Probabilistic Transmission Expansion Planning: On the effects of outcome variability on decision-making

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As the system on which decisions are made evolves, the used criteria and decision-making approaches must evolve with it. The increasing share of renewable and less price sensitive energy generation has decreased the predictability of energy flows on the electrical transmission grid. This has resulted in efforts for deploying probabilistic criteria which allow taking this indeterminacy into account. As the outcome of a decision for a system whose future state is based on a probability distribution is a probability distribution itself, there is no longer a deterministic outcome to base decisions on. Several ways to deal with this distribution exist (average, shortfall etc.). Each of these approaches has its value within a certain context related to among other things the timescale, variability and absolute value of the outcomes. As probabilistic indicators are added to the decision-making process, several situations have been identified where it is not immediately clear how to strike the balance between optimizing the average while reducing the variability of the outcome. In this work two of these cases are subjected to a probabilistic study and it is shown how changing the decision time-horizon and/or outcome variability could lead to a different decision. The paper concludes with future prospects and the next steps that are to be taken to ensure the validity of decisions made using a well-chosen decision-making approach that enables the optimal use of the potential of probabilistic criteria.

Keywords: Probabilistic Criteria, Transmission Expansion Planning, Risk management, Power Systems, Outcome variability, Decision making.

1. Introduction

1.1. *Context*

Historically, electricity generation happened in controllable, centralized production hubs (coal, nuclear etc.) with a quasi-static maximum capacity. In this situation, the location and quantity of produced energy can be estimated in advance within small intervals and at high confidence levels for extended periods of time. When the location and quantity of produced and consumed energy are well known, the energy flows on the transmission network can be approximated within small margins. This availability of high confidence, long-term forecasts has lead to the development and deployment of deterministic criteria in reïnforcement and expansion planning of the Electrical transmission grid. From these criteria, the N-1 criterion is perhaps the most well known. The N-1 criterion stipulates the network should continue to work without curtailment when one (and any) element is lost. Today, the increasing share of difficult-to-predict and less price sensitive energy generation (wind power, solar power,...) has resulted in a strong reduction of the confidence level for both location and quantity of energy production. This in turn leads to a decreasing confidence for forecasts for long and short term transmission capacity requirements. As the future states of the grid become harder to predict, the ability of probabilistic indicators (Expected Energy Not Supplied (EENS), Loss Of Load Expectation (LOLE), (Anders (1989))) to take into

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account uncertainty makes them a more and more attractive option for the evaluation of transmission planning variants (Lumbreras and Ramos (2016)). Transmission System Operators (TSO's) have recognized these advantages and efforts have and are being made to include probabilistic criteria in their decision-making processes (Bronmo et al. (2015)).

1.2. *The move towards probabilistic criteria*

Moving towards probabilistic criteria brings with it a significant increase in information available to the decision-makers Kirschen and Jayaweera (2007)). As the outcome of a decision for a system whose future state is based on a probability distribution is a probability distribution itself, there is no longer a deterministic outcome to base decisions on. One way to deal with this distribution of possible outcomes is to take the average of the possible outcomes weighted by their probability (Expected Energy Not Supplied, Average Outage Frequency, ...). This approach is widely known and is already being applied for the evaluation of grid variants. Another option could be to follow a minimum regret approach based on the k% worst possible outcomes, allowing to limit the consequences of the decision should the odds not be in the favor of the consequence-bearer. Each of these approaches has its value within a certain context. Choosing to optimize for the average results makes sense when the actual outcome will be close the average outcome. On the other hand, for decisions where the variability of the consequences is very large, criteria based on the tails of the distribution may be necessary. Additionally, whether or not the consequences could be so large they become unbearable (e.g. Nuclear disasters) and even the cultural context (Kermisch (2012)) may have an important effect on the risk-appetite of the decision-maker. The two cases studied in this paper show that the decisions made for the electrical transmission system can be positioned on both sides of the spectrum. As the typical decisions made on the electrical grid are positioned in between the extremes, the optimal approach for Transmission Expansion Planning (TEP) decision making should be able to deal with both.

1.3. *Transmission System Planning*

A transmission system planning study is initiated by the identification of a need. This need could be, for example, the connection of a new client or the upcoming replacement of important grid assets. Several grid variants that satisfy this need are then generated and subjected to a multistage decision-making process. During this process, two principal types of assessment (acceptance and selection) can be identified. The assessment of the acceptability of a grid variant is made using binary acceptance criteria. These criteria represent a minimum quality standard variants must adhere to. A well known acceptance criterion linked to reliability is the N-1 compliance at all times. N-1 compliance at all times stipulates that at any time, the outage of one (and any) single element must not lead to the loss of a generator or consumer of the system. Safety linked criteria such as the short circuit level and voltage limits are also often part of the acceptance criteria. Selection criteria on the other hand are used to pick the solution that is to be implemented from the list of acceptable grid variants. Selection criteria are mostly non-binary criteria and can be "easy" or "hard" to quantify. Examples of easy to quantify selection criteria are the capital and operational expenses (CAPEX and OPEX) of a variant. Public acceptance is an example of a typical "hard" to quantify selection criterion. Probabilistic criteria can be applied in both the acceptability (Is the yearly ENS below a maximal acceptable level?) and selection (quantification of the benefits and costs) assessment. As new probabilistic indicators are added to the decision-making process, several situations have been identified by experts where it is not immediately clear how to strike the balance between optimizing the average while reducing the variability of the outcome. In this work (Section 2) several of these cases are subjected to a probabilistic study and it is shown how changing the decision time-horizon and/or outcome variability could lead to a different decision. For example, some situations have been identified where, even though the situation was covered by both N-1 and probabilistic acceptance criteria, the advantages of making the investment was deemed to outweigh the costs. In these situations, the decision to invest was made despite the acceptability criteria indicating investments were unnecessary (see subsection 2.2. On the other hand, in some situations (see subsection 2.1) not covered by the N-1 criterion, the nature of the situation dictates the investment cost would not outweigh the benefits (see Gouvernement Wallon (2016) for the legislative context on this issue in Wallonia). Today, the variability of the outcome is probed implicitly by studying so called "worst cases". These "worst cases" are defined as the worst consequences a state that will only be observed very rarely (usually the outage of 2 elements or N-2) can have. As this type of event will typically be situated at the tails of the outcome distribution, analyzing it provides the decision-makers with an idea of the variability of the outcomes. This second type of cases is nowadays solved on a case-by-case basis and there is interest in finding criteria capable of aiding decision makers in this type of situations. As these criteria are defined, a decision making method that can efficiëntly use these updated criteria to compare different grid developments is then to be developed. Because of the implications of such an approach on all stakeholders of the electrical grid (how much are we willing to pay to be more certain of the outcome of a decision?) and its political and techno-economical implications there is a need to identify a methodology able to make the decision-making process more clear and open to input from all stakeholders.

1.4. *DeMOCrite*

DeMOCrite (Definition of Macro Objective-based Criteria for the optimal assessment of grid development alternatives) is a joint project between the Universit libre de Bruxelles and Elia System Operator S.A., funded by the Brussels capital region Innoviris that started on January 2018. DeMOCrite seeks to deal with the challenges mentioned in the previous sections. The DeMOCrite project's early stages consist of detailed case studies of selected situations experienced in the industry. This paper communicates some of the findings of these case studies. The final objectives of the project are to develop a methodology that could be used to update TSO grid development criteria. These criteria are mainly used to ratify the choice for a certain grid alternative. The focal point of the project is not to define the exact criteria to compare and select the most suitable grid development candidate but the approaches used to select the criteria for ratification of a grid expansion decision could serve to compare different development alternatives. In a later stage of the project, a general structure of the criteria is to be developed. This general structure should make the link between the macro objectives and criteria for a TSO. The final goal is then to move away from today's expert vision of the criteria based on deterministic assessments and towards a version of the criteria that is understandable by the general public and for which the consequence of political and strategic consequences are understood. To enable the industrial application of the developed method, a procedure select and tune the criteria will be delivered. Expert elicitation methods will be considered for this part of the project. An expert elicitation process starts with the selection of a group of experts who have predictive expertise for the issue at hand. This group is then interviewed in a structured fashion in order to support the experts in providing all relevant evidence (Ayyub (2001)). Using the data collected durin this interviews an educated guess of the elicited parameters and their uncertainty in the issue at hand is made. Procedures and criteria for eliciting this information while limiting the risk of biases are available in the scientific literature (see e.g. (Cooke and Goossens (2000)). Expert elicitation has often been conducted in situations where not a lot of specific experimental data is available or it is undesirable to conduct these experiments. Examples include the disposal of radioactive waste (Zio and Apostolakis (1996)), food safety studies (Authority (2014)), but also climate change (de França Doria et al. (2009)) and other environmental issues. The implementation of this field of knowledge in grid development strategies will be an important innovative part of the project. Finally, to aid in the selection of a variant to be implemented, a decision-making methodology is to be defined. The goal of this decision-making methodology is not to search and select the optimal alternative, which most of the time does not exist by itself, but to support the decision-makers in their decision by helping them to express their preferences to be able to differentiate between acceptable variants. This methodology is to be used to compare the alternatives while taking an absolute basis into account. This basis will be used as base case against which the relative differences between solutions can be compared. From the large pool of candidate decision-making approaches either one or a combination of methods can be used. To take into account a penalty for deviating from set objectives for example, fuzzy multi-criteria optimization could be used. Other methods methods such as the PROMETHEE methods, the Analytical Hierarchy Process (AHP), decision-rule based methods and others are also to be considered. Finally, more recent methods that explicitly allow the inclusion of multiple stakeholders (or actors) in the decision-making process (Macharis (2007)) will be evaluated for their applicability to the specific problem. As part of the basis for the DeMOCrite project, it has been decided to perform an analysis of several relevant test cases based on actual situations encountered on the Belgian transmission grid. The results of these analyses are detailed later in this communication and will be used as an input for future stages of the project. The cases themselves will continue to be used in later stages to evaluate the performance of the developed methodologies. For confidentiality reasons the case studies shown in this paper have been made anonymous. In the next section two test cases are described, the methods that have been used in the analysis are detailed and followed by the result of the application of these methods. Each case study is terminated with a short conclusion. Afterwards, the paper is concluded, stating the main results of the case studies and future prospects.

2. Case Studies

This section contains the results of two case studies for which the outcome variance is important in the final decision. The first case concerns the connection of an onshore wind farm to the electrical transmission grid. As using classical deterministic N-1 approach on this type of cases entails the design of the system for the maximal power output of the farm. As this maximal power output is only rarely obtained, we risk investing in an asset that is only rarely used. The use of a probabilistic criterion allows taking to incorporate this in the decision-making process, limiting the risk of investing in stranded assets. The second case concerns an electrical grid in an important Belgian city. The decision whether or not to invest in a cable for a five year transition period has to be made. Both classic deterministic and probabilistic criteria were used for the making of the decision. For this second case the decision outcome is available, allowing a direct comparison of the results of the analysis with the decisions that were made.

2.1. *Connection of a new wind farm*

Before a new producer can to connect to a node on the electrical grid, the Transmission System Operator first has to verify the technical feasibility of such a connection. One of the elements to be verified is the possibility of the network to evacuate the additional connected power from the node. Traditionally the N-1 criterion was used, ensuring that all generator power can be evacuated at any time, even when one transformer is out of service (foreseen or unforeseen). When the system does not comply this criterion, the generator has to wait for the installation of additional grid elements before completing the connection. For thermal base load energy production this approach avoids the curtailment of power for long periods of time. For thermal peak units it ensures the full availability of these units at times where the production margin is small. For intermittent generation the trade-off may not be as clear. On one hand the energy production of this type of generation is rarely the nominal power output [a], which means we cannot evaluate them as thermal base-load units. On the other hand, intermittent energy production is hard to control and often independent of energy prices means that it cannot be regarded the same way as peaking units. In Belgium, so called ”flexible” capacity has been introduced to deal with these intermittent units. A unit connected to this ”flexible” capacity accepts curtailment in case the need should arise. An advantage of this approach to the generator is that he does not have to wait for the completion of the installation of additional grid infrastructure. The Walloon regulator CWaPE (Commission Wallone Pour l'Energie) provides a legal basis for a cost-benefit analysis for the adaptation of the grid to better accommodate an installation benefiting from green certificates (a certificate guaranteeing that the energy is produced by a renewable source), see Gouvernement Wallon (2016). In this case study we investigate the connection of an intermittent, renewable generator to an existing node. The situation is schematically represented in figure 1. The wind power and residential consumption were set close to the points where the trade-off based on the CWaPE criteria occurs as determined in earlier research on the same case study (Willems et al. (2018)).

2.1.1. *Methods*

Using measured production and consumption profiles the sum of power to be evacuated from or injected in the node is calculated. The amount of power to be curtailed is then calculated using the present transformers' characteristics. To extract the variability of the outcome a simple sequential monte carlo simulation is used. More specifically, outages are randomly sampled in a predefined period and the ENS is calculated. This simulation is then repeated to obtain the distribution of possible outcomes. As we now have the distribution of possible outcomes we have made explicit not only the average result but also the cases in which we are lucky and cases in which we are not. A financial risk measure (Expected Shortfall or ES Acerbi and Tasche (2002)) was used to represent the tails of the outcome. The ES at k% represents the expected return in the worst k% of outcomes. The expected value of the decision as well as the expected shortfall at the above-mentioned levels were calculated for time periods of different lengths. The results are presented in figure 2. To facilitate the comparison with the second first case, results have been divided by the expected yearly load shedding.

2.1.2. *Discussion*

The expected shortfall at 0.5% after five years is only 7.8% larger than the expected outcome. We can thus conclude that the variability of the

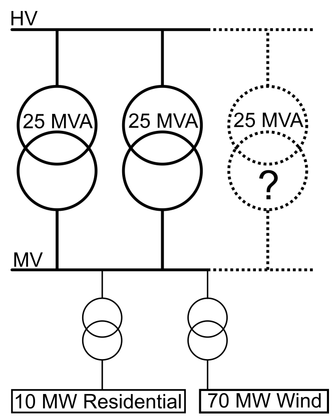

Fig. 1. System under study in subsection 2.1.

[a]For example, Elia measurements suggest that a typical on-shore wind farm produces less than 90% of its nominal capacity for 97 % of the time

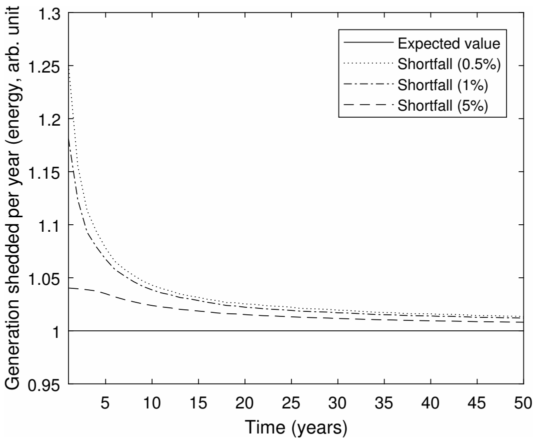

Fig. 2. Yearly expected load shedding and evolution of the expected shortfall of the yearly load shedding.

outcomes is quite limited. This small variability is due to the large frequency of occurrence of overloads compared to the simulation times and thus the number of samples where generation is shed. Indeed, if we calculate the expected shortfall for simulations of longer duration and compare it to the average outcome, the relative difference between them becomes smaller (see Figure 2). In this case we are dealing with a decision where we can be confident that the actual outcome will be quite close to the average outcome. Using the expected outcome to make this decision is therefore justified.

2.2. *City cable network*

The second case study in this work concerns a cable network in a large Belgian city. The network is, as required by today's standards, N-1 secure and is only susceptible to losses in case more than one element is out of service. This N-2 event has a very low probability of occurring but could have very large consequences. The system under study is shown in Figure 3. Substations have been named alphabetically and the connections between them are made by means of underground cables. Circuit breakers are represented by means of empty (open circuit breaker) or filled (closed circuit breaker) squares. For this simulation loads are assumed constant and the cables free of overloads (which conforms to the actual case study). The network is in the presented state for a five year transition period after which a cable between substation C and D is planned to be installed. The installation of this cable could be advanced to before this five year period, reducing the probability that energy cannot be supplied to consumers by allowing energy to flow over an additional path. The possibility of advancing the investment was evaluated by experts through use of the traditional N-1 method, a probabilistic cost benefit analysis and finally the analysis of a worst case incident.

2.2.1. *Methods*

We can estimate the financial incentive for delaying an investment by calculating the financial discounting of the cable (CAPEX) and adding to it the costs avoided for not having to maintain it. To assess the cost of not investing three methods are applied. First, the network is controlled for N-1 compliance at all times. Secondly, the expected energy that cannot be supplied (EENS) over the five year period is calculated. From this EENS the EENS that we would have if we would not invest is subtracted, resulting in the value of energy that we can avoid shedding if we invest today. We then multiply it by a factor that estimates the financial costs linked to the loss of energy supply (Value of lost load or VoLL) and compared to the financial incentive of not investing. If the financial incentive of not investing is larger than the costs for investing we should not invest. On the other hand if the cost of taking the additional risk for outages outweighs the benefit gained from not investing we should install the cable now. Finally, the distribution of possible outcomes should we not invest is estimated using a sequential Monte Carlo analysis. We obtain this outcome distribution by randomly sampling five year periods and sorting them by the resulting energy not supplied. This last method is more computationally expensive, but it allows for a more detailed overview of the effects of the decision. The results of this simulation contain the worst case that was also calculated during the actual decision-making process.

2.2.2. *Results*

As the cables are congestion-free, there will never be ENS in case of N-1 events. If only this criterion is used, the decision makers will not make the decision to invest. When we compare the cost linked to the additional EENS should we not invest with the financial incentive of investing later

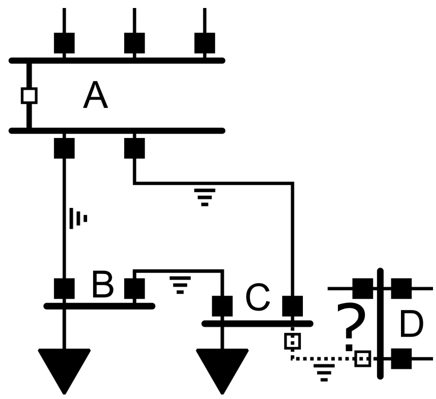

Fig. 3. System under study in subsection 2.2.

we see that the latter is a factor three smaller. Using the second method, the decision not to invest should therefore also be made. From the outcome distribution resulting from the third method (see Figure 2 however we can see that the average only tells part of the story. In this case there is only a small percentage of the cases where there load shedding and when it happens, the consequences could be huge. In particular, there is one N-2 event (the loss of cables A-B and A-C) that results in the loss of the substations at B and C and could lead to the curtailment of five days for a total of approximately 17 GWh of energy.

2.2.3. *Discussion*

When confronted with the results of the N-1 and cost-benefit analysis, the conclusion seems that it is not worth it to invest. Since the effects of a loss of power in this major city could be enormous, the experts investigated what would happen if the dice rolled against them and an important incident would occur. To this end, they performed a so-called "worst case" analysis. In such an analysis incidents with a very low probability, and large consequences, are analyzed. Typically this is the outage of an element during the maintenance of another element, leading to the unavailability of two elements at the same time. Here, the worst of this type of outages could lead to the loss of a large part of the city for several days. This "worst" incident is the outage of cables A-B and A-C and while the risk it carries is limited (very low probability, very large consequences), treating it like any other incident might not be optimal. In the end, the experts decided against delaying the investment and installed the cable early. When we use the methods to visualize the variability of the outcome described in the first case study, it is clear that the expected value of the outcome does not reflect the actual possible outcomes. The expected shortfall at 0.5% after five years is a factor 40 larger than the expected outcome.

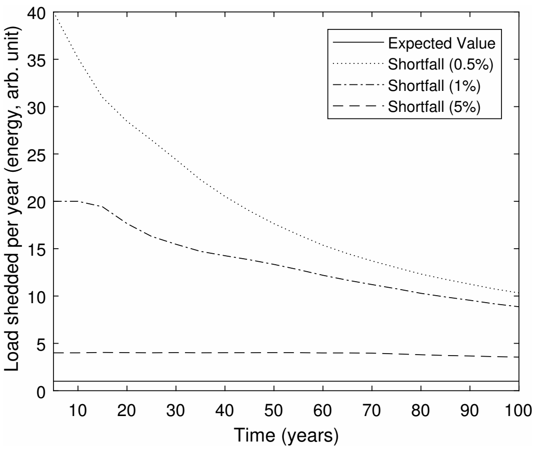

Fig. 4. Yearly expected load shedding and evolution of the expected shortfall of the yearly load shedding.

3. Conclusion

Deterministic criteria have been used to plan the majority of today's network infrastructure. The increasing uncertainties on the electrical grid have lead to a situation where the range of outcomes of a decision that is made today is becoming larger and larger. In this new context the use of probabilistic criteria capable of capturing this uncertainty could provide important additional information to the decision-makers. If the input data becomes a probability distribution, the outcome become a probability distribution as well. In particular, in case the variability of possible outcomes becomes large, the expected value alone might not be sufficient to make a decision. This is especially the case for the sectors such as the electric power system, where often trade-offs are made between outages with extreme consequences but a small probability of occurrence and a smaller but certain investment cost. Three cases where a decision to invest is to be made have been treated in this work. Each of these cases had its own unique characteristics that made them interesting to study. In the first case, both the expected outcome and existing deterministic criteria dictated that the investment should not be made. When confronted with the decision, the experts made the choice to invest. This decision was based on the possibility of an incident with catastrophic consequences. In cases where the outcome variability is small, the average can be a good indicator of the actual outcome. In cases variability of the outcomes is large, making the decision based on an average might not be the right choice as we are not at all certain if the actual result will be close to the value used to make the trade-off. In the second example the variability of possible outcomes was much smaller. It could therefore be argued that in this case the expected outcome is a good estimator of the final costs. It was shown that increasing the duration for which the decision has to be made reduced variability of the outcome. This is a natural result as we increase the observation time and thus the number of samples. More in general, it could be argued whether or not the amount of similar decisions also has to be taken into account as they also generate 'samples'. For the second case this would likely not change the decision as the variability is already quite low. If we look at the first example this could have an impact on the decision. It could be argued that if it was not a singular case but a decision that had to be made for a lot of cities that the magnitude of the additional investments justified the acceptance of the risk. The third case concerned an investment decision in between both extremes. Using the same techniques as in cases

1 and 2, it was shown that dependant on the risk the decision-maker is willing to take as well as the timescale (or again, amount of 'experiences') could have an important impact on the decision-making process. The definition of a methodology to select criteria and objectives to aid in the decision-making process is part of the DeMOCrite project described in subsection 1.4. It must be highlighted that in practice these types of decisions include a lot more factors than the reliability and cost of a network. Elements such as public acceptance, robustness to future scenarios, safety measures etc. are indispensable in the decision making process for transmission expansion and reïnforcement planning and are therefore also to be included in the project.

4. Future prospects

It was shown that the capability of probabilistic indicators to more accurately capture the distribution of possible outcomes of a decision could add important information to the decision making process. An additional advantage of probabilistic criteria with respect to binary (yes or no) deterministic criteria, is their inherent capability of revealing nuances between variants. This property enables more precise trade-offs compared to using deterministic criteria. While maximizing the information available to decision makers enables them to make more complete decisions, it must be made sure that the criteria themselves remain understandable and their number minimal. To this end, the elements critical to the decision must be identified and a procedure to quantify them should be defined. To capitalize on the advantages of these new criteria, a decision-making methodology enabling the use of these criteria to their full potential is to be developed. This methodology should help the decision-makers take the different aspects of the decision into account. In case of the electrical transmission grid these aspects include both easily quantified (cost,...) and hard to quantify (public acceptance,...) elements. Seen the multitude of available decision-making approaches, the study of the applicability of such methods is an important part of the DeMOCrite project. In a final step the sensitivity of the results to the input data must be investigated. This sensitivity analysis should help ensure that the robustness of the proposed methodology is sufficient to allow it to be used in the current context of increasing uncertainty.

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