The effect of including societal consequences for decisions on critical infrastructure vulnerability reductions

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Abstract: Critical infrastructures provide society with services that are essential for its functioning and extensive disruptions of these give rise to large societal consequences. Vulnerability analysis gives important decision information concerning improving their ability to withstand strains. To analyze vulnerabilities in infrastructures models for estimating consequences due to failures are needed. Consequences arising from a critical infrastructure disruption can be estimated from an infrastructural or a societal viewpoint. Most risk and vulnerability related studies of critical infrastructures, however, focus rather narrowly only on the direct infrastructural consequences, e.g. expressed as services not supplied. An integrated model, consisting of a physical model of a critical infrastructure (the Swedish electric transmission system) and an inoperability input-output model to estimate societal consequences is used. The paper analyze and contrast how the two viewpoints may affect the decision of which vulnerability reducing measures to implement. Vulnerability reducing measures are implemented as addition of branches to the existing power system. The results show a relatively large difference when considering estimated effectiveness but the ranking of the measures is to some extent, congruent, however it is concluded that accounting for societal consequences in the decision-making process, when prioritizing between different vulnerability reducing measures, is of importance.

Keywords: Critical infrastructures, vulnerability reducing measures, societal consequences, electric power system, decision context

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1. INTRODUCTION

Critical infrastructures provide indispensable goods and services to society and extensive disruptions of these can give rise to large societal consequences. The development towards a more complex society, with increasing interdependencies affects our society's ability to manage critical infrastructure disruptions. The increase of interdependencies have many positive effects as well, e.g. the advantages with automatized subways and to be able to pay bills over the Internet. However, increase of interdependencies may also lead to an increase of the vulnerability for society. The society as a whole are getting increasingly dependent on goods and services that infrastructures provide us with, and a loss of infrastructures services in general, and electric power supply in particular, may give rise to large negative consequences [1]. Furthermore, private companies and industries will not be able to continue production, potentially resulting in large economic consequences. Lastly, public actors will be unable to provide vital societal services such as health care and emergency response in cases of infrastructure collapses. It is therefore of utmost importance to analyze the vulnerability of critical infrastructures not only from an infrastructural viewpoint but also from a societal viewpoint

To inform decisions on infrastructure vulnerability reducing measures from the two viewpoints, a model of the infrastructure of interest is needed together with a model to estimate societal consequences arising from infrastructure failures. Furthermore it is also necessary to estimate and contrast the effectiveness of proposed measures in a decision context, which is the main focus of the paper. Traditionally most risk-related studies of power systems focus rather narrowly on the direct consequences for each individual infrastructure, typically described in terms of non-supplied commodities such as amount of

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water, heat, power, or as monetary cost of the non-supplied commodity. However, since considerable dependencies and interdependencies exist between infrastructures and societal sectors, a failure in an infrastructure is likely to cascade throughout this complex system. By only considering direct infrastructure consequences, the negative effects can potentially be severely underestimated. Previous research by other researchers [2], [3] as well as by the authors [4] shows that it is important to estimate the impact of infrastructure failures in a wider societal context, incorporating also the consequences that arise in the society. The latter since the societal consequences are not always linearly proportional to the infrastructural ones. Some integrated models trying to capture both an infrastructural and societal viewpoint above have been proposed earlier, see e.g. [5] for an overview. Previous research by the authors [4] combined two models that enabled analysis of the consequences of failures from the two viewpoints. A representative model of the Swedish power transmission system was used to enable the analysis of the consequences of failures from an infrastructural standpoint. To assess the societal consequences arising from infrastructure failures, a regional inoperability input-output model was used, with real-life national economic data.

It is important to realize, though, that it is not only relevant to what extent the negative consequences might be underestimated when societal consequences of infrastructure failures are ignored, but also whether the decisions to be made, as a result of the performed vulnerability analyses, will be affected depending on whether societal consequences are included or not. If the same decision alternative is recommended when considering infrastructure consequences as when accounting for societal consequences, it would be enough to only estimate the direct infrastructure consequences in that particular decision context. If this is not the case, on the other hand, vulnerability reducing measures for critical infrastructure systems might be misdirected to strengthen parts of the system that if they fail give rise to high infrastructural consequences but relatively small societal consequences.

In the present paper a case study with a representative model of the Swedish electric transmission systems, as electric power systems are generally regarded as one of the most vital critical infrastructures, and twelve suggested vulnerability reducing measures is carried out. Vulnerability reducing measures can roughly be divided into two categories: proactive measures and reactive measures. Proactive measures include, but not limited to, implementation of redundancies [6] or protecting critical system components [7]. Reactive measures include taking actions after a failure has occurred to e.g. avoid cascading failures [8] or to restore system functionality [9]. In the present paper the proactive approach, in terms of implementing redundancy, is used to reduce the system vulnerability. More specifically, vulnerability reducing measures are implemented as addition of branches, those planned by the transmission system operator and additional measures suggested by the authors, to the existing power system to make it more robust towards failures. These measures are then evaluated from the two viewpoints to contrast if and how decisions of which measures to implement differ. If both viewpoints leads towards the same decision, there are few reasons for using both viewpoints in that particular decision context.

2. METHODS AND MODELS

2.1. Power System Model

The system studied in the present paper is a representative model of the Swedish transmission system (see Figure 1), which has been derived from publicly available data. The system is modelled in accordance with the modelling approach developed by two of the authors [10], where the system is represented with two parts: a structural part that describes the components of the system and a functional part that describes the effects of failures in the system. In the representative model the two highest voltage levels in the Swedish transmission system are represented, 400 and 220 kV; i.e. the lower voltage levels of the power system (sub-transmission and distributions systems) is not part of the system model. The structural model of the system consists of 119 buses (nodes) and 186 power lines (edges). The functional model of the power system is a DC power flow model implemented through Matpower [11] to calculate the optimal power flow given any configuration of the system. Total available generation capacity, distributed among 71 generators, is 29 940 MW and total loading is 15 000 MW, distributed among 46 load points. The load points have further been assigned to a specific geographical region (numbered 1 to 21 in Figure 1) in order to keep track on regional power outages. It should be noted that region 6 is not supplied by the modelled transmission system, but from a non-represented sub-transmission system (130kV), and is hence omitted from the analysis. For a more detailed account of the system, assumptions and modelling approach see Johansson et al. [4].

In order to analyze system vulnerabilities, failures were simulated and system performance evaluated. The type of failures considered here consists of randomly removing power lines (edges) of different order of magnitudes and evaluate the consequence that arise in terms of the amount of power curtailed given specific system states. One iteration consist of randomly removing one (N-1) up to twenty (N-20) power lines and calculating power curtailed for each incremental step. In total 10 000 iterations were simulated for the original system and for each of the 12 improved systems. The number of iterations was chosen to give a representative number of failure scenarios with an acceptable convergence. As convergence criteria the coefficient of variation was used [12]. The convergence of the mean power supply reduction over N-1 to N-20 for 1000 iterations for the original system was 3.3% and ranging from 2.3% to 6.5% for the improved systems.

For each vulnerability scenario the amount of power not supplied for the system as a whole and for each region are calculated. These regional unsupplied power reductions are then translated into a disruption for the electricity sector in the IIM model, described in the next section, to estimate higher-order societal consequences. Since each load point in the system has been matched to one of the 21 geographical regions (counties), the amount of power supply reduction for each region *i* can be calculated and translated into an electricity sector supply reduction (SR) as input to the regional IIM model according to equation 1:

$$\mathrm{SR} = 1 - \frac{\mathrm{P_{Curtailed}}}{\mathrm{P_{Total}}} \qquad (1)$$

where SR_i is used as a perturbation to the electricity sector in a region, i.e. as an element in z* for the regional supply-driven IIM (see Eq. 2 below), $P_{reduction}$ is the amount of unsupplied power and P_{total} is the total load for each region. Hence, it is assumed that the fraction of power supply reduction corresponds to an equal perturbation of the electricity sector.

2.2. The Inoperability Input-Output Model (IIM)

As addressed in the previous section, an inoperability input-output model is used to estimate higher-order societal consequences across sectors due to power supply disruptions. The inoperability input-output model is derived from the Leontief input-output (I-O) model that describes the equilibrium behaviour of a nation's or region's economy. Leontief I-O model can be used to study and quantify the interactions between producers and consumers in an economy. For a detailed introduction to Leontief I -O model and its applications, see Miller & Blair [13].

IIM was first introduced by Santos & Haimes [14] and describes how the inoperability of one or more sectors can propagate throughout the economy, due to economical interdependencies between various societal sectors. The original IIM were derived from Leontief's demand-driven I-O model, although there have been several approaches using the supply-driven model, e.g. Crowther & Haimes [15]. In the demand-driven model, the initiating events are considered to be perturbations to the final demands, i.e. it describes backward ripple effects. The supply-driven IIM describes and addresses inoperability as degraded production capacity. Leung et al. [16] exemplify this as damage to facilities and equipment, inability of the workforce to work, or shortage of materials results in lower production output and thereby limiting the supplies available to other sectors and to the final consumer, i.e. it describes forward ripple effects.

In this paper the supply-driven IIM is used and not a demand-driven IIM, since power sector has higher downstream (supply) than upstream (demand) consequences [4] and the downstream effects spread more rapidly. It is formulated as (for a more detailed description, see e.g. Leung et al. [16]):

$$q^{(s)} = \left[I\text{-}A^{(s)^*}\right]^{-1} z^* \tag{2}$$

Where $A^{(s)^*}$ is the supply-driven interdependency matrix, and z^* is the perturbation vector expressed as reduced supply normalized with respect to the as planned (domestic) production output.

In the present paper, a regionalized IIM is used, where each of the 21 Swedish counties are treated as a region. The regional decomposition is conducted using the cross-industry location quotient called CILQ [17], [18] and no interregional feedback where taken into account. The societal consequences for each region are then summed to get the total consequences for the nation given a vulnerability scenario. Here import and export are included as separate sectors, however there are also other ways of managing international trade, see e.g. [19]. This assumptions as well as additional ones made in this modeling approach, including assuming that the level of economic dependency between various sectors is the same as the level of physical dependency and the fundamentally linear nature of the model, is addressed in the discussion section. For a more detailed description and discussion of assumptions and limitations of the present IIM modelling approach, see Johansson et al. [4].

The national economic I-O account used as a basis for the IIM in this case study was provided by SCB (Statistics Sweden) and is valid for the year of 2008. The original I-O data consists of 59 sectors. In this case study, sectors without production in Sweden were removed (6 sectors) and the sector for electricity, gas, steam and hot water were divided into two sectors, one for electricity and one for gas, steam and hot water by using additional data provided by SCB, resulting in 54 sectors. When adding import and export the final sum of sectors is 56. The regional decomposition was conducted using regional and national employment data also provided by SCB.

2.3. Evaluating the effectiveness of vulnerability reductions

In order to make decisions about which vulnerability reducing measures to implement, it is essential that the effectiveness of the measure, $E(M_i)$ can be estimated, i.e. to what extent the measure reduces the system vulnerability. Therefore, first the concept of vulnerability needs to be defined and operationalized. The present paper adopts a common definition of vulnerability where the term is seen as the magnitude of the negative consequences given that the system is exposed to strains (cf. [20]). The metric used here to operationalize vulnerability is the *average negative consequences,* $\bar{C}$,, given that the system is exposed to a strain of a certain type and a certain size. In the present paper we restrict our focus to strains that are random in nature, and limiting the study to random removal of system components. In addition, we restrict our focus to strains of a size up to 20 simultaneously removed components. The effectiveness of a vulnerability reducing measure is then defined as the fractional reduction of the average negative consequences for the original system compared to the improved system given a particular strain *S*:

$$E(M_i) = \frac{\bar{C}_0 \;|S \text{ -} \bar{C}_{M_i}|S}{\bar{C}_0|S} \tag{3}$$

where $\bar{C}_0$ is the average negative consequences for the original system and $\bar{C}_{M_i}$ is the average negative consequences given that the measure M_i has been implemented. The unit of C will depend on whether the infrastructural viewpoint is chosen (MW) or whether the societal viewpoint is chosen (MSEK). However, since E is defined as the fractional reduction in the average consequence due to a measure it is a dimensionless number and hence can be compared between the two viewpoints.

2.4. Selection of vulnerability reducing measures

In the present paper a total number of 12 vulnerability reducing measures is used to gain insights into the effect of accounting for societal consequences of power disruptions. Four of these were identified based on "Perspektivplan 2025" [21], which is a strategic document published by the Swedish Transmission System Operator (TSO), who e.g. is responsible for the operations, monitoring and development of the Swedish electric transmission system. In this document a number of planned improvements are described of which four was deemed plausible for the present paper since they concerned network improvements in terms of adding power lines. In addition, 8 other potential vulnerability reducing measures were defined by the authors based on topological and geographical characteristics of the Swedish transmission system. An overview of the measures evaluated in this paper is presented in Figure 1.

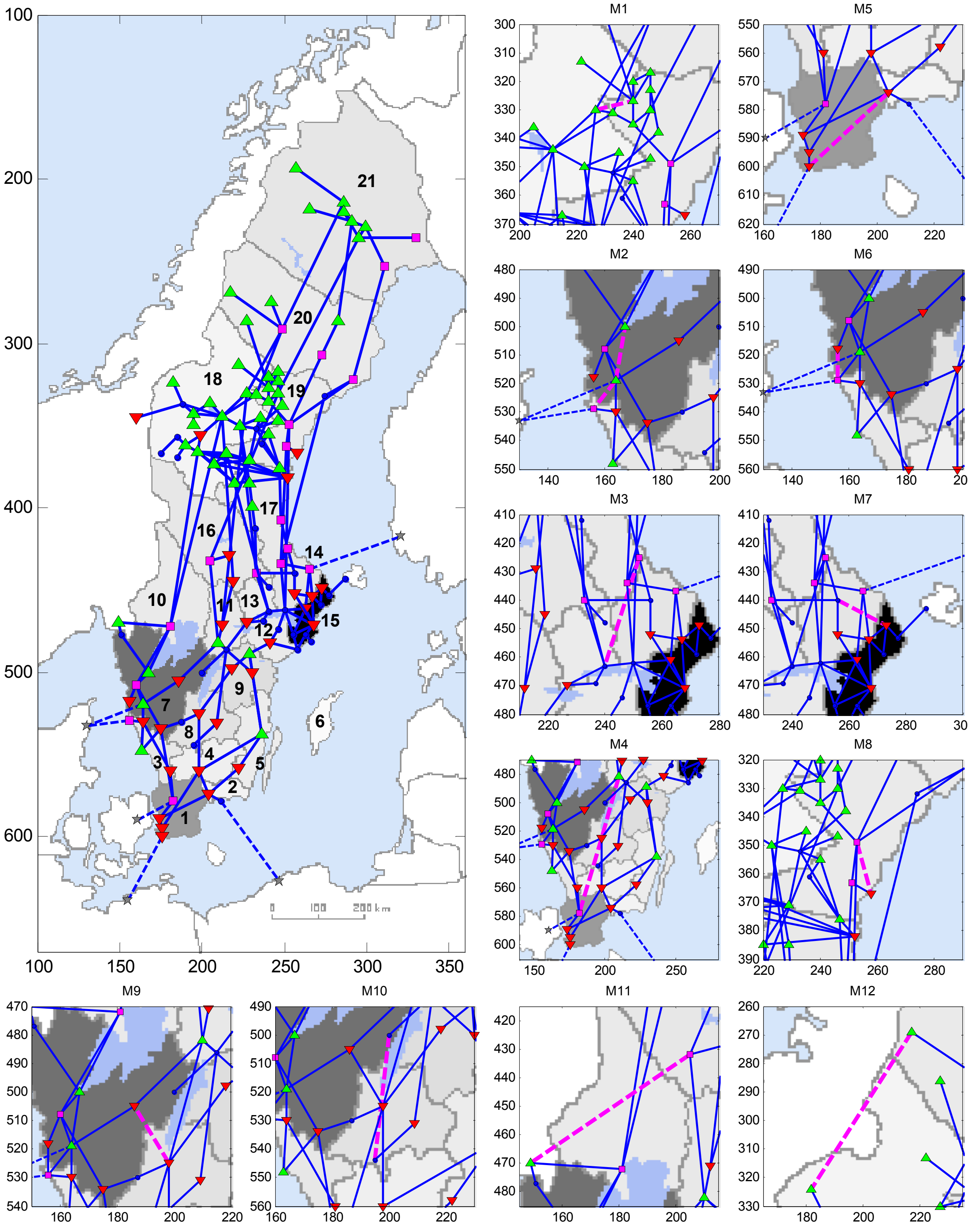
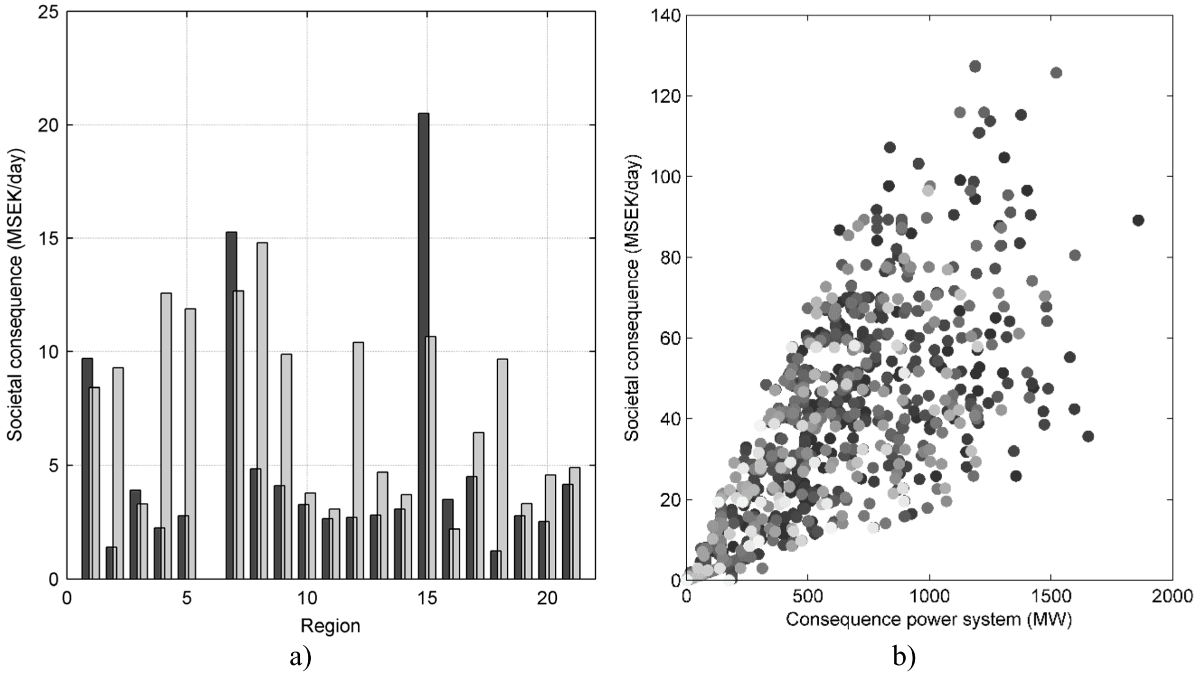


Figure 1. Overview of the original system setup (top left) and each vulnerability reducing measure M1 to M12. Each region has a number ranging from 1 to 21 (south to north) and the colour of each region corresponds to linear grayscale of the regions yearly GRP, ranging from 15 billion SEK (region 6) to 950 billion SEK (region 15).

3. RESULTS

In order to clarify the societal impact of power disruption in the different geographical regions we first conducted a study using only the economical IIM. In Figure 2a, the societal consequences, calculated using the regional IIM, of a fixed power disruption in each regions is presented. The figure shows how severe the societal consequences would be if each of the 21 regions would be exposed to 1) a 10% perturbation of the total power supply in the region 2) a 100 MW disruption in the power supply. Since the different regions have different power demands a 10% disruption corresponds to 13 MW disruption for the smallest region (region 18) and a 192 MW disruption for the largest region (region 15). Furthermore, a 100 MW disruption would mean a 79 % disruption for the smallest region (region 18) and a 5.2 % disruption for the largest region (region 15). The results in Figure 2a reveal that a 10% disruption would have very different societal consequences depending on which region affected (varies by about a factor 20). This is mainly due to the varying economical size of the regions, in terms of their GRP (cf. Figure 1), and to some degree that the different regions have varying power dependence. To more clearly reveal the region's power dependence a study was also carried out with a fixed power disruption, here 100 MW. The results reveal that rather different magnitude of societal consequences arises (varies with about a factor of 7). In some regions, such as region 8, the societal dependence on electric power is very strong, i.e. the region is very sensitive to power supply reductions, whereas in other regions the dependence on the electric power sector, such as region 16, is less.

To further explore the coupling between power outage and societal consequences, Figure 2b gives an overview of each individual scenario from simulation of the original system. For each scenario both the infrastructure consequences in terms of power not supplied (MW) and the societal consequences in terms of MSEK/day is presented. It can be seen that the regional power dependence differences shown in Figure 2a are propagated to the vulnerability scenarios in Figure 2b. From Figure 2b it is clear that a certain magnitude of power outage can give rise to significant different societal consequences, consider for example a power outage of 1000MW which can give rise to societal consequence in the range from 15 MSEK/day to 100 MSEK/day depending on the region affected. For the scenarios that have the largest difference between the infrastructure consequences and the societal consequences this difference is about a factor of 4-5.



a) b)

Figure 2. a) Societal consequences of a 10% power reduction for each region (dark gray) and 100MW power reduction for each region (light gray). b) Consequence from the viewpoint of the power system (MW) versus societal (MSEK/day), each marker representing one individual scenario (in total 20*10 000) from simulation of the original system ranging from light gray, representing N-1 scenarios, to dark gray, representing N-20 scenarios, with a linear scale.

The evaluation of the vulnerability reducing measures from the societal and infrastructure viewpoint will be influenced by, firstly, in accordance with the discussion above, the differences in the regions' power dependence and the societal consequences that arise and secondly since a certain size of power outage at the national level could be a result of very different regional power outages. To further analyze the effects on the vulnerability reducing measures, Table 1 shows the simulation results for the original system and the systems with the measures implemented (M1-M12). Studying the data it is clear that many of the scenarios are associated with zero or low consequences, since the 75th percentile values are close to the mean values. The maximum consequences found in the simulations are roughly in the order of a factor two to three higher than the 99th percentile values, indicating a heavy tail distribution of the consequences. The minimum consequence of zero found in the simulations indicates that the system can typically withstand at least one component failure without any consequence arising (i.e. N-1 secure). Furthermore, it is clear that all the measures has an effect on reducing the overall vulnerability of the power system, but with varying effectiveness. From an infrastructural viewpoint M8 has the largest improvement while from a societal perspective M6 is dominant.

Table 1. Summary of the simulation results with consequences for the infrastructure (Inf.) given in MW and societal consequences (Soc.) given in MSEK/day. Included is also mean percentage improvement for each vulnerability reducing measure (M1-M12) in comparison to original system.

System	Mean		Minimum		Maximum		75th percentile		90th percentile		99th percentile		Mean Impr. (%)	
	Inf.	Soc.	Inf.	Soc.	Inf.	Soc.	Inf.	Soc.	Inf.	Soc.	Inf.	Soc.	Inf.	Soc.
Orig.	118.4	7.04	0	0	1858.6	127.4	175.0	9.8	427.5	22.8	895.4	57.8	---	---
M1	117.6	7.01	0	0	2028.7	166.5	175.0	9.8	405.5	22.8	895.4	57.7	0.62	0.38
M2	117.3	6.93	0	0	2155.3	149.3	175.0	9.8	405.5	22.8	895.4	57.9	0.91	1.61
M3	116.8	6.82	0	0	2027.8	202.2	175.0	9.8	403.2	20.4	894.3	57.7	1.35	3.18
M4	116.1	6.84	0	0	2337.5	120.3	175.0	9.8	388.9	20.4	895.4	57.7	1.92	2.89
M5	103.5	5.82	0	0	1892.0	141.5	131.0	0.1	302.4	19.4	894.3	51.3	12.52	17.38
M6	108.2	5.26	0	0	1966.8	142.8	175.0	9.8	361.5	19.4	894.3	49.5	8.61	25.28
M7	117.0	6.89	0	0	1864.7	142.9	175.0	9.8	427.5	20.4	895.4	57.7	1.15	2.18
M8	101.8	6.37	0	0	2377.1	192.8	131.0	0.1	306.0	19.4	894.3	57.7	14.04	9.57
M9	116.3	6.84	0	0	1948.4	148.3	175.0	9.8	405.5	21.5	895.4	57.7	1.77	2.87
M10	114.9	6.27	0	0	2377.1	192.8	175.0	9.8	405.5	19.6	895.4	57.7	2.93	10.97
M11	115.8	6.93	0	0	2589.4	138.9	175.0	9.8	405.5	22.4	889.5	57.7	2.19	1.60
M12	117.0	6.99	0	0	2014.4	163.2	175.0	9.8	405.5	22.8	895.4	58.2	1.14	0.72

To further explore the effectiveness and ranking of the vulnerability reducing measures, each measure has been evaluated in terms of its vulnerability reduction in comparison to the original system configuration. The effectiveness of the 12 vulnerability reducing measures is shown in Figure 3 regarding their overall effectiveness over a) N-1 to N-20, b) N-5, c) N-10 and d) N-15. From the figures it is clear that the ranking of which measure to regard most effective clearly differs if an infrastructural or societal viewpoint is taken. However, both the infrastructural and the societal viewpoints agree on which measures that are ranked top four: M8, M5, M6, M10. Studying the differences of the measures more closely for different strain sizes (Figure 3b, c, and d) reveals that their absolute effectiveness differs, but overall the ranking of the measures is to some extent congruent. The measure with highest overall societal vulnerability reduction (25%) is M6. This measure has larger reduction, relative the other measures, for smaller strain sizes (N-5) compared to larger strain sizes (N-10 and N-15). This measures strengthens a normally radially fed supply point in the power system which is situated in a region (region 7) with high GRP and relative high power dependence (cf. Figure 2a), which hence significantly improves the robustness of the power system and especially for smaller strain sizes. Measure 8, which has the highest overall infrastructure vulnerability reduction, is also strengthening a normally radially fed supply point (region 19). It is interesting to contrast M6 to M8 since these are considered the overall best measures from the two different viewpoints. One reason behind this result is the different societal consequences that arise for a given power supply reduction (see Figure 2a), where the societal consequences for region 6 is roughly a factor of 4 higher compared to region 19 for a power outage of 100MW, leading to a higher societal vulnerability reduction for M6 compared to M8. On the other hand, M8 has a higher infrastructure vulnerability reduction compared to M6. Measures M1 to M4 are those planned by the transmission system operator, which are all but M4 ranked low in comparison to the measures suggested by the authors. Measures M1 to M3 are however planned in accordance with expected production increases (mostly wind power) and not with the main purpose of strengthening the overall robustness of the power system. Measure 4, however, is planned with the aim of improving robustness of the power supply to southern Sweden, an improvement which effectiveness is supported by the results presented here.

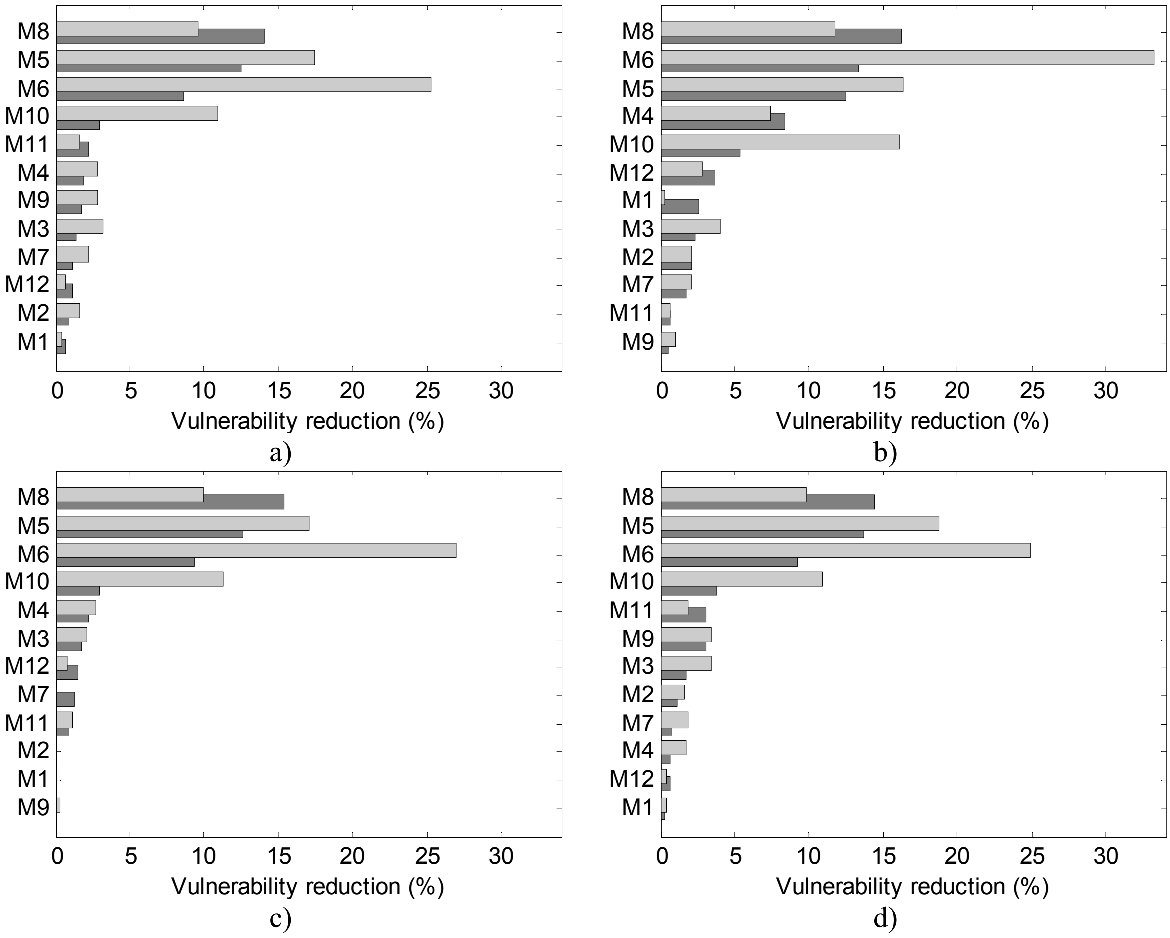


Figure 3. Percent vulnerability reduction for measures M1 to M12, infrastructure (dark gray) and societal (light gray) viewpoint for: a) N-1 to N-20, b) N-5, c) N-10, and d) N-15. Sorted in accordance to infrastructure vulnerability reduction.

4. DISCUSSION

The results presented reveal that it is important to account for societal consequences in the decision-making process when prioritizing between different vulnerability reducing measures as they may differ significantly from infrastructure consequences. When evaluating vulnerability reducing measures from both an infrastructural viewpoint and a societal viewpoint, the results show a relatively large difference when it comes to the effectiveness of the measures while the ordinal rankings are to some extent congruent. As such the two viewpoints do not, however, provide totally conflicting results. For example, four measures (M8, M5, M6, M10) stand out as the most effective ones from both an infrastructural and a societal viewpoint, although their effectiveness differ significantly from the two viewpoints. The planned measures by the Swedish TSO [21] where not among those with the largest vulnerability reduction effectiveness in comparison to those suggested by the authors, neither from an infrastructural viewpoint nor from a societal viewpoint. Three of these measures are aimed at accounting for increased power production in the future (M1 to M3) while measure 4 is the only one with the explicit purpose of reducing the system vulnerability for the southern parts of Sweden, which is the most effective vulnerability reducing measure of the four ones proposed by the TSO in accordance with the results presented.

The power system model and the societal consequence model (IIM) used in the present paper have some limitations that should be addressed. One of the limitations of the power system model is the resolution of the model, where only the transmission system is included and not sub-transmission systems and lower voltage levels. Each region's power consumption is based on the buses' location with respect to regional geographical borders, however in the real system there are also sub-transmission systems that support the buses (i.e. they may interconnect transmission buses in two regions and support power transfer between these buses). This is likely to have an effect on the estimated power reduction for a region for the analyzed vulnerability scenarios. In effect, the absolute effectiveness for each of the 12 measures, and specifically those that aim to strengthen a node that is only connected to one edge in the transmission system model (e.g. M6 and M8), may be overestimated. Furthermore, the power system model does not include transmission capacity from neighboring countries, i.e. only buses in Sweden are included and connections to other countries are excluded. This limitation will have similar effect on the results as the resolution discussion above.

There are also several limitations and assumptions related to the use of IIM to estimate societal consequences, and specifically the use of economic data as input to the model [3]. When applying an economic IIM it is assumed that the level of economic dependency between various sectors is the same as the level of physical dependency, i.e. in general, two sectors that have a certain level of economic interaction is assumed to have a similar level of physical interdependency. Using economic I-O data as an approximation of physical interdependencies is often the only option since there is a lack of data on actual physical interdependencies – an area that deserves extensive research. Hence there are uncertainties regarding the estimations of the societal consequences that arise due to power outages. Furthermore the IIM is fundamentally linear in nature, i.e. for any given input, if increased by two the resulting output will also increase by two – a model limitations that should be further evaluated and contrasted against other type of models. As mentioned in the method section, import and export are included in the present model, although in most IIM modeling approaches the effects of international trade is not taken into account. This might be an accurate assumption when considering large economies, as the US, but for smaller economies, such as the Swedish, that heavily depends on import and export, this assumption is less accurate. For some sectors the imported quantity of the main commodity can even be several times larger than the domestically produced quantity. Hence a temporary disturbance to import or export would significantly affect domestic production. To explicitly include export and import in the model, it is believed to more accurately capture the societal consequences that arise.

Another assumption made in the paper that may affect the results is that the fraction of power supply reduction from the power system model corresponds to an equal perturbation of the electricity sector for the IIM analysis. As not all economic dependence on the electricity sector, although a significant part (roughly 85%), can be related to the commodity electricity but also to other commodities, it is expected that the societal consequences may to some lesser degree be overestimated. Further research should address the relation between infrastructure commodity disruptions and economical sector perturbations.

Although the above limitations and assumptions will affect the result, i.e. ordinal ranking and absolute values of the effectiveness of the studied vulnerability reducing measures, the main purpose of this paper was to explore the effect of including a model to incorporate societal consequences when making decisions regarding implementing vulnerability reducing measures for critical infrastructure, and hence not solely rely on infrastructure models. The results support the overall thesis that the decision of which measures to implement differs whether an infrastructure or a societal viewpoint is taken. To extend the research, it would be interesting to evaluate if other models for accounting societal consequences would also support this thesis, for example by using a General Equilibrium Model (GEM) [22], which is also an economic model but that can account for non-linear interactions, or to construct a model derived from more traditional willingness to pay studies [23].

The focus of this paper has been on the electric transmission system, but the ideas and approaches presented are applicable to other critical infrastructures as well. Future research is encouraged to include other critical infrastructure system, e.g. transportation and communication infrastructures, as well as other decision contexts and decision criteria, e.g. from an optimization problem point of view such as maximizing expected utility or minimizing maximum consequences.

5. CONCLUSION

In the present paper, vulnerability reducing measures have been evaluated from both an infrastructural viewpoint, power supply reduction, and a societal viewpoint, economic consequences across societal sectors. The vulnerability reducing measures consisted of twelve different addition of branches to the existing system in an effort to strengthen the system. The results show a significant difference when considering their estimated effectiveness in terms of vulnerability reduction from the two viewpoints, but the overall ranking of the measures is to some extent, but not entirely, congruent. It is concluded that accounting for societal consequences in the decision-making process is of importance when evaluating critical infrastructure improvements.

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