheapest resource until the cross-zonal lines are commercially congested) and then +10 MW from location 5. Despite the solution being commercially feasible according to the zonal model, it results in an overloading of line L23 (in the actual network). The solution is shown in the figure below.

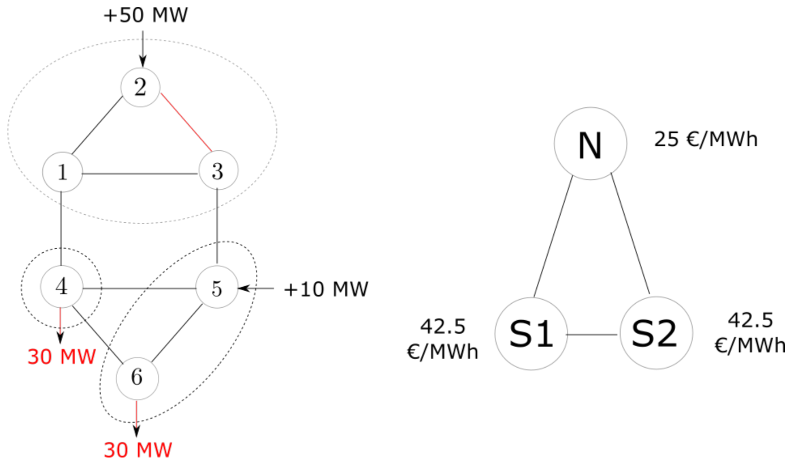


Figure 7: Balancing with a zonal model in the North-South commercially uncongested scenario. Violated line constraints are indicated with red in the left.

The nodal balancing solution is presented in the following figure. Note that the flow on line L23 is 170 MW, which is exactly the flow limit of the line. 2. In this solution, generator 2 is activated a little less, and the remainder is provided by generator 3 instead of generator 5 (which has a better effect over the line L23.)

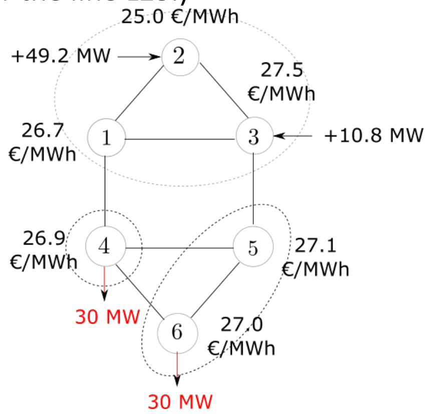


Figure 8: Balancing with a nodal model in the commercially uncongested scenario.

As in the case of the commercially congested scenario, we present the following settlement table.

	Day-ahead	Balancing	Total
G1 (BSP)	6000	0	6000
G2 (BSP)	4000	1230	5230
G3 (BSP)	0	297	297
L3 (BRP)	-6000	0	-6000
South BSP	0	0	0
South BRP	-4000	-1620	-5620
North TSO	0	94	94
South TSO	0	-3	-3
Total	0	-3	-3

Table 4: Settlements under nodal balancing in the commercially uncongested scenario.

Note that the day-ahead auction does not produce congestion surplus for the TSOs (since we are in the commercially uncongested case, and zonal prices are uniform across the entire system). By contrast, there is congestion in the physical system at the balancing stage, which generates a non-zero TSO surplus. As in the case of Table 3, any non-zero entry in the last row of the table is due to rounding error, since we are only considering prices up to one significant digit when computing congestion revenue.

The following table presents the welfare breakdown for the nodal balancing solution.

	Producer (BSP) cost	Consumer (BRP) value	Total revenue / Cost	Profit
G1 (BSP)	4500	N/A	6000	1500
G2 (BSP)	4730	N/A	5230	500
G3 (BSP)	297	N/A	297	0
L3 (BRP)	N/A	300000	-6000	294000
South BSP	0	N/A	0	0
South BRP	N/A	260000	-5620	254380
North TSO	N/A	N/A	94	94
South TSO	N/A	N/A	-3	-3
Total	9527	560000	-3	550470

Table 5: Welfare breakdown under nodal balancing in the commercially uncongested scenario.

1.4 Unit bidding and portfolio bidding

In the report, we adopted “unit bidding” notation (i.e. each unit is considered separately with its marginal cost curve) as it eases the way we keep track of the BSPs behaviour in each step of the process. Nevertheless, let’s notice that this would be perfectly translatable into a “portfolio bidding” nomenclature (i.e. where units can be aggregated into market orders). Intuitively, the BSP marginal cost curves simply have to be translated into merit orders of stepwise bids curves of both upward and downward reserve. This is further detailed in the text below.

Bidding format in day-ahead. The bids that are submitted to the day-ahead platform, and presented in figure 1, can be translated exactly to the so-called simple bid products that are used in EUPHEMIA. It is our understanding that MARI will also use simple bids[4]. For example, in figure 1 we see an increasing supply function. This can be interpreted in different ways. (i) In the physical (e.g. individual resource in a central dispatch system) sense, it could correspond to *three* different generators, each of which has a *constant* marginal cost. (ii) Also in a physical (e.g. individual resource in a central dispatch system) sense, it could correspond to a *single* generator with an *increasing* marginal cost. (iii) In the nomenclature of EU power exchanges, it could correspond to a *simple bid* for a portfolio with the following specifications (using simple bid stepwise bid curve notation):

- $(P_0, Q_0) = (10{,}0)$
- $(P_1, Q_1) = (10{,}100)$
- $(P_2, Q_2) = (15{,}100)$

[4] MARI also support indivisible bids and certain links between adjacent periods, but that is less relevant in the present context.

- $(P_3, Q_3) = (15{,}200)$
- $(P_4, Q_4) = (20{,}200)$
- $(P_5, Q_5) = (20{,}300)$

Thus, we see that portfolios or individual assets can be represented with the exact same notation.

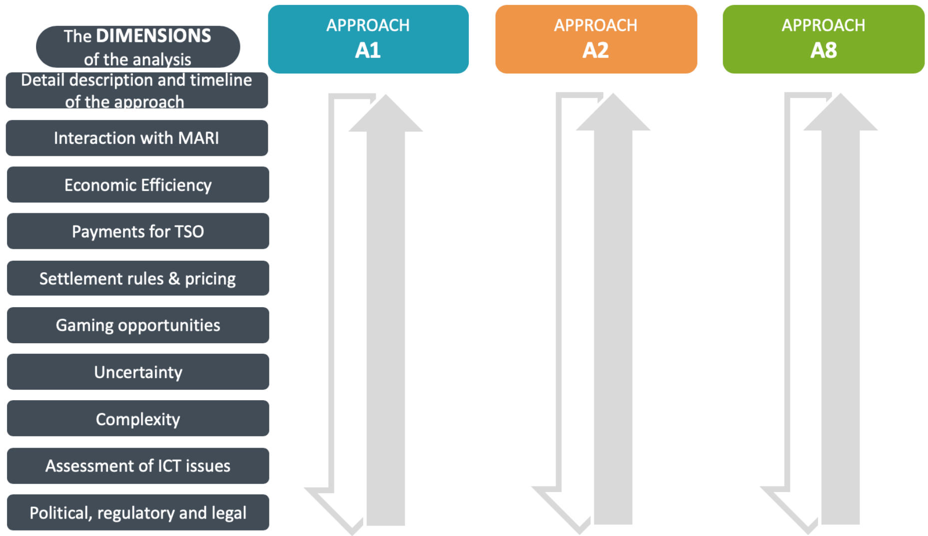
Bidding format in MARI. MARI clears for balancing actions, which correspond to *changes* in the positions of individual resources. The clearing for the setpoint of an asset or portfolio versus a change/delta is largely identical. With the day-ahead market clearing outcome that is presented in figure 3, the resources could be bid in two equivalent ways in MARI: (i) identically as in the previous paragraph (i.e. simple bid for the entire quantity), or (ii) in terms of INC and DEC offers. Let us consider, for example, how the assets in node 2 can be bid in the INC/DEC format. Recall that 250 MW have been cleared for this location in the day-ahead market. Assuming that each resource G2A, G2B, and G2C, is bid separately in MARI, then, under the assumption that bids are submitted truthfully, G2C submits (i) an inc bid of 50 MW @ 25 €/MWh (meaning it is asking to be paid at least 25 €/MWh for each additional MW of balancing upward, and provides up to 50 MW of upward balancing power) and (ii) a dec bid of 50 MW @ 25 €/MWh (meaning that it is willing to pay up to 25 €/MWh for each MW of balancing downward, and provides up to 50 MW of downward balancing capacity). Or, equivalently, if node 2 is bid as a single portfolio, then it submits an INC bid of 50 MW @ 25 €/WMh, and a downward sloping DEC bid of 50 MW @ 25 €/MWh followed by 100 MW @ 20 €/MWh followed by 100 MW @ 15 €/MWh (which is a three-segment simple bid in EUPHEMIA nomenclature).

Highlights and main conclusions

Three approaches have been selected and are investigated in this report:

- *Approach A1: BSPs represented individually within MARI*. Individual BSPs are bid directly into MARI. In case the activation causes a network violation, Statnett restores the network feasibility with post-MARI corrective actions.
- *Approach A2: BSPs aggregated in MARI*. Norwegian BSPs are aggregated by Statnett into a system-wide residual supply function, which is bid as a single aggregate BSP in MARI (so implicitly considering network constraints).
- *Approach A8: Nodal Norway in MARI*. MARI platform uses a representation of the Norwegian system with a nodal resolution.

These three approaches will be studied and compared towards several "dimensions" as illustrated below:



In order to bring a valuable insight, this comparison and analysis are supported by an illustration of the three approaches on two corner cases which are assumed to be representative of the kind of issue that can result from MARI zonal model. These corner cases rely on a modelisation where multiple bids are located in 6 nodes aggregated in MARI into 3 zones (and therefore neglecting intra-zonal network constraints) : a North zone - assumed to be Norway, and two South zones). The two corner cases are:

- **Commercially congested exporting scenario**: in DA, there is an export of power from the North zone to the Southern zones such that there is a congested North-to-South ATCs line. This is followed by an **imbalance in the Northern zone**, resulting in activation in MARI creating internal congestion in the Northern zone.
- **Commercially uncongested exporting scenario**: in DA, there is an export of power from the North zone to the Southern zones but such that there is space left available on the North-to-South ATCs. This is followed by an **imbalance in the Southern zones**, resulting in activation in MARI creating internal congestion in the Northern zone.

2 Approach A1 - BSPs Represented Individually in MARI

In this section we discuss procedure A1, according to which Norwegian BSP bids are represented within the MARI platform. The timeline of approach A1 is outlined in the following figure. We then proceed to explain each of the steps in detail.

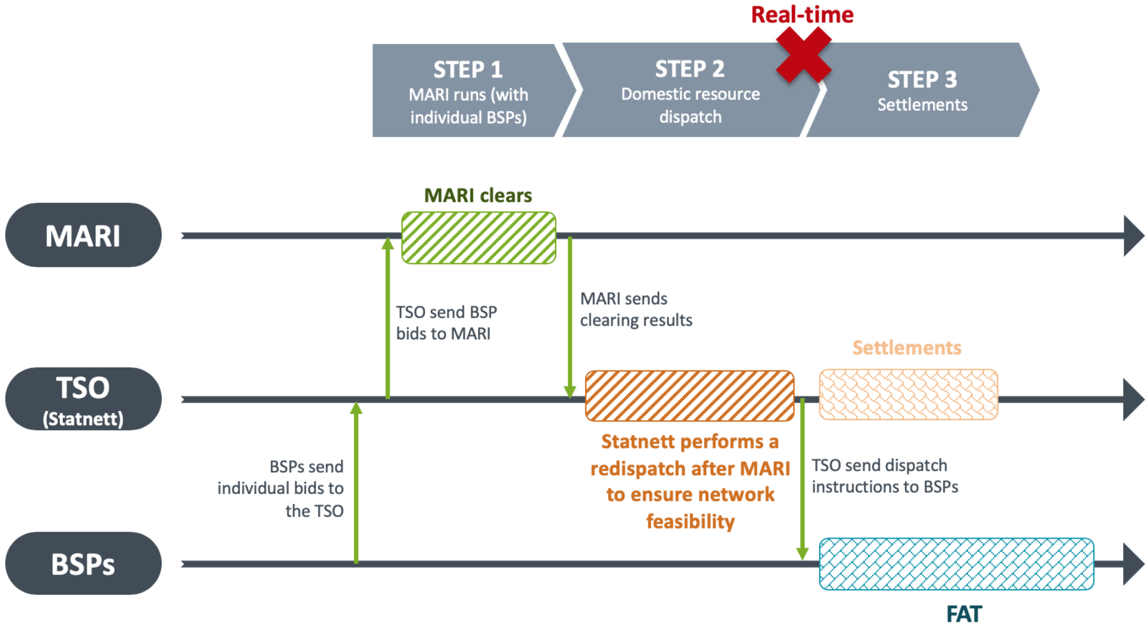


Figure 9: Timeline for approach A1.

2.1 Detailed description and timeline of the approach

The assumption in this approach, which has been confirmed by Statnett, is that there probably will be sufficient time[5] to execute an optimal power flow after the clearing of the MARI platform, since a run time for an optimal power flow lasts for 2 seconds, not including the time that is required for data exchange with the control center. Thus, we assume in what follows that we have enough time after MARI to perform a re-dispatch, with the same bids that are available in MARI. Nevertheless, while this is our working assumption for this section, appendix B extends this discussion and considers a separate faster product for performing the re-dispatch.

Step 1: MARI execution

In this step, the MARI platform is executed with the BSP resources of the Northern zone being represented individually within the platform (i.e. standard MARI use). The platform produces a market clearing quantity for each BSP, as well as a clearing price (pay-as-cleared) to which each BSP is entitled.

[5] It may also be possible to extend the 30-second time slot, e.g. through an agreement with BSPs that activations may be recalled within the 2.5-minute preparation time of the standard bid.

Step 2: domestic resource dispatch (after MARI, before real time, in case of constraint violation)

Come real time, the TSO can execute an optimal power flow in order to respect its internal and inter-zonal constraints. Note that the execution of this step is not strictly required if the execution of MARI results in a feasible dispatch within the Northern zone. The dispatch instructions may deviate from those of MARI, and settlements will be handled in step 3. Note that, although individual BSPs may be asked to deviate from the results of MARI, the zone as a whole maintains the balance that is dictated by the MARI platform, and since the MARI platform settles on a uniform price, there should be no net payments towards the platform as a result of the override instructions. The OPF that is solved is based on the gross MARI request, and finds the optimal solution to the resulting imbalance problem while respecting all the cross-border flows into and out of Norway (but possibly changing the position of individual Norwegian bidding zones).

The solution is optimal in the sense of aiming at minimizing deviations from MARI positions. An alternative objective for the Northern TSO could have been to maximize economic surplus. The role of the TSO in real time (maximizing benefits from economic trade versus minimizing deviations from BSP setpoints) has been the subject of debate also in the MARI design (in particular the role of counter-activations in the platform) and is a recurrent question in European balancing market design. Whereas the concept of merit order activation in balancing is conformant to the goal of maximizing economic efficiency in real time, the idea in our present analysis is that this goal will be handled by the MARI platform. Instead, the role of Statnett in the post-MARI stage will be assumed to **restore feasibility in the network flows while minimizing deviations from the MARI** outcome. In this sense, the post-MARI stage of approach A1 resembles an **out-of-market correctio**n. We discuss the connection with out-of-market corrections, and how this argument influences our settlement logic, further in the later sections of the report.

Step 3: settlements of instructed deviations (after real time)

At this step, the TSO settles instructed deviations using side payments (pay-as-bid). We consider this step as an-out-of-market correction, and discuss the pay-as-bid logic of this step subsequently. However, we also note that these side payments may create INC-DEC gaming opportunities.

2.2 Interaction with MARI

Approach A1 is consistent with the MARI rules, in the following sense. (i) All Norwegian BSPs are represented within MARI. Moreover, (ii) the settlement of any corrections is financially neutral with respect to MARI. Conceptually, it could be seen as two fully distinct steps: while the first step fully abides with the MARI rules and principles, the second step can be seen as an internal redispatch process, which only relates to MARI in the sense that the same resources/bids are used. Note, however, that congestion can occur outside the Norwegian zone, as a result of Norwegian actions in the post-MARI step, even if the Norwegian TSO has no financial settlement due to MARI as a result of the post-MARI corrections.

2.3 Illustration on the stress tests

We proceed by illustrating the approach on the two stress tests that have been described in section 1.

2.3.1 Commercially congested scenario

Step 1: MARI execution

The execution of the MARI platform produces the results that are presented in figure 4.

Step 2: Domestic resource re-dispatch

The re-dispatch that the Northern TSO issues after the clearing of MARI is presented in the following figure. Note that this dispatch differs from the one in figure 5, because in the dispatch of figure 5 the southern resources can also be re-dispatched and the goal in approach A1 is to minimize deviations from the MARI outcome. As we discussed above, this procedure essentially amounts to an out-of-market corrective action with side payments which are paid as bid in US-style pools. Therefore, step 2 relies on the bids that resources have already submitted to MARI, meaning that resources are not called to bid prices anew. If resources would be allowed to submit new inc and dec bids, this could have implications for gaming opportunities.

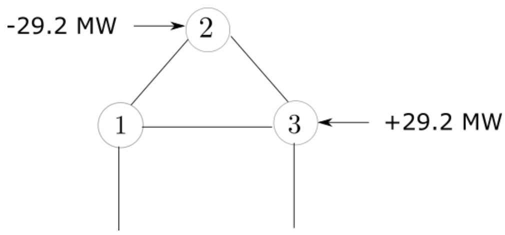


Figure 10: Domestic resource dispatch of approach A1 in the commercially congested scenario.

Note that we assume that, in activating Northern resources, the Northern TSO uses PTDFs and capacity limits for all lines in the network (including non-Northern lines). In this sense, the activation decisions cannot lead to violations of the constraints on the inter-zonal lines 1-4 and 3-5, or in the Southern zone lines. Arguably, PTDFs and capacity limits change dynamically according to the state of the system, and cannot be estimated unilaterally by the Northern TSO, in which case we could easily relax this assumption.

Let's notice that in case the non-Northern lines would be excluded from our computations, this would not change the results in our case, as our toy example is such that the Southern lines are not really congested. Nevertheless, this is not the case in general and if in reality, Norway performs the calculations without considering Swedish constraints, activations in Norway could then lead to overloads in Sweden.

It is interesting to point out that the optimal dispatch presented in the above figure in this case (but not in general[6]) is identical for both the case where the TSO aims at maximizing economic benefit from trade or minimizing deviations from the MARI outcome. By contrast,

[6] Let's stress that this is not generally the case and could be due to the size of the example, with few degrees of freedom.

in approach A8 that is presented later in the report, these two different goals produce very different BSP instructions.

Step 3: Settlements

The following table illustrates how resources are settled at every step of approach A1. Note that the post-MARI adjustments in step 2 are paid as bid. The (North TSO, Step 2) cell computes the balance that the Northern TSO needs to come up with in order to override the instructions of the MARI platform. This is always guaranteed to be non-positive (in the sense of creating a financial obligation for the TSO), since more expensive resources are being re-dispatched up and cheaper resources are being re-dispatched down, so as to restore feasibility in the flow limits. Note that the TSOs collect congestion surplus from BRPs in the MARI clearing stage. BRPs are not involved in the settlements that take place in step 2, at the post-MARI stage.

Remuneration principle in step 3. Although this topic is discussed more extensively in other parts of the report, we briefly discuss the logic of how step 3 is settled. Step 3 essentially amounts to an out-of-market correction, where the TSO corrects the instructions of MARI, and uses side payments in order to 'convince' the resources that are being asked to engage in out-of-market corrections to follow the TSO requests. Payments for out-of-market corrections come under various names in the academic literature and among practitioners (with various terms referring to them, such as 'make-whole-payments', 'side payments', and so on). The general principle is that resources are paid as bid in order to do something different from what the market platform has asked them to do[7]. Fixed cost remuneration in security constrained unit commitment of US markets, and INC-DEC settlements for congestion management in the original California zonal markets followed the same principle. In the context of our example, as we show later in the text, resource / INC bid G2C is asked to move down by 29.2 MW relative to its MARI cleared quantity. An implicit assumption that we make in the following examples is that, in this third step (which is essentially an out-of-market correction) <u>no market participant can submit updated bids</u>, i.e. the TSO uses the same information that it had available when BSPs were bidding to MARI. Since G2C is asked to produce 29.2 MW less than what was originally planned in MARI, the pay-as-bid principle requires the resource to pay back the cost it avoided by doing so to the TSO, namely a payment of 29.2 * 25 = 730 € is due from G2C to the TSO. Similarly, G3A is asked to produce 29.2 MW more than what was foreseen in MARI, and its INC cost, as declared in MARI, is 27.5 €/MWh. The application of the pay-as-bid principle implies that a payment of 29.2 * 27.5 = 803 € is due from the TSO to G3A.

[7] In general, out-of-market corrections are deemed undesirable because they are non-transparent. When an investor is deciding whether or not to invest in a resource, it does not have access to the full set of information that will allow this investor to assess the true profitability of potential investments, since certain cash flows are not disclosed transparently. Moreover, if implemented carelessly (with a sequence of markets that are not consistent in terms of product definitions, such as introducing artificially incompleteness in the market), these side payments can create opportunities for gaming. Most often, out-of-market payments are expected to compensate the costs of deviating from the market outcome. Therefore, the paid-as-bid approach is typically expecting cost-based bids (and are also therefore frequently the outcome of a regulated formula).

	Day-ahead	Step 1: MARI	Step 2: post-MARI	Total	Total MARI + post-MARI
G1 (BSP)	7500	0	0	7500	0
G2 (BSP)	6250	1000	-730	6520	270
G3 (BSP)	0	0	803	803	803
L3 (BRP)	-7500	-1000	0	-8500	-1000
South BSP	17281	0	0	17281	0
South BRP	-30750	0	0	-30750	0
North TSO	3375	0	-73	3302	-73
South TSO	3844	0	0	3844	0
Total	0	0	0	0	0

Table 6: Settlements under approach A1 in the commercially congested scenario.

2.3.2 Commercially uncongested scenario

Step 1: MARI execution

The execution of the MARI platform produces the results that are presented in figure 7.

Step 2: Domestic resource re-dispatch

The adjustment to the MARI dispatch is presented in the following figure. Note that this dispatch differs from the one in figure 8, because in the dispatch of figure 8 the southern resources can also be re-dispatched and the goal in this approach is to minimize deviations from MARI. Instead, in the present approach, Southern resources have been fixed to the MARI outcome in step 1, and therefore their position differs generally from the position that would be obtained in the nodal clearing. For example, the final position of G5 in approach A1 is 10 MW, whereas in the nodal balancing model G5 is not producing.

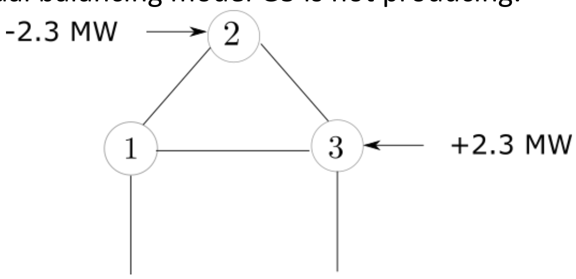


Figure 11: Domestic resource dispatch of approach A1 in the commercially uncongested scenario.

As in the case of the commercially congested scenario, we observe again that for this case the dispatch of the above figure is identical, regardless of whether the goal of the TSO is to minimize deviations from the MARI outcome, or to maximize economic benefits in the post-MARI step.

Step 3: Settlements

The following table illustrates how resources are settled in every step of approach A1.

	Day-ahead	Step 1 (MARI)	Step 2 (post-MARI)	Total	Total MARI + post-MARI
G1 (BSP)	6000	0	0	6000	0
G2 (BSP)	4000	1250	-58	5193	1193
G3 (BSP)	0	0	63	63	63
L3 (BRP)	-6000	0	0	-6000	0
South BSP	0	425	0	425	425
South BRP	-4000	-2550	0	-6550	-2550
North TSO	0	438	-6	432	432
South TSO	0	438	0	438	438
Total	0	0	0	0	0

Table 7: Settlements under approach A1 in the commercially uncongested scenario.

2.4 Economic efficiency

The following results are based on the assumption of truthful bidding, and do not address the case where the agents game the system, in which case one can expect a deterioration in efficiency. As we mention in section 1, and in order to establish a consistent basis for comparison, we will consider the efficiency of the *entire* system, without limiting our attention to the Norwegian zone. Recall that the only metric that changes from one approach to another is the total BSP cost, since load is always served in our example, and since total payments net out to zero[8].

Commercially congested case: In the congested case, the total welfare in the system amounts to 913,146 €. The welfare breakdown is presented in the following table. The production cost amounts to 26,854 €, which is higher than the nodal cost of 24,110 €. Concretely, the Southern BSPs were dispatched in the day-ahead stage, and are not redispatched in the MARI stage, which is contrary to what is happening in the nodal balancing.

[8] Other metrics that could be considered for a more extensive analysis of the 44-node Nordic system could be system slack or number of lines operating at limit.

	Producer (BSP) cost	Consumer (BRP) value	Total revenue	Surplus
G1 (BSP)	4500	N/A	7500	3000
G2 (BSP)	5021	N/A	6520	1499
G3 (BSP)	802	N/A	803	1
L3 (BRP)	N/A	340000	-8500	331500
South BSP	16531	N/A	17281	750
South BRP	N/A	600000	-30750	569250
North TSO	N/A	N/A	3302	3302
South TSO	N/A	N/A	3844	3844
Total	26854	940000	0	913146

Table 8: Welfare breakdown under approach A1 in the commercially congested scenario.

Commercially uncongested case: In the congested case, the total welfare in the system amounts to 550,319 €. The production cost amounts to 9,681 €, as compared to 9,527 € in the nodal pricing solution. The welfare breakdown is presented in the following table.

	Producer (BSP) cost	Consumer (BRP) value	Total revenue	Profit
G1 (BSP)	4500	N/A	6000	1500
G2 (BSP)	4693	N/A	5193	499
G3 (BSP)	62	N/A	63	1
L3 (BRP)	N/A	300000	-6000	294000
South BSP	425	N/A	425	0
South BRP	N/A	260000	-6550	253450
North TSO	N/A	N/A	432	432
South TSO	N/A	N/A	438	438
Total	9681	560000	0	550319

Table 9: Welfare breakdown under approach A1 in the commercially uncongested scenario.

The efficiency metrics are further compared between all approaches and the nodal pricing baseline in the comparative assessment section.

2.5 Payments for TSO

Note that, as mentioned earlier, although individual BSPs may be asked to deviate from the results of MARI, the zone as a whole maintains the balance that is dictated by the MARI platform, and since the MARI platform settles on a uniform price, there are no net payments due to the platform as a result of the post-MARI corrections in step 2. On the other hand, the TSO typically pays out side-payments to the BSPs in order for them to deviate from the MARI results.

Commercially congested case: The total TSO payments to the MARI platform are assumed to be zero, since we assume that the TSO demand which is submitted to the platform is essentially bid on behalf of the Northern BRPs, which are responsible for the payment of 1000 €. The total payments due from the TSO to BSPs in the post-MARI corrections amount to **73 €**.

Commercially uncongested case: The TSO is entitled to 438 € of congestion rents in the MARI clearing stage. The total payments due from the TSO to northern BSPs in the post-MARI corrections amount to **5.8** €.

2.6 Uncertainty

The conclusion of the MARI clearing step resolves a significant amount of uncertainty in the system, especially related to unknown platform requests. Insofar as the next imbalance interval is concerned, demand and renewable supply are largely foreseeable. The most uncertain aspect is the flow across the border. There could also be uncertainty related to the change of BRP/BSP positions.

In the approach considered in figure 9, all this uncertainty is revealed to a large extent in step 2, where we assume that there exists enough time to run an optimal power flow *after* the MARI platform has cleared. With perfect hindsight regarding the requests of the MARI platform and the realized imbalances, we conclude that there is negligible uncertainty involved in approach A1.

Nevertheless, let's stress that as approach A1 doesn't do anything beforehand to solve possible upcoming issues, it somehow assumes that all possible issues arising from MARI could in theory be solved afterwards. This might not be the case and solving all the issues afterwards might turn out to be infeasible at the end, which can be viewed as a major source of uncertainty.

Regarding financial uncertainty, the post-MARI variations in TSO settlements seem to be limited when comparing the commercially congested and uncongested cases. In fact, the congestion revenues of MARI introduce much more financial uncertainty for the Northern TSO than the post-MARI settlements. This is of course not a general statement and remains limited to the example.

2.7 Complexity

A particularly appealing aspect of the approach is the fact that relatively minor adjustments take place in step 2 of the process, which overrides the MARI results. This should be contrasted, for example, to the significant re-dispatch corrections which take place after the clearing of MARI in approach A8[9]; even if again, this is what can be concluded from the examples and might not be true in general.

Moreover, it is appealing that approach A1 does not create changes in the balance of the Northern zone relative to the MARI outcome. On the other hand, the fact that BSPs in the Northern zone are being requested to change their set-point relative to the MARI results could be perceived as being contentious because individual BSPs are not following the MARI instructions individually, but only in the aggregate. Concretely, on behalf of the BSPs this is acceptable because they are indifferent about being marginal versus inframarginal, but the post-MARI adjustments can affect non-Northern network flows, so it may be contentious from the point of view of the non-Northern TSOs.

2.8 Assessment of ICT issues

One aspect of approach A1 is the fact that it is necessary to solve an optimal power flow *after* the MARI market clearing. This is considered as being computationally feasible, however we caution to the fact that a contingency constrained optimal power flow may require at least a few seconds of solution time[10]. Moreover, the resulting instructions need to be communicated to and executed by the affected Northern BSPs. The additional settlement that takes place in step 3 of the process also requires post-balancing transactions between the Northern TSO and Northern BSPs, which increases the implementation complexity to some extent. These challenges also exist in approach A8, therefore we assign the same ICT score to both approaches.

[9] This statement regarding approach A8 is true when the TSO post-MARI objective is to maximize economic surplus, instead of minimizing the deviations of BSPs from the MARI outcome. If the TSO objective is to minimize post-MARI deviations, then as long as the MARI outcome is feasible for the network, no post-MARI adjustments are required in either approach A1 or approach A8.

[10] For the time being, Statnett does not use a security constrained OPF, but N-1 security is ensured through pre-calculated limits on transfer corridors. Nevertheless, security constrained OPF is a long-term goal. See also footnote 3.

Highlights and main conclusions
• After MARI deviations are made only for BSPs located in the relevant TSO's area, and the objective is to minimize deviations from MARI positions • Straightforward interaction with MARI, all BSPs are represented in MARI, and net settlements are in accordance with MARI, i.e. there are no net payments to MARI from after MARI deviations • Deviations from MARI are considered to be out-of-market corrections and are settled pay-as-bid • The TSO pays side payments to deviating BSPs • Necessary deviations from MARI positions to ensure feasibility could be considerable, however seem to be modest, since both Day-ahead and MARI are based on the same zonal network model, and the post MARI deviations are minimized • A main challenge is if there is time to make necessary corrections after MARI

3 Approach A2 - BSPs Aggregated in MARI

Approach A2 is a hierarchical approach that has also been implemented for the SmartNet project [1] (it is referred in that publication as the "Decentralized Common TSO-DSO Market"). The idea is to design a **residual supply function**, which is submitted to the MARI platform, instead of submitting the BSP bids individually. Suppose that the dispatch of other TSOs does not change from the most recently metered value. We can then fix their net injections, and pose the question of what is the cheapest way (i.e. the total cost *TC(e)* below) in which we can export a given amount of power (*e* in the mathematical model below) from our zone. In terms of a generic DC optimal power flow problem, the formulation reads as follows:

$$TC(e) = min(\sum_{g \in G} MC_g \cdot q_g - \sum_{l \in L} MB_l \cdot d_l)$$

$$r_n = \sum_{g \in G_n} q_g - \sum_{l \in L_n} d_l, n \in N_{North}$$

$$f_k = F_k^{South} + \sum_{n \in N} PTDF_{k,n} \cdot r_n, k \in K_{North}$$

$$-FMax_k \leq f_k \leq FMax_k, k \in K_{North}$$

$$(\pi): \sum_{n \in N_{North}} r_n = E^0 + e$$

$$q_g \leq P_g^{max}$$

$$Q_g = Q_g^0, g \in G^{Slow}, d_l = D_l^0, l \in L^{Slow}$$

The notation here is as follows. Lower case corresponds to decision variables, upper case corresponds to parameters. $TC(e)$ is the total cost of having an excess supply of e MW of power from a zone[11]. The set of loads is denoted as L, the set of generators is denoted as G, the set of lines is denoted as K, and the set of nodes is denoted as N. Resources that are located in node n are represented with a subscript, so for example G_n is the set of generators located in node n. We denote by K_{North} the set of lines that are located in the Northern zone (including the inter-zonal links) and by N_{North} the set of nodes that are located in the Northern zone. We have F_k^{South} corresponding to the flows that are induced in the Northern control area by resources that are not under the control of the Northern TSO[12]. The net

[11] Mathematically, we express a classical optimization program which is parametrized in e. For a given e there will be a corresponding x* which is an optimal set of decision variables for the parameter e, as well as a corresponding objective value. This can be expressed as a function of e : TC(e).

[12] Ideally, this parameter should also account for the impact of the MARI activation of Southern resources on the Northern network. This is not realistic, however, because the moment in time in which the residual function is computed is before MARI clears. Therefore, **there is some inherent uncertainty regarding the actual value of this parameter**. But as we argue later by means of a numerical illustration, this is not necessarily a major issue, since the market clearing outcome of approach A2 is not necessarily overly sensitive to inaccuracies in the estimation of the residual function. Concretely, we show later in this section that the outcome of approach A2

injection in node n is denoted as r_n. The flow along a line k is denoted as f_k. The production of generator g is denoted as q_g, and the demand of consumer l is denoted as d_l. Consumers have a marginal benefit of MB_l and generators have a marginal cost of MC_g. The power transfer distribution factor from node n to line k is denoted as $PTDF_{k,n}$. The flow limit along line k is denoted as $FMax_k$. The total export of the Northern zone is denoted as e. The set of generators and loads that cannot be moved in real time are denoted as G^{Slow} and L^{Slow} respectively. The day-ahead schedules are denoted as Q_g^0 and D_l^0 for generators and loads respectively. The parameter E^0 corresponds to the day-ahead net export of the zone, therefore e is measuring incremental exports *relative* to E^0.

The objective function is the difference of generator cost and consumer benefit, which in the context of balancing can be interpreted equivalently as the cost of up-regulation minus the cost-saving of down-regulation. The first constraint defines the net exports of each node. The second constraint defines the flow of power along each line of the network as the sum of the flows implied by non-North resources, as well as flows resulting from Northern resources (where the latter are approximated by a linearization of Kirchhoff's power flow equations using power transfer distribution factors). The third constraint imposes limits on the line flows due to thermal or stability limits. The fourth constraint defines the net export of the zone (we explain the meaning of the multiplier π in the next paragraph). The last set of constraints fixes the set-points of resources that are not flexible to their day-ahead (or intraday) nominations. It is a simple result of convex analysis to note that $TC(e)$, is a convex function of e because the economic dispatch problem is convex[13]. The slope of the function is the dual multiplier of the last constraint, and we denote it as π[14].

In order to gain a more explicit understanding of the notation used above, consider the following function TC(e) that is calculated in the congested stress test. This function TC(e) indicates the opposite of the total welfare that the Northern zone can gain by having a net position of e. When computed at e = 0 MW, the achievable welfare is 290750 €/h. When computed at 20 MW, the achievable welfare decreases to 290250 €/h (because the Northern zone needs to source those extra 20 MW from increased production in its zone, or curtailing price-responsive consumers). So the welfare decrease is 500 €/h for a total of 20 MW, hence 25 €/MWh. Thus, at a net position of 0 MW, the Northern zone should bid 25 €/MWh for the first 20 MW of upward response. This turns out to be exactly the value of the dual multiplier $\pi$when we solve the problem above for e = 0. The slope of this function TC(e), which is

does not change too much if in step 2 we ignore the transmission line limits of the Northern network. We explain the intuition of this result later in the chapter.

[13] If non-divisible orders are allowed, then the statement that the residual supply function is convex is no longer true. Nevertheless, even in this more complex realistic setting there exist straightforward computational methods for deriving the closest "well-behaved" (i.e. convex) residual supply function. This generalization goes beyond the scope of the present work, but we point out that the computational extensions for handling non-divisible orders can be handled straightforwardly (taking the convex envelope of the cost curve), both in theory as well as computationally.

[14] This can be shown with the definition of the subgradient of the function.

presented in the following figure, is exactly the bidding curve of the Northern zone in the MARI platform, and is depicted in the following figure for the congested stress test.

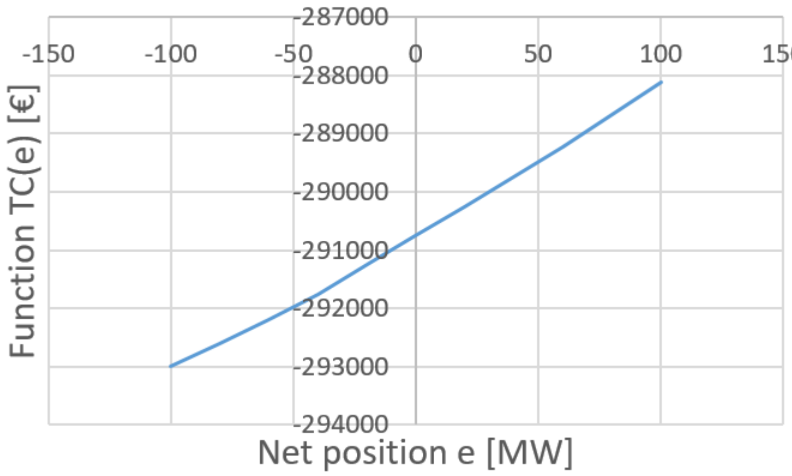


Figure 13: The function TC(e) that is computed for the congested stress test of approach A2.

Note a subtle aspect of the model: since the constraints on line flows are only enforced for the North zone, this residual supply function does not account for potential congestion of Southern lines resulting from the activation of Northern resources.

An important observation is that the residual supply function is one-dimensional as long as we are focusing on a single dispatch interval, even if we have multiple zones to which the zone in question is connected. The fact that there may be multiple zones to which the North zone is connected does not mean that the total cost function is multi-dimensional. This may not be true if the interzonal connectors are HVDC lines[15] (and therefore have a controllable flow), or if we are considering total cost over multiple periods. In these latter cases, the total cost function is defined in more than one dimension.

An important consideration in this approach is how it performs when multiple zones are applying the same concept (suppose, for example, that Norway consists of 5 zones, each of which is applying this procedure independently). The challenges that arise in this context are similar to those that arise in the post-MARI adjustments of all approaches. In all approaches, we assume that the post-MARI adjustments account for the fact that non-Northern resources have *already* reacted to the MARI dispatch signals. In approach A2, such an assumption is obviously internally inconsistent: if two zones A and B are applying approach A2 simultaneously, it is impossible for zone A to be reacting to the step 4 dispatch of zone B and for zone B to be reacting to the step 4 dispatch of zone A, because one excludes the other. Inevitably, therefore, post-MARI adjustments introduce uncertainty into the process. Of course, this remark is not unique to approach A2. If multiple zones apply approach A1, or A8, for example, the same concerns emerge. The degree of ex post corrections should be

[15] For the HVDCs, it is expected that the MARI instructions will be executed as they come out of the platform.

systematically different in approach A1, A2, and A8 since for A1 all corrections take place after MARI, whereas A2 and A8 involve a certain level of pre-processing. This would be interesting to quantify in the 44-node example.
In terms of the post-MARI disaggregation that takes place in step 4, the degree of uncertainty is reduced when all of Norway is treated as a single zone. On the other hand, this might be inconsistent with the representation of Norway as 5 or 6 zones in the day-ahead market clearing. This tradeoff warrants further investigation (see section 6). Since approach A2 is the only one among the approaches for which a post-MARI step is required regardless of the MARI outcome[16], this tradeoff is especially pertinent for approach A2. On the other hand, representing Norway as a single bidding zone may imply that network constraints are no longer adequately represented for the adjacent TSO(s), which may in turn make it inacceptable for them. Such a theoretical consideration is however not further considered in this analysis (notably because it can not be determined whether this is a pure theoretical consideration or whether it is a practical real-life concern).

3.1 Detailed description and timeline of the approach

We now outline in detail the sequence of events of approach A2. The sequence is depicted at a high level in the following figure.

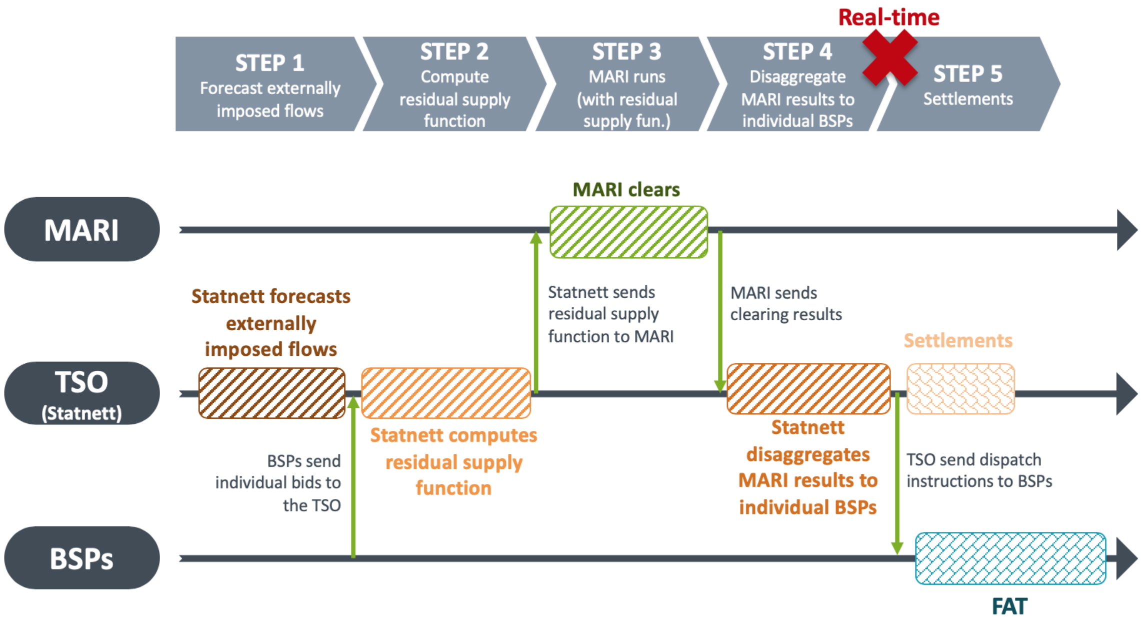


Figure 14: Timeline for approach A2.

Note that the TSO has to relate to the aggregate bid curve and not the individual BSPs behind it. Thus, the only bid that the Northern TSO can buy is from the "aggregate Northern BSP". This will become part of the total export target that the Northern TSO needs to meet, and it will be sourced from the optimization of step 4.

[16] In approach A1 and A8, post-MARI corrections are not needed if MARI results in a feasible dispatch; equivalently, if the TSO objective in post-MARI corrections is to minimize deviations from MARI dispatch instead of maximizing economic surplus, then the post-MARI corrections will be null in approaches A1 and A8.

Step 1: forecast externally imposed flows (before MARI)
The idea of step 1 is to 'filter out' the impact of the resources that cannot be controlled by the Northern TSO. Essentially, this implies assigning values to F_k^{South} in the formulation above, which is a straightforward calculation for the Northern TSO based on its locally observable information: the Northern TSO subtracts from the measured flows on its lines the impact of the dispatch of the Northern resources in the previous imbalance interval. Thus, no communication is required between the Northern TSO and non-Northern TSOs in order for this step to be executed. If steps 2 - 4 of approach A2 can be executed fast enough, then this calculation can be performed after the activation of non-Northern MARI resources (i.e. within the new imbalance interval). If this is not possible, it is still acceptable to use a reasonable approximation of the southern-induced flows, since the residual supply function does not have to be estimated perfectly in order for approach A2 to perform effectively. We illustrate this point further below, where we show that approach A2 reproduces a near-optimal dispatch, even if we ignore the transmission constraints of the Northern zone in step 2 of the process.

Step 2: Compute residual supply function for submission to MARI
In this stage, the Northern TSO estimates the residual supply function that it plans to submit to MARI. The estimation of the residual supply function requires the resolution of as many OPFs as the points around which we wish to approximate the residual supply function. As correctly pointed out by Statnett, the sum of the ATC capacities defines the outer boundary of this calculation, meaning that the total cost function does not need to be approximated beyond this boundary.
A possible implementation of this calculation is that the North TSO has access to the day-ahead nominations of generators, in order to be able to compute the *incremental* cost relative to the day-ahead nominations, and thereby the residual supply curve[17]. In effect, this means that the bids should be locational. This is how our simulations have been run.
Implicit in our definition of $TC(e)$ above is the fact that the day-ahead nominations are cost-minimizing choices for meeting the day-ahead clearing schedule. If this were not the case, we would need to reformulate the model as one in which the day-ahead nominations are fixed, resource by resource. This would increase the notational complexity of the exposition, but the main concepts would remain unchanged. Such considerations should be further studied.

Step 3: Clear MARI with Northern residual supply function
In this stage, the residual supply function that is computed in step 2 is converted into synthetic BSP bids (i.e. the function is discretized, each piece being considered as a bid for MARI) and inserted in the MARI market clearing platform. The idea is that the North zone will export its scheduled volume, and any imbalances will be dealt with via a delta on the net position

[17] The balancing bids are used for this calculation, but one needs to also account for internal congestion in the Northern zone, so the balancing bids cannot be used alone.

(relative to a day-ahead or intraday schedule), the marginal cost of which is computed from the residual supply function of the previous step.

Step 4: Disaggregate the results of MARI in the Northern zone
In this step, the Northern TSO needs to allocate the activation decided by MARI to the BSPs within its zone. The idea will be for the Northern TSO to run an optimal power flow limited to its own zone. This implies that the dispatch actions of the Northern TSO may cause problems outside of the Northern zone. Note, however, that if the entire zone is bid as a single 'BSP' by the Northern TSO, then there is nothing inconsistent with the actions of the Northern TSO (even if the Northern TSO causes congestion outside the Northern zone through its actions[18]). The platform instructions are followed, and there is no net payment due to the platform.
One important difference between step 4 of approach A2 and the post-MARI step of the other approaches is that in the other approaches the post-MARI part is optional if the system is feasible after MARI clears. In A2, the post-MARI process in step 4 is necessary in order to have a well-defined set of dispatch instructions.

Step 5: Settlements
The Northern TSO implements a nodal system within its own zone when disaggregating resources. The Northern TSO thus collects a payment as an aggregate BSP (step 3, MARI), and then uses these funds to procure balancing power in the disaggregation phase (step 4) The approach does not involve gaming opportunities between the MARI and post-MARI steps (even if there are still gaming opportunities between the day-ahead market clearing and real time).

3.2 Interaction with MARI

The approach bends the MARI rules by collapsing all Norwegian BSPs into a single aggregated Norwegian BSP. In this respect article 27(3) of the Electricity Balancing Guideline regarding central dispatch systems is relevant:

3. Each TSO applying a central dispatching model shall convert as far as possible the integrated scheduling process bids pursuant to paragraph 2 into standard products taking into account operational security. The rules for converting the integrated scheduling process bids into standard products shall:
(a) be fair, transparent and non-discriminatory;
(b) not create barriers for the exchange of balancing services;
(c) ensure the financial neutrality of TSOs.

The process proposed under approach A2 is fair, transparent and non-discriminatory, insofar as it is an implementation of a hierarchical nodal pricing solution. It creates no barriers for the exchange of balancing services, since the entire BSP capacity of the Northern zone is made

[18] The original MARI zonal design by construction ignores this aspect, and it is precisely the objective of this study to address this point for the Norwegian case - which suffers from a highly congested grid. Would there be a more global need to address this point, then a redesign of MARI (or more general) should be investigated. This is clearly out of the scope of this analysis.

available to MARI. Regarding item c, the MARI clearing step may not exactly cancel out with the post-MARI uniform price settlements, nevertheless we note that the deviations in our numerical illustrations are minor. However, whereas article 27 applies to central dispatch systems, we note that Statnett is *not* a central dispatch system.

3.3 Illustration on the stress tests

We illustrate the performance of the approach for the case of the congested and uncongested stress test.

3.3.1 Commercially congested scenario

We consider first the case where the North-to-South links are congested.

Step 1: forecast externally imposed flows (before MARI)

Based on telemetry data from the most recently observed imbalance interval, the Northern TSO forecasts the following flows on its network from resources that are dispatched out of its jurisdiction. For the sake of this illustration, we assume that the telemetered dispatch is the one that corresponds to the day-ahead zonal market clearing (figure 3), and *not* the infeasible MARI activation (figure 4).

- Line 1-2: -11.6 MW
- Line 1-3: -36.8 MW
- Line 1-4 (inter-zonal): 48.4 MW
- Line 2-3: -11.6 MW
- Line 3-5 (inter-zonal): -48.4 MW

Step 2: Compute residual supply function for submission to MARI

We approximate the residual supply function around 10 points, which are centered around the day-ahead net export quantity. The horizontal axis in the residual supply function below corresponds to the change in export, relative to the day-ahead schedule.

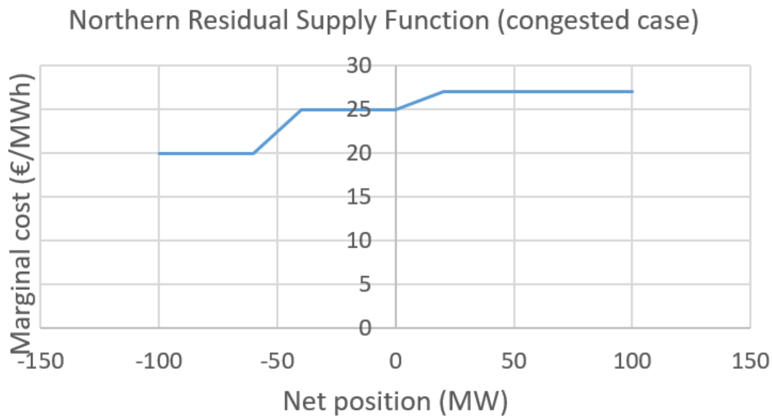


Figure 15: Residual supply function that is bid into the MARI platform for the congested case.

Concretely, the residual supply function is read as follows: the marginal cost for a marginal increment in the net position of the Northern zone (relative to the day-ahead or intraday net position) when the current net position of the Northern zone is 20 MW is 27.0 €/MWh. Notice the kink (change in slope) of the marginal cost function when moving from -60 MW to -40 MW and from 0 MW to 20 MW. The first kink corresponds to the marginal unit in the Northern zone moving from G1C to G2C. The second kink corresponds to line constraints in the Northern zone (specifically the upward limit of line 2-3) becoming active. We discuss this further below, when we address the complexity of the method. Note that the residual function is a piecewise constant curve, which is consistent with the MARI bidding format for simple continuous orders.

To see more clearly how the residual supply function is formed, consider the optimal dispatch of the Northern zone for the increasing levels of export that are targeted in the horizontal axis of the figure above. The table of optimal dispatch is presented below. Note the switch from G1C to G2C when moving from a target export of -60 MW to a target export of -40 MW, which is the cause of the first kink. Note also the switch from G2C to a mixture of G2C and G3A when moving from a target export of 0 MW to a target export of +20 MW, which explains the second kink in the residual supply function.

	-100	**-80**	**-60**	**-40**	**-20**	**+0**	**+20**	**+40**	**+60**	**+80**	**+100**
G1A	100	100	100	100	100	100	100	100	100	100	100
G1B	100	100	100	100	100	100	100	100	100	100	100
G1C	50	70	90	100	100	100	100	100	100	100	100
G2A	100	100	100	100	100	100	100	100	100	100	100
G2B	100	100	100	100	100	100	100	100	100	100	100
G2C	0	0	0	10	30	50	64.5	68.1	71.8	75.4	79.1
G3A	0	0	0	0	0	0	5.5	21.9	38.2	54.6	70.9
G3B	0	0	0	0	0	0	0	0	0	0	0
G3C	0	0	0	0	0	0	0	0	0	0	0

Table 10: Optimal levels of North generator dispatch for the different target net position levels for the congested case. The net position levels are indicated in MW in the first row of the table in bold font.

Step 3: Clear MARI with Northern residual supply function

The MARI platform clears with the residual supply function of the previous step. The activated supply from the Northern aggregate supply function is +40 MW. The Northern clearing price amounts to 27.0 €/MWh, which indeed corresponds to the marginal cost function that is plotted in the above figure. The resulting clearing quantities and prices are presented in the following figure. The MARI price is now higher than in approach A1, and reflects the congestion on line 2-3. As such, this approach indirectly allows the MARI platform to anticipate the marginal cost of congestion when activating resources in the Northern zone.

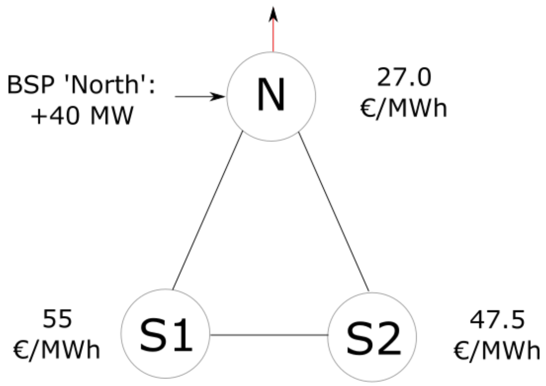


Figure 16: Dispatch result of MARI in step 3 of approach A2 for the congested case.[19]

Step 4: Disaggregate the results of MARI in the Northern zone
Given an instruction of +40 MW upward activation by the MARI platform, and given the observed imbalances within the Northern zone, the Northern TSO can solve an OPF in order to clear its imbalances and deliver its promised net injection to the platform. The assumption here is that the forecast of the Northern TSO about the effect of non-North resources on the flows of Northern lines is accurate (whereas, in reality, the actual physical flow may deviate). The actual dispatch of the system is presented in the following figure. The dispatch within the Northern zone[20] turns out to be identical to that of the nodal proxy approach that was presented in the previous paragraph.

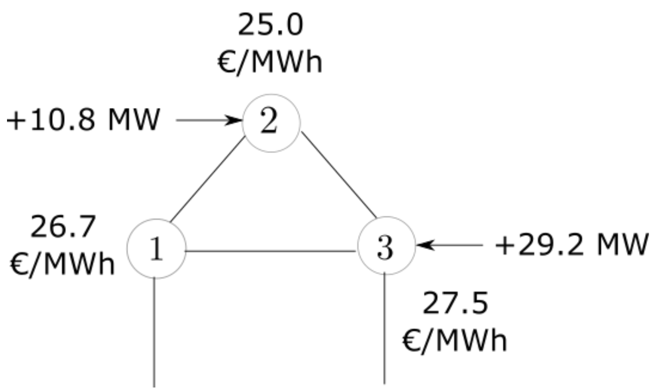


Figure 17: Disaggregation of MARI results in step 4 in the Northern zone using approach A2 in the congested case.

Let's notice that, unlike approach A1, the Southern zones constraints were ignored in our computations. In our case, this did not lead to any violation. Nevertheless, this would not be

[19] Note that the prices of S1 and S2 are purely indicative here, as no volume is activated at this price in the example

[20] The step 4 problem is a PTDF that is slightly different from the one solved in step 2, because when an imbalance occurs in the Northern zone then the Northern TSO knows precisely where the imbalance is located, whereas when the imbalance occurs in the South, the Northern TSO is simply aiming at exporting the target quantity from its zone.

the case in general and therefore, the activations performed by Norway without considering Swedish constraints could lead to overloads in Sweden.

Note that each node of the Northern grid has an associated nodal price. We comment on this in the following section, where we discuss the settlements. Also note that the nodal prices are different at every location. We therefore expect to have congestion in at least one line of the network. Indeed, it turns out that line L23 is congested, with a flow of 170 MW going through it in step 4.

Step 5: Settlements
The following table presents the settlements.

	Day-ahead	Step 3 (MARI)	Step 4 (post-MARI)	Total	Total MARI + post-MARI
G1 (BSP)	7500	0	0	7500	0
G2 (BSP)	6250	0	270	6520	270
G3 (BSP)	0	0	803	803	803
BSP 'North'	0	1080	0	1080	1080
L3 (BRP)	-7500	-1080	0	-8580	-1080
South BSP	17281	0	0	17281	0
South BRP	-30750	0	0	-30750	0
North TSO	3375	0	-1073	2302	-1073
South TSO	3844	0	0	3844	0
Total	0	0	0	0	0

Table 11: Settlements under approach A2 in the commercially congested scenario.

Note that the Northern TSO represents all of its individual BSPs as an "aggregate Northern BSP" in the MARI platform. The 1080 € in the (BSP North, Step 3) cell is due from the MARI platform to the "aggregate Northern BSP", i.e. essentially the Northern TSO. This total amount is computed as the total upward activation of the "aggregate Northern BSP" (40 MW) times the Northern zone price, as determined in the MARI clearing process (27 €/MWh). Note that, in step 3, we charge the imbalance to the BRPs instead of the Northern TSO (even if the power is procured in MARI from a 'TSO need' bid), because essentially the Northern TSO is buying this power on behalf of its domestic BRPs which are off balance. Since we assume that the BRPs are charged imbalance charges equal to the MARI balancing price, we directly charge the 1080 € to BRPs in step 3. In step 4, the Northern TSO pays a uniform nodal price to the Northern BSPs for their post-MARI adjustment. For example, the nodal price in the location of G2C is 25 €/MWh, and G2C is paid for 10.8 MW of upward activation. The total financial exposure of the Northern TSO is effectively the sum of the 'North TSO' and 'BSP North' rows.

3.3.2 Commercially uncongested scenario

We consider next the case where the North-to-South links are not congested.

Step 1: forecast externally imposed flows (before MARI)
Based on telemetry data from the most recently observed imbalance interval, the Northern TSO forecasts the following flows on its network from resources that are dispatched out of its jurisdiction:

- Line 1-2: -3.0 MW
- Line 1-3: -9.4 MW
- Line 1-4 (inter-zonal): 12.4 MW
- Line 2-3: -3.0 MW
- Line 3-5 (inter-zonal): -12.4 MW

Step 2: Compute residual supply function for submission to MARI
As in the congested case, we approximate the residual supply function around 10 points, which are centered around the day-ahead net export quantity. The horizontal axis in the residual supply function below corresponds to the change in export, relative to the day-ahead schedule. The residual supply function is a horizontal translation of the congested case to the right by 50 MW, and is generally cheaper than that of the congested case, which is expected since the net position of the North zone in the uncongested stress test is lower than in the congested stress test.

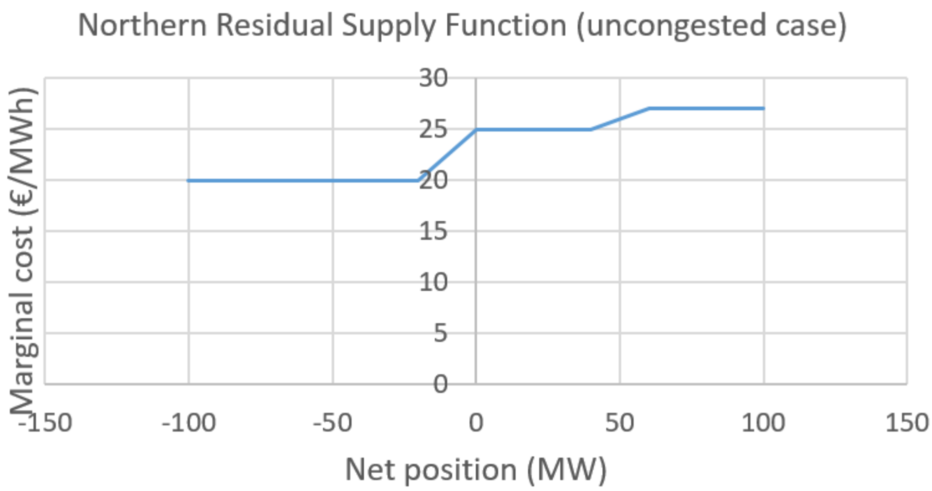


Figure 18: Residual supply function that is bid into the MARI platform for the uncongested case.

As in the case of the congested stress test, we can obtain the table of optimal dispatch of the different resources in the North zone for different levels of target export.

	-100	-80	-60	-40	-20	+0	+20	+40	+60	+80	+100
G1A	100	100	100	100	100	100	100	100	100	100	100
G1B	100	100	100	100	100	100	100	100	100	100	100
G1C	0	20	40	60	80	100	100	100	100	100	100
G2A	100	100	100	100	100	100	100	100	100	100	100
G2B	100	100	100	100	100	100	100	100	100	100	100
G2C	0	0	0	0	0	0	20	40	47.7	51.3	55
G3A	0	0	0	0	0	0	0	0	12.3	28.7	45
G3B	0	0	0	0	0	0	0	0	0	0	0
G3C	0	0	0	0	0	0	0	0	0	0	0

Table 12: Optimal levels of North generator dispatch for the different target net position levels for the uncongested case. The net position levels are indicated in MW in the first row of the table in bold font.

The explanation of the two kink points of the residual supply function is identical to the congested case, and relates to a switch in marginal generator for the first kink, and a binding constraint on line 2-3 for the second kink.

Step 3: Clear MARI with Northern residual supply function

The MARI platform clears with the residual supply function of the previous step. The activated supply from the Northern aggregate supply function is +50 MW. The Northern clearing price amounts to 27.0 €/MWh, which indeed corresponds to the marginal cost function that is plotted in the above figure. The resulting clearing quantities and prices are presented in the following figure.

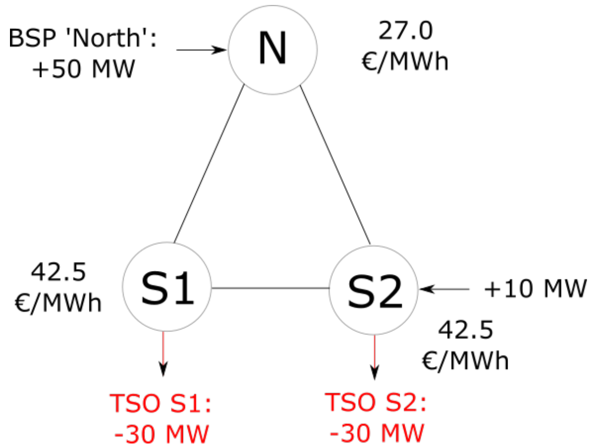


Figure 19: Dispatch result of MARI in step 3 of approach A2 for the commercially uncongested case.

Step 4: Disaggregate the results of MARI in the Northern zone

Given an instruction of +50 MW upward activation by the MARI platform, the Northern TSO solves an OPF in order to deliver its promised net injection to the platform. The actual dispatch of the system is presented in the following figure. As in the congested case, the nodal price differences emerge due to congestion on line 2-3 of the Northern zone, which is loaded at its capacity at 170 MW.

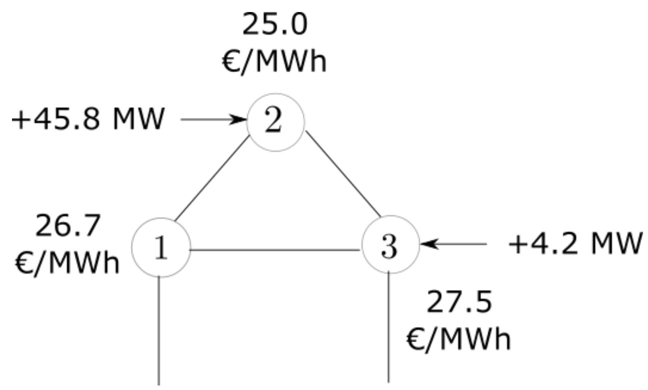


Figure 20: Disaggregation of MARI results in step 4 in the Northern zone using approach A2 in the commercially uncongested case.

Step 5: Settlements

The following table presents the settlements.

	Day-ahead	Step 3 (MARI)	Step 4 (post-MARI)	Total	Total MARI + post-MARI
G1 (BSP)	6000	0	0	6000	0
G2 (BSP)	4000	0	1145	5145	1145
G3 (BSP)	0	0	116	116	116
BSP 'North'	0	1350	0	1350	1350
L3 (BRP)	-6000	0	0	-6000	0
South BSP	0	425	0	425	425
South BRP	-4000	-2550	0	-6550	-2550
North TSO	0	388	-1261	-873	-873
South TSO	0	388	0	388	388
Total	0	0	0	0	0

Table 13: Settlements under approach A2 in the commercially uncongested scenario.

The Northern TSO earns 1350 € from the MARI market clearing platform, since it offers 50 MW to the platform. It then needs to distribute 1261 € from this total to the BSPs that actually deliver this response in the disaggregation of step 4. As in the commercially congested scenario, the total financial exposure of the Northern TSO is the sum of the 'North TSO' and 'BSP North' rows.

3.4 Economic efficiency

Commercially congested case: In the congested case, the total welfare in the system amounts to 913,146 €. The producer cost (i.e. an interesting metric, demand being price-taker in our case) amounts to 26,854 €. The welfare breakdown is presented in the following table.

	Producer (BSP) cost	Consumer (BRP) value	Total revenue	Profit
G1 (BSP)	4500	N/A	7500	3000
G2 (BSP)	5021	N/A	6520	1499
G3 (BSP)	802	N/A	803	1
L3 (BRP)	N/A	340000	-8580	331420
South BSP	16531	N/A	17281	750
South BRP	N/A	600000	-30750	569250
North TSO	N/A	N/A	3382	3382
South TSO	N/A	N/A	3844	3844
Total	26854	940000	0	913146

Table 14: Welfare breakdown under approach A2 in the commercially congested scenario.

Commercially uncongested case: In the congested case, the total welfare in the system amounts to 550,319 €. The producer cost amounts to 9,681 €. The breakdown is presented in the following table.

	Producer (BSP) cost	Consumer (BRP) value	Total revenue	Profit
G1 (BSP)	4500	N/A	6000	1500
G2 (BSP)	4693	N/A	5145	452
G3 (BSP)	62	N/A	116	53
L3 (BRP)	N/A	300000	-6000	294000
South BSP	425	N/A	425	0
South BRP	N/A	260000	-6550	253450
North TSO	N/A	N/A	477	477

South TSO	N/A	N/A	388	388
Total	9681	560000	0	550319

Table 15: Welfare breakdown under approach A2 in the commercially uncongested scenario.

3.5 Payments for TSO

Commercially congested case: The total payments from the platform to the Northern TSO amount to 1080 €, which the TSO collects as an 'aggregate BSP'. The total payments due from the TSO to BSPs in the post-MARI corrections amount to 1073 €. The total budget surplus of the TSO thus amounts to 7 €. This is slightly less than what the TSO would have paid (1080 €) if it had been satisfying its needs on the MARI platform at the uniform price of MARI. In general, there is no reason to expect that these two numbers should be comparable (i.e. that the former should be smaller than, equal to, or greater than the latter).

Commercially uncongested case: The TSO collects 1350 € for offering an upward activation as an aggregate Northern BSP to the MARI platform. A part of this income (1261 €) is then redistributed to the Northern BSPs. Moreover, the North TSO collects congestion revenues of 388 € at the MARI clearing stage (even if the day-ahead zonal model is uncongested - recall that at the MARI clearing stage there is an imbalance in the South, which could trigger congestion in MARI).

3.6 Uncertainty

Recall from the timeline of approach A2 that step 1 requires the estimation of flows on Northern grid lines induced by non-Northern resources, which is in turn used for computing a residual supply function for the 'aggregate North BSP'. This residual supply function is introduced into the MARI platform.

Although this process appears to introduce additional uncertainty in the dispatch process, there are two reasons why this uncertainty may not be severe: (i) flows induced by non-Northern resources can be estimated by information that is locally measurable / observable by the Northern TSO, and (ii) the market clearing model may be robust to estimation errors in the residual supply function estimation. We discuss these points briefly in turn.

Local estimation of flows induced by non-Northern resources. In order to compute the residual supply function, we need to estimate F_k^{South} in the problem that appears in the beginning of this section. Due to the linearity of the DC power flow equations, this quantity can be estimated by subtracting the flows induced by Northern resources on the Northern grid (this computation is based on data that the Northern TSO can monitor locally, i.e. net injections in Northern zones, without requiring communication with other TSOs) from the flows measured on Northern lines. These measurements and estimations would ideally take place based on the latest information, a natural choice would be the state of the grid in the immediately preceding imbalance interval. This issue is discussed further in section 3.9.

Sensitivity of dispatch on residual supply function estimation. As long as the residual supply function is not highly sensitive around the optimal level of net injection of the Northern TSO to the rest of the system, minor inaccuracies in the estimation of the Northern residual supply function should not affect the dispatch of approach A2 significantly, and should bring it close to the optimal dispatch. The intuition for this is that, as long as we get the slope of the residual supply function approximately right, step 3 which is the MARI market clearing will tend to request a near-optimal amount of net injection from the North to the rest of the system, and the inner optimization of step 4 will then ensure that resources within the North are dispatched exactly optimally in order to deliver this level of net injection. This intuition is illustrated by example in the following section, where we illustrate that, for the congested stress test, we get a very similar result from approach A2 when we account for or ignore the internal Northern network constraints in estimating the residual supply function in step 2.

3.7 Complexity

In this section we illustrate the value of the residual supply function approach, by considering an alternative scenario under which the residual supply function is submitted into MARI in a 'careless' fashion, i.e. by not accounting for the internal constraints of the Northern zone. We develop the following example for the congested stress test, in order to illustrate the main point of our analysis.

The residual supply function that is derived when we do not account for the internal constraints of the Northern zone in step 2 is 'cheaper' on the aggregate, which is not surprising, since the Northern zone can deliver power at a lower cost when the Northern constraints can be ignored. The residual supply functions with and without the Northern transmission constraints are presented in the following figure.

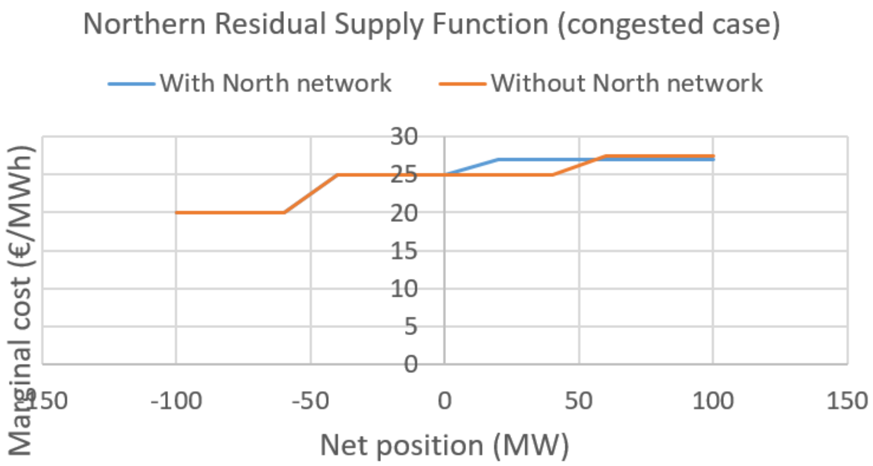


Figure 21: Residual supply function of step 2 of approach A2 for the congested stress test with and without accounting for the Northern transmission constraints.

The resulting clearing of the MARI platform in step 3 with the orange supply function is very close to the one obtained with the blue supply function, as shown in the following figure. Concretely, the Northern BSP is dispatched identically on the platform, and the market clearing price of the MARI platform decreases from 27.0 €/MWh to 25.0 €/MWh for the North zone (i.e. the only difference is that the price of the North zone decreases, which is a consequence of the fact that the Northern zone appears 'cheaper' since we have ignored the internal Northern constraints). In fact, when the constraints of the North zone are completely ignored, one obtains the same result as what would have occurred by bidding the Northern BSPs directly into MARI (figure 4), which is intuitive and is the result obtained in the first step of approach A1.

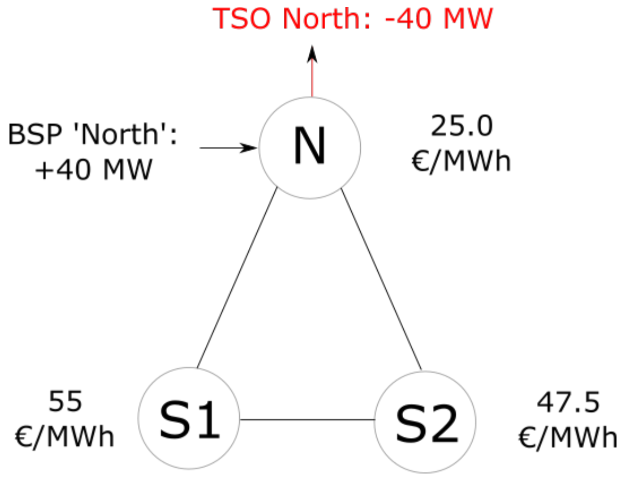


Figure 22: Dispatch result of MARI in step 3 of approach A2 for the congested case when the residual supply function of the Northern TSO is approximated without Northern network constraints.

The dispatch in the disaggregation of step 4 is identical, which is expected since the export in the MARI platform is identical to the one obtained with the blue supply function. The settlements in step 5 therefore proceed identically as well.

Two main conclusions emerge from this discussion. (i) The interest in building an accurate supply function in step 3 is for the Northern TSO to be charged with the optimal amount of export, as would be derived from a perfectly coordinated model. Even though this may not be possible in all cases, getting close to this outcome for a multitude of cases is still valuable. (ii) The most important aspect of approach A2 is step 4, where the Northern TSO can use a nodal model for perfectly coordinating its internal network and generating signals that provide efficiency short- and long-term incentives. Such a final nodal step appears as important in any of the approaches explored in this study.

Note that the conclusions presented in this section regarding the robustness of the method are example-specific, and are also linked to the fact that the case study which we analyze involves resources in the Northern zone that have close marginal cost values. In a setting with more accentuated marginal cost differences among BSPs, the impact of not estimating the residual supply function accurately could have been more pronounced. The sensitivity of our analysis to this effect is an interesting topic for further investigation.

3.8 Assessment of ICT issues

Approach A2 entails a notable level of ICT complexity in step 2, which is also time critical. As we explain in section 3.7, ideally we would like to use the latest network information in order to estimate F_k^{South} as accurately as possible in step 1, so that we can obtain a more accurate estimation of the residual supply function in step 2. Step 1 in itself would therefore ideally rely on the grid measurements (net nodal injections in the Northern network and flows on Northern lines) of the most recent imbalance interval, which leaves only a few minutes for step 2, where we need to solve repeated (possibly parallelized) optimal power flows in order to estimate the residual supply function.

In the case of a one-dimensional residual supply function, the number of OPFs that need to be solved is equal to the number of breakpoints in the residual supply function. In more general implementations of the method that would involve multi-dimensional residual supply functions (e.g. in the case of TSO-DSO integration with reactive power flows at the interface, or multi-period market clearing, or co-optimization of energy and reserve capacity), the number of points that need to be estimated grows exponentially with the dimension of the residual supply function, and an additional approximation procedure would be required for obtaining an approximately separable residual supply function that can be input into market clearing engines. Thus, the ICT complexity in the case of multi-dimensional residual supply functions grows significantly. Even for the case of a one-dimensional residual supply function, solving something in the order of 10 OPFs within a few minutes from one imbalance interval to the next could be a tight timeline. Instead, and based on the observations of paragraph 3.8, we could settle with pre-computing residual supply functions from older metered data (e.g. from day-ahead forecasts or intraday data). Since the results of approach A2 appear to be somewhat insensitive to the precision of estimation of the residual supply function, this could be a workable approximation in practical settings.

Highlights and main conclusions

- The TSO interacts with MARI by giving an "anonymous" aggregate bid curve for the whole zone, which is consistent with the MARI rules for a central dispatch system
- The bid curve is made by computing the minimum cost of having different amounts of residual supply, e, where e can take on both positive (export) or negative (import) numbers
- The MARI result is disaggregated by the TSO after MARI is cleared, by running an OPF for the TSOs own zone, and the results are communicated to the individual BSPs
- MARI quantities and settlements are respected, but the revenue that the TSO can collect based on the MARI prices does not necessarily cover exactly the payments that the TSO has to make, i.e. the TSO may have a surplus or a deficit
- An unresolved question is how the approach can be adapted to multiple price zones within the area of one TSO
- Another issue is how the method works if two or more TSOs use the same method
- This introduces uncertainty in the system
- A potential challenge is whether Statnett can use the rules of a central dispatch system

4 Approach A8: Nodal Norway in MARI

In this section we describe approach A8, which is based on the idea that the Northern zone is represented in full detail as a nodal network in the MARI platform. The timeline of approach A8 is outlined in the following figure. We then proceed to explain each of the steps in detail.

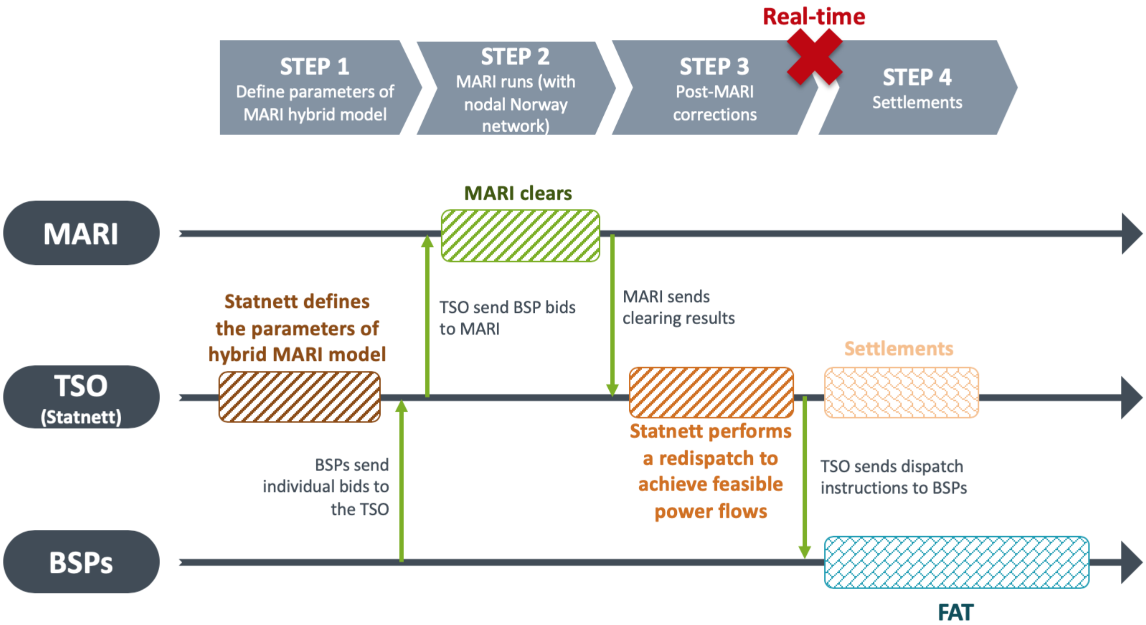


Figure 23: Timeline of events in approach A8.

It is worth noting that this is a simpler timeline than that of approach A2. Note, in particular, that steps 3 and 4 are optional in the examples that we demonstrate below, meaning that the dispatch is already feasible from step 2. Instead, approach A2 involves post-MARI operations (in order to disaggregate the "aggregate BSP North" activation to individual BSPs in the Northern zone) which also necessitates certain settlements out of the MARI platform in approach A2.

4.1 Detailed description and timeline of the approach

The general idea of the approach is to (i) use a transportation / ATC model for non-Northern links, (ii) represent intra-zonal lines linking the Northern zone to the remainder of the system essentially as HVDC links with controllable flow (we discuss later how the capacity of these links should be decided), and (iii) represent the interior of the Northern zone using linearized power flow equations (note that this latter representation is not yet foreseen in the MARI requirements).

Step 1: Define parameters of MARI hybrid model

One notable aspect of approach A8 is the need to define the zonal capacities that are used in the MARI model. When disaggregating a zonal model (day-ahead) to a more granular hybrid model (MARI), three types of links may emerge in the MARI model:

- *Type 1 links*: the DA zonal links are unaffected.
- *Type 2 links*: the MARI zonal links correspond to physical lines. Note that type 2 links can be inter-zonal, or intra-zonal.

- *Type 3 links*: neither the first nor the second possibility, i.e. the MARI zonal links correspond to neither day-ahead zonal links nor physical lines, i.e. they are still aggregations of physical lines, but finer aggregations than those of the day-ahead zonal model.

In order to illustrate these definitions, let us consider the following figure. In the left box of the figure below, we present the aggregation of the nodal system into the day-ahead zonal market clearing model. In the right box of the figure, we present the aggregation of the nodal system into the MARI zonal model. We can classify the MARI zonal model links as follows:

- **Type 1 links**: S1-S2: the S1-S2 link exists already in the day-ahead zonal model, and is replicated identically in the MARI zonal model.
- **Type 2 intra-zonal links**: N1-N2, N2-N3 and N1-N3: these links are type 2, because they correspond to physical lines (lines 1-2, 2-3 and 1-3 of the nodal model respectively). They are intra-zonal because they are subsumed in the Northern zone in the day-ahead zonal market clearing model.
- **Type 2 inter-zonal links**: N1-S1, and N3-S2: these links are type 2, because they correspond to physical lines (lines 1-4 and 3-5 of the nodal model respectively). They are inter-zonal because they are connecting the Northern zone of the day-ahead zonal market clearing model to other zones of the day-ahead market clearing model.
- **Type 3 links:** no such links exist for this example.

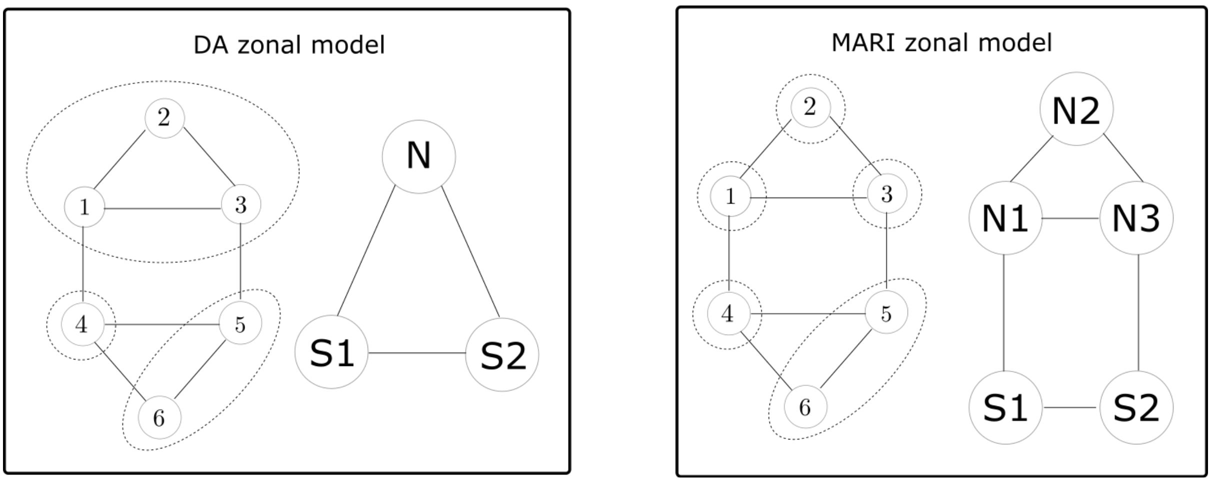


Figure 24: The aggregation of the nodal system to a DA zonal model (left) and to a MARI zonal model (right).

It is natural to assign capacities for type 1 links as being equal to those of the DA model. For type 2 intra-zonal lines, these can be assigned to their physical capacity. For type 2 inter-zonal lines, two possible choices of capacities are the physical capacities, or the DA capacities. We will refer to the former as "**aggressive capacity assignment**", and the latter as "**conservative capacity assignment**". A more advanced approach towards determining ATC capacities is based on the concept of *optimal zonal capacities* [5]. The idea here is to use the output of the nodal model in order to set ATC limits, and to also use the results of the nodal model in order to pre-determine the bids that should be bid into the MARI platform. However, note that the implementation of this idea is out of scope for the present report.

Another part of the MARI zonal model which is subjective is the definition of the constraints that map zonal net injections to flows on zonal links. There are two possible approaches that one can consider for the linearization of the power flow constraints: (i) generation shift keys, and (ii) a susceptance-based formulation. We discuss them briefly in turn.

Generation shift keys. If we wish to develop the MARI market clearing model as a model based on power transfer distribution factors[21], then we need to determine how zonal injections out of the North zone affect flows on Northern lines. This introduces an element of subjective judgement, since we need to 'guess' which nodes of the Southern zones the MARI zonal responses will come from. One could adopt the approach followed currently by TSOs for flow-based market coupling, namely the following formula:

$$f_{l,z} = \sum_{n \in N_{North}} PTDF_{l,n} \cdot r_n + \sum_{n \in N_{South}} \sum_{g \in G_n} GSK_{g,z} \cdot PTDF_{l,n} \cdot p_g$$

where N_{North} and N_{South} denotes the set of nodes in the Northern and Southern zones respectively, $GSK_{g,z}$ denotes the generator shift key, and $PTDF_{l,n}$ denotes the PTDF of node n on line l. The challenge[22] here is in estimating GSKs for the Southern zones. In this approach, one could use the results of the dispatch in the preceding imbalance interval, assuming that these GSKs can be computed sufficiently quickly. We formulate the GSK model for the three-node Northern network in a table below, in order to illustrate the concept more clearly.

GSK estimation would be a general challenge for MARI. The reason it is especially challenging in the context of approach A8 is that the MARI model deviates from the day-ahead model, so the default values of the day-ahead model cannot be used in the MARI hybrid model. Although the inaccuracies introduced by zonal models can be handled in the day-ahead time frame through redispatch, there is no time for such redispatch in real time, when MARI clears.

Susceptance-based formulation[23]. The approach based on susceptance has been proposed by Professor Bjorndal in the context of a hybrid market clearing model for Central Europe [2]. The idea is that the linearized flows on the Northern lines are represented using the so-called B-theta, or susceptance-based, formulation. We specifically introduce bus angle variables for the Northern nodes, and express the flows on the Northern lines as the difference between the Northern bus angles, scaled by the line susceptance. By contrast, the inter-zonal links that connect the Northern nodes to non-Northern zones are assumed to have controllable flow, hence the flow on these links is part of the ATC-based model. In addition, no bus angles are

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[21] Note, however, that MARI will be based on a transportation model with ATCs for the first years of its implementation.

[22] Each TSO has a different method for computing these GSKs in day-ahead flow-based market coupling. Some will use only the installed capacity of generators, while some will use the base case. Moreover, some TSOs will use the same GSKs during a long period while some will update them every day.

[23] We can implement the susceptance-based model by modeling bus angles explicitly. Alternatively, we can drop the bus angles, and model the power balance constraint at each node and the requirement that the flows along any cycle amount to zero.

represented on the zones that are adjacent to Northern nodes. Technically, one can interpret this as a model whereby the Northern zone is connected via DC connectors (with controllable flow) to the rest of the system, and where the linearized Kirchhoff equations only apply to the Northern nodes. We explicitly note that this is an approximation, and does not correspond to the physical reality, since the connections of Norway to Sweden do not correspond to DC links.

The susceptance-based formulation is the approach that we will adopt in the subsequent analysis. The susceptance values for the Chao-Peck network considered in our examples are available in the third column of table 1 of the first report. We point out explicitly that neither the susceptance-based formulation or the GSK approach overcome the problem of knowing which Southern zones the MARI zonal requests come from.

<u>Relation between the two approaches</u>. The two approaches are NOT equivalent, because the underlying assumptions are fundamentally different: while the GSK model starts from a fully nodal representation (i.e. nodal $PTDF_{l,n}$) and uses an artificial construct (i.e. $GSK_{g,z}$) to convert into a zonal representation, the susceptance-based formulation uses a strong assumption (i.e. the independence between the cross-zonal flows and the within-zone shifts) as the construct to solve the problem. Given that the congestions (and hence flows) that could occur outside of the North area are not to be monitored, this second approach seems more appropriate for Approach A8.

In order to highlight the two approaches more clearly, we present the formulation for the three-node Northern zone in the table below. On a level of physical intuition, we have the following major difference between the two models: (i) GSK is 'exactly' a nodal model with the exception that it guesses what the marginal unit is, and ignores the linearization of the power flows for the non-Northern zones; (ii) The susceptance-based model is assuming that the interfaces of the North with the rest are essentially HVDC lines with controllable flows, and assumes that the Northern zone is a separate AC network, which means it assumes different PTDFs.

Susceptance	**GSK**
Power flow linearization and hub node definition: $\theta_1 = 0$ $f_{1-2} = B_{1-2} \cdot (\theta_1 - \theta_2)$ $f_{1-3} = B_{1-3} \cdot (\theta_1 - \theta_3)$ $f_{2-3} = B_{2-3} \cdot (\theta_2 - \theta_3)$	Power flow linearization and hub node definition (assuming the Southern response comes from location 4): $f_{1-2} = PTDF_{1,1-2} \cdot r_1 + PTDF_{2,1-2} \cdot r_2 + PTDF_{3,1-2} \cdot r_3 + PTDF_{4,1-2} \cdot r_4$ $f_{1-3} = PTDF_{1,1-3} \cdot r_1 + PTDF_{2,1-3} \cdot r_2 + PTDF_{3,1-3} \cdot r_3 + PTDF_{4,1-3} \cdot r_4$ $f_{2-3} = PTDF_{1,2-3} \cdot r_1 + PTDF_{2,2-3} \cdot r_2 + PTDF_{3,2-3} \cdot r_3 + PTDF_{4,2-3} \cdot r_4$

Energy balance:	Energy balance:
$q_1 = d_1 + f_{1-2} + f_{1-3} + f_{1-4}$ $q_2 = d_2 + f_{2-3} - f_{1-2}$ $q_3 = d_3 - f_{1-3} - f_{2-3} + f_{3-5}$	$r_1 = q_1 - d_1$ $r_2 = q_2 - d_2$ $r_3 = q_3 - d_3$ $r_4 = q_4 - d_4$ $r_5 = q_5 - d_5$ $r_6 = q_6 - d_6$ $r_1 + r_2 + r_3 + r_4 + r_5 + r_6 = 0$

Table 16: Formulation of power flow linearization for the GSK approach (left) and the susceptance-based formulation (right) for the Northern zone.

Step 2: MARI market clearing
In the MARI market clearing, we assume that the imbalance that will occur in the system has already been revealed through a TSO need on the MARI platform. Note that the ATC transportation-based model which will be the basis for the short-term implementation of MARI does not have the level of generality that is present in the susceptance-based model that we analyze in this section[24]. Therefore, the approach analyzed here would likely not be implementable in the short-term horizon of the first years of implementation of MARI[25].

Step 3: Post-MARI corrections (optional)
If step 2 turns out to cause infeasible flows for the Northern network, a post-MARI correction is executed, where the Northern TSO adjusts the dispatch of BSPs in order to achieve feasible power flows, while aiming at minimizing deviations from the MARI clearing result. Note that an alternative objective for the Northern TSO could have been to maximize economic benefits of trade in step 3. However, this is deemed inappropriate in practice because (i) it can be shown to cause 'oscillations' between step 2 and step 3 (with BSPs being activated upwards in step 2, only to be activated downwards in step 3, and vice versa), and (ii) such an objective would encounter challenges in being accepted in practice by stakeholders.

Step 4: Settlement (optional)
If step 3 is needed in order to prevent a violation of flows in the Northern network, then this is considered as an out-of-market (OOM) correction. Step 4 settles these OOM corrections on a pay-as-bid basis, as in the case of the post-MARI corrections in approach A1.

4.2 Interaction with MARI

Note that the zonal day-ahead market model and the zonal MARI model are different. Historically, Statnett has decided about the definition of zones. Until about 2000, this was rather flexible, and the number of zones varied (and has reached up to 30 zones). After 2000,

[24] Regardless of how we go about representing the susceptance-based formulation (see previous footnote), we have a more general model than the ATC-based model, which is limited to representing zone-to-zone transactions and box constraints on these transactions. To put it differently, there are constraints on zonal net injections implied by the susceptance-based model which cannot be represented through the ATC-based model.

[25] With that being said, note that cut constraints have been introduced in the PCR day-ahead market clearing model, such as total export constraints leaving the Swedish zone.

the number of zones has been more stable. For a long time there were only 2, and then gradually, when experiencing more problems, more zones have been defined, and there has been adjustments to the exact borders of the zones.

Currently, Statnett is suggesting a 6th zone for Norway, splitting NO4 in two. This request has to first be discussed in stakeholder hearings, and the final decision rests with the national regulator (NVE). Sweden is also considering a new zone around Stockholm, which eventually may merge with SE3. Both of these suggestions are part of a joint Nordic investigation about future zones, following procedures in EU Regulation 2019/943/EU.
In practice, the implementation of A8 would have 5 zones in Norway (or 6 if the change is decided by NVE) in the day-ahead market with an ATC model (flow-based is being tested). Then there would be a nodal model for Norway in MARI.

4.3 Illustration on the stress tests

We illustrate the performance of the approach for the case of the commercially congested and commercially uncongested stress test.

4.3.1 Commercially congested scenario

As explained earlier, two main strategies for determining the capacity of “type-2 inter-zonal” links have been identified. We briefly illustrate these two strategies on the congested scenario and we highlight why the “aggressive capacity assignment” strategy has to be avoided while the “conservative capacity assignment” strategy should be preferred.

Step 1: Define parameters for MARI zonal model under aggressive capacity assignment - NOT RECOMMENDED
We recall the distinction between different types of lines. Consider the disaggregated network in the following figure.

- *Type 1 links* are links that are the same in the MARI model as in the DA model: link S1-S2. The capacity of these links remains unchanged in MARI relative to the DA model.
- *Type 2 links* are MARI links that correspond to physical lines. Intra-zonal links are N1-N2, N2-N3, and N1-N3, and their capacity is unambiguously set to the capacity of the physical lines. Inter-zonal MARI links are N1-S1 and N3-S2. In the aggressive capacity assignment, we set their capacity to the physical capacity of the lines.
- *Type 3 links* are links that are neither type 1 or type 2. No such links exist in this example.

Step 2: MARI market clearing under aggressive capacity assignment
The result of the market clearing of MARI is presented in the following figure.

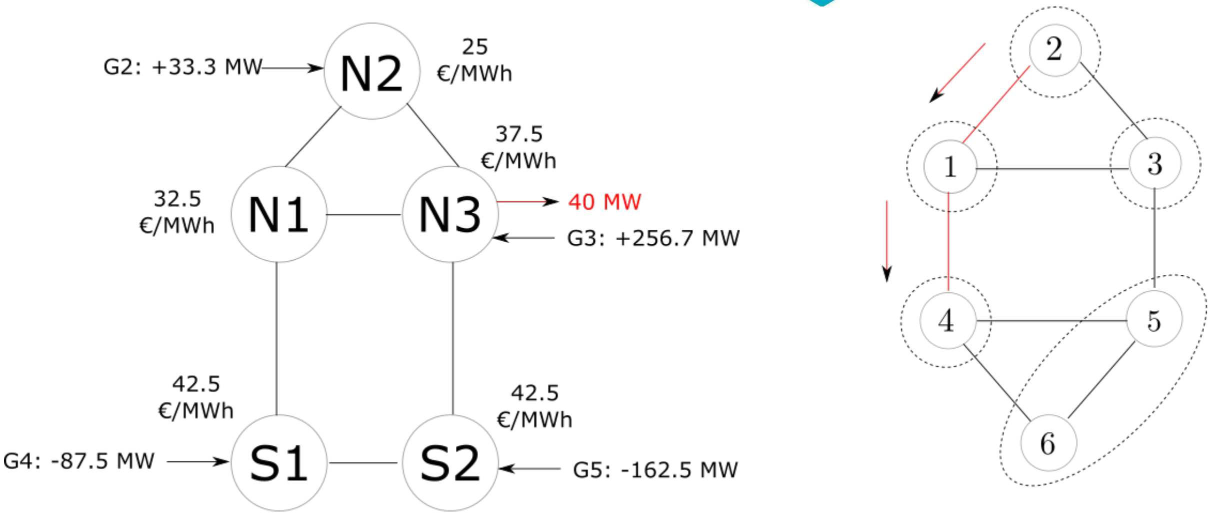


Figure 25: Outcome of MARI in the commercially congested scenario of A8 with aggressive capacity assignment (left) and resulting congestion in the actual grid (right).

It is noteworthy that the dispatch which is taking place at the MARI market clearing stage is far greater than the imbalance that actually occurs in the system[26]. Note, in particular, that the imbalance in the system has an absolute value of 40 MW, but the total upward activations amount to 290 MW in absolute value, whereas the total downward activations amount to 250 MW in absolute value. This is due to the fact that the resources participating in MARI are adjusting not only to the imbalances that have been revealed in the MARI platform, but also to the fact that they are now being dispatched against a different network model. In practice, certain resources are not flexible (in the sense of being dispatchable both in the day-ahead market clearing stage as well as in MARI), thus this effect may be less pronounced in practice compared to what we observe in the simple illustrative example that we have developed in this report.

Note that this dispatch actually results in overloading on Northern internal lines (L12), as well as inter-zonal lines (L14). Concretely, the upwards dispatch of G2 in N2 is causing an overloading in the line 1-2 in the direction from node 2 to node 1, and the downwards dispatch of G4 in N4 is causing an overloading in the line 1-4 in the direction from node 1 to node 4.

One could argue that this congestion is due to a poor choice in the parameters that define the zonal network for the MARI market clearing model. However, we have followed a very straightforward procedure for generating the MARI model. Despite this very natural way of constructing the MARI zonal model, congestion occurs when MARI clears, <u>even if there is no imbalance in the grid</u>.

It would be tempting to argue that the fact that the Northern zone is represented with nodal resolution should prevent congestion from occurring in the Northern zone. Given the susceptance-based model that we are using for representing the power flows on Northern lines [2], this intuition is wrong, because we are effectively collapsing the effect of Southern

[26] This could maybe be avoided by letting MARI minimize the adjustments instead of minimizing costs. Nevertheless, as the purpose of the present analysis is to study the effect of having a nodal representation of Norway in MARI, the other market rules of MARI were left untouched and, therefore, the objective of MARI which is to minimize the costs was considered.

resources in S1 on a nodal net injection in node N1 (without any ensuing impact on the Northern lines, which is physically incorrect) and we are collapsing the effect of Southern resources in S2 on a nodal net injection in node N2 (without any ensuing impact on the Northern lines, which is also physically incorrect). Of course, the GSK approach would also have led to potential violations, because we would have needed to guess which would be the marginal units that would respond in the Southern zones. There is no easy way out in terms of mitigating physical violations in approach A8.

In conclusion, this approach results, in step 2, in an **infeasible problem**. What has happened is that the capacity of link N1-S1 and link N3-S2 are increased substantially relative to the day-ahead model, and this is causing a reshuffling of generation in MARI which is causing congestion that cannot be recovered in step 2. For this reason, we recommend against step 1 with an aggressive capacity assignment.

Step 1: Define parameters for MARI zonal model under conservative capacity assignment - RECOMMENDED

The rationale of the conservative capacity assignment is that, if the day-ahead zonal model does not cause congestion, then we should aim at retaining its characteristics at the interface of the Northern zone with the Southern zones. Note that the same conservative approach is adopted in the work of Professor Bjorndal [2]. Concretely, for links N1-S1 and N3-S2, even though they correspond to physical lines, we will not assign their physical capacity in the MARI model, but instead retain their day-ahead zonal model capacities.

- *Type 1 links* are links that are the same in the MARI model as in the DA model, i.e. link S1-S2. The capacity of these links remains unchanged in MARI relative to the DA model.
- *Type 2 links* are MARI links that correspond to physical lines. Intra-zonal links are N1-N2, N2-N3, and N1-N3, and their capacity is unambiguously set to the capacity of the physical lines. Inter-zonal MARI links are N1-S1 and N3-S2. In the conservative capacity assignment, we set their capacity to the capacity of the DA zonal model.
- *Type 3 links* are links that are neither type 1 or type 2. No such links exist in this example.

Step 2: MARI market clearing under conservative capacity assignment

The resulting dispatch from MARI is presented in the following figure.

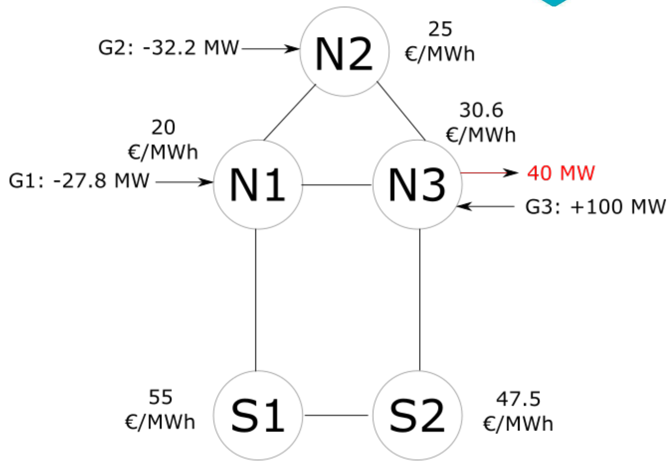


Figure 26: Outcome of MARI in the commercially congested scenario of A8 with conservative capacity assignment.

Note that the actual volumes that are being adjusted by MARI are now closer to the imbalance that occurs in the network. Note, however, that there is still a certain degree of "counter-activations" in the Northern zone, with the total upward activation being 250% the imbalance that occurs in the Northern zone. This is due to the fact that the MARI model has a finer resolution regarding the internal capacities of the Northern zone, and is moving generation from G1 and G2 to G3 (which increases the cost of dispatch) in order to relieve Northern congestion[27]. The resulting flow turns out to be feasible for the physical network for this specific example.
The outcome of the settlement creates a net payment to the TSO from the generators. This is driven by the fact that the cheaper generators are being dispatched up (and are paid by the TSO to do so), and the more expensive generators are being dispatched down (and are paying the TSO to do so). Since the latter are paying more than the former due to their higher costs, the TSO collects a net surplus.

Step 3: Post-MARI corrections

For the aggressive implementation of A8 which is depicted in figure 25, there is no way to recover a dispatch that respects the physical limits of lines if only resources of the Northern zone are going to be asked to deviate from MARI. Therefore, we advise against an aggressive implementation of A8.
For the conservative implementation of A8 which is depicted in figure 26, it turns out that the resulting physical flows are feasible. If the goal of the Northern TSO would be to maximize the value of economic trade in step 3, then this would result in significant adjustments in step 3, which would occur because the actual physical capacities seen by the Northern operator exceed the restricted capacities determined in step 1 of approach A8. The resulting dispatch that would occur under economic surplus maximization is presented in the following figure. Note that this step does not contribute in any way to managing overloads of lines, but rather on decreasing system costs by exploiting the additional capacity that is visible in step 3.

[27] To see why this is the case, note that in the day-ahead clearing of figure 3 we have 550 MW being produced from generators 1 and 2 in zones N1 and N2, whereas the aggregate ATC capacity of the links that connect these zones to the rest of the network in the MARI model (N1-S1, N2-N3, N1-N3) is limited to 500 MW. These 500 MW correspond to 150 MW in N1-S1, 170 MW in N2-N3, and 180 MW in N1-N3.

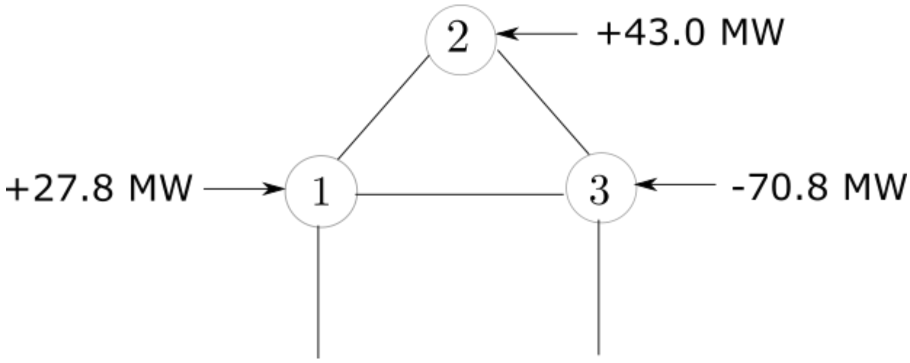


Figure 27: Outcome of step 3 of approach A8 for the congested scenario if the goal of the Northern TSO would be to maximize economic benefit.

Note that the dispatch of the above figure seems to largely be undoing the decisions of step 2, in the sense that:

- MARI is adjusting G1 by -27.8 MW, and step 3 under economic benefit maximization is adjusting it back by +27.8 MW
- MARI is adjusting G2 by -32.2 MW, and step 3 under economic benefit maximization is adjusting it back by +43.0 MW
- MARI is adjusting G3 by +100.0 MW, and step 3 under economic benefit maximization is adjusting it back by -70.8 MW

Thus, step 3 under economic benefit maximization increases welfare in the system, however it does so by largely undoing the MARI dispatch instructions. The intuitive reason for that is that in step 2 in MARI, the interfaces with the outside world were estimated in a very conservative way to ensure feasibility (as recommended and explained above) while in step 3 this capacity is made available in the network model.

Instead, if the goal of the TSO is to minimize deviations from MARI, step 3 is optional whenever the network flows are already feasible from step 2. This is exactly the case in our example, and the payment and welfare results that are reported for approach A8 correspond to the case where BSPs are not redispatched in step 3.

Step 4: Settlements

The settlements in the following table are computed under the assumption that step 3 aims at minimizing deviations from MARI, while restoring feasibility in the network (as opposed to maximizing economic surplus in step 3). For the specific case of our example, therefore, the column corresponding to step 3 involves no payments.

	Day-ahead	Step 1 (MARI)	Step 3 (post-MARI)	Total	Total (MARI + post-MARI)
G1 (BSP)	7500	-556	0	6944	-556
G2 (BSP)	6250	-805	0	5445	-805
G3 (BSP)	0	3060	0	3060	3060

L3 (BRP)	-7500	-1224	0	-8724	-1224
South BSP	17281	0	0	17281	0
South BRP	-30750	0	0	-30750	0
North TSO	3375	-475	0	2900	-475
South TSO	3844	0	0	3844	0
Total	0	0	0	0	0

Table 17: Settlements under approach A8 in the commercially congested scenario.

The computation of congestion rents at the MARI stage is non-trivial, because there is no unique way to translate the usage of the capacity in the MARI zonal network model from the DA zonal model, so as to compute incremental usage of network capacity and the resulting congestion rents. For the case of our specific example, we need to solve the following linear system, which ensures that the flows in the zonal DA model are consistent with the flows in the zonal MARI model:

- Zone N1: f12 + f13 = 300 - 150
- Zone N2: - f12 + f23 = 250
- Zone N3: - f13 - f23 = 0 - 100

For example, the first equality above expresses the fact that the zonal MARI model should have baseline flows which are consistent with the injection of power in the DA model (300 MW) minus whatever power flows over the link N-S1 (150 MW).
The linear system above has a unique solution (three linearly independent equalities in three unknowns), and yields the following mapping of DA zonal flows to MARI zonal flows:

- Link N1-N2: - 75 MW
- Link N1-N3: 225 MW
- Link N2-N3: 175 MW

Note that there is no a priori reason to expect that this flow should be compatible with the MARI zonal network ATC capacities (and in fact it is not, the flow on line N1-N3 exceeds the MARI ATC capacity, which is equal to 180 MW). Notwithstanding, these flows can be used for computing congestion revenues at the MARI stage.

4.3.2 Commercially uncongested scenario

Steps 1&2: MARI market clearing under conservative capacity assignment
Having excluded the aggressive capacity assignment in step 1, we directly simulate the **conservative approach** to capacity assignment in step 1. The MARI market clearing outcome is presented in the following figure.

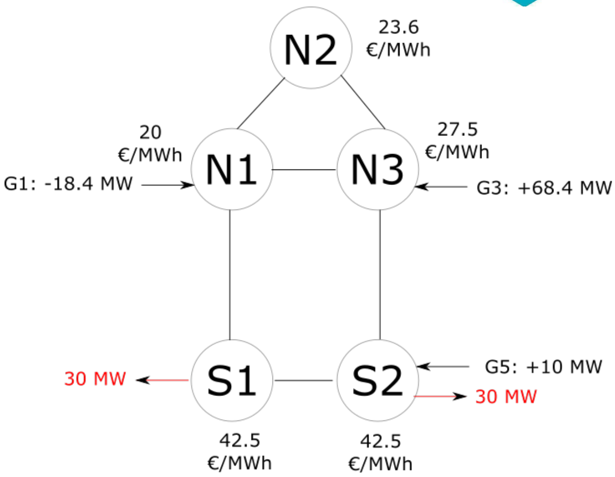


Figure 28: Outcome of MARI in the commercially uncongested scenario of A8 with conservative capacity assignment.

As in the case of the congested scenario, the MARI market clearing outcome causes no congestion to the system.

Step 3: Post-MARI corrections

The adjustments in step 3 that would occur under the goal of economic surplus maximization are presented in the following figure. As in the commercially congested case, this redispatch contributes in no way to managing overloads of lines, but rather on decreasing system costs by exploiting the additional capacity that is visible in step 3.

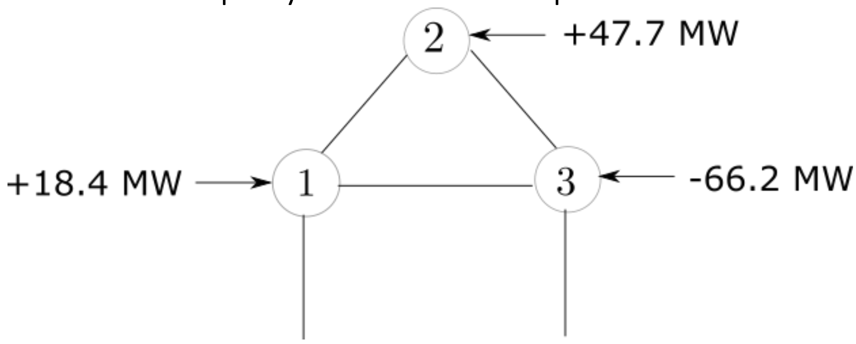


Figure 29: Outcome of step 3 of approach A8 for the commercially uncongested scenario if the goal of the Northern TSO would be to maximize economic surplus.

As in the commercially congested case, executing step 3 with the goal of economic surplus maximization largely undoes the decisions of step 2, in the sense that:

- MARI is adjusting G1 by -18.4 MW, and step 3 under economic surplus maximization is adjusting it back by +18.4 MW
- MARI is adjusting G3 by +68.4 MW, and step 3 under economic surplus maximization is adjusting it back by -66.2 MW

Thus, step 3 under economic surplus maximization increases welfare in the system, however it does so by largely undoing the MARI dispatch instructions.

By contrast, when the goal is to minimize deviations from MARI while restoring network feasibility, then for this specific example no BSPs are redispatched.

Step 4: Settlements

The settlements are presented in the following table, under the assumption that the goal in step 3 is to minimize deviations from MARI.

	Day-ahead	Step 1 (MARI)	Step 3 (post-MARI)	Total	Total (MARI + post-MARI)
G1 (BSP)	6000	-368	0	5632	-368
G2 (BSP)	4000	0	0	4000	0
G3 (BSP)	0	1881	0	1881	1881
L3 (BRP)	-6000	0	0	-6000	0
South BSP	0	425	0	425	425
South BRP	-4000	-2550	0	-6550	-2550
North TSO	0	61	0	61	61
South TSO	0	581	0	581	581
Total	0	30	0	30	30

Table 18: Settlements under approach A8 in the commercially uncongested scenario.

As in the commercially uncongested case, the computation of congestion rents at the MARI stage requires translating the usage of the capacity in the MARI zonal network model from the DA zonal model, so as to compute incremental usage of network capacity and the resulting congestion rents. For the case of our specific example, we need to solve the following linear system, which ensures that the flows in the zonal DA model are consistent with the flows in the zonal MARI model:

Zone N1: f12 + f13 = 300 - 100

Zone N2: - f12 + f23 = 200

Zone N3: - f13 - f23 = 0 - 100

For example, the first equality above expresses the fact that the zonal MARI model should have baseline flows which are consistent with the injection of power in the DA model (300 MW) minus whatever power flows over the link N-S1 (100 MW).

The linear system above has a unique solution (three linearly independent equalities in three unknowns), and yields the following mapping of DA zonal flows to MARI zonal flows:

- Link N1-N2: - 50 MW
- Link N1-N3: 250 MW
- Link N2-N3: 150 MW

Note that there is no a priori reason to expect that this flow should be compatible with the MARI zonal network ATC capacities (and in fact it is not, the flow on line N1-N3 exceeds the MARI ATC capacity, which is equal to 180 MW). Notwithstanding, these flows can be used for computing congestion revenues at the MARI stage. The non-zero values in the last row of the table are due to rounding error.

4.4 Economic efficiency

Commercially congested case: In the congested case, the total welfare in the system amounts to 912,830 €. The cost of approach A8 amounts to 27,170 €, compared to 26,854 € under approach A1 and A2. **The cost under approach A8 increases due to the fact that the MARI clearing uses a conservative capacity assignment**, which limits access to cheaper resources, whereas the post-MARI corrections are not geared towards minimizing cost but instead minimizing deviations from the MARI clearing result. The welfare breakdown is presented in the following table.

	Producer (BSP) cost	Consumer (BRP) value	Total revenue	Profit
G1 (BSP)	3944	N/A	6944	3000
G2 (BSP)	3944	N/A	5445	1501
G3 (BSP)	2750	N/A	3060	310
L3 (BRP)	N/A	340000	-8724	331276
South BSP	16531	N/A	17281	750
South BRP	N/A	600000	-30750	569250
North TSO	N/A	N/A	2900	2900
South TSO	N/A	N/A	3844	3844
Total	27170	940000	0	912830

Table 19: Welfare breakdown under approach A8 in the commercially congested scenario.

Commercially uncongested case: In the commercially uncongested case, the total welfare in the system amounts to 550,059 €. The cost under approach A8 amounts to 9,938 €, as compared to 9,681 € under approach A1 and approach A2. The cost increase, as in the commercially congested case, can be attributed to the conservative capacity assignment in the MARI hybrid model, and also to the fact that the post-MARI corrections are centered towards minimizing deviations from the MARI outcome, instead of minimizing cost. The welfare breakdown is presented in the following table.

	Producer (BSP) cost	Consumer (BRP) value	Total revenue	Profit
G1 (BSP)	4132	N/A	6000	1868
G2 (BSP)	3500	N/A	5230	1730
G3 (BSP)	1882	N/A	297	-1585
L3 (BRP)	N/A	300000	-6000	294000
South BSP	425	N/A	0	-425
South BRP	N/A	260000	-5620	254380
North TSO	N/A	N/A	94	94
South TSO	N/A	N/A	-3	-3
Total	9938	560000	-3	550059

Table 20: Welfare breakdown under approach A8 in the commercially uncongested scenario.

4.5 Payments for TSO

Commercially congested case: In the MARI clearing stage, the Northern TSO collects a considerable amount of congestion rent. This is related to the conservative capacity assignment, which limits the amount of trade from North to South, and increases TSO congestion revenues.

Commercially uncongested case: Note that, for the commercially uncongested case, we move from a day-ahead clearing outcome that does not exhibit congestion, to a hybrid MARI zonal model that exhibits congestion. This generates congestion revenues for the Northern TSO in the MARI clearing stage.

4.6 Uncertainty

If one were to adopt the **GSK approach** to A8, the need to define zonal network parameters for MARI implies the need for a *base scenario*, according to the nomenclature of flow-based market coupling. In simple terms, this means the estimation of the real-time conditions in the network, such that, when the balancing platform is solved with the parameter values chosen by the Northern zone operator, the resulting dispatch will not cause congestion. Given the uncertainty that the Northern zone operator faces regarding real-time conditions, step 1 of the A8 procedure may lead to a determination of ATC parameters which may cause congestion in step 2 of A8.

If one adopts the **susceptance approach** to A8, then we have observed that congestion can still occur in the Northern zone. This is due to the fact that the susceptance approach collapses the effect of non-Northern zones to nodal injections in the Northern zone, without accounting for the precise physical implication of these injections on Northern lines. One could argue that, if anything, this accentuates the impact of non-Northern zones on the Northern network and should therefore prevent congestion (because effectively it is as if we are placing non-

Northern generators' injections at the interfaces of the Northern zone with the rest of the network, which exaggerates the perceived impact of Southern injections on the Northern network), however the examples of this section have demonstrated that this still results in congestion when we assign capacity to inter-zonal lines aggressively (which implies a significant reshuffling of generation in the system).

4.7 Complexity

A complex aspect of this approach is the definition of a zonal model for MARI, and how it should relate to the physical model of the network, as well as the zonal model of the day-ahead market. In our small test example we have only one zone in the North in the day-ahead market, and then we have a nodal representation of the three nodes in MARI. This is not trivial to implement, because we have to decide how the nodal area interacts with the other zones. The complexity specifically arises in two dimensions, which are up to the subjective judgement of the TSO:

- How to assign ATC capacity on inter-zonal lines which, when moving from a DA zonal model to a MARI model, also correspond to physical lines. Two options here are *aggressive capacity assignment* (set the ATC capacity equal to the physical capacity of the lines), or *conservative capacity assignment* (set the ATC capacity equal to the DA capacity).
- How to model the influence of non-Northern net injections on Northern lines. Two options here are the *susceptance-based approach* [2], or the approach based on *generation shift keys*. Both options can lead to violations of Northern zone physical constraints, especially under aggressive capacity assignment (even though we have only demonstrated this for the case of the susceptance-based approach).

The complexity of the approach also relates to dispatch (beyond network definition), as illustrated in figure 15. In the example, the amount of re-dispatch that takes place due to the fact that the MARI network is different from the day-ahead network model is in the order of 600% (c.f. 40 MW of imbalance occurs, and 290 MW of upward activation takes place, i.e. 250 MW are activated upwards for dealing with the new network, as opposed to relieving the imbalance).

4.8 Assessment of ICT issues

The approach presents no particular ICT challenges in the case of the susceptance-based approach. The post-MARI computation is an optimal power flow that is restricted to the Northern zone.

In the case of the GSK approach, it would be meaningful to estimate GSKs based on the results of the previous imbalance interval in step 1 of approach A8, which may impose requirements for rapid communication between the MARI platform and the TSO control centers. This would impose a major IT communication challenge for MARI.

Highlights and main conclusions

- The MARI platform clears with a hybrid pricing model, in which the area of a TSO can be represented by a detailed nodal pricing model, while other areas are represented by a zonal pricing model
- The nodal pricing model consists of a detailed electrical flow model for the nodal pricing area, and aggregated commercial capacity constraints between the nodal pricing area and all other areas
- An important issue is how to **set the commercial capacity limits** : an outstanding challenge of this approach is how to set the capacities of the interconnections between the nodal and the zonal bidding zones. Let's however notice that, in the (hypothetical) situation that the whole Nordic synchronous area would go for this solution, all interconnectors would be HVDC, in which case the setting of the capacities would be straightforward, and this would therefore increase the economic efficiency, probably significantly. Another option is the case where Norway and Sweden together go for this approach, which would already largely reduce the interconnectors to HVDC only, with the exception of two "semi radial" interconnectors to Finland and East Denmark.
- The aggregated commercial links introduce some uncertainty in the system, since the actual ex-post flows may not be exactly as in the market clearing model
- When the network model changes from a zonal pricing model in the day-ahead market to a hybrid nodal and zonal model in the balancing market, large redispatches may result only because of the change in the network model
- There may also be large redistributions in post-MARI corrections if the objective is to maximize welfare or minimize cost
- Post-MARI corrections may be small or not even needed if the objective is to minimize deviations from the MARI schedules
- The MARI platform may not be ready to clear the market with a nodal pricing area

5 Cross-comparison

In this section we provide a comparative discussion of the different approaches. The overall assessment is then summarized in table 25.

5.1 Economic efficiency

In terms of economic efficiency, we focus on reporting two performance indicators: (i) cost throughout the system, and (ii) cost in the Northern zone. We report the profits of different agents, including BSPs, BRPs and the TSO, in the welfare breakdown tables of sections 2-4.
We present the cost results in the following table. Nodal refers to the fully nodal resolution as presented in section 1. “Business as Usual” approach (BAU) refers to the approach where MARI design remains unchanged, all bids are transmitted to MARI and no post-correction takes place.

	Commercially congested	**Feasible in RT**	**Commercially uncongested**	**Feasible in RT**
Nodal	System: 24,110 (-10.2%) North: 13,684 (+32.6%)	Y	System: 9,527 (-64.5%) North: 9,527 (+2.9%)	Y
BAU	System: 26,781 (-0.3%) North: 10,250 (-0.7%)	N	System: 9,675 (-0.1%) North: 9,250 (-0.1%)	N
A1	System: 26,854 (0%) North: 10,323 (0%)	Y	System: 9,681 (0%) North: 9,256 (0%)	Y
A2	System: 26,854 (0%) North: 10,323 (0%)	Y	System: 9,681 (0%) North: 9,256 (0%)	Y
A8	System: 27,170 (+3.1%) North: 10,639 (+1.2%)	Y*	System: 9,938 (+2.8%) North: 9,513 (+2.7%)	Y*

Table 22: comparison of the economic efficiency of each approach

The table indicates the cost of each approach, as well as its relative performance compared to approaches A1 and A2, which we consider the benchmark for our analysis, since these are the most efficient dispatch options under the constraint of zonal pricing. We point out the following observations:

- Nodal pricing achieves a superior welfare.
- The BAU approach performs seemingly better in terms of cost, both for the overall system as well as for the Northern zone. However, this is an artefact of the fact that the BAU dispatch is actually not feasible for the network.
- Approaches A1 and A2 attain identical performance. Indeed, it turns out that the final dispatch of resources is identical in both approaches. This is driven by the fact that the MARI clearing step in both approaches is fixing southern resources to identical schedules. Both approaches will arrive at an efficient dispatch of Northern resources given day-ahead commitment of inflexible resources and given southern schedules,

and therefore the efficiency of both approaches is also identical. **This is specific to our illustrative examples, and cannot be generalized as an observation**.

- Let's notice that, despite what is concluded by the analysis of the toy example, **in theory, A2 would be expected to be more efficient than A1**, as the MARI bids in A2 already contain implicit information on congestion while in A1, the congestion are fully solved in the post-MARI corrections which could intuitively lead to costlier actions. The reason is that there is an irrevocable decision of net position that is made in MARI. For example, we can imagine a case where MARI would activate a bid at 20€ (located in the North) and then would need to correct it afterwards with a bid of 80€ (located in the North), while if it would have known it in advance, it would have activated a bid at 40€ (located in the South) in the first place. This is not shown in our toy examples, but would in practise happen and would likely be more visible on a broader test set.
- Approach A8 exhibits notable efficiency losses, both from a system level, as well as for the North in particular. This observation is consistent for both stress tests.

We note that the efficiency results based on truthful bidding cannot be conclusive, and instead **it is important to examine the influence of the different designs on gaming behavior of agents. Under strategic behavior, the efficiency results can be substantially different** [3, 4].

5.2 TSO payments and revenues

We summarize the TSO cash flows (a positive number means a revenue, a negative number means a payment) in the following table. For the "Nodal" entries, the "MARI" column corresponds to a real-time dispatch with a nodal model, as shown in section 1 of the present report. The "Business as usual" entry corresponds to application of MARI market clearing, without post-MARI corrections. This is what would effectively occur if neither of the approaches would be implemented. This entry effectively amounts to the MARI congestion revenues that are collected in approach A1. Since the BAU approach is in fact not feasible for the network, there will be additional redispatch costs involved in the BAU approach that we do not quantify in this analysis.

	Commercially congested DA			**Commercially uncongested DA**		
	MARI	**Post-MARI**	**Total**	**MARI**	**Post-MARI**	**Total**
Nodal	1,070	N/A	1,070	94	N/A	94
Business as usual	0	N/A	0	438	N/A	438
Approach A1	0	-73	-73	438	-6	432
Approach A2	1,080 ('BSP-N')	-1,073	7	1,350 ('BSP-N') + 388	-1,261	477

				(cong rev)		
Approach A8	-475	0	-475	61	0	61

Table 23: Summary of TSO payments. Figures are in €. Positive values correspond to revenues collected by the TSO, negative values correspond to payments made by the TSO.

We note that approach A2 results in the highest TSO revenues in the commercially congested case, whereas the contrary is the case in the commercially uncongested case. On the one hand, the net of the 'BSP North' activation and the nodal uniform payments after disaggregation generate a slight surplus for the Northern TSO, i.e. the TSO collects slightly more in MARI as an 'aggregate North BSP' than it pays out to its domestic BSPs for disaggregation. On the other hand, the congestion revenues collected by the Northern TSO are slightly higher in A1 than in A2 in the commercially uncongested case, and identically equal to zero in the commercially congested case.

In approach A1, the Northern TSO has a slight financial exposure at the post-MARI phase, since post-MARI settlements are typically towards more expensive BSPs being dispatched up and paid as bid, while cheaper BSPs are being dispatched down and pay the TSO as bid. This creates a slight financial deficit for the TSO, which is added to its congestion surplus from the MARI clearing stage.

Approach A8 is the least favorable towards TSO revenues. In the commercially congested case, the payment at the MARI stage is dominated by payments to BSP G3, which are due to the change in network model. In fact, there is no congestion rent associated with the inter-zonal links in the commercially congested case: the negative congestion rent originates from the fact that more expensive BSPs are activated upwards, whereas cheaper BSPs are activated downwards. Similarly, for the commercially uncongested case the performance of approach A8 is lower than the competing methods.

5.3 Gaming Opportunities

5.3.1 INC-DEC gaming opportunities shared by all the approaches

All the models presented above ultimately rely on a nodal representation of the grid, which is conceptually appropriate given the intra-zonal congestions that need to be solved before real-time. Though, a zonal model is used for all the preceding timeframes (i.e. day-ahead, intraday and cross-border balancing).

This discrepancy in pricing zone definitions undeniably induces challenges in terms of INC-DEC possibilities. This issue has been well-documented by Hirth (2019)[28], although in a slightly different context. We undoubtedly consider this paper as a must read.

In a nutshell, the paper explains, in case an asset can be traded on different markets with different price delineations, the consequences of the natural incentive to exploit the price differences between these markets, especially when congestions are highly predictable. Consequently, and even in the full absence of market power, inc-dec gaming may easily occur and actors can in effect exacerbate the congestions and increase asset revenues through windfall profits (which are typically paid by the grid users through the tariffs): in regions of

[28] https://ideas.repec.org/p/zbw/esprep/194292.html

scarcity, the bidders will have incentives for underbidding and so to withhold capacity; while in regions of oversupply, the market parties will have incentive for overbidding and so to overproduce - these two behaviours aggravating the congestion.

It is important to realize that it is the discrepancy between the zonal DA spot market and the nodal balancing/redispatch mechanism which is the cause of the phenomenon, and that consequently, INC-DEC is thus generally unavoidable as long as such a discrepancy exists. As such, the opportunity is already currently existing in the internally congested Norwegian areas. Nevertheless, in what follows, we focus on the differences of the different proposed approaches in order to identify whether some approaches are more prone to abuse than others.

Note that Hirth paper [6] suggests two plausible ways forward for addressing the concern: either implementing full-fledged nodal pricing in all time frames, or relieving intra-zonal congestion through regulatory redispatch with cost compensation. As the implementation of a nodal pricing scheme on all timeframes is clearly out of the scope of this study, we concentrate on the second proposal.
The paradigm of a zonal market is that all assets within a given zone should be treated equally, irrespective of the intra-zonal congestions (which are in effect assumed to be economically inexistent). Hence, if an asset in a deficit node is activated due to a local congestion - although it is out of the money with respect to the zonal price - it should not realize profits. This is why this asset should only be compensated for its actual costs (in the nomenclature used in this paper, this means an out-of-market paid-as-bid compensation assuming truthful bidding).
Similarly, an asset in a surplus area that is redispatched down should remain entitled to make the same profit as if the local congestion was nonexistent, and shall be allowed to "rebuy" its power at cost. This is why it should only be allowed to claim its costs.
This is why cost-based bidding should in principle be enforced in any redispatch approach.
Note however that the above mentioned paper [6] basically assumes a market solely based on traditional thermal plants and inflexible load (the paper actually focuses on Germany), so that marginal costs are fairly easy to compute. However, the Norwegian system is primarily based on hydro generation for which marginal costs are more intricate to assess (and to monitor from a regulatory perspective). Taking into account flexible load is equally challenging. Methods for monitoring costs of hydro assets and load flexibility are out of the scope of this study. Rather, the analysis below focuses on which are the approaches which provide the best incentives for truthful cost-bidding.

5.3.2 Differences between the approaches

In what follows, we highlight the differences in the way each of the approaches is vulnerable to gaming.

Approach A1

In approach A1, the first step consists of a "normal" MARI execution, where marginal cost bidding is the theoretically optimal bidding strategy and where intra-zonal congestion is not

considered whatsoever. The same bids are then used in step 2 to correct the dispatch and make it feasible.
Because the settlement of step 1 completely ignores the possible upcoming congestion patterns (while they can often be anticipated by the asset owners), and because there are effectively **two distinct settlements** for step 1 and step 2, INC-DEC between MARI and post-MARI stages is in principle possible under approach A1. One may indeed "force" an activation in step 1 (paid-as-cleared) by submitting an overly optimistic price, while anticipating to be deactivated in step 2 (paid-as-bid) because of a local congestion. The windfall profit will in this case be the infra-marginal rent acquired in step 1. This is further illustrated on an example below.

Let's notice that such windfall profits are prevented, or largely mitigated, in approaches A2 and A8 as by design the network constraints are taken into account before MARI and because there is a unique settlement.

However, despite approach A1 is vulnerable to such types of gaming, let's notice that using the same bids in the two steps makes it somewhat harder to play INC-DEC: a bidder who oversells in MARI and is bought back in the redispatch step can only make a windfall profit in case he has obtained an infra-marginal profit in the step 1. This implies that the marginal price of his price zone is set by another bid further down in the merit order.
If we assume that the grid is uncongested prior to the MARI process, and that MARI activation volume is typically thin, an INC-DEC strategy might be risky compared to the small expected gains.

If the grid suffers from congestion prior to MARI, INC-DEC is definitely possible against the day-ahead market. This latter point can not be resolved with any approach focusing only on MARI-related processes.

Approach A2

Approach A2 probably creates better incentives than paying the disaggregated instructions at the MARI price and using pay-as-bid settlements for any deviations between disaggregated dispatch and the MARI price signal, as was the case in A1. This is because the **A2 approach already largely takes into account the likely congestions** when computing the residual supply function. For example, a bid that has no chance to remain activated at the end will simply not be included in the residual supply function, and therefore can not be activated in MARI. The volumes of corrections required after the MARI process are therefore more limited.
In particular, if the grid is uncongested prior to MARI, and if imbalances are generally speaking unforeseeable (at least for those out of the control of the asset owner, e.g. imbalances in another country), INC-DEC gaming becomes very challenging and risky: not only is it visible
As for any other approaches, if the grid is congested prior to the MARI process, INC-DEC gaming opportunities with the spot market exist and can hardly be resolved.

Approach A8

An important property that mitigates gaming the MARI / post-MARI step in approach A8 is the fact that the approach produces nodal prices at the MARI clearing stage. However, we note that both approach A8 as well as A2 effectively produce a different price for the same location when moving from day ahead to real time (due to the *explicit* change in network model in A8, and the *implicit* change in network model in A2), and this may have undesirable effects in terms of extracting liquidity from the day-ahead market in case asset owners believe that their assets are better valued in real time.

5.3.3 Illustration on a simple example

The following example is inspired by Alaywan [3], and serves to illustrate some of the concepts discussed above. Consider the system presented in the following figure.

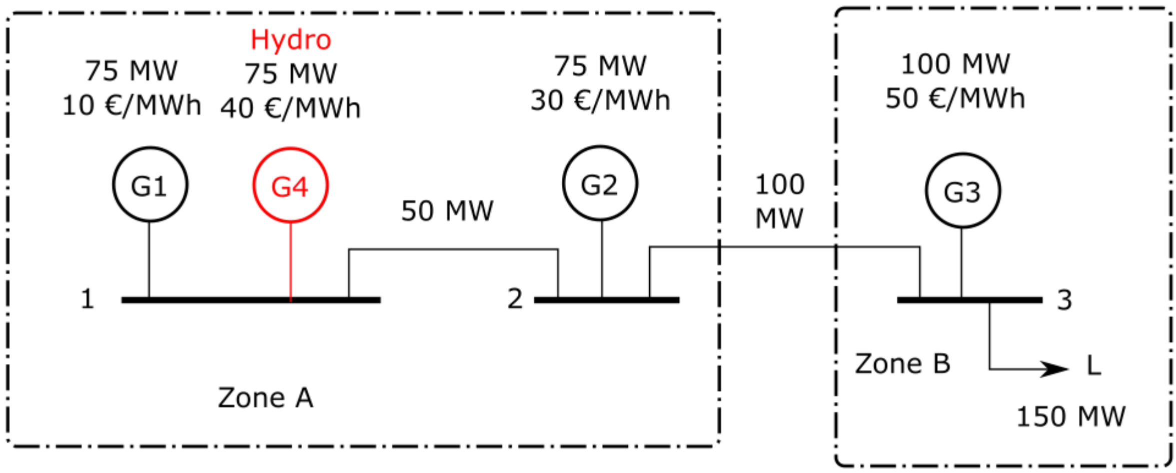


Figure 27: Illustration of the gaming concepts on a simple example inspired by Alaywan [3].

The system consists of three nodes, and two zones. The left zone, referred to as zone A, has three BSPs, whereas the zone to the right, referred to as zone B, has one BSP. The true marginal costs of the BSPs are indicated in the figure, along with the capacities of the BSPs. The two zones are interconnected by a line with a capacity of 100 MW. Nodes 1 and 2 are interconnected by a line with a capacity of 50 MW. Zone B has a load that is equal to 150 MW. All BSPs except G4 are assumed to correspond to thermal units, and it is therefore assumed that the regulator can apply cost-based market monitoring, with a fairly accurate knowledge of their true marginal cost. On the other hand, G4 which is marked with red font is assumed to be a hydro resource, with a marginal cost that is difficult to estimate, and therefore in a position to bid strategically in this market.

Economically efficient dispatch. The optimal dispatch in this example is for G1 to produce 50 MW (since no more can be transported over line 1-2), for G2 to produce 50 MW (since line 2-3 can only carry a total of 100 MW), and for G3 to produce the remaining 50 MW in order to fully satisfy the demand in node 3. Nodal pricing would then produce a uniform price of 10 €/MWh in node 1, 30 €/MWh in node 2, and 50 €/MWh in node 3. The hydro BSP G4 is not producing anything in the economically efficient dispatch.

Nodal pricing. In the case of nodal pricing, the strategic BSP G4 has no incentive to deviate from truthful bidding. By bidding less than its true cost and in particular below the cost of G1, it runs the risk of actually being cleared, and since it would be setting the price at its node, it would be producing at a loss. On the other hand, there is no consequence from the BSP bidding above its marginal cost, since it is anyways out of the money with respect to the nodal price.

Approach A1

BSP G4 has an interest in positioning itself so as to be activated in MARI (without setting the MARI price, otherwise it gains nothing), and then redispatched down due to the transmission constraint on line 2-3. Thus, it can offer its first 24.9 MW at 10.1 €/MWh (and the remainder of its capacity at any price above 30 €/MWh). This allows G4 to undercut G3 in MARI, thereby being activated, but also to extract as much rent as possible from being dispatched down in the post-MARI procedure, without actually having to produce. Concretely, the first 24.9 MW of G4 are paid the zonal price of 30 €/MWh, which is determined by G2 (who is cleared for 0.1 MW). Then G4 is dispatched down by 24.9 MW, and has to buy back its position at its bid price. It thus extracts a payment of 24.9 MW * (30 - 10.1) € = 495.5 € for offering no power whatsoever to the system. **It is therefore clear that this approach is vulnerable to gaming**.

Approach A1 with bid update from MARI to post-MARI

As we have mentioned previously in the report, allowing BSPs to update their bid between MARI and the post-MARI correction makes matters even worse in terms of gaming opportunities. BSP G4 is now in a position to extract exorbitant payments in the post-MARI stage by pretending that it is extremely cheap for it to be dispatched down. Let us suppose a price floor of -150 €/MWh for the sake of the example, meaning that BSPs may ask to be paid up to 150 €/MWh for being dispatched down (some renewable resources, for example, submit negative balancing bids which reflect the value of renewable energy credits which are foregone when they are dispatched down). The example may be exaggerated, but this serves to bring across our message.
Consider, now, the following strategy by G4: undercut G1 in MARI (even if it means producing at a loss) and make up for the losses in the post-MARI stage. Concretely, G4 can bid 9.9 €/MWh or less in MARI for all 75 MW. It is then cleared for 75 MW in MARI, with the price in zone A being set by G1 at 10 €/MWh. Then G4 bids a dec bid of -150 €/MWh in the post-MARI stage. Although this dec bid is not competitive, it must be accepted because of the capacity limit in line 1-2. Assuming away the line capacity in the zonal model does not imply that this capacity is not binding in reality. Thus, G4 produces 50 MW at a loss of 30 €/MWh per unit of production, implying an economic loss of 1500 €. But it profits by 150 € for each of the 25 MW that are dispatched down in the post-MARI stage, implying a revenue of 3750 € in the post-MARI stage. The net profit from the MARI and post-MARI clearing thus amounts to 75 MW * 10 € (MARI payment) + 25 MW * 150 € (post-MARI payment) - 50 MW * 40 € (actual production cost) = 2500 €, which is 5 times higher than the pure A1 market manipulation. To make matters worse, G4 actually produces, even though it is 4 times more expensive than G1.

Thus, **the outcome in this case is not only resulting in much higher profits from market manipulation, but also results in significant efficiency losses**. It is for this reason that the efficiency statements that we have arrived at in the main body of the report should be considered as being robust if incentives are in place for BSPs to bid truthfully. Concretely, they are rather reliable for A2, but should be considered as best-case scenarios for the other approaches.

Approach A2

As a hierarchical implementation of nodal pricing, A2 is rather robust to gaming. For the same reasons as in the nodal approach, G4 has no interest in overbidding or underbidding its cost. In the former case it is anyways out of the money, in the latter case it runs the risk of producing at an economic loss.

Approach A8

Approach A8, in this example, behaves identically to approach 2, since the network is radial.

5.4 Settlement rules & pricing

It is a given that in MARI all bids within a given area (which is deemed to be composed by several nodes) will be cleared uniformly, and that any subsequent step then uses a nodal granularity to render the dispatch feasible within Norway. Due to the reasoning held in the previous section, cost-based bidding should be enforced in such a final step.

These are some alternatives pricing scheme that can be envisioned:

- **Paid-as-bid – same bids**: all the resources activated in the post-MARI step are settled with the price of their bids, such prices being **the same** as the prices used in MARI
- **Paid-as-bid – different bids**: all the resources activated in the post-MARI step are settled with the price of their bids, such prices being **different** than the prices used in MARI
- **Zonal paid-as-cleared**: all the resources activated in the post-MARI step are settled based on the marginal activated prices of the post-MARI step, computed over the entire zone (as in MARI).
- **Nodal paid-as-cleared**: all the resources activated in the post-MARI step are settled based on the marginal locational activated prices of the post-MARI step (i.e. the prices being per node).
- Etc.

Of course, one can envisioned different combinations of things, but these are not further discussed in this report. Some are suggested in section 6 and could be subject of further work.

The following table summarizes the settlement rules that has been implemented in this report for the different steps of each approach:

	MARI step	Post-MARI step
Approach A1	Zonal pay-as-cleared	Pay-as-bid (out of market correction, same bid as in MARI)
Approach A2	Zonal pay-as-cleared (on the aggregated residual supply curve)	Pay-as-bid (desegregating the residual supply curve)
Approach A8	Nodal (for Norway) pay-as-cleared	Pay-as-bid (same bid as in MARI)

5.5 Legal aspects and political acceptability

The following discussion on legal aspects is based on the examination of regulation 2017/2195 (the electricity balancing guideline / EBGL), and how it interacts with each of the approaches. There are consistent statements in the EBGL which raise encouraging signals but also potential challenges with each of the approaches. We group each of these statements under collections of articles that convey the same message, and we comment on our interpretation of these statements in relation to the approaches.

ALL

1. Compatibility with operational security and network constraints. The way in which zonal modeling is implemented in MARI and PICASSO may contradict the requirement of the EBGL for ensuring operational security and satisfaction of network constraints through the balancing procedures. This requirement for operational security is expressed in articles 0(14), 0(18), 3(1c), 3(2d), 3(2f), 31(1b), 58(4a), 58(4b).

Approach A1

Approach A1 relies on out of market (OOM) corrections to the MARI result. These OOM corrections rely on side payments which are typically paid as bid. <u>The question is whether such side payments are acceptable according to the EBGL</u>.

1. Economic efficiency objective. There are articles in the EBGL which emphasize the fact that balancing should promote economic efficiency. This may challenge the objective of minimizing deviations in the post-MARI step. This is reflected in articles 0(6), 2(1), 3(1e), 3(2c).

2. Transfer of balancing capacity. The post-MARI process whereby one BSP activation is excluded and counteracted with the activation of another one could be interpreted (loosely) as a transfer of balancing capacity. Transfer of balancing capacity is defined in articles 2(26), 34(1). However, it is not clear whether the interpretation of this transfer of balancing capacity is compatible with the timelines envisioned for transfer of balancing capacity, as explained in article 34(2).

3. Level playing field. We have explained in the report why the post-MARI step may be susceptible to INC-DEC gaming. By contrast, the EBGL stipulates rules that lead to a level playing field, see article 3(1f).

4. Deviations from merit order. Deviation from the common merit order list activation is foreseen through fallback procedures. These are discussed in articles 28(3), 29(5), 31(11). It is clarified in article 30(1b) that out of merit actions shall not set the marginal price, which justifies the side payments proposed under this approach.

Approach A2

Approach A2 relies on the Norwegian TSO representing its BSP bids as an aggregate BSP in MARI, and then disaggregating the MARI results to its domestic BSPs. The question is whether this aggregation / disaggregation procedure is compatible with the EBGL. It is possible that a similar approach has been adopted in Poland, it may eventually be worth for Statnett to exchange views with the Polish TSO.

1. Merit order. The fact that approach A2 produces a merit order list for MARI is consistent with EBGL requirements on submitting merit order lists in order to ensure cost-efficient activation of bids. Relevant articles are 0(11), 21(3k).

2. Compatibility with TSO-TSO model. The definition of a TSO-TSO model is one in which the BSPs interact with non-domestic TSOs through their domestic TSO (as opposed to directly). This seems compatible with what is being proposed in A2. Relevant article is 2(21).

3. Forwarding BSP bids to the platform. There are certain provisions in EBGL which suggest that the TSO is required to forward its domestic bids directly to the platform. These provisions may be at odds with the aggregation that is being proposed in the pre-MARI step of approach A2. Relevant articles are 2(38), 12(b), 16(2), 21(6a), 29(9), 33(3). Limitations on this practice are foreseen, subject to regulatory approval, in article 5(4e).

4. Integrated scheduling process in central dispatching. There are explicit provisions in the EBGL regarding the conversion of bids, by TSOs operating an integrated scheduling process within a central dispatching context. The conversion of bids from an integrated scheduling process is discussed explicitly in articles 12(3c), 12(3d), 18(8d), 27(3). TSOs that wish to apply a central dispatching model need to notify the relevant regulatory authority, as foreseen in article 14(2).

Focusing on article 27(3), the text reads as follows:

Each TSO applying a central dispatching model shall convert as far as possible the integrated scheduling process bids pursuant to paragraph 2 into standard products taking into account operational security. The rules for converting the integrated scheduling process bids into standard products shall:
(a) be fair, transparent and non-discriminatory;
(b) not create barriers for the exchange of balancing services;
(c) ensure the financial neutrality of TSOs.

One concern about this interpretation is that the spirit of these provisions is to allow the mapping of bids submitted in a unit commitment tool to bids that are submitted to an exchange. Concretely, the integrated scheduling process receives information about startup cost, min up/down times, ramp rates, technical minima, min load cost, etc., whereas the balancing platforms will require much simpler bids which internalize many of these factors. Therefore, the interpretation of the integrated scheduling process articles as a means of avoiding congestion could be challenged.

Approach A8

Approach A8 relies on defining a finer resolution for the MARI model, and then possibly resorting to out of market corrections with side payments in order to settle congestion problems. The question is whether the post-MARI settlements are compatible with legislation, and whether a different zonal model can be used in MARI.

1. Consistency between zonal day-ahead model versus zonal MARI model. The EBGL requires consistency between zonal models in the day-ahead, intraday and balancing timeframe. This is reflected in articles 0(5), 3(1d), 30(1e). In this perspective, A8 could be in contradiction with EGBL unless DA and ID are also modelled through a nodal representation.

2. Economic efficiency objective. There are articles in the EBGL which emphasize the fact that balancing should promote economic efficiency. This may challenge the objective of minimizing deviations in the post-MARI step. This is reflected in articles 0(6), 2(1), 3(1e), 3(2c).

3. Transfer of balancing capacity. The post-MARI process whereby one BSP activation is excluded and counteracted with the activation of another one could be interpreted (loosely) as a transfer of balancing capacity. Transfer of balancing capacity is defined in articles 2(26), 34(1). However, it is not clear whether the interpretation of this transfer of balancing capacity is compatible with the timelines envisioned for transfer of balancing capacity, as explained in article 34(2).

4. Level playing field. We have explained in the report why the post-MARI step may be susceptible to INC-DEC gaming. By contrast, the EBGL stipulates rules that lead to a level playing field, see article 3(1f).

5. Multiple common merit order lists. The separation of the MARI model into more granular zones introduces additional common merit order lists. Multiple common merit order lists are foreseen in the regulation in article 25(3b).

6. Deviations from merit order. Deviation from the common merit order list activation is foreseen through fallback procedures. These are discussed in articles 28(3), 29(5), 31(11). It is clarified in article 30(1b) that out of merit actions shall not set the marginal price, which justifies the side payments proposed under this approach.

Fast products

The fast product approach relies on running a post-MARI auction, which is exclusively Norwegian. The question is whether a separate fast product auction is permitted in EBGL.

1. Standardization of products. There is a strong push in the EBGL for standardizing products, which may raise challenges with introducing a separate fast product only for Norway. Relevant article is 0(13).

2. Definition of specific products. In case the Norwegian fast product can be interpreted as a specific product, the specific product is defined in article 2(36). Specific products are foreseen in articles 5(4d), 25(1) subject to justification and regulatory approval. From article 30(4), it appears that specific products are traded outside the platforms.

3. Overriding skipped bids. It is not clear that the Norwegian TSO would be able to override bids that are skipped in the merit order without being financially liable. The rules for settlement are outlined in article 46, table 1. The question is whether ‘positive balancing energy’ is interpreted physically (i.e. energy that was actually activated) or financially (i.e. energy that was cleared in MARI).

Bid filtering

Although this is out of scope for our own analysis, the bid filtering procedure where certain bids are blocked from being input into the platform seems to be foreseen in article 29(14).

Based on these observations, we assign the higher score for legal compatibility to approach A1, since the only major obstacle to legal implementation of A1 is the deviation from merit order, which may anyways be foreseen under the EBGL articles that relate to operational security and respecting network constraints. Approach A2 attains a modest score, with the major unknown being whether the approach can be interpreted under the light of article 27. If this is the case, then the approach seems promising from a legal perspective, if not, then serious concerns are raised with the violation of articles that require the TSO to forward BSP bids to the platforms. Approach A8 achieves the lowest score due to the fact that there are articles in EBGL that require consistency between day-ahead, intraday, and balancing time frames, whereas approach A8 is in violation of this principle.

5.6 Uncertainty

There is a generic aspect of uncertainty, which relates to all approaches. (i) We do not know the details of the neighboring networks (i.e. where the MARI requests and activations take place). (ii) In general, we also do not have access to imbalance measurements at a nodal resolution.

Regarding the first aspect, the stylized models that have been presented in the report assume that the Northern TSO can measure left-over capacity in its lines before resorting to post-MARI corrections, i.e. it is implicitly assumed that Northern resources are sufficiently rapid (e.g. hydro) to respond very rapidly to post-MARI correction signals, which themselves are computed by assuming that the leftover capacity on the Northern network has been estimated *after* non-Northern resources have been activated to respond to MARI instructions. This assumption is clearly optimistic. Regarding the second aspect, Statnett has explained their disaggregation procedure and considers the assumption of observable nodal imbalances to be acceptable for the illustration of the numerical examples, despite the fact that this assumption may not be perfectly precise in practice.

Approach A1

Step 2 of A1 benefits from perfect hindsight regarding the results of the MARI platform, as well as the upcoming imbalances. Therefore, A1 can be seen as robust towards uncertainty, since the optimal power flow that is being solved in step 2 (post-MARI) has all information available for selecting an optimal dispatch from the point of view of Statnett. Nevertheless, as approach A1 doesn't do anything beforehand to solve possible upcoming issues, it somehow assumes that all possible issues arising from MARI could in theory be solved afterwards. This might not be the case and solving all the issues afterwards might turn out to be infeasible at the end.

Approach A2

The flows induced by non-Norwegian injections can be estimated based on information that is monitored locally by the Norwegian TSO. Therefore, Statnett can estimate the input that is required for the execution of the residual supply function estimation without the need for explicit communication with other TSOs.

Approach A8

Step 1 of A8 involves the estimation of zonal network parameters. The uncertainty that the system operator faces regarding real-time demand across the network implies that the zonal network parameters of MARI may be chosen such that the clearing of MARI could cause congestion to the Norwegian network.

5.7 Complexity

By complexity, we mean here the complexity of implementing the whole process implied by the approach.

Approach A1

Three main appealing attributes of approach A1 are the fact that (i) the zonal network of MARI is consistent with that of the day-ahead market, (ii) there are relatively minor changes (if any) in the post-MARI dispatch, and (iii) the net position of the Northern zone is unchanged in the post-MARI step. On the other hand, the post-MARI step actively overrides the MARI results. Therefore, we assign a high, but not perfect, score to approach A1 in terms of implementation complexity.

Approach A2

Intuition suggests, and numerical experiments confirm, that approach A2 can perform well even if there are inaccuracies in the estimation of the residual supply function. The intuition for this behavior is that, as long as the marginal cost of the aggregate Norwegian network is estimated reasonably at the optimal point of dispatch, then the post-MARI disaggregation ensures that this aggregate net position is sourced optimally within the Norwegian network without violating its local constraints.

Approach A8

A significant element of complexity in A8 relates to the definition of the zonal network in MARI, which is far from obvious. Certain links in the ATC model of MARI may be associated with physical lines (within Norway or inter-zonal), and may therefore admit relatively obvious values. For other links (inter-zonal MARI links which correspond to physical lines), the capacity that should be assigned is not obvious, and this will in general impact the pricing results of MARI. The same general observation applies to the model that is used for representing linearized power flows in the Northern network. Two possible choices here are based on GSKs and susceptances, and in general both may result in a market clearing within MARI which would not allow the Northern TSO to restore feasibility after MARI.

Another significant element of complexity in A8 relates to the fact that the activations within MARI may exceed significantly the actual level of imbalances that is occurring in the system. Effectively, MARI reacts to the fact that the MARI zonal network model appears to be different from the day-ahead zonal network model. Thus, it may turn out that resources are being activated more in response to the different network model and less for the sake of relieving imbalances in the system.

5.8 Assessment of ICT issues

The following table summarizes the ICT requirements of each approach.

Approach A1	Step 2: Solution of a nodal optimal power flow restricted to the Norwegian zone *after* MARI (time critical).
Approach A2	Step 1: Estimation of non-Statnett injections based on previous Norwegian line flow measurements and Norwegian net injections (e.g. day-ahead or previous imbalance interval) Step 2: Estimation of residual supply function based on repeated solution of multiple OPFs, using results of step 1 as input. Can be computationally challenging in case of multi-dimensional residual supply functions. Step 4: Estimation of non-Statnett injections based on previous Norwegian line flow measurements and Norwegian net injections, in **real time, <u>after</u> MARI activation**
Approach A8	Step 1: One significant issue is the ICT complexity of transferring more or less on line Scada data to the MARI platform. Indeed, this implies a technical issue, but also an ICT security issue, as these are highly confidential data, which means getting the approval for that might be difficult. Step 4: Solution of one nodal optimal power flow problem restricted to the Norwegian zone *after* MARI (time critical). In a GSK approach, the results of the previous imbalance interval dispatch may need to be communicated to the MARI platform in order to compute the GSKs for the upcoming interval.

Table 24: Summary of ICT requirements of each approach.

5.9 Summary

The following table summarizes the comparison of the different approaches. The table assigns a score to each approach along each dimension of analysis. The scores range from '- -' (lowest possible ranking) to '+ +' (highest possible ranking). A score of '0' indicates the medium ranking.

Of course, let's bear in mind when reading the table that the different dimensions should not have the same weight. Furthermore, two additional criteria, not investigated in this report but which might bring some valuable insight have been added at the end of the table.

	Approach A1	**Approach A2**	**Approach A8**
Economic efficiency	0	+	0
Robust to **Gaming**	--	+	+
Financial neutrality of the **TSO**	+	+	-
Compatibility **with MARI processes**	+ +	+ +	- -
Political acceptability	+ +	+	-
Compatibility with **EU legislation**	+	-	- -
Robust to **Uncertainty**	-	+	+
Keep **Complexity** manageable	+	0	+
Manageable **ICT issues**	+	0	-
Compatible to **TSO / DSO coordination**[29]	0	++	0
Generate proper **grid investment** incentives	-	+	+

Table 25: Summary of cross-comparison.

[29] The main reasoning behind this score, even if not detailed in the report, is that in case some BSP located at the DSO grid want to send their flexibility to MARI, approach A1 and A8 would not scale while approach A2 would remain applicable (as studied in H2020 SmartNet project).

6 Further work

In this report, we developed, analyzed and compared three approaches to mitigate and solve the possible congestions that could result from activations in MARI. The main conclusions have been presented in the last table of the previous section. Nevertheless, it should be noted that these "three approaches" should in fact be understood as "three families of approaches" for which one instance has been implemented in this report. It means that within each of these families, multiple variations are possible and therefore, if the main differences between these families have been correctly highlighted in the report, some more nuances remain to be explored within each family and could therefore lead to further work.

In particular, there are outstanding open questions that remain on some of these approaches and more specifically on approach A2 which, based on the analysis, seems to be really attractive but is also conceptually complex and is a broad topic in itself. Furthermore, there are overall some *quantitative* insights which are missing in the analysis, as it relies on a 6-node example. These two aspects (the outstanding questions on the approaches and the quantitative analysis) are detailed in this chapter and could be tackled together, for instance, in the scope of an extension of the present study.

6.1 Outstanding open questions

Approach A1

- A1: when solving the re-dispatch, we solve the nodal problem with the target of having the same net exports as the one set by MARI. But there would actually be multiple ways to do it. Further, the approach may in theory lead to infeasibilities. To what extent such infeasibilities would be a practical concern remains to be investigated.

Approach A2

- In our analysis, the efficiency of A1 and A2 is the same while the intuition is that A2 should be economically more efficient. It would be interesting to get a better illustration of this.
- We could investigate whether it might be preferable for Norway to participate in MARI as a single zone or not.
- How to implement exactly the supply function? A possible implementation of this calculation is that the North TSO has access to the day-ahead nominations of generators, in order to be able to compute the incremental cost relative to the day-ahead nominations, and thereby the residual supply curve. In effect, this means that the bids should be locational. This is how our simulations have been run. Implicit in our definition of TCe above is the fact that the day-ahead nominations are cost-minimizing choices for meeting the day-ahead clearing schedule. If this were not the case, we would need to reformulate the model as one in which the day-ahead nominations are fixed, resource by resource. This would increase the notational complexity of the exposition, but the main concepts would remain unchanged. Such considerations could be further studied.
- There could be another way to build the curve taking into account the settlement rules of MARI. Basically, what we did was a pay-as-cleared in MARI with the aggregated

curve. Then, when disaggregating the curve, the settlement is pay-as-cleared, but nodal (not zonal). One alternative would be to perform a pay-as-cleared zonal when disaggregating the curve (which would lead to results closer to the “bid filtering approach), another to exclusively rely on paid-as-bid principles, etc.

- Another design issue that remains around A2 is linked to the fact that the aggregate bidding curve could be multi-dimensional when a bidding zone is connected to several others. However, the MARI format will not allow multi-dimensional bid curves – so the question is: how much is lost by using a single bid curve instead of the required/preferred multi-dimensional?[30] A one-dimensional bid curve will thus be an approximation, but it still takes into account some of the internal constraints – as opposed to A1, that does not do this at all. This is one of the issues where simulations of the real system will give better insights in what this means in practice.
- More generally, A2 has multiple variants depending on how the 5 bidding zones of Norway are treated: should they be treated separately or together, both when making the aggregation (step 2 of the approach) and the disaggregation (step 4).
- Another correlated open point is linked to the treatment of HVDC cables. This should be studied in the scope of a more quantitative analysis on a realistic network. The 6 node example is indeed not adequate to capture these effects.

Approach A8

- There are numerous assumption which need to be taken in the A8 model, and in particular for what concerns the way capacities towards other bidding zones are set (i.e. worst case, conservative, best guess, …). The performance of the model will strongly depend on these elements, which therefore deserve further analysis

6.2 Quantitative simulations and analysis to address these open questions

In this section, we sketch how a quantitative analysis would differ from the analysis that has been conducted in this study, and what are the kind of new insights that could be brought with such an analysis.

6.2.1 Input to our 6 node example

The three main inputs in such market simulations are : (1) the network model, (2) the imbalance (demand-side bids) and (3) the BSP bids or units (supply-side bids). The 6-nodes instance used in this report was created in order to make “stress tests” or “corner cases” which were generated to highlight the main differences between the approaches. In this perspective, its input were :

- **Network**: a 6 nodes model (quite small), where the lines and nodes **did not have any link with the real network** (despite the fact that for the sake of the example, some nodes/zones were labeled “Norway”, “South”...)
- **Imbalance**: the imbalance was created for the sake of these examples and had **no link to the past realised imbalance**, neither in magnitude nor in frequency of

[30] Somehow Statnett has faced a similar problem in their work with bid-filtering, which also requires Statnett to identify bids even though Statnett does not know where requests will come from.

occurrence. There was also an underlying assumption that the imbalance could be located at a nodal level.
- **Bids**: the supply bids (BSP units) were created from scratch to illustrate the corner cases but **did not have any link with the technical or financial setup of the Norwegian power units** (so no link with the actual liquidity, quantities or prices that such a market would have in reality).

As such, and as highlighted in the description of these three inputs, the examples are only “stress tests” which remain purely theoretical.

6.2.2 Input to the quantitative simulations

These quantitative simulations, even if they are conducted on the so-called “44-nodes” system which remains a simplification of the real network, will be **based on reality** and will therefore allow to get a more realistic quantitative insight. These simulations would include the following inputs:
- **Network**: more **realistic network**, linked to the physics of the Norwegian network, even if remains an approximation of the reality (e.g. if these simulations are conducted on the 44-nodes system, while the real network have more than 1000 nodes)
- **Imbalance**: **realistic imbalance** based on historical time series and therefore including the right magnitude and frequency of the imbalances in Norway.
- **Bids**: **realistic set of BSP bids** based on the historical bids (better evaluation of the liquidity, bid prices and bid quantity)

So our understanding of such a quantitative analysis, is that its added value does not only lay in the usage of a more granular network but also in the implementation of realistic bids and imbalances.This would allow to obtain a better feeling about whether the theoretical observations raised in the present report appear to be material in (quasi) practice.

6.2.3 Additional insights achievable with quantitative simulations

Compared to what is achievable with the 6-node example of this study, such a quantitative analysis would allow to better assess:
- **Frequency of the issues**. The corner cases in the study show the reasoning of what would happen in case of issue but it does not tell anything about the frequency of such an issue (combination of imbalance, network and bid activation creating congestion).
- **Realistic costs, economical efficiency and payment for TSO**. The study can compare in relative value what are the performances of one approach with respect to another but does not give a realistic figure of what each approach and each design choice will mean in € per year.
- **More realistic network** status, results and congestions created. Furthermore, such a network would enable to model the HVDC cables as well as modelling the effect of multiple bidding zones in Norway (rather than a single bidding zone for Norway).

On top of these general insights that such an analysis would produce, it would of course also be the occasion to address some of the outstanding open points listed earlier. Regarding the **different dimensions** we studied in this report, a quantitative simulation could mainly bring more information on: (1) **Economic Efficiency**, (2) **Payments for TSO**, (3) **Settlement rules**

& pricing. Regarding the **gaming opportunities**, this would hardly be tested as the bids that will be used are historical bids, not generated by the traders for the tested market design. Regarding the **ICT issues**, as the simulation would rely on a prototype less performant than an industrial tool, the computational time would remain quite different to what will be reached in production. Nevertheless, it would still provide a good and possibly instructive upper bound.

Let's finally mention the following specific ideas have also been raised during the project and could be tested in a quantitative analysis:

- How a growing share of renewable could impact the analysis? Qualitatively, one can say that:
    - More RES will likely mean more frequent infeasibilities as well as (possibly) more severe infeasibilities. Therefore, the drawbacks of approach A1 which does not attempt to do anything beforehand to solve possible congestion, would likely be more severe as well; which would reinforce the strengths of A2 or A8 and make them more suited for such a situation.
    - Furthermore, one could probably argue that T/D coordination might be more important in case RES increases, as some RES would be located on the DSO grid. This would be an argument in favor of A2, as it is an approach which is suited for T/D coordination as well and that could therefore be extended for such a use case.

  Now how to quantify it and how to make a more granular assessment? This would typically be the kind of question where a quantitative analysis (with simulations and where projections of data are possible) would be able to bring more conclusions.
- Getting a more accurate estimation on how congestion rent is split could be valuable.
- Additional metrics could be evaluated such as the "system slack" or number of lines operating at limit, to assess the efficiency of the approaches.
- The degree of ex post corrections should be systematically different in approach A1, A2, and A8 since for A1 all corrections take place after MARI, whereas A2 and A8 involve a certain level of pre-processing. This would be interesting to quantify in the 44-node example. Indeed, it seems reasonable that there will be systematically different degrees of post MARI effects, since A8 takes into account more constraints in the MARI execution and A2 tries to do this beforehand, while A1 relies completely on an ex post adjustment. This would be interesting to simulate in the 44-nodes example too.

6.3 How to perform these quantitative simulations

Two main possibilities of simulation have been discussed with Statnett: (a) conduct simulations on a 44-nodes network, which remains an approximation of the real network (i.e. as highlighted above, a quantitative analysis would remain quite informative, even if conducted on a network which remains a simplification of reality); or (b) conduct simulation on the full network.

Depending on the choice, two options would be possible to conduct the simulations and the analysis that comes with it:

- One option would be to let N-SIDE perform the simulations and the analysis on the 44 nodes network.

- One other way would be that Statnett makes the simulations, possibly on the full network (as Statnett has already something in place for their bid filtering approach), and then let N-SIDE perform the analysis.

7 Annex A – Discussion on Approach A7 : Zonal Norway in MARI

In this section we describe approach A7, which is based on the idea that the **topology** of the Northern zone network is represented in greater detail in the MARI platform than in the day-ahead zonal platform. The principal difference with approach A8 is that (i) Northern nodes may still be aggregated to zones, but at a higher resolution than in the day-ahead zonal model, and (ii) we do not account for linearized power flow equations in approach A7, but rather restrict ourselves to an ATC-based model for the Northern zone. In an actual implementation of A7, it would be possible to have 5 zones in Norway (or 6 if the change is decided by NVE) in the day-ahead market with an ATC model, and a multitude of zones (e.g. 15 Norwegian zones) in MARI.

As agreed in the terms of reference, we will develop a separate discussion of this approach in the present section, without however advancing to a full-blown comparison with the other three short-listed approaches. Thus, the discussion for approach A7 is limited to the present section and is not discussed in the cross-comparison section.

The timeline of approach A7 is outlined in the following figure. Note that the timeline of approach A7 is identical to that of approach A8. Notably, step 1 is required in both approaches, even if the A8 approach accounts for a linearized approximation of power flows. And once step 1 is introduced in the process, the (optional) execution of steps 3 and 4 also becomes part of the procedure.

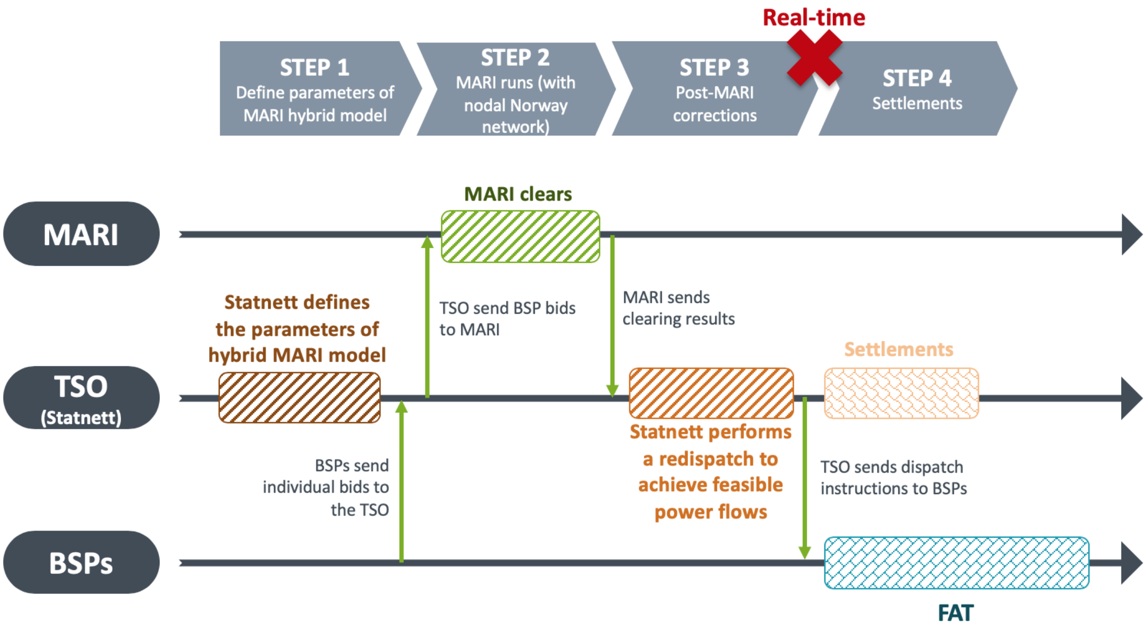


Figure 30: Timeline of events in approach A7.

7.1 Detailed Description and Timeline of the Approach

Step 1: Define parameters of MARI zonal model

As in the case of approach A8, we have three types of links for which we need to decide on ATC capacities in step 1 of the process. Nevertheless, we point out that step 1 of the process is simpler than that of approach A8, in the sense that we do not need to decide on how to model linearized power flows in step 1 of approach A7 (recall the discussion on GSKs versus susceptance-based models of power flow in section 4), since linearized power flows are ignored altogether in approach A7. We recall the definition of the three types of links for which we need to decide on ATC capacities:

- *Type 1 links*: the DA zonal links are unaffected

- *Type 2 links*: the MARI zonal links correspond to physical lines
- *Type 3 links*: neither the first nor the second possibility, i.e. the MARI zonal links correspond to neither DA zonal links nor physical lines, i.e. they are still aggregations of physical lines, but finer aggregations than those of the DA zonal model.

As in the case of approach A8, aggressive capacity assignment refers to setting the ATC value of type 2 links that correspond to inter-zonal lines equal to their physical value. We find an identical outcome in the numerical illustrations below: this can lead to overloading, and is therefore an unreliable procedure. The overloading may be so extensive that the Northern operator may not be able to restore flows that respect the physical limits of lines in step 3 of the procedure. For the same reason as in approach A8, we adopt instead the conservative capacity assignment procedure. Recall that the conservative capacity assignment procedure sets the ATC value of type 2 links that correspond to inter-zonal lines to the same value as the day-ahead market clearing zonal model.

Step 2: MARI market clearing
In the MARI market clearing, we assume that the imbalance that will occur in the system has already been revealed through a TSO need on the MARI platform.

Step 3: Post-MARI corrections
Under aggressive capacity assignment in step 1, it is possible (and is demonstrated in the stress tests) that the outcome of step 1 causes flows which overload lines. This can happen even if there is no imbalance in the system when we move from the zonal network of the day-ahead market to the zonal network of MARI. In this case, it is necessary to adjust the position of resources in the Northern zone, so as to relieve the resulting congestion.

Step 4: Settlements
If out-of-market corrections take place in step 3, side payments are settled in step 4 for those resources which are asked to deviate from the MARI dispatch in step 3. We assume that the upward or downward corrections relative to MARI are paid as bid.

7.2 Illustration on the Stress Tests

We now illustrate the performance of the approach for the case of the commercially congested and commercially uncongested stress test. In the following stress tests, we assume that the Northern zone is represented in full nodal detail, meaning that every node of the Northern zone is represented as a separate zone in the MARI hybrid model. The difference with the numerical illustration of approach A8 is that linearized power flows are not included in the MARI hybrid model, i.e, an ATC based approach is used.

7.2.1 Commercially congested scenario

Steps 1 & 2: MARI market clearing under aggressive capacity assignment - NOT RECOMMENDED
The result of the market clearing of MARI is presented in the following figure.

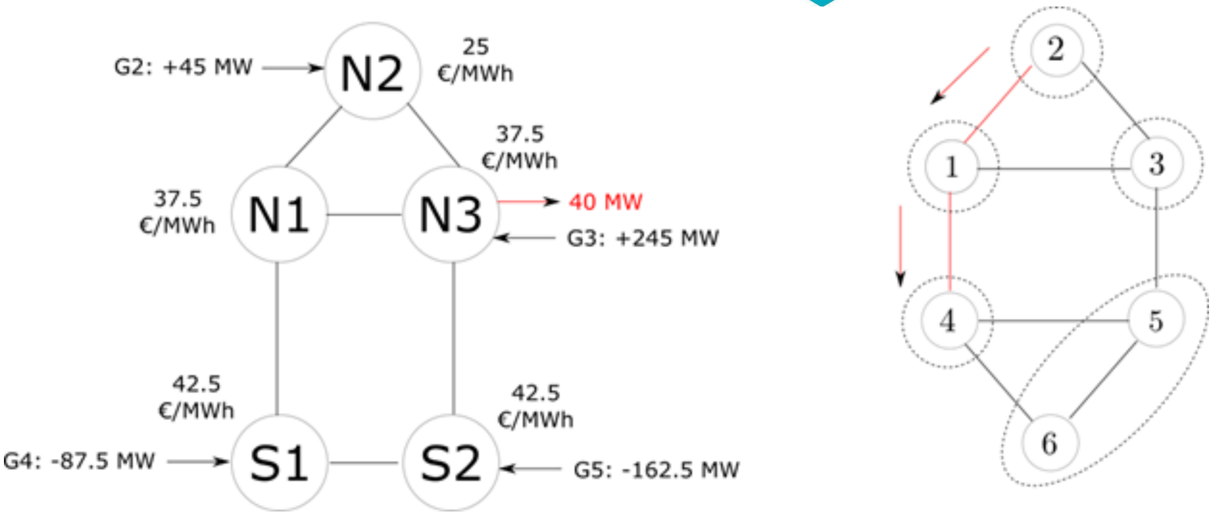


Figure 31: Outcome of MARI in the congested scenario of A7 with aggressive capacity assignment (left) and resulting congestion in the actual grid (right).

Note that the total upward activation remains the same as in approach A8. We therefore see that adding the susceptance formulation in the Northern zone under approach A8 has no clear benefit: what drives the upward dispatch of 290 MW is the large price difference between the Northern and Southern zones. Thus, when we increase the capacity between the Northern and Southern zones under the aggressive capacity assignment, the first thing that happens is that we reshuffle generation from the South to the North, even if we add restrictions on the nodal part of the network. Note also that the same lines are congested in the right part of the figure as in the case of approach A8. There are slight differences in clearing prices and individual dispatch results, but the overall picture remains the same as in the case of approach A8.
As in the case of approach A8, this approach results, in step 2, in an infeasible problem. For this reason, as in approach A8, we discard step 1 with an aggressive capacity assignment.

Steps 1 & 2: MARI market clearing under conservative capacity assignment - RECOMMENDED
Following the same rationale as approach A8 (if the day-ahead zonal model does not cause congestion, then we should aim at retaining its characteristics at the interface of the Northern zone with the Southern zones), we now examine the performance of the conservative approach. The resulting dispatch from MARI is presented in the following figure. Note that the dispatch is actually quite different from that of approach A8 (Figure 26), and the settlements are affected accordingly. Nevertheless, the main insights remain similar in both approaches, as we explain below.

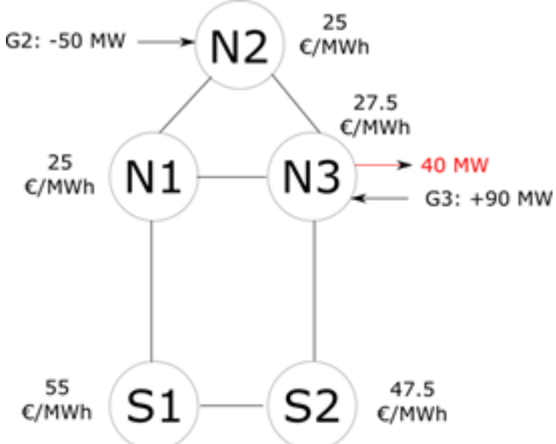


Figure 32: Outcome of MARI in the congested scenario of A7 with conservative capacity assignment.

The observations follow closely those of approach A8: the actual volumes that are being adjusted by MARI are now closer to the imbalance that occurs in the network. However, there is still a certain degree of 'counter-activations' in the Northern zone, with the total upward activation amounting for more than 200% of the imbalance that occurs in the Northern zone. This is due to the fact that the MARI model has a finer resolution regarding the internal capacities of the Northern zone, and is moving generation from G2 to G3 (which increases the cost of dispatch) in order to relieve Northern congestion. The resulting flow turns out to be feasible for the physical network for this specific example.

Step 3: Post-MARI corrections

For the aggressive implementation of A7, there is no way to recover a dispatch that respects the physical limits of lines if only resources of the Northern zone are going to be asked to deviate from MARI.

For the conservative implementation of A7, the resulting physical flows are feasible for this specific example. Therefore, if the goal of the Northern TSO is to minimize deviations from the MARI outcome, then there are no post-MARI corrections.

On the other hand, if the goal of the Northern TSO in step 3 would be to maximize economic benefits from trade, then re-dispatching occurs if the actual physical capacities seen by the Northern operator exceed the restricted capacities determined in step 1 of approach A7. The resulting dispatch of step 3 under economic surplus maximization is presented in the following figure. Note that this step contributes in no way to managing overloads of lines. This follows closely the observations that we have already made regarding approach A8.

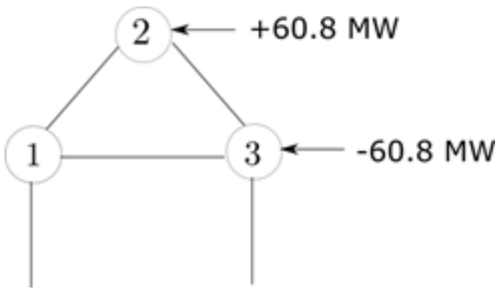


Figure 33: Outcome of step 3 of approach A8 for the commercially congested scenario, if the goal of the Northern TSO in step 3 is to maximize economic benefits of trade.

Step 4: Settlements

The settlements presented in the following table are computed under the assumption that the goal of the Northern TSO in step 3 would be to minimize deviations from MARI.

	Day-ahead	Step 1 (MARI)	Step 3 (post-MARI)	Total	Total (MARI + post-MARI)
G1 (BSP)	7500	0	0	7500	0
G2 (BSP)	6250	-1250	0	5000	-1250
G3 (BSP)	0	2475	0	2475	2475
L3 (BRP)	-7500	-1100	0	-8600	-1100

South BSP	17281	0	0	17281	0
South BRP	-30750	0	0	-30750	0
North TSO	3609	-125	0	3484	-125
South TSO	3609	0	0	3609	0
Total	0	0	0	0	0

Table 26: Settlements in step 4 of approach A7 in the commercially congested scenario.

As in approach A8, the computation of congestion rents at the MARI stage requires translating the usage of the capacity in the MARI zonal network model from the DA zonal model, so as to compute incremental usage of network capacity and the resulting congestion rents. For the case of our specific example, we need to solve the following linear system, which ensures that the flows in the zonal DA model are consistent with the flows in the zonal MARI model:
Zone N1: f12 + f13 = 300 - 150
Zone N2: - f12 + f23 = 250
Zone N3: - f13 - f23 = 0 - 100
For example, the first equality above expresses the fact that the zonal MARI model should have baseline flows which are consistent with the injection of power in the DA model (300 MW) minus whatever power flows over the link N-S1 (150 MW).
The linear system above has a unique solution (three linearly independent equalities in three unknowns), and yields the following mapping of DA zonal flows to MARI zonal flows:

- Link N1-N2: - 75 MW
- Link N1-N3: 225 MW
- Link N2-N3: 175 MW

7.2.2 Commercially uncongested scenario

Steps 1 & 2: MARI market clearing under conservative capacity assignment
Having excluded the aggressive capacity assignment in step 1, we directly simulate the conservative approach to capacity assignment in step 1. The MARI market clearing outcome is presented in the following figure.

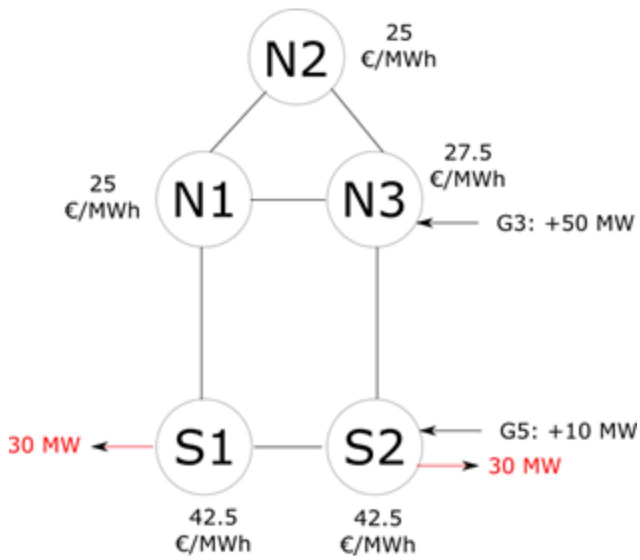


Figure 34: Outcome of MARI in the commercially uncongested scenario of A7 with conservative capacity assignment.

As in the case of the commercially congested scenario, the MARI market clearing outcome causes no congestion to the system. Therefore, if the goal of the TSO is to minimize deviations from MARI in step 3, no redispatch occurs.

Step 3: Post-MARI corrections

When the TSO aims at minimizing deviations from the MARI outcome, no redispatch occurs in step 3. On the other hand, if the goal of the Northern TSO would be to maximize economic surplus, then redispatch may occur in step 3, and it is due to the fact that additional capacity can be used by the nodal pricing model. The results of step 3 for approach A8 when the goal of the Northern TSO is to maximize economic surplus are presented in the following figure.

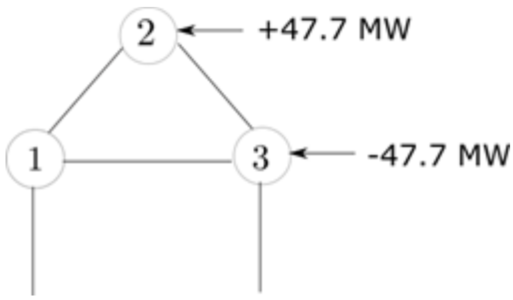


Figure 35: Outcome of step 3 of approach A7 for the uncongested scenario if the goal of the Northern TSO would be to maximize economic surplus.

The effects are essentially identical to those of the congested scenario. Concretely, there is no congestion as a result of the MARI dispatch in step 2, but additional transmission capacity can be used. The resulting dispatch turns out to be feasible for the entire network, although there exists no guarantee that this should be the case in general.

Step 4: Settlements

The settlements under the assumption that the Northern TSO minimizes deviations from the MARI outcome in step 3 are presented in the following table.

	Day-ahead	**Step 1 (MARI)**	**Step 3 (post-MARI)**	**Total**	**Total (MARI + post-MARI)**
G1 (BSP)	6000	0	0	6000	0
G2 (BSP)	4000	0	0	4000	0
G3 (BSP)	0	1375	0	1375	1375
L3 (BRP)	-6000	0	0	-6000	0
South BSP	0	425	0	425	425
South BRP	-4000	-2550	0	-6550	-2550
North TSO	0	313	0	313	313

South TSO	0	438	0	438	438
Total	0	0	0	0	0

Table 27: Settlements in step 4 of approach A7 in the uncongested scenario.

As in the commercially uncongested case, the computation of congestion rents at the MARI stage requires translating the usage of the capacity in the MARI zonal network model from the DA zonal model, so as to compute incremental usage of network capacity and the resulting congestion rents. For the case of our specific example, we need to solve the following linear system, which ensures that the flows in the zonal DA model are consistent with the flows in the zonal MARI model:
Zone N1: f12 + f13 = 300 - 100
Zone N2: - f12 + f23 = 200
Zone N3: - f13 - f23 = 0 - 100
For example, the first equality above expresses the fact that the zonal MARI model should have baseline flows which are consistent with the injection of power in the DA model (300 MW) minus whatever power flows over the link N-S1 (100 MW).
The linear system above has a unique solution (three linearly independent equalities in three unknowns), and yields the following mapping of DA zonal flows to MARI zonal flows:

- Link N1-N2: - 50 MW
- Link N1-N3: 250 MW
- Link N2-N3: 150 MW

7.3 Economic efficiency

Commercially congested case: In the commercially congested case, the total welfare in the system amounts to 912,996 €. The cost of approach A7 amounts to 27,006 €, compared to 27,170 € under approach A8. Surprisingly, therefore, even though the hybrid MARI model in approach A7 is less accurate than that of approach A8, the resulting dispatch is actually more efficient (it would be reasonable to assume that this is a peculiarity of the example and not a general result)! The welfare breakdown is presented in the following table.

	Producer (BSP) cost	Consumer (BRP) value	Total revenue	Profit
G1 (BSP)	4500	N/A	7500	3000
G2 (BSP)	3500	N/A	7088	3588
G3 (BSP)	2475	N/A	4098	1623
L3 (BRP)	N/A	340000	-8800	331200
South BSP	16531	N/A	11228	-5304
South BRP	N/A	600000	-30750	569250
North TSO	N/A	N/A	4445	4445
South TSO	N/A	N/A	5194	5194

Total	27006	940000	3	912996

Table 28: Welfare breakdown under approach A7 in the commercially congested scenario.

Commercially uncongested case: In the commercially uncongested case, the total welfare in the system amounts to 550,197 €. The cost under approach A7 amounts to 9,800 €, as compared to 9,938 € under approach A8. The same surprising outcome occurs in this stress test, therefore: even though the hybrid zonal model of MARI in approach A7 is less accurate than that of approach A8, the resulting dispatch can turn out to be more efficient. As a general observation, therefore, it is difficult to argue that adding approximations to zonal models which attempt to come closer to the physics of the network is an adequate remedy. The results are suggesting that if the physical reality of the network is not represented properly, then patches in a zonal model can backfire.

	Producer (BSP) cost	Consumer (BRP) value	Total revenue	Profit
G1 (BSP)	4500	N/A	6000	1500
G2 (BSP)	3500	N/A	5230	1730
G3 (BSP)	1375	N/A	297	-1078
L3 (BRP)	N/A	300000	-6000	294000
South BSP	425	N/A	0	-425
South BRP	N/A	260000	-5620	254380
North TSO	N/A	N/A	94	94
South TSO	N/A	N/A	-3	-3
Total	9800	560000	-3	550197

Table 29: Welfare breakdown under approach A7 in the commercially uncongested scenario.

8 Annex B – Discussion on Approach A1 : redispatch with specific faster product

8.1 Introduction

Approach A1 was assuming that the time left after MARI is sufficient to resort to a re-dispatch (understood as an out-of-market correction after MARI, relying on the resolution of an OPF and assuming a pay-as-bid scheme) of the bids submitted to MARI as such. Somehow, it was neglecting the timing constraint or the heterogeneous flexibility of the various BSPs towards this constraint.

Timing constraint. As a reminder from the first phase of the study, the more detailed timing of MARI is presented in the next figure. Any action performed “after MARI” needs to fit, in theory, within the 30-second period foreseen for TSO-BSP communication. If it happens that the redispatch proposed in approach A1 does not fit within these 30 seconds, alternatives need to be designed. One way to extend these 30 seconds is to rely on the 12.5-minute period foreseen for the full activation of the BSP (2.5 minutes to prepare and 10 minutes to ramp up, half of this ramp-up period being foreseen before the ISP starts), in which case it is an advantage to have *faster products*.

Let us notice that, depending on the actual timing, (e.g. if the process requires 60 seconds instead of the accepted 30 seconds), it could also be envisaged to ignore this time discrepancy and accept a delay in the activations. This would result in a small imbalance, possibly tolerable for the BSPs. Nevertheless, as such a design is similar to approach A1 (with delay in the activations), this possibility is not further considered in this section.

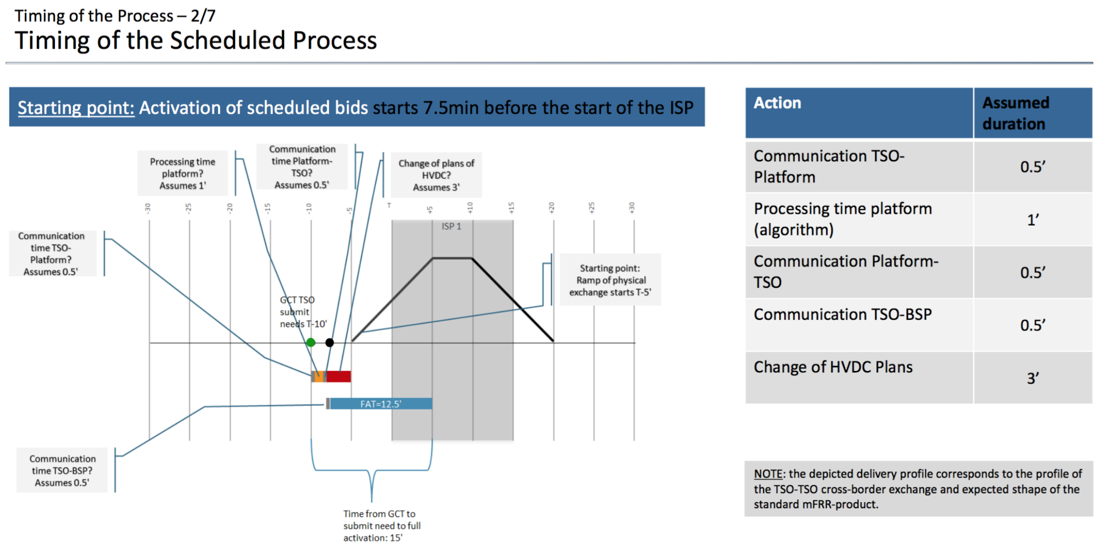


Figure 36: Timing of MARI as described in the “MARI Stakeholder Workshop” of the 4th of September 2017 at ENTSO-E.

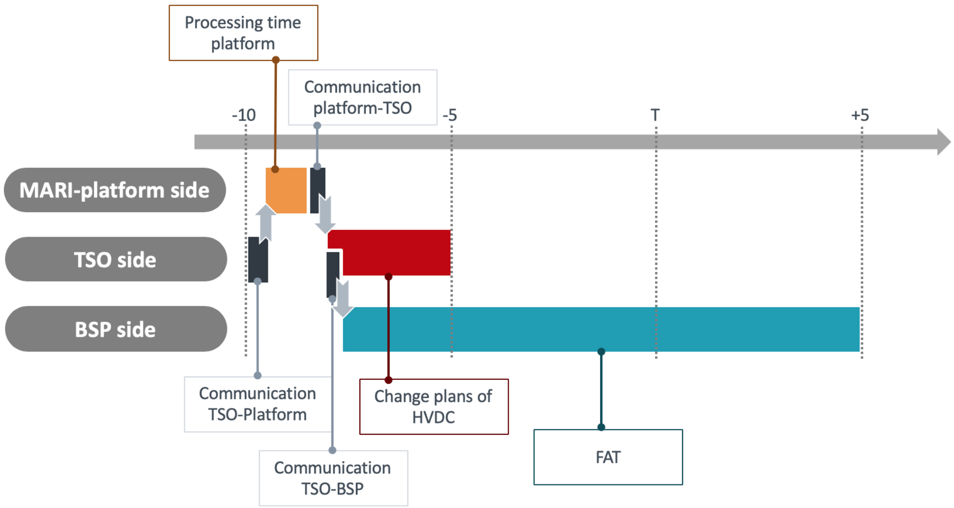


Figure 37: Timing of MARI, with (1) a more detail split of the task between the responsible parties and (2) a visualization of the communication taking place between the stakeholders (constructed based on the figure from the "MARI Stakeholder Workshop" of the 4th of September 2017 at ENTSO-E).

BSP flexibility. Most of the flexibility in Norway comes from hydropower which is not significantly ramp-constrained. This means that many BSPs in Norway have a faster response time than what is currently proposed in MARI. Such flexibility could be exploited to allow more time for re-dispatching. One way to exploit this flexibility is to design a specific product, available for these "fast-ramp BSPs", with a shorter FAT, e.g. 5 minutes, which could be introduced for re-dispatch purposes. This product could be leveraged in order to solve undesired effects of MARI activations with a subset of the bids that can react faster.

One way of implementing these "fast products" is to rely on the mFRR product of MARI in which we introduce a slight variation allowing the Norwegian BSPs to somehow check a box "also available for fast activation". In this way, after MARI returns the activated bids, a redispatch is performed by Statnett with the subset of the bids marked as "fast".

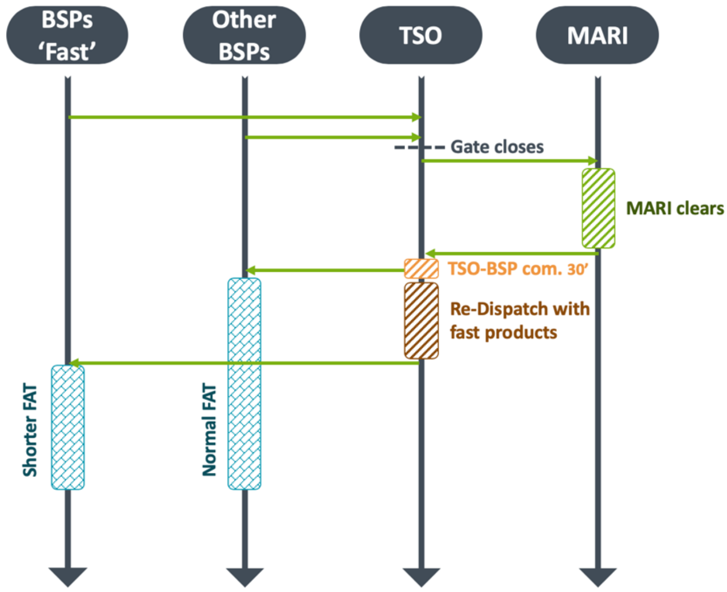
The next section describes more precisely the processes, timeline and interaction with MARI of this approach. The following one discusses alternative design choices that have not been retained while the remaining sections perform an economic analysis of the selected approach.

8.2 Process, timeline and interaction with MARI

The more detailed process is illustrated in the next figure.

The BSPs are split in two groups : (1) the "normal" BSPs which face the standard FAT of MARI and (2) the "fast" BSPs which allow the TSO to re-dispatch them in a timeframe that extends beyond 30 seconds after MARI clears and therefore face smaller FAT. It is therefore the assumption that the BSPs of Norway are split into two groups and that a subset of the BSPs (the BSPs "fast") are used to perform a re-dispatch. Let us notice that it is likely that a high share of the Norwegian BSPs can be fast (probably more than 60%). The share will of course vary, depending on the exact definition of the FAT of these fast products. Nevertheless, assessing the potential of Norwegian resources to act as fast products goes beyond the scope of this study which simply aims to assess the market impact of having a fast product with two categories of BSPs.

All the BSPs send their bids to Statnett before the gate closes. These bids are transmitted by the TSO to MARI which clears and publishes the market results. Afterwards, Statnett has the standard 30 second timeframe to communicate the results to the "normal" BSPs while, in parallel, the redispatch is conducted with the Fast BSPs. The final results of both MARI and the redispatch are then published to the fast BSPs which therefore face a shorter FAT.



Let us notice that there is no interference with MARI in this procedure, except for the MARI direct activation (MARI-DA). Indeed, the MARI protocol foresees, in case of contingencies (i.e. generator contingencies) happening after the MARI auction, a "direct activation" procedure which corresponds to on-the-spot activation of units through MARI. The redispatch performed by Statnett with the "fast BSP" would therefore interfere with this MARI-DA procedure. This is detailed further in the next section.

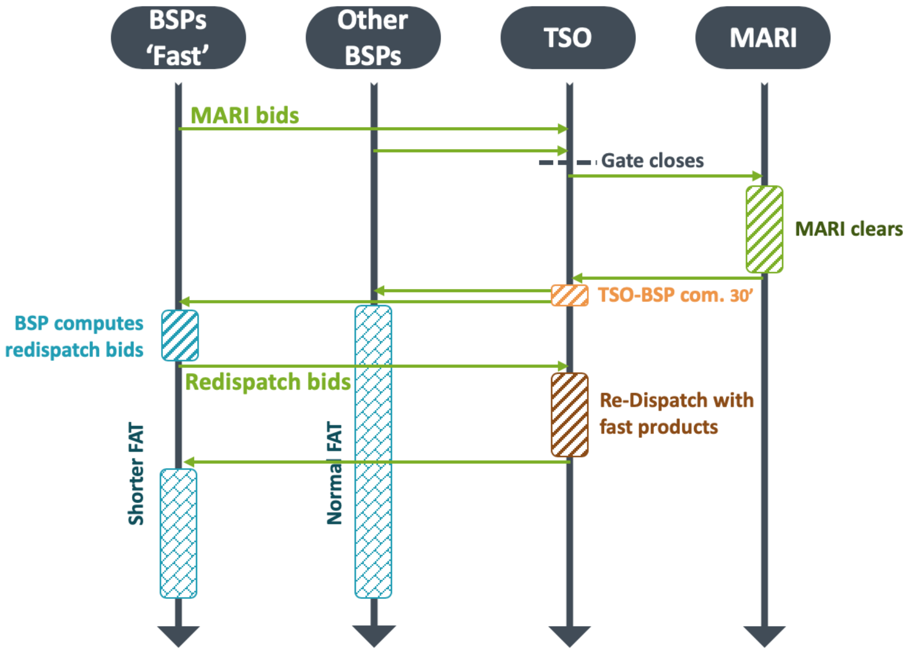
8.3 Alternative designs and methodologies

Let us bear in mind that this fast product strategy implemented as just described is just one way to design such a strategy and is only one methodology among others to mitigate an undesirable effect created by MARI. In this section, we'll put it in the perspective of other design possibilities and other mitigation strategies.

8.3.1 Alternative design #1 : Independent product from MARI

Instead of being an mFRR product bid in MARI with a “fast activation” option, one could wish to design a brand new product only available in and for the Norwegian market, completely decoupled from MARI (separated bids), possibly in between mFRR and aFRR products.

In this case, there are separate bids for MARI and for the re-dispatch. The process is illustrated in the next figure:



However, this possibility is discarded as a faster product, different from mFRR, is already available with aFRR and as this mechanism is likely to be more vulnerable to gaming.

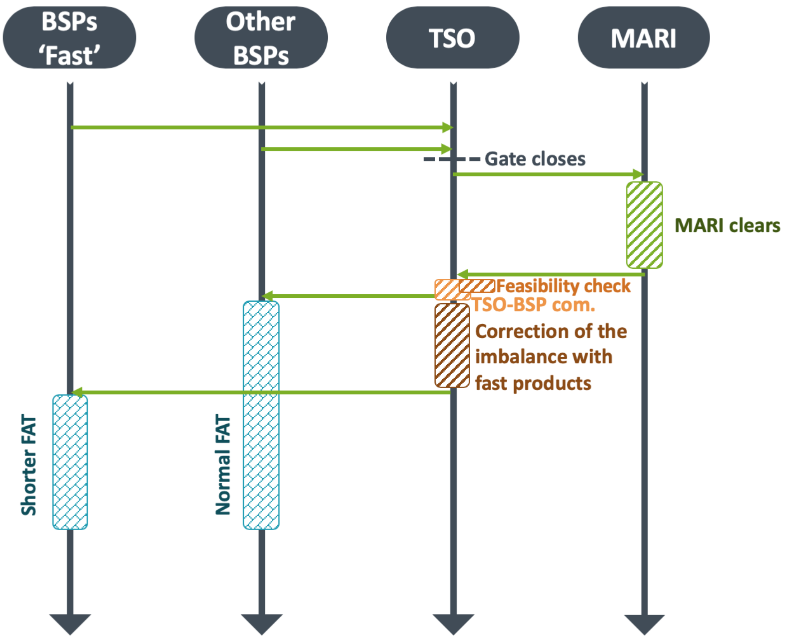
8.3.2 Alternative design #2 : Feasibility check followed by imbalance correction

This alternative procedure uses a similar product as the one considered in this annex: a variant of mFRR for which the BSP crosses a box to state his assets have “faster FAT”. However, it differs from our retained design (as detailed in the previous section and as considered in the analysis of the next sections), with respect to how these fast products are used.

The procedure is presented schematically in the next figure. After MARI returns the activated bids:

- First a "post-MARI feasibility check" is performed, within 30 seconds, to identify the bids that should not be activated as deemed problematic. If no problematic bids are identified, the results are communicated to all the BSPs and the process terminates. If some bids are deemed problematic, their activation is cancelled and the results are communicated to the “standard BSPs”. This ends up with a situation of imbalance which triggers a second step.

- The second step can be seen as a step of determination of alternative bids: the imbalance created previously by cancelling some bids is corrected using the fast BSPs. This procedure is settled pay-a-bid and aims to correct the imbalance and to minimize the deviations from MARI. In order words, the activation of the fast products is exclusively to compensate for infeasible MARI activations.



This alternative procedure has nevertheless not been selected as:

- It is unlikely there would be enough time to make a "feasibility check" within 30 seconds while there would not be enough time to make a "redispatch" within the 30 seconds. Indeed, both are based on the resolution of an OPF and should mean a similar computational effort. Therefore, either the 30 seconds are sufficient to make a residspatch, which is studied in approach A1, or it is not sufficient in which case there is no time to make a feasibility check either.
- Even in case there would be a significant difference of complexity between the "feasibility check" and the "redispatch", as far as the scope of this study is concerned, the design of this procedure is in essence the same as approach A1 (and therefore already well detailed in chapter 2): a "correction of the imbalance" cleared pay-as-bid which attempts to minimize the deviations with MARI. The sole difference lies in the fact there is only a subset of the bids that participate.

8.3.3 Alternative strategy #1 : aFRR product

This possibility is studied in more detail, and more broadly than the scope of this annex, in Annex C.

8.3.4 Alternative strategy #2 : Local direct activation

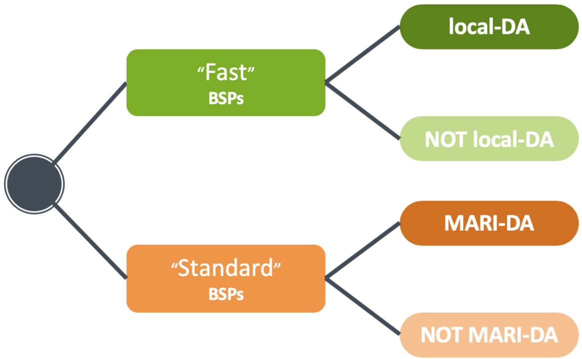
Let's make a distinction between the direct activation procedure as it is foreseen within MARI (MARI-DA) and the local-DA (local direct activation) which is a direct activation locally performed by Statnett.

On the one hand, the **MARI-DA** procedure is foreseen for contingencies and cannot be used for congestion management. Furthermore, in case a BSP wants to be used for the redispatch performed by Statnett (as a "fast BSP"), **he would not be able to participate in the MARI-DA procedure**[31].
As this procedure is meant to be used for generator contingencies only, which are not so frequent, it should not be a major constraint for the BSPs wishing to participate in the fast product redispatch.
Let's also notice that Statnett would still be able to use MARI-DA for its purposes (i.e. without the activated fast-BSPs, so with a more limited set of bids) although it might be more interesting to rely mostly on the fast product redispatch. Statnett could also participate in MARI DA for the purposes of other TSOs.

On the other hand, the **local-DA** would remain an option for managing congestions. Furthermore, as this process would be conducted by Statnett only, the fast-BSP could still be leveraged in a local-DA.
Nevertheless, as local-DA and MARI-DA are not common merit order, it means Statnett would either completely refrain from using MARI DA or he will be in a hard configuration where he needs to to decide if local or MARI DA should be used in an upcoming situation. One methodology could be to use local-DA by default until it is exhausted and then use MARI-DA. Establishing the methodology would nevertheless require further effort and should probably be based on a finer description of the liquidity and the merit order of both local and MARI-DA.

The next figure synthesizes the possibilities: each BSP would have the possibility to "cross a box" in order to offer his flexibility as a "fast BSP" or as a "standard BSP". In the first case, he cannot participate in the MARI-DA but still has the possibility to participate in the local-DA or not. In the second case, he has the possibility to participate in the MARI-DA or not.

[31] One way to overcome this would be to let the BSP cross the box "direct activation in MARI" and then let Statnett uncheck the box in case the BSP is activated in redispatch. Nevertheless, there is probably not time or procedure to convey this information.



Let's notice that the direct activation is also a procedure which could in theory create a congestion:

- if another TSO activates a resource in Norway via MARI-DA procedure;
- if another TSO activates a resource in a foreign country, via MARI-DA procedure, creating a loop flow in Norway;
- if Statnett activates a resource in Norway via MARI-DA procedure;
- if Statnett activates a foreign resource via MARI-DA procedure;

These are all cases that could in theory create congestion on the Statnett network. So in principle, congestion checks and mitigation procedures should be performed one more time after each DA procedure.

Let's notice:

- In any case, the least that can be done, after the post-MARI correction, would be to flag the bids that were creating issues in MARI also as unavailable for further MARI-DA rounds.
- To some extent, this remark on DA procedure is a significant argument for pre-analysis so it is determined once and for all what are the bids which can participate in the whole balancing process and what are the bids which could create problems and should therefore be excluded.
- One tradeoff would be to have A1 or A2 working as described in this report but including an additional pre-processing step where bid filtering would be performed only for MARI-DA activation: bids would not be filtered out of MARI but simply out of the MARI-DA procedure.

Defining a robust methodology more precisely would require further analysis.

8.4 Illustration on the stress tests

For the sake of illustration, we rerun the stress tests that have been analyzed in the previous sections in order to clarify the workings of the fast product. Let us assume, first, that all BSPs qualify as fast products. It is tempting to interpret this as being equivalent to an implementation of approach A1 whereby the redispatch actions performed in step 2 receive a uniform price when settled in step 3 instead of being paid as bid. This interpretation is in fact incomplete, and ignores the fact that a market for a fast reserve product is still a market:

it aims at maximizing benefits from trade, as opposed to minimizing deviations from the MARI outcome.

In order to highlight some of the incentive effects of the fast product, we modify the data slightly so as to illuminate certain pricing inconsistencies that may emerge.
(i) We exclude some of the BSPs from the fast product auction. This assumption can be justified by the fact that only a subset of the BSPs would be fast enough to be eligible for the fast product auction. Concretely, we assume that the cheaper Northern resources are not sufficiently fast to participate in the fast product auction, which will tend to cause an upward pressure on the nodal prices produced by the fast product auction. Concretely, we assume that the following BSPs are not fast enough to participate in the fast product auction: G1A, G2A, G3A.
(ii) Moreover, we split the BSP in G2C into smaller segments, in order to create a difference in prices between the MARI auction and the fast product auction. Concretely, we change the data as follows:

- The capacity of G2C (100 MW) is split into two segments, G2C-1 with 80 MW, and G2C-2 with 20 MW
- The marginal cost of G2C (25 €/MWh) is split into two segments, G2C-1 with 25 €/MWh, and G2C-2 with 30 €/MWh

MARI clearing
The MARI outcome is presented in the following figure.

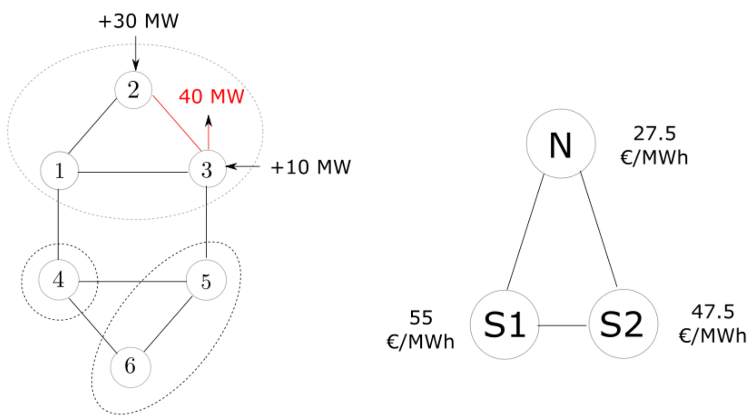


Figure 38: Zonal MARI clearing in the commercially congested scenario under modified data for BSP2 with all flexible units participating in the fast product auction.

There are a couple of notable changes in the MARI outcome relative to the simulations that we have seen so far. The first is that part of the MARI upward activation now shifts to node 3 (since the segment G2C-2 is more expensive than G3A), and consequently the zonal price in the North increases slightly to the marginal cost of G3A, i.e. 27.5 €/MWh. We will discuss some of the implications of this change in relation to the fast product auction in the following paragraphs. On the other hand, the congestion in line 2-3 remains, and the fast product auction is aimed at relieving this congestion.

Commercially congested scenario

The result of the fast product auction is presented in the following figure. The fast product auction dispatches down the BSPs in node 2 and dispatches up the BSPs in node 3 in order to decongest line 2-3. The nodal prices resulting from the fast product auction are also presented in the figure. There are two important messages from this illustration:

- Windfall profits for BSP G2C-1: BSP G2C-1 which is located in node 2 is dispatched up by 30 MW in MARI, and 19.2 MW of this upward activation are subsequently cancelled in the fast product auction. In this process, the BSP collects the price differential between the fast product auction and the MARI auction for those 19.2 MW which were activated upwards in MARI and then back down in the fast product auction[32]. This implies a windfall profit of 19.2 MW * 2.5 €/MWh = 48 € for offering essentially nothing to the system. Although this profit in itself is not very large, the effect is important: the fast product auction (at least as envisioned under our specific settlement assumptions) can lead to windfall profits to BSPs for offering nothing to the system. Let's notice that this is not specific to this fast products design and can also happen in approach A1 (see gaming sub-section in the cross comparison section) ; while, by design, approaches A2 and A8 prevent such cases.
- Tension between MARI and the fast product price: The BSP in location 3 is first activated upwards for 10 MW at 27.5 €/MWh in MARI, and then activated further upwards for another 19.2 MW at 32.5 €/MWh in the fast product auction. There is a clear motivation for the BSP in location 3 to wait for the fast product auction and pocket the higher locational marginal price, instead of making its capacity available to MARI.

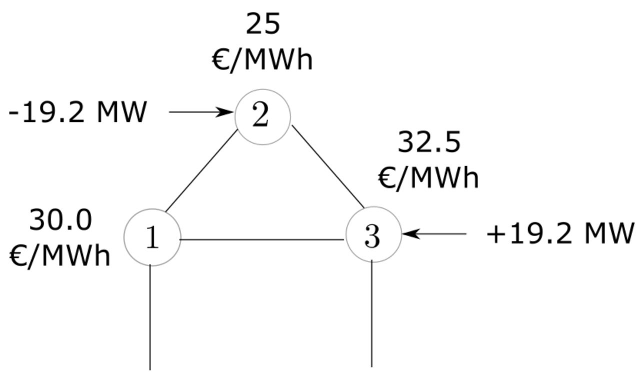


Figure 39: Clearing of fast product auction with nodal uniform prices for the congested scenario.

Note that the exclusion of certain BSPs from the fast product auction is not the essential driver of this inconsistency in prices. Even if all BSPs are included in the fast product auction, the BSP in node 2 still collects windfall profits, since the MARI price is still 27.5 and drops to 25 in the fast product auction, with the BSP in location 2 being dispatched upward in MARI and then downward in the fast product auction. Nevertheless, we note that the shortage of BSPs

[32] One remedy that has been proposed by Statnett is that the bid from G2C can be (partly or fully) "jumped over", but not compensated (which is the current practice). However, it is not clear that this practice is compatible with article 46, table 1 of the EBGL.

in the fast product auction exacerbates the price inconsistencies: the price in node 3 when BSPs are fast is 27.5 €/MWh, as it was in MARI. We present the fast product results in the following figure when all BSPs are present in the fast product auction (the MARI results do not change) for the sake of comparison with the case where only a subset of BSPs participate in the fast product auction.

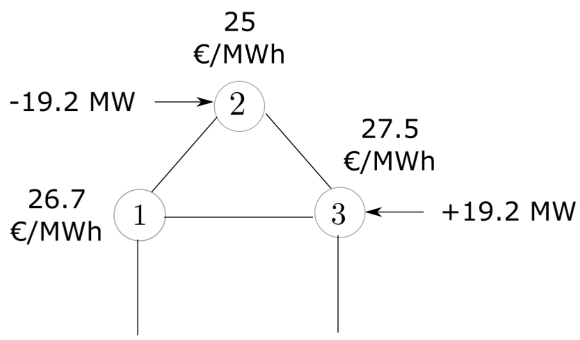


Figure 40: Clearing of fast product auction with nodal uniform prices for the congested scenario when all BSPs can participate in the fast product auction.

The dispatch remains identical to the case of the previous figure. However, the prices change. The price change in node 3 is not surprising, since G3A can now contribute to price formation, thereby putting a downward pressure on the fast product prices. The price change in node 1 may seem less intuitive, since it appears that the dispatch in node 1 does not change. This price increase can be understood from two effects[33]: the equilibrium conditions of the network operator (i.e. the fact that prices should be such that the network does not have an incentive to deviate from the auction result) and the price drop in node 3. But in any case, the price in node 1 does not contribute to our main observation.

To recap our main observation, the fast product auction creates two unintended consequences that are related to pricing:

- Certain BSPs can collect windfall profits by being activated upward in MARI at a higher price and activated downward by the fast product auction at a lower price (considering that the activations in MARI are to be paid in any case - see legal discussion and footnote 24).
- Certain BSPs can be activated in both MARI and the fast product auction, with higher prices at the fast product auction, and may therefore be tempted to abstain from MARI.

[33] In particular, these equilibrium conditions state that the nodal price is the price at the hub plus a congestion premium on line 2-3. Since the prices in nodes 2 and 3 are determined uniquely by the marginal BSPs in these nodes, this implies a congestion rent for line 2-3, based on the following network price equilibrium condition: \rho_3 - \rho_2 = (PTDF_{2-3, 2} - PTDF_{2-3, 3}) * \lambda_{2-3}^+, which implies \lambda_{2-3}^+ = (27.5 - 25)/(0.47 + 0.105) = 4.5 €/MWh. And since the price difference between node 1 and node 3 (or 2) only depends on this congestion rent (due to the network equilibrium conditions), the price in node 1 is implied by the prices in nodes 2 and 3. Concretely, \rho_1 = \rho_3 + (PTDF_{2-3, 3} - PTDF_{2-3, 1}) * \lambda_{2-3}^+ = 27.5+4.3*(-0.088 - 0.105) €/MWh.

Commercially uncongested scenario with a subset of the BSPs in the fast product auction
We reproduce the analysis for the uncongested stress test, with a subset of the BSPs being available for the fast product auction. As in the previous case, the subset of units that are too slow to participate in the fast product auction are the cheaper BSPs of the Northern zone: G1A, G2A, G3A. The dispatch and prices of the fast product auction are presented in the following figure. As in the case of the previous paragraph, the prices of the fast product auction are significantly higher than the MARI result for the North zone (which was 25.0 €/MWh).
The effects that we report in the congested case are not as apparent in this example. Concretely, the BSP in node 2 is not collecting windfall profits, and the BSP in location 3 is facing indeed a higher price in the fast product auction than in the MARI auction, nevertheless is it not being activated in both auctions. The incentive to wait for the fast product auction remains, but the fact that the BSP is activated in both auctions makes the effect even more evident in the congested scenario illustration.

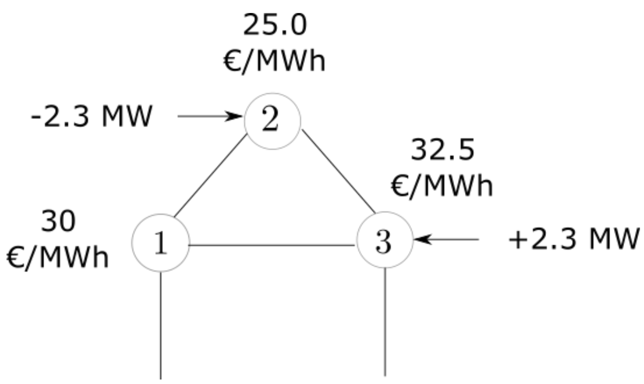


Figure 41: Clearing of fast product auction with nodal uniform prices for the uncongested scenario with only a subset of the BSPs being fast enough to participate in the post-MARI auction.

8.5 Settlement and pricing
The following table summarizes how the "fast product" variant differs from A1, as it is developed in section 2 of the report, with respect to settlement rules.

	Fast product redispatch	**A1** (out of market correction)
Objective	Welfare maximisation	Deviation minimisation
Pricing scheme	Pay-as-cleared	Pay-as-bid

Highlights and main conclusions

- Approach A1 was assuming the time left after MARI is sufficient to resort to a re-dispatch (post-MARI consolidation). Meaning any action performed after MARI needed to fit within the 30-second foreseen for TSO-BSP communication.
- But, if the redispatch proposed in approach A1 does not fit within these 30 seconds, alternatives need to be designed. One way to extend these 30 seconds is to rely on the 12.5-minute period foreseen for the full BSP activation, in which case it is an advantage to have **faster products**.
- Moreover, most of the flexibility in Norway comes from hydropower which is not significantly ramp-constrained. Such flexibility could be exploited to allow more time for re-dispatching.
- We considered a design where these “fast products” rely on the mFRR product of MARI in which a slight variation is introduced allowing the Norwegian BSPs to somehow check a box “also available for fast activation”.
- The main differences with approach A1 is that: (1) a subset of the BSPs is used for redispatch (the "fast BSPs" only) and (2) it aims at maximizing benefits from trade (maximize welfare), as opposed to minimizing deviations from the MARI outcome.
- The analysis highlighted the following **upward**: it enables having faster reaction, which can be advantageous in certain cases.
- The analysis highlighted the following **downward**:
    - Tension between MARI and the fast product price: The fast product auction produces price discrepancies which will tend to push BSPs at high-price locations to wait for the second stage, and vice versa.
    - The fewer the BSPs that can participate in the fast product auction, the stronger this effect becomes.
    - Certain BSPs can collect windfall profits by being activated upward in MARI at a higher price and activated downward by the fast product auction at a lower price (considering that the activations in MARI are to be paid in any case - see legal discussion). This does not differ from A1.
    - Compared to approach A1, the fast auction produces a slightly higher financial deficit for the TSO
- The analysis also triggered a discussion on the **Direct Activation procedure**, which is not specific to the fast product and is valid for all cases. One important conclusion is that the direct activation procedure could in theory create congestion on the Statnett network as well. So in principle, congestion checks and mitigation procedures should be performed one more time after each DA procedure. This is not further studied here but could be a subject of further work.

9 Annex C – Discussion on the interactions with aFRR & PICASSO

This annex focuses on aFRR, and discusses two interlinked aspects:

- how can congestions be prevented from arising due to aFRR activations - in particular in a PICASSO context ;
- whether aFRR bids could be used to resolve congestion that arose earlier, and in particular from/after the MARI process.

9.1 Assumptions (to be confirmed by Statnett):

- The Nordic aFRR market design is under major reform. As there are still significant uncertainties over this design (see for example http://www.nordicenergyregulators.org/wp-content/uploads/2020/03/Annex1_Non-paper_AFRR_.pdf), this reform is not considered in our analysis. Unless where Statnett has provided specific assumptions, the conceptual discussion below is based on a "standard EU market design" that follows the currently available PICASSO rules.
- There is in theory no time available for any calculations after the PICASSO process (even "simple" calculations cannot be carried out) as this is a full real-time process. However, the PICASSO results are in practice not directly activating resources. Rather, a PICASSO activation has as effect a cross-zonal commercial schedule which influences the ACE of the corresponding bidding zones. Consequently, the Automatic Generation Controller (AGC) activates its aFRR resources by taking into account the ACE (possibly modified by PICASSO). Given the so-called "open-loop" effect (i.e. there always is a delay between the observed ACE and the actual delivery of the activated energy), it is in principle possible to influence the resources activated by AGC ahead of the actual delivery.
- Not all Norwegian bidding zones offer sufficient aFRR capacity to resolve their own imbalances. The use of aFRR cross-zonal mechanisms via PICASSO (or a similar more local Norwegian mechanism) is therefore essential for balancing the grid of some specific bidding areas (i.e. the ones with large load and little production).

9.2 Preventing congestions caused in PICASSO

Let us distinguish different cases where PICASSO could in principle cause congestions in the Norwegian bidding areas:

9.2.1 Activations abroad to resolve imbalances abroad, creating loop flows resulting in congestions on the NO areas.

Such cases cannot be directly addressed (at least without a major reinforcement of the TSO coordination, which goes beyond the scope of this study) and can only be prevented by including adequate levels of reliability margins in the capacity calculation process. These should indeed be considered as "unpredictable flows" for which any capacity calculation should cope with.

9.2.2 Activations within Norway to resolve imbalances from abroad.

- Despite its lower granularity (compared to nodal models), the zonal capacity calculation process can in principle prevent such cases by limiting the imports or exports in PICASSO. This is done by providing more restricted cross-zonal capacities to

PICASSO (at the extreme, setting all capacities to zero will surely prevent such cases). However, the downside of such an approach is that cross-zonal capacities may quickly become overly conservative, creating dissatisfaction for Norwegian BSPs who are restricted from providing aFRR services abroad. Also, from a regulatory perspective, limiting cross-zonal capacities because of intra-zonal congestion is typically a very disputed method.

- If, within a Norwegian bidding area, some assets would be able to provide aFRR energy abroad without creating congestion, while others would not, a "bid filtering approach" could be considered.
- A similar process has already been analyzed by Statnett in the mFRR context, and would consist of only submitting a subset of the aFRR bids to PICASSO, thereby excluding only the "problematic" assets. Note however that there is a substantial difference between MARI and PICASSO in the way the energy is activated. In the PICASSO context, a bid filtering approach would imply not only to submit a subset of the aFRR bids to MARI, but also to the AGC. In theory, the AGC could even integrate a load flow model that optimizes the congestion together with restoring the balance, and return to PICASSO the bids that should be excluded for the subsequent periods. Such approaches are however probably unrealistic in practice, and well beyond the scope of this study. In summary, there are several technical variants of bid filtering in the PICASSO context. However, all of them are imperfect in any case, mainly because the location of the imbalances to be resolved (and which are abroad) is not known at the time of bid filtering. Therefore, the filtering methodology may remain somewhat conservative, at least if it relies on worst-case scenarios.

9.2.3 Activations abroad to resolve Norwegian imbalances

- Similarly to the previous case, congestion created by a Norwegian imbalance resolved by aFRR bids from abroad can be avoided by restricting the cross-zonal capacities (at the extreme, restricting any cross-border flow in PICASSO will definitely avoid such cases). Such cross-zonal capacities thereby possibly become overly conservative. This would imply that less efficient resources are activated, resulting in an increase of the regulated balancing costs.
- However, preventing such cases with a "bid filtering approach" is not conceivable, as Statnett is not entitled to exclude bids from other TSOs, so that limiting cross-zonal capacities appears as the most credible approach.

9.2.4 Activations in Norway to resolve imbalances in Norway.

- Adjustment of cross-zonal capacities are not necessarily able to avoid intra-zonal congestion. This is surely the case when an imbalance in a specific bidding area is resolved by a bid in the same bidding area which causes an intra-zonal congestion.
- This case is for example illustrated in Figure 4 (page 10) of the report. In this example, an imbalance of 40 MW on node 3 is resolved by an activation of 40 MW in node 2, which congests the line 2-3. No restriction of commercial capacity would avoid the congestion.

- Filtering the bids which are possibly creating congestion appears as the only feasible approach (under our assumption - see above - that no calculations can be performed after the PICASSO process). In the illustrated example, node 2 bids are excluded. In this example, the node 3 imbalance would be resolved by the node 3 asset, which obviously would not create further congestion.
- However, there may exist situations where the filtering of bids leads to infeasible solutions. In particular, in case the cross-zonal capacities are conservatively restricted (see previous case), it might be that the availability of aFRR bids after filtering has become insufficient to resolve the imbalance. **The severity of the issue cannot be determined in this scope.**

9.2.5 Key take-aways

- There exist a limited set of options to resolve congestions caused by aFRR activations
- **Conservative cross-zonal capacities**, despite their regulatory and public acceptance challenges, appear as the only way to avoid some of the congestion caused by activations of resources outside of the perimeter controlled by Statnett.
- Equally, a **bid filtering** approach appears to be the only way to avoid some of the congestion caused by activations within the perimeter of Statnett. There exist several variants of "bid filtering" in the aFRR context, with different levels of complexity and efficiency (from a simple ex-ante exclusion to a dynamic load-flow model directly implemented in AGC).
- Two other theoretical alternative solutions exist: (1) not participating in PICASSO or (2) implementing a fully nodal model in PICASSO. **These alternatives are not further elaborated at this stage.**

9.3 Preventing congestions existing before PICASSO with aFRR bids

- Given the above, it is clear that it is not possible to resolve all pre-existing congestions with the current PICASSO mechanism (since it is not even possible to guarantee that new congestions are not created by PICASSO) .
- If aFRR capable resources are very abundant, it is thought in theory possible to use (at least a subset of) the aFRR bids for congestion management. In practice, this could be seen as a way to implement the "fast products" that are discussed in Annex B: aFRR bids would be activated instead of the mFRR bids which are ticked "fast activation", using similar calculation schemes. The key advantage is that it avoids creating a new specific product. However, the expected disadvantages relate to (1) the complexity of the activation scheme in real-time, (2) the likelihood that aFRR bids are typically more expensive than mFRR bids and (3) the availability of sufficient aFRR bids to cover both congestion management and balancing needs at the same time.

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