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Abstract

The value of lost load (VOLL) is an essential parameter for transmission system reliability management. It represents the cost of unserved energy of electricity interruptions. Various empirical studies have estimated this parameter for different countries and more recently, for different interruption characteristics – such as interruption duration, time of interruption and interrupted consumer. However, most applications only use one constant VOLL. Our theoretical analysis shows that using more-detailed VOLL data allows to make better-informed transmission reliability decisions. To illustrate this, we estimate the efficiency gains of including consumer and time characteristics in short-term transmission reliability management using VOLL data from Norway, Great Britain and the United States. Depending on the VOLL data and the method of demand curtailment, our five-node network indicates efficiency gains up to 43%. However, increased efficiency leads to decreased equity. Striking the balance between these opposing objectives is crucial for social acceptance.

Keywords: Value of Lost Load, Transmission Reliability Management, Power Systems, Interruption Costs, Electricity Interruption Characteristics
JEL: L94, H40, Q40, Q41, D63

1. Introduction

Electricity is the backbone of modern society: we want electricity to be available at all times. However, blackouts and interruptions of electricity consumers occur, because of component outages and uncertainty of demand and intermittent supply. Preventing this requires a more redundant, and thus costly, power system. To keep costs under control, national regulators and transmission system operators (TSOs) aim for an adequate level of reliability (NERC, 2007). That is, a reliability level that balances the costs of reaching a reliability level and the costs of electricity interruptions.

The cost of electricity interruptions is strongly determined by the interruption duration and the value of lost load (VOLL). VOLL is a parameter representing the cost of unserved electricity and is generally expressed in €/kWh or €/MWh. It is an essential parameter to determine the optimal reliability level of a power system. VOLL is used in many applications such as load curtailment contracts (Joskow and Tirole, 2007), network investment decisions (Electricity Authority, 2013), cost-benefit analyses, quality incentive schemes of transmission and distribution networks[1], energy legislation, and reliability standards[2] (Munasinghe and Gellerson, 1979). Most of these applications simplify the VOLL to a single, constant value.

Precise knowledge of VOLL is paramount to make correct reliability decisions. Various empirical studies have estimated VOLL for different countries and for different interruption characteristics, such as interruption duration, time of interruption, interrupted consumer, location and advance notification. These detailed VOLL data allow to make better-informed reliability decisions. By providing more information about the benefits of reliability management, they ensure a better balance between the costs and benefits.

The most advanced use of detailed VOLL data to date is the Norwegian cost of energy not supplied (CENS) regulation. In the CENS regulation, TSO and DSO revenue caps depend on the interruption costs in their area. Interruption costs are calculated for different consumer groups, and both the time and duration of interruptions have an ef-

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[1] In such schemes, a network operator's allowed revenue depends in part on its reliability level. For TSOs, France uses a VOLL of 12,000 €/MWh and Italy a VOLL of 15,000 €/MWh (CEER, 2011).

[2] In Great Britain, a loss of load expectation (LOLE) of 3 hours per year corresponds to a VOLL of 17,000 £/MWh (Newbery and Grubb, 2014).

fect on interruption costs (Kjolle et al., 2008). The CENS quality regulation is expected to give network operators better incentives to achieve an optimal reliability level. For example, to provide a higher level of reliability to high-VOLL consumers or at high-VOLL moments – e.g. by taking more conservative operating decisions or speeding up restoration times. In the Italian quality regulation of distribution networks, VOLL of residential consumers is set at 10,800 €/MWh, while VOLL of non-residential consumers is set at 21,600 €/MWh (Cambini et al., 2016). Interruptions of non-domestic consumers are thus more costly and therefore network operators have an incentive to provide them a higher level of reliability. However, apart from being used in reliability incentive schemes, available detailed VOLL data are not widely used in reliability decision making.

This paper is the first to assess the impact of using different degrees of VOLL detail in reliability management. We develop a theoretical model that shows the efficiency gains – defined as the (relative) cost decrease – of using a VOLL that differs over time and between consumers. Realizing the full efficiency potential of consumer-differentiated VOLL depends on the technological curtailment possibilities. We make a distinction between perfect curtailment (Crew and Kleindorfer, 1976), random curtailment (Chao, 1983), and spatial curtailment – an intermediate option where a network operator curtails load in regions depending on their VOLL. The theoretical model is illustrated using a numerical example that focuses on expected total system cost of TSOs' operational planning and system operation using different levels of VOLL detail. In addition we study the impact of VOLL differentiation on specific consumer groups, with a focus on equity and social acceptance.

This paper is organized as follows. Section 2 surveys the growing literature that estimates VOLL as a function of different interruption characteristics for different countries. VOLL data of Norway, Great Britain and the United States are discussed in more detail. Section 3 studies analytically the efficiency gains of using a VOLL that differs over time and between consumers. Section 4 expands this analysis to a five-node illustrative network with realistic assumptions on network data, generation plants, intermittent generation, failure probabilities, demand, and demand uncertainty. Section 5 discusses the results and policy implications. Section 6 concludes.

2. Literature review of detailed VOLL data

VOLL depends on many factors (de Nooij et al., 2009):

- Interruption time: season, day of the week, time of the day;
- Interrupted consumers: residential, commercial, industrial, public;
- Interruption duration;
- Weather at the time of interruption;
- Number of consumers affected;
- Current reliability level;
- Advance notification of the interruption;
- Mitigating measures.

Various empirical studies have estimated VOLL as a function of these different factors. In this section we survey these detailed VOLL studies. We restrict ourselves to studies published since 2007 that estimate the effect on VOLL of at least two interruption characteristics. Table 1 lists 13 studies and shows the level of VOLL detail for each study.

The table shows that almost all studies estimate VOLL for different consumer types. Some estimate as much as 15 consumer types (Growitsch et al., 2013; Reichl et al., 2013; Linares and Rey, 2013; Zachariadis and Poullikkas, 2012), while others estimate only two or three (Sullivan et al., 2009; Electricity Authority, 2013; London Economics, 2013). Many studies also include the influence of the interruption time on VOLL. Most of them distinguish between time of the day, day of the week and season. In addition, some studies estimate the influence of interruption duration, advance notification and location.

As an illustration, Table 2 to Table 4 present detailed VOLL data of Great Britain (London Economics, 2013), Norway (EnergiNorge, 2012), and the United States (Sullivan et al., 2009). These data show VOLL for different consumer groups as a function of season, day of the week, and time of day. The Norwegian data consider four consumer types (residential, industry, commercial, and public) and 36 interruption times (three times of interruption, three days, and four seasons). The British data consider two consumer types and eight interruption times. Finally, the United States' data consider three consumer types and 16 interruption times. All data are expressed in both the home currency and in 2015€/MWh.[3] All three studies use stated-preference methods to determine the VOLL data.[4] However, comparison of VOLL between countries should be done with care (Mitchell and Carson, 1989) since all stated-preference methods differ to some extent in terms of formulation of questions, cost normalisation factors, scenario designs and data formats and since countries differ culturally.

The British and United States data show VOLL as a single value for each time of interruption. The Norwegian

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[3] Purchasing power parities (OECD, 2016) are used for conversion.

[4] Stated-preference methods involve asking consumers their willingness-to-accept (WTA) payment for an outage and willingness-to-pay (WTP) to avoid an outage (contingent valuation or choice experiments), or asking the cost of specific interruptions (direct worth). Several cost estimation methods exist, each of them having its advantages and disadvantages (de Nooij et al., 2007). Best-practice guidelines provide recommendations for correct VOLL estimation (CEER, 2010; Hofmann et al., 2010; Sullivan and Keane, 1995).

Table 1: Studies that estimate VOLL as a function of different interruption characteristics.

Country	Consumer type	Time	Duration	Advance notification	Location	Source
Australia	x		x			(CRA International, 2008)
Austria	x	x	x			(Reichl et al., 2013)
Cyprus	x	x				(Zachariadis and Poullikkas, 2012)
Germany	x				x	(Growitsch et al., 2013)
Great Britain	x	x				(London Economics, 2013)
Ireland	x	x			x	(Leahy and Tol, 2011)
Netherlands	x	x			x	(de Nooij et al., 2007)
New Zealand	x	x	x		x	(Electricity Authority, 2013)
Norway	x	x	x	x		(EnergiNorge, 2012)
Portugal	x	x				(Castro et al., 2016)
Spain	x				x	(Linares and Rey, 2013)
Sweden		x	x			(Carlsson and Martinsson, 2008)
United States	x	x	x	x	x	(Sullivan et al., 2009)

data are displayed differently. Table 3 shows multipliers for the time of day, day of the week and season. Norwegian VOLL for a particular time is found by multiplying the standard VOLL with the corresponding multipliers:[5]

$$V(c, t(h, d, y)) = V(c) f_h(c, h) f_d(c, d) f_y(c, y) \qquad (1)$$

$V(c)$ corresponds to the base VOLL per consumer group c, while $f_h(c, h)$, $f_d(c, d)$ and $f_y(c, y)$ are the multipliers to incorporate the effect of respectively the time during the day h (e.g. day vs. night), the type of day d (e.g. week vs. weekend) and the season y.[6]

Comparison of the three datasets shows that residential consumers have a lower VOLL than industrial consumers. On weekdays, VOLL of industrial consumers is between 5 (GB, not winter, not peak weekday) and 300 (US, winter weekday afternoon) times higher than for residential consumers. During weekends, their VOLL is more similar. Residential VOLL in Great Britain is higher and closer to industrial VOLL than in the United States and in Norway. Industrial VOLL is the same order of magnitude in all three countries, except for small commercial and industrial consumers in the United States, which have a substantially higher VOLL.[7]

The detailed VOLL data of Great Britain, Norway and the United States are further used in the numerical illustration of section 4, but the level of detail is restricted to consumer type and time of interruption.

3. Theoretical Analysis

Costs decrease if detailed VOLL data are used instead of one constant VOLL at all times and in all regions. This efficiency gain is shown using a simple model.

Suppose a cost $C(\rho)$ is needed to supply 1 MWh of electricity at reliability level ρ. This reliability cost is constant throughout the year. It is increasing convex in the reliability level and approaches infinity at $\rho = 1$. Reliability $\rho \in [0, 1]$ is here defined as:

$$\rho = \frac{\text{total demand - curtailed load}}{\text{total demand}} \qquad (2)$$

That is, ρ is the fraction of all demanded load [MWh] that is supplied to consumers in a certain period.

The optimal reliability level ρ^* is found by minimizing the sum of reliability costs $C(\rho)$ and interruption costs $(1 - \rho)V$:[8]

$$\min_{\rho} \{C(\rho) + (1 - \rho)V\} \qquad (3)$$

This is at the point where marginal reliability costs equal marginal interruption costs:

$$C'(\rho^*) = V \qquad (4)$$

This first-order-condition shows that VOLL influences the optimal reliability level. Since the reliability cost increases in ρ, a high VOLL calls for a high reliability level and a low VOLL for a low reliability level. For example, if VOLL is higher in winter than in summer ($V_w > V_s$), the reliability level should also be higher in winter than in summer. If a TSO, however, bases its reliability level on the yearly-average VOLL $\bar{V}$, it will aim for a constant reliability level

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[5] This assumes that the effect of time, day and season on VOLL is independent. For example, the relative decrease of VOLL in summer for residential consumers is the same irrespective of the time or day.

[6] The Norwegian data also include the effect of interruption duration on VOLL. In the remainder of this paper we assume VOLL to be linear in duration, while in general VOLL is concave in duration.

[7] Note that VOLL of a consumer type is an average of individual consumers of this type, in between which large differences are possible.

[8] If the reliability cost $C(\rho)$ includes all social costs of reaching a reliability level ρ, the optimal reliability level is also the welfare optimum. If only private TSO costs are included, the optimal TSO value differs from the welfare-optimal reliability level.

Table 2: Great Britain VOLL as a function of time characteristics and consumer groups (London Economics, 2013, Table 1 and Table 2). (a) is expressed in [2011£/MWh], (b) in [2015€/MWh].

		Not winter				Winter			
		Weekday		Weekend		Weekday		Weekend	
		Peak	Not peak	Peak	Not peak	Peak	Not peak	Peak	Not peak
(a)	Residential	9,550	6,957	9,257	11,145	10,982	9,100	10,289	11,820
	SMEs	37,944	36,887	33,358	34,195	44,149	39,213	35,488	39,863
(b)	Residential	11,093	8,081	10,753	12,946	12,757	10,571	11,952	13,730
	SMEs	44,077	42,849	38,749	39,722	51,284	45,551	41,224	46,306

Table 3: Norwegian VOLL as a function of time characteristics and consumer groups (EnergiNorge, 2012, Table A and Table B).

		Residential	Industry	Commercial	Public
VOLL [2010 NOK/MWh]		5,000	116,000	192,000	170,000
VOLL [2015 €/MWh]		469	10,926	17,984	15,888
Season $f_y(c, y)$	Winter	1	1	1	1
	Spring	0.57	0.87	1	0.67
	Summer	0.44	0.86	1.02	0.51
	Autumn	0.75	0.88	1.06	0.58
Day $f_d(c, d)$	Weekday	1	1	1	1
	Saturday	1.07	0.13	0.45	0.3
	Sunday	1.07	0.14	0.11	0.29
Time $f_h(c, h)$	2 AM	0.4	0.12	0.11	0.43
	8 AM	0.69	1	1	1
	6 PM	1	0.14	0.29	0.31

Table 4: United States VOLL as a function of time characteristics and consumer groups ((Sullivan et al., 2009, Table 3-10, Table 4-10 and Table 5-11)). (a) is expressed in [2009$/MWh], (b) in [2015€/MWh].

		Summer							
		Weekday				Weekend			
		Morning	Afternoon	Evening	Night	Morning	Afternoon	Evening	Night
(a)	Residential	3,412	2,559	2,428	2,428	4,002	3,018	2,887	2,887
	Small C&I	306,833	372,941	196,500	196,045	188,750	236,621	112,156	110,332
	Large C&I	17,774	24,978	21,054	15,688	12,771	18,191	14,857	11,088
(b)	Residential	2,947	2,210	2,097	2,097	3,457	2,607	2,493	2,493
	Small C&I	265,004	322,100	169,713	169,319	163,019	204,364	96,866	95,291
	Large C&I	15,351	21,573	18,184	13,550	11,030	15,711	12,831	9,576
		Winter							
		Weekday				Weekend			
		Morning	Afternoon	Evening	Night	Morning	Afternoon	Evening	Night
(a)	Residential	2,428	1,706	1,378	1,378	2,821	2,034	1,640	1,640
	Small C&I	423,091	530,688	248,931	244,828	250,299	32,370	135,863	131,760
	Large C&I	14,539	21,360	16,232	12,161	10,035	14,992	10,963	8,231
(b)	Residential	2,097	1,473	1,190	1,190	2,437	1,757	1,417	1,417
	Small C&I	365,415	458,343	214,996	211,452	216,177	279,967	117,342	113,798
	Large C&I	12,557	18,448	14,019	10,503	8,667	12,948	9,468	7,109

$\bar{\rho}$ throughout the year.[9] As a result, its network is too reliable in summer and not sufficiently reliable in winter. This is shown in Figure 1, where the reliability levels are found at the intersection of the VOLL and the marginal interruption cost, which is increasing in ρ. In this figure, the reliability cost is the area below the marginal reliability cost $C'(\rho)$, up to the reliability level ρ, while the interruption cost is the area below the VOLL up to $1-\rho$.

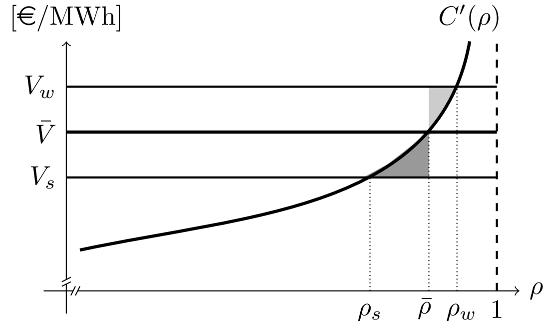

Figure 1: Efficiency gains if VOLL differs over time.

If the TSO modifies the reliability level with changing VOLL ($\rho_s < \bar{\rho} < \rho_w$), instead of aiming for a constant reliability level $\bar{\rho}$, the sum of reliability costs and interruption costs will be lower. This efficiency gain is defined as:

$$[C(\rho) + (1-\rho)V] - [C(\rho^*) + (1-\rho^*)V] \ [€] \qquad (5)$$

Or

$$1 - \frac{C(\rho^*) + (1-\rho^*)V}{C(\rho) + (1-\rho)V} \ [\%] \qquad (6)$$

Figure 1 shows these efficiency gains as the dark grey triangle in summer ($\rho = \bar{\rho}$, $\rho^* = \rho_s$) and the light grey triangle in winter ($\rho = \bar{\rho}$, $\rho^* = \rho_w$). In summer, reliability costs are too high and interruption costs are too low; in winter, reliability costs are too low and interruption costs are too high.

Next, suppose that VOLL is constant throughout the year but differs between consumers. In this case, efficiency gains are achievable by providing low-VOLL consumers with a lower reliability level than high-VOLL consumers. The highest efficiency gain is achieved if demand is curtailed from lowest to highest VOLL (Crew and Kleindorfer, 1976). Perfect curtailment is only possible when the TSO has the technical capabilities to curtail individual consumers. When this is not possible, efficiency gains are still achievable when curtailment is performed first in low-VOLL regions. Spatial curtailment leads to lower interruption costs than random curtailment.

Figure 2 illustrates the efficiency gains of perfect, spatial, and random curtailment. VOLL is assumed to be uniformly-distributed between V_{min} and V_{max}. This is the downward-sloping line. Moving from random curtailment (with average VOLL $\bar{V}$) to spatial curtailment (with regional VOLLs V_1 and V_2) leads to an efficiency gain equal to the light grey area. This is the sum of lower reliability costs (A) and lower interruption costs (B). The dark grey area is the additional efficiency gain of moving from spatial to perfect curtailment. This is the sum of additional lower reliability costs (C) and additional lower interruption costs (D). Interruption costs are lower because low-VOLL consumers are curtailed first. For spatial curtailment these are consumers in the low-VOLL area 1; for perfect curtailment these are the consumers with the lowest VOLL, in both region 1 and 2. Moving from random curtailment to perfect curtailment, the decrease of reliability costs is thus A+C+E and the net decrease of interruption costs is B+D-E.

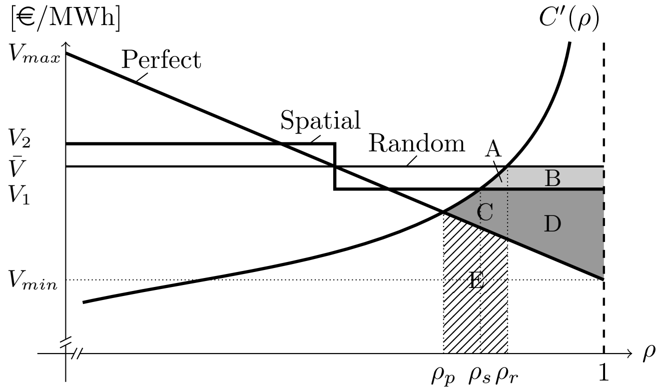

Figure 2: Efficiency gains and reliability level of random, spatial, and perfect curtailment, if VOLL differs between regions.

The regional VOLLs, represented by V_1 and V_2 in Figure 2, depend on the correlation of VOLL between regions. They differ more if low-VOLL consumers are all concentrated in one region. In that case, the reliability level ρ_s is closer to the optimal reliability level ρ_p and interruption costs of spatial curtailment are lower.

The next section illustrates the theoretical concepts of the current section in a numerical five-node case study.

4. Numerical illustration of short-term reliability management

During operation of the electricity system TSOs face many challenges: line outages and generation outages occur, unscheduled loop flows pass through the network, and demand and intermittent supply differ from forecasts. As a result, the TSO takes preventive and corrective actions – such as upward and downward dispatch of generation, phase shifting, transformer tap changing, topological actions and demand curtailment – to ensure that demand and supply are always balanced without overloading any

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[9] Obviously, in reality the reliability cost is not constant throughout the year. For example, if $C(\rho)$ is higher in winter and VOLL is constant, it is optimal to have a lower reliability level in winter than in summer. But for the sake of our argument we restrict our focus here to the change of VOLL over time.

transmission line. Determining appropriate preventive, corrective and curtailment actions is denoted as short-term reliability management.

4.1. Evaluation of short-term reliability management

Short term reliability management consists of two parts: real time operation and operational planning. Both aim at minimizing total expected system costs

4.1.1. Real time operation

When disturbances occur in the power system, the TSO takes corrective actions or curtails load to keep the system in balance. Possible corrective actions a_c^{RT} during real time (RT) operation are generation redispatch, phase shifting transformer tap changing and branch switching. The TSO takes at each time instant t those actions that minimize the cost of corrective actions and the cost of demand curtailment, subject to operational constraints (Van Acker and Van Hertem, 2016).

$$\min_{a_c^{RT}, P_{curt}^{RT}} C_{RT}(v) = \min_{a_c^{RT}, P_{curt}^{RT}} \left[C_{corr}(a_c^{rt}) + P_{curt}^{rt}(c) \cdot v\right] \tag{7}$$

$$\text{s.t. operational limits}$$

Load curtailment costs are the product of curtailed load $P_{curt}^{rt}(c)$ and VOLL v. The specification of v depends on the level of VOLL detail:

$$v \in \Upsilon = \{V, V(t), V(n,t), V(c,t)\} \tag{8}$$

That is, VOLL is constant (V); VOLL differs over time t ($V(t)$); VOLL is aggregated per node n and differs for all time instants t ($V(n,t)$); or VOLL differs between consumer groups c and over time t ($V(c,t)$). Equation (7) shows that different levels of detail in VOLL data change the trade-off between corrective actions and load curtailment and affect which consumers and which regions to curtail. The level of detail has an effect on the choice of corrective actions a_c^{rt} and load curtailment P_{curt}^{rt}, which, in turn, affects total system cost.

4.1.2. Operational planning

Real time operation is preceded by the operational planning stage. Operational planning (OP) is executed some time before real-time operation. For example, in day-ahead for the 24 hours of the next day. During operational planning the TSO determines the optimal dispatch of electricity generation, taking into account uncertainties about future real-time states s of the system. The difference between the unconstrained day-ahead market dispatch and the dispatch after operational planning is the cost of preventive redispatch. The TSO determines the dispatch actions a_p that minimizes the sum of preventive redispatch costs $C_{prev}(a_p)$ and expected real-time costs in state s, consisting of the cost of corrective actions $C_{corr}(a_c^s)$ and load curtailment $P_{curt}^s(c) \cdot v$, subject to operational constraints:

$$\begin{aligned}\min_{a_p, a_c^s, P_{curt}^s} C_{OP}(v) = \min \Big[& C_{prev}(a_p) + \\ & \sum_{s \in S} \pi_s \left(C_{corr}(a_c^s) + P_{curt}^s(c) \cdot v\right)\Big]\end{aligned} \tag{9}$$

$$\text{s.t. operational limits } \forall s \in S$$

Where π_s is the probability of occurrence of a possible future real-time state s. The TSO takes into account a set of possible future real-time states S when deciding on its preventive actions a_p. The set S is the cartesian product of the most probable contingencies up to a cumulative probability of 99% and 7 possible real time realizations of net total demand derived from a normal distribution with mean equal to the forecast value of net total demand at time instant t and standard deviation 4%. As a result, VOLL does not only affect corrective actions and demand curtailment, but also preventive actions of forward-looking TSOs.

Equation (3) of our theoretical analysis is a simplified version of equation (9). While in the theoretical analysis the TSO chooses the reliability level ρ directly, in our case study it takes a number of preventive (a_p) and corrective (a_c) actions, which lead to a certain reliability level. The reliability cost $C(\rho)$ of the theoretical analysis includes both the cost of preventive and corrective actions.

4.1.3. Evaluation

Performance of short-term reliability management for various levels of VOLL detail is evaluated in terms of expected total cost (ETC). ETC consists of costs of preventive actions, costs of corrective actions and cost of load curtailment.

$$\begin{aligned}\text{ETC}(v) = \sum_{t \in T} \Big[& C_{prev}(a_p(v,t)) + \sum_{rt \in RT} \pi_{rt} \left(C_{corr}(a_c^{rt}(v,t))\right. \\ & \left. + P_{curt}^{rt}(c,v,t) \cdot V(c,t)\right)\Big] \quad \forall t\end{aligned} \tag{10}$$

Preventive, corrective and curtailment actions

$$[a_p(v,t), a_c^{rt}(v,t), P_{curt}^{rt}(c,v,t)] \tag{11}$$

are taken by a TSO based on the available VOLL information, i.e. the level of detail in the VOLL data, $v \in \{V, V(t), V(n,t), V(c,t)\}$. Load curtailment costs are evaluated at the true VOLL of a consumer, $V(c,t)$. ETC is calculated as the expected total cost, averaged over a year.

Evaluating all possible future real-time system states rt is not feasible in practice. Therefore the set RT is the Cartesian product of the most probable contingencies up to a cumulative probability of occurrence of 99.6 % and 11 possible real time realizations of net total demand derived from a normal distribution with mean equal to the forecast value of net total demand at time instant t and standard deviation 4%. This set of system states is larger than the set S considered in decision making in order to evaluate reliability management also in system states that are not considered in advance.

Since more detailed VOLL data lead to better-informed TSO decisions, it is expected that

$$\mathrm{ETC}(V(t)),\ \mathrm{ETC}(V(n,t)),\ \mathrm{ETC}(V(c,t)) \leq \mathrm{ETC}(V)$$

In addition to ETC, two other important indicators are the overall reliability level and equity between consumers. The reliability level is expressed in terms of average interruption time (AIT) (Cepin, 2011):

$$AIT = (1-\rho)\cdot 8760\cdot 60 \qquad \text{[min/year]} \tag{12}$$

Equity of the reliability level between consumer groups and consumers at different nodes is evaluated similarly to the Gini coefficient (Atkinson, 1970), but based on the share of total demand that is supplied to the different consumer groups and consumers:

$$G = |1 - (\sum_k (X_k - X_{k-1})\cdot(Y_k + Y_{k-1})| \tag{13}$$

with X the cumulative share of demand, Y the cumulative share of energy not supplied and k an index counting over the groups under comparison, i.e. consumer groups at nodes. The groups are ordered based on decreasing reliability values. A Gini coefficient of 0 means that all consumer groups in all regions have the same reliability level[10]. A Gini coefficient closer to 1 means that all interruptions are concentrated in one or a few consumer groups or nodes. The equity coefficient G indicates how consumers perceive the distribution of reliability between consumer groups in different nodes to be fair.

4.2. Data

The numerical illustration uses a five-node test system and considers VOLL data of three different countries (Great Britain, Norway and the United States). The same analysis is repeated for each of the countries, which allows to determine a range of potential improvements increases in short term power system reliability management if more detailed VOLL data are used.

4.2.1. Network

Our illustrative five-node test system is based on the Roy Billinton reliability test system (Billinton et al., 1989), as shown in Figure 3. Generation is located in node 1 and 2; demand is located in node 2 to 5. Table 5 shows the reactance (x)[11], capacity and failure probability for the seven transmission lines. All electricity interruptions are assumed to last for 1 hour, implying a linear relationship between VOLL and duration.

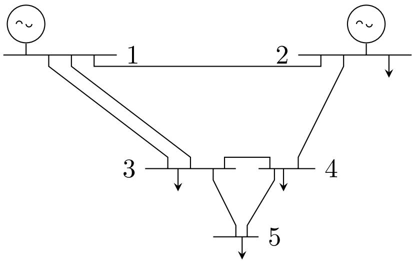

Figure 3: Circuit diagram of the test system

Table 5: Line data

From node	To node	x [pu] [MW]	Capacity [MVA]	Failure probab.
1	3	0.18	85	0.0017
2	4	0.6	71	0.0057
1	4	0.48	71	0.0046
3	4	0.12	71	0.0011
3	5	0.12	71	0.0011
1	3	0.18	85	0.0017
4	5	0.12	71	0.0011

4.2.2. Generation

The generation park consists of coal-fired power plants with a high marginal cost and wind power plants with a marginal cost near zero, but uncertain availability. Table 6 summarizes generators' marginal costs and outage probability data. Upward and downward redispatch costs depend on the marginal cost of the generator and differ between the preventive and corrective stage, as shown in equation (14). Wind generators are not available for pos-

Table 6: Generation data

Node	Capacity [MW]	Type	C_{marg} [€/MWh]	Failure probab.
1	40	coal	13.83	0.0062
1	40	coal	13.83	0.0062
1	10	coal	13.83	0.0062
1	20	wind	0.04	0.0062
2	40	coal	13.83	0.0062
2	20	coal	13.83	0.0062
2	20	wind	0.01	0.0062
2	20	wind	0.03	0.0062
2	20	wind	0.05	0.0062
2	5	coal	13.83	0.0062
2	5	coal	13.83	0.0062

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[10] Note that the Gini coefficient can not be calculated if reliability is 100% for all consumer groups in all nodes. In that highly exceptional case Gini equals 0.

[11] The reactance of transmission lines determine the distribution of the power flow in the network: the higher the reactance (compared to other lines), the lower the flow through the line.

itive redispatch.

$$\begin{aligned} c_{prev}^{+} &= 1.5 \cdot C_{marg} + 5 \\ c_{prev}^{-} &= -0.5 \cdot C_{marg} + 5 \\ c_{corr}^{+} &= 5 \cdot C_{prev}^{+} \\ c_{corr}^{-} &= -\frac{1}{5} \cdot C_{prev}^{+} \end{aligned} \tag{14}$$

4.2.3. Demand and VOLL

Total system demand is based on the hourly load profile defined for the Roy Billinton Reliability system over a whole year (Billinton et al., 1989). For simplification a year is represented by 6 x 3 x 4 = 72 time instants, each with its probability of occurrence. That is, the set T is the cartesian product of 6 seasons (early spring, late spring, summer, early autumn, late autumn and winter), 3 days (weekday, Saturday and Sunday), and 4 times of day (morning, noon, evening and night). Each temporal case has its own probability of occurrence. Total system demand at each of the 72 time instants is calculated as the mean over all valid hours. Table 7 gives the reference share of total demand per node that is attributed to a particular type of customer $LS_{ref}(c)$ together with the share of the total demand at that node. Table 7 shows that most demand is located in node 3, consisting mostly of residential demand. Node 4 contains mostly industrial demand, while node 5 contains mostly commercial demand.

This numerical illustration uses VOLL data from Great Britain (Table 2), Norway (Table 3) and the United States (Table 4). The three datasets consider a different number of consumer types and temporal cases, resulting in different levels of detail. The 72 typical time instants introduced above constitute all temporal cases. In order to unify the data with respect to consumer types, we split consumers into only two categories: residential and non-residential customers. Non-residential customers correspond to the aggregated share of all customers except the residential ones, i.e. large and small C&I combined in the United States and industry, public and commercial combined in Norway. This unified test set allows to compare the results in Norway, GB and the US, although their VOLL data have different levels of detail.

The share of residential and non-residential demand in total system demand changes throughout the year. Table 8 shows the multiplication factors that take this effect into account. The demand share of consumer group c in total system demand at time t is calculated as:

$$LS(c,n,t) = \frac{LS_{ref}(c,n) \cdot f_H(c,h) \cdot f_D(c,d) \cdot f_Y(c,y)}{\sum_{c \in C} LS_{ref}(c,n) \cdot f_H(c,h) \cdot f_D(c,d) \cdot f_Y(c,y)} \tag{15}$$

with $c \in$ {residential,non-residential} and t determined by the time of day h, type of day d and time of the year y.

If more detailed VOLL data are used, three cases are distinguished. On the one hand, different consumer groups are considered each with their respective VOLL $v_c = V(c,t)$ and are considered to be curtailable at their respective VOLL. VOLL is on the other hand aggregated per node using a weighted average of the VOLL of the different customer types $v_n = V(n,t) = \sum_{c \in C} LS(c,n,t) \cdot V(c,t)$. In the third case, VOLL is aggregated per time instant using a weighted average of the VOLL at different nodes and the share of total load at that node: $v_t = V(t) = \sum_{n \in N} r_T(n,t) \cdot V(n,t)$.

Table 8: Time dependent multiplication factors for the demand share of different consumer groups

		Residential	Non-residential
Time $f_H(c,h)$	2 AM	0.7	1.3
	8 AM	1.3	0.7
	2 PM	0.8	1.2
	6 PM	1.3	0.7
Day $f_D(c,d)$	Weekday	0.8	1.2
	Saturday	1.15	0.85
	Sunday	1.3	0.7
Season $f_Y(c,y)$	Winter	1	1
	Spring	0.9	1.1
	Summer	1.1	0.9
	Autumn	1	1

4.3. Results

Our numerical illustration is simulated using a model developed within the GARPUR project [12] (Heylen et al., 2016), (GARPUR consortium, 2015) and is implemented in AMPL (Fourer et al., 1987) using a MATLAB interface. Probabilistic reliability management is simulated using a probabilistic security constrained DC optimal power flow (Van Acker and Van Hertem, 2016).

Table 9 shows the relative change of expected total system costs ΔETC for the 5 node test system, which is defined as

$$\Delta ETC = \frac{ETC(v) - ETC(V)}{ETC(V)} \tag{16}$$

where v equals VOLL differentiated per consumer group ($v_c = V(c,t)$), VOLL differentiated per node ($v_n = V(n,t)$), or VOLL differentiated per time instant ($v_t = V(t)$), depending on the case under investigation. V represents a constant VOLL for all nodes and consumer groups in all temporal cases.

Table 9 shows that potential cost savings differ between Norway, Great Britain and the United States. They strongly depend on the absolute value of lost load. As expected from the theoretical analysis, cost savings are largest with VOLL differentiated per consumer group and perfect curtailment (v_c). Norway and US have the largest cost savings, because residential consumers have a low

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[12] `www.garpur-project.eu`

Table 7: Demand shares of different consumer groups at different nodes and of demand shares of different nodes in total demand

	Node	Residential	Industry	Commercial	Public	Total demand share r_T
$LS_{ref}(c,n)$	2	0	0.8	0.2	0	0.125
	3	0.4	0	0.4	0.2	0.5
	4	0.3	0.5	0.1	0.1	0.25
	5	0.8	0.1	0.1	0	0.125

Table 9: Relative expected total system cost savings for three countries using VOLL data with different levels of detail

ΔETC [%]	v_t	v_n	v_c
Norway	-10.68	-20.27	-43.28
GB	-0.01	-3.03	-9.37
US	-0.95	-11.14	-29.52

VOLL compared to other consumer groups. As this difference is lower in GB, its cost savings are also lower. With a VOLL per node and spatial curtailment (v_n) cost savings are lower, but still significant. Again, cost savings are higher for Norway and US then for GB. Lastly, when VOLL is constant throughout the country but differing over time (v_t), cost savings are low in GB and US, but still significant in Norway. This is because the Norwegian data has much more temporal variability than the GB and US data, likely due to the larger relative difference between cold winters and temperate summers. Since its national VOLL differs over time, the TSO's level of preventive actions will also differ over time.

Figure 4 takes a closer look at how the cost savings of Table 9 depend on preventive, corrective and curtailment actions. Norway's costs decrease primarily because it takes less preventive actions, as its cost of curtailing residential consumers is low. GB and US decrease their cost of preventive actions and decrease their curtailment cost when shifting to spatial (v_n) and perfect curtailment (v_c).

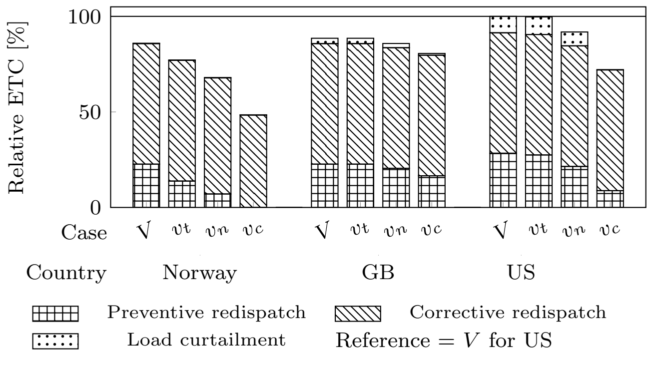

Figure 4: Evolution of cost terms in expected total system cost for different levels of detail of VOLL

Another important aspect to consider in the discussion is equity of the reliability level between different consumers. If more detailed VOLL data are used and TSOs are able to curtail load based on VOLL, particular consumer groups might experience lower reliability levels. Table 10 shows the average interruption time per node and consumer group. The last column shows the reliability Gini coefficient, as defined in equation (13). Table 10 shows first that spatial curtailment (v_n) considerably decreases equity. In all three countries, curtailment is almost completely limited to node 5, which has mostly cheap residential consumers. Second, perfect curtailment (v_c) also decreases equity, but less than spatial curtailment. Curtailment is almost completely limited to residential consumers, as they have the lowest VOLL most of the time. Third, changing VOLL over time (v_t) does not decrease equity. In Norway and US, equity slightly increases; in GB it is constant.

National AIT does not change if more detailed VOLL data are used, except when Norway uses spatial and perfect curtailment based on v_n and v_c respectively. In that case AIT increases because curtailing consumers is cheaper than expensive preventive actions. This is because the absolute level of VOLL is lower in Norway than in GB and US.

5. Discussion

The trade-off between efficiency and equity of reliability is an important aspect to consider when introducing more detailed VOLL data. Table 11 summarizes the reduction of expected total cost (ETC) and the Gini coefficient (G) for the different levels of VOLL detail and for the three countries. If VOLL is equal for all nodes but differs over time, total costs decrease, without a significant effect on equity. In Norway and US equity increases, but this seems to be by chance, as the TSO curtails nodes more randomly[13]. Detailed VOLL data per node v_n or per consumer group v_c, however, have a larger potential for cost savings, but at the expense of increasing inequity. Interestingly, inequity is higher for spatial curtailment than for perfect curtailment. This is because spatial curtailment focuses mostly on the same node (node 5). Perfect curtailment, by contrast, focuses those consumers with the

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[13] Although not completely randomly, because the network topology and the cost of preventive and corrective actions also affect curtailment decisions.

Table 10: Average interruption time [min/year] (per node and consumer group), consumption weighted average AIT and equity measure (G) for different levels of VOLL detail and different countries.

		Nodes									
	VOLL	2		3		4		5		AIT_{avg}	
Country	Detail	Res	Non res	Res	Non res	Res	Non res	Res	Non res	[min/year]	G
Norway	V	-	1.12	0.31	0.49	1.1	0.37	3.48	16.59	1.91	0.66
Norway	v_t	-	1.04	0.42	0.76	0.66	0.57	3.91	13.59	1.91	0.58
Norway	v_n	-	0.05	0	0	0.16	0.09	23.09	45.54	6.25	0.81
Norway	v_c	-	0.06	14.16	0	127.8	0.03	109.16	0	27.86	0.75
GB	V	-	0.8	0.31	0.31	1.01	0.39	3.5	18.11	1.91	0.7
GB	v_t	-	0.8	0.31	0.31	1.02	0.39	3.5	18.11	1.91	0.7
GB	v_n	-	0	0.05	0.05	0	0	6.52	15.2	1.91	0.82
GB	v_c	-	0.02	1.9	0.01	2.51	0	8.81	0.07	1.91	0.74
US	V	-	1.19	0.92	0.1	0.37	0.72	3.71	15.74	1.91	0.68
US	v_t	-	1.19	0.3	0.49	1.06	0.51	3.94	14.78	1.91	0.64
US	v_n	-	0.11	0.02	0.02	0.02	0.01	4.91	19.95	1.91	0.85
US	v_c	-	0.02	2.45	0	1.87	0	8.48	0.13	1.91	0.73

Table 11: Summary table presenting the trade-off between efficiency and equity

	Norway				GB				US			
	V	v_t	v_n	v_c	V	v_t	v_n	v_c	V	v_t	v_n	v_c
ΔETC	0	-10.68	-20.27	-43.28	0	-0.01	-3.03	-9.37	0	-0.95	-11.14	-29.52
G	0.66	0.58	0.81	0.75	0.7	0.7	0.82	0.74	0.68	0.64	0.85	0.73

lowest VOLL. Because they are different groups over time, curtailment is more diversified and inequity is lower. This means that if VOLL data is available but perfect curtailment is technologically infeasible, a country should carefully assess if the efficiency gains of spatial curtailment make up for the increased inequity. Increased inequity can also be dealt with by altering network tariffs. If decreased reliability levels are accompanied by sufficiently lower tariffs, affected consumers could consider this to be fair.

Two issues merit more discussion. First, currently most TSOs do not use even a constant VOLL in their short-term reliability management. Especially not one that is based on extensive VOLL studies. TSOs' reliability decisions are guided by the N-1 criterion. This criterion states that an unexpected outage of a single system component may not result in a loss of load. That is, when a single system component fails, the transmission system should still be able to accommodate all flows without load curtailment. The necessary detailed data (failure rates, forecast errors, wind and solar data, detailed demand and generation data, and, of course, VOLL) are not yet widely available. However, advances in communication and information technologies facilitate gathering this data. With more data available, TSOs can gradually introduce probabilistic methods and interruption costs into reliability management.

Second, actual VOLL strongly depends on the currently perceived reliability level, which is high with currently used reliability management (Munasinghe, 1981). Therefore, VOLL values are in fact not absolute, but conditional upon the perceived reliability level in the country at the moment of the survey. If the reliability level is high, people do not take many actions to prepare for an interruption. While a low reliability level encourages local investments, e.g. in storage or local generation, to prepare for interruptions. If spatial or perfect curtailment is implemented, the reliability level would change for different consumer groups, which in turn changes their VOLL. Due to its low VOLL values, Norway might be mostly impacted by this effect, as people will experience lower reliability levels if exact VOLL data are taken into account in reliability management. Taking into account behavioural feedback effects of VOLL is important, but a lengthy learning process.

6. Conclusions

Many empirical studies have estimated how VOLL depends on interruption characteristics – especially consumer type and time of interruption. However, few applications actually use detailed VOLL data to improve power system reliability. A theoretical analysis and a numerical illustration of short-term reliability management both show that incorporating detailed VOLL data leads to considerable efficiency gains. Our numerical illustration leads to potential gains between 3% and 20% when spatial curtailment is used, and between 9% and 43% when perfect curtailment is used[14].

Our analysis showed that this efficiency gain has a downside. Equity of reliability, represented as a Gini coefficient, decreases when more cost effective spatial and perfect curtailment are used. Striking the balance between these opposing objectives is the role of a regulator, based on society's preferences.

When only temporal aspects of VOLL are incorporated, efficiency gains are lower, but without a significant effect on equity. Therefore, the benefits are clear for countries with much temporal variability of VOLL, like Norway in our numerical illustration.

To reap the benefits of detailed VOLL data in short-term reliability management, two conditions need to be met. First, TSOs need to move away from the currently-used N-1 reliability criterion and move towards probabilistic reliability management. This allows to make better-informed decisions. Second, more VOLL studies are needed to improve detailed VOLL data. A widespread roll-out of smart meters have the potential to facilitate the determination of VOLL for different consumer types and different interruption times. Smart meters combined with price-contingent priority rationing contracts will also help to achieve perfect curtailment (Chao and Wilson, 1987; Joskow and Tirole, 2007).

In this paper we focused on the efficiency gains in short-term reliability management. However, considerable gains are also possible in the mid term and long term. A better understanding of interruption costs will lead to better maintenance and system expansion decisions.

Lastly, the increase of intermittent generation will require significant expansions in transmission infrastructure (Van der Weijde and Hobbs, 2012). However, the high costs of transmission investments and the difficulties to build new lines in both rural and urban areas could hinder this development (Cohen et al., 2016). This will push power system operation closer to its limits. In such a stressed power system, the use of detailed VOLL data will yield even higher benefits.

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[14] A back-of-the-envelope calculation, based on 2015 consumption data (ENTSO-E) and the 2015 annual reports of Elia, RTE, Statnett and Terna (only considering operating costs, excluding system losses), leads to an average operating cost of 0.9 €/MWh. Since, total electricity consumption in the ENTSO-E network was 3174 TWh in 2015, this amounts to potential gains between 80 million and 1,200 million per year in the ENTSO-E network.

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