How Detailed Value of Lost Load Data Impact Power System Reliability Decisions

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Abstract

The value of lost load (VOLL) is an essential parameter for power system reliability. It represents the cost of unserved energy during power interruptions. Various 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, it is common practice in system operation and the literature to use only one uniform VOLL. Our theoretical analysis shows that using more-detailed VOLL data leads to more cost-effective transmission reliability decisions. Using actual consumer- and time-differentiated VOLL data from Norway, Great Britain and the United States, numerical simulations of short-term power system reliability management indicate a potential operational cost decrease of up to 43% in a five-node network, and between 2% and 18% in a more realistic 118-node network – mainly because of lower preventive redispatch costs in response to lower expected interruption costs. However, changed reliability practices could lead to opposition, if some consumers are disproportionately interrupted and not adequately compensated. Although the first policy measures to collect more detailed and harmonized VOLL data have been taken, future policy should improve transmission-distribution coordination and enable the participation of all consumers in curtailment programs, through smart meters and smart appliances.

Keywords: Value of Lost Load, Electric Power System Reliability, Power System Management, Interruption Costs, Power Interruption Characteristics
JEL: L94, H40, Q40, Q41, D63

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1. Introduction

Electricity is the backbone of modern society: we want electricity to be available at all times. However, blackouts and power interruptions 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, regulators and system operators[1] 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 power interruptions.

The cost of power interruptions is strongly determined by the interruption duration and the value of lost load (VOLL). VOLL is a parameter representing the cost of unserved power and is generally expressed in monetary units per kWh or MWh. It is an essential parameter to determine the optimal reliability

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[1] We use the term 'system operator' to indicate any electricity entity that deals with power system reliability issues such as network reliability and electricity balancing: e.g. transmission system operators (Europe), distribution system or network operators (Europe), regional transmission organizations (North America), independent system operators (North America) or integrated utilities.

Preprint submitted to Energy Policy *June 16, 2019*

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[2], generation reserve procurement (Baldursson et al., 2018), generation capacity investment[3], and reliability standards (Munasinghe and Gellerson, 1979).

Various studies have recently estimated VOLL for different countries and for different interruption characteristics, such as interruption duration, time of interruption, type of interrupted consumer, location and advance notification. Despite these available detailed VOLL data, most of the above applications still simplify the VOLL to a single, constant value. Notable exceptions are the Norwegian and Italian quality incentive schemes that directly tie a system operator's revenue to the interruption costs in their area. In Norway, VOLL depends on the interrupted consumer groups, the time and duration of interruption (Kjolle et al., 2008), while in Italy VOLL of residential consumers is set at 10,800 €/MWh and at 21,600 €/MWh for non-residential consumers (Cambini et al., 2016). Because these system operators are exposed to detailed VOLLs, they have an incentive to provide a higher reliability level to high-VOLL consumers and at high-VOLL times. When only a single VOLL is used, system operators will only respond to the average cost of interruptions.

It has long been the policy objective in many countries to provide all consumers the same level of reliability of power supply. While in other public service sectors it is regular practice to explicitly discriminate among consumers in terms of quality of service (transport classes on trains and buses, priority mail, toll roads, etc.), policy makers have been rather reluctant to do so for electric power. In this paper we will show that a considerable decrease of operational costs is possible by prioritizing the reliability of supply based on consumers' VOLL. However, there could be opposition against this paradigm shift from a policy objective of universal reliability to one that is based on willingness to pay for reliable power supply, when the changes in reliability are not fairly distributed and those affected are not adequately compensated. In this paper, we will use a Gini-based indicator to measure the extent that some consumer groups are disproportionately interrupted.[4]

To support the development of an effective, efficient and fair policy on power system reliability with detailed VOLL data, we assess the socio-economic impact of considering consumer and time-differentiated VOLL data in short-time system operation. This paper makes three contributions to the existing scientific literature on VOLL. First, the paper provides a summary of detailed VOLL studies and analyze detailed VOLL data of Great Britain, Norway and the United States. Second, the paper presents a small theoretical model of how total expected operational costs change when considering detailed VOLL data in power system reliability management. We make a distinction between random (Chao, 1983), regional and perfect curtailment (Crew and Kleindorfer, 1976).[5] Third, the paper discusses the impact on the different components of total expected operational costs (preventive redispatch, corrective redispatch and interruption costs) and the effect on different consumer groups, if consumer- and time differentiated VOLL data are applied in a small-scale and large-scale test system. Based on the results of this analysis, we discuss practical issues and policy changes needed to implement system reliability management that is based on detailed VOLL data.

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 cost decrease of using a VOLL that differs over time and between consumers. Section 4 expands this analysis to five-node and 118-node illustrative networks with realistic assumptions on network data, generation plants, intermittent

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[2] In such schemes, a system operator's allowed revenue depends in part on its reliability level. For transmission, France uses a VOLL of 20,500 €/MWh (Commission de Régulation de l'Energie, 2016) and the United Kingdom a VOLL of 16,000 £/MWh (Ovaere, 2017).

[3] 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).

[4] Currently the reliability level is already unequally distributed, but this inequality is mainly due to nature of power systems, like rural versus urban consumers. The paradigm shift that this paper discusses is that a consumer's reliability level could now depend on personal aspects like VOLL and willingness to pay for electricity reliability.

[5] Note that the European Commission is empowered since 2016 to establish network codes in the areas of demand curtailment rules (European Commission, 2016, Article 55(1)n).

generation, failure probabilities, demand, and demand uncertainty. Section 5 concludes and discusses policy implications.

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 19 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.

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

Country or region	Consumer type	Time	Duration	Advance notification	Location	Source
Australia	x		x			(CRA International, 2008)
Austria	x	x	x			(Reichl et al., 2013)
Belgium		x	x	x		(Pepermans, 2011)
Cameroon			x	x		(Diboma and Tamo Tatietse, 2013)
Cyprus	x	x				(Zachariadis and Poullikkas, 2012)
Germany	x				x	(Growitsch et al., 2013)
Great Britain	x	x				(London Economics, 2013)
Europe		x	x		x	(Cohen et al., 2016b)
Europe		x			x	(Shivakumar et al., 2017)
Ireland	x	x			x	(Leahy and Tol, 2011)
Japan	x	x				(Yoshida and Matsuhashi, 2013)
Netherlands	x	x			x	(de Nooij et al., 2007)
New Zealand	x	x	x		x	(Electricity Authority, 2013)
North West England	x	x	x			(Morrissey et al., 2018)
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)

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 2018€/MWh.[6] All three studies use stated-preference methods to determine the VOLL data.[7] 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, interruption scenarios and reference time, data formats, normalisation factor, and since countries differ culturally. For example, because VOLL is normalised using a unit of energy, high levels of consumption have a downwards effect on VOLL (ACER, 2018). For correct VOLL estimation and comparison, we refer to best-practice guidelines and recommendations, such as (ACER, 2018; CEER, 2010; Hofmann et al., 2010; Sullivan and Keane, 1995)

The British and United States data show VOLL as a single value for each time of interruption. The Norwegian 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 reference VOLL[8] with the corresponding multipliers:[9]

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

$V(c)$ 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.[10]

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 (C&I) consumers in the United States, which have a substantially higher VOLL.[11]

The detailed VOLL data of Great Britain, Norway and the United States are further used in the numerical illustration of section 4.

3. Theoretical Analysis

This section demonstrates using a simple model that total expected operational costs decrease if detailed VOLL data are used instead of one constant VOLL at all times and in all regions.

Suppose a reliability cost $C(\rho)$ is needed to supply 1 MWh of electricity at reliability level ρ. This reliability cost is constant throughout the year and is increasing convex in the reliability level. That is,

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[6] Purchasing power parities (OECD, 2019) are used for conversion.

[7] 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).

[8] The reference time is 5 pm on a winter weekday for residential VOLL and 10 pm on a winter weekday for all other groups.

[9] 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.

[10] 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. To keep our paper insightful, we decided to focus on the two dimensions that are the most straightforward to integrate in short-term system operation: consumer groups and time.

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

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 [2018€/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	11,363	8,278	11,014	13,261	13,067	10,827	12,242	14,064
	SMEs	45,147	43,889	39,690	40,686	52,530	46,657	42,225	47,430

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

		Residential	Industry	Commercial	Public
Reference VOLL [2010 NOK/MWh]		5,000	116,000	192,000	170,000
Reference VOLL [2018 €/MWh]		480	11,133	18,427	16,315
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 [2018€/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	3,052	2,289	2,171	2,171	3,580	2,700	2,582	2,582
	Small C&I	274,444	333,574	175,759	175,351	168,826	211,644	100,317	98,686
	Large C&I	15,898	22,341	18,832	14,032	11,423	16,271	13,288	9,917

		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	2,171	1,526	1,232	1,232	2,524	1,819	1,467	1,467
	Small C&I	378,432	474,676	222,655	218,985	223,878	289,941	121,522	117,852
	Large C&I	13,004	19,105	14,518	10,878	8,976	13,409	9,806	7,362

the cost of increasing the reliability level (e.g., increased maintenance or investment) increases with the reliability level. Reliability $\rho \in [0,1]$ is here defined as:

$$\rho = \frac{\text{total demand - curtailed load}}{\text{total demand}} \tag{2}$$

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 $(1-\rho)V$,where V is the VOLL (Ovaere and Proost, 2018):

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

This is at the point where marginal reliability cost (the cost of increasing the reliability level) equals marginal interruption cost (the cost of decreasing the reliability level, i.e. the VOLL V):[12]

$$C'(\rho^*) = V \tag{4}$$

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 ($V_w > V_s$), equation (4) dictates that the reliability level in winter $\rho^* = \rho_w$ should be higher than the reliability level in summer $\rho^* = \rho_s$. If a system operator, however, bases its reliability level on the yearly-average VOLL $\bar{V}$, it will aim for a constant reliability level $\bar{\rho}$ throughout the year.[13] 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 reliability cost $C'(\rho)$, which is increasing in ρ. In this figure, the reliability cost is the area below the marginal reliability cost, up to the reliability level ρ, while the interruption cost is the area below the VOLL up to $1-\rho$.

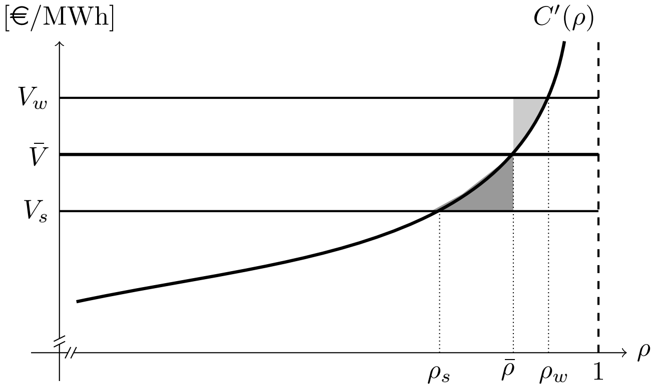

Figure 1: Total cost decrease if VOLL differs over time.

If the system operator modifies the reliability level with changing VOLL , instead of aiming for a constant reliability level $\bar{\rho}$, the sum of reliability costs and interruption costs will be lower. This cost decrease is defined as:

$$[C(\bar{\rho}) + (1-\bar{\rho})V] - [C(\rho^*) + (1-\rho^*)V] \;\; [€] \tag{5}$$

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

[13] 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.

In Figure 1, $C(\rho)$ is the area underneath the increasing $C'(\rho)$ curve and left of ρ, while $(1-\rho)V$ is the area underneath V and right of ρ. The dark gray triangle is the cost decreases in summer ($\rho^* = \rho_s$) and the light gray triangle the cost decrease in winter ($\rho^* = \rho_w$). When using an average VOLL $\bar{V}$; 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, total operational costs will decrease by providing low-VOLL consumers with a lower reliability level than high-VOLL consumers. Total operational costs decrease most if demand is curtailed from lowest to highest VOLL (Crew and Kleindorfer, 1976) – so-called perfect curtailment.[14] Perfect curtailment is only possible when the system operator has the technical capabilities to curtail individual consumers or individual appliances, e.g. when a smart meter with connect/disconnect capabilities or a smart appliance is installed (Faruqui et al., 2010). When this is not possible, costs can still decrease when curtailment is performed first in regions where the average VOLL of consumers is lower – so-called regional curtailment.

Figure 2 illustrates the costs decreases of using an average VOLL, a VOLL per region (regional curtailment), and a VOLL per consumer group (perfect curtailment). VOLL is assumed to be uniformly distributed between V_{min} and V_{max}. This is the downward-sloping line. For example, residential consumers are around V_{min}, small C&I consumers are around V_{max} and large C&I consumers have an intermediate VOLL. Moving from an average VOLL $\bar{V}$ to regional curtailment (with regional VOLLs V_1 and V_2) leads to a costs decrease equal to the light grey area.[15] This is the sum of lower reliability costs (A) and lower interruption costs (B). The dark grey area is the additional cost decrease of moving from regional 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 regional curtailment these are consumers in the low-VOLL region 1; for perfect curtailment these are the consumers with the lowest VOLL, in both region 1 and 2. Moving from an average VOLL to perfect curtailment, the decrease of reliability costs is A+C+E and the net decrease of interruption costs is B+D-E.

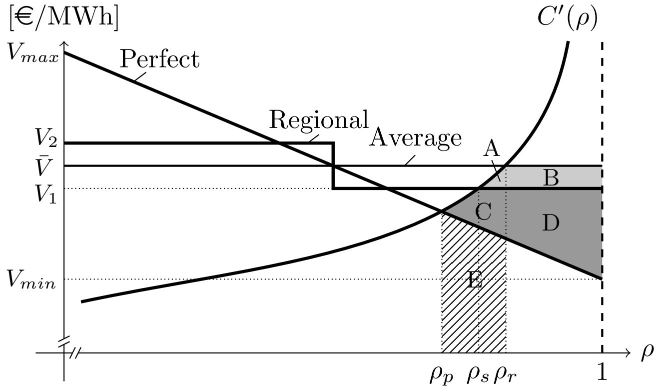

Figure 2: Total cost decrease and reliability level if using an average VOLL, a VOLL per region (regional curtailment), and a VOLL per consumer group (perfect curtailment)

The next section illustrates the theoretical concepts of the current section in a five-node and a 118-node case study.

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[14] A system operator will always first try to balance supply and demand using the bids in the real-time market, but as currently only a small portion of total demand is responsive to real-time prices, additional non-market curtailment actions could be needed to restore the balance.

[15] 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.

4. Numerical illustrations of the effect of detailed VOLL data on power system reliability

4.1. Formulation of power system reliability management

During operation of the power system, system operators 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 system operator needs to take actions to ensure that demand and supply are always balanced without overloading any transmission line. Determining appropriate preventive, corrective and curtailment actions is denoted as short-term power system reliability management. It consists of two parts: real-time operation and operational planning. Both aim at minimizing total expected operational costs.

When disturbances occur in the power system, the system operator 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 system operator takes those actions that minimize the cost of corrective actions and the cost of demand curtailment, subject to the power flow equations, Kirchoff's laws, physical limits on the equipments (such as bounds on generators' active and reactive power output, the ratio of controllable transformers and reactance of shunts) and operational constraints (Van Acker and Van Hertem, 2016) on branch currents and voltage magnitudes. The objective function equals:

$$\min_{a_c^{RT},P_{curt}^{RT}} C_{RT}(v) = \min_{a_c^{RT},P_{curt}^{RT}} \left[C_{corr}(a_c^{rt}) + P_{curt}^{rt}(c) \cdot v\right] \tag{6}$$

Interruption 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:

$$v \in \{V, V(t), V(n,t), V(c,t)\} \tag{7}$$

That is, VOLL V is constant; VOLL $V(t)$ differs over time t; VOLL $V(n,t)$ differs over time t and is aggregated per node n; or VOLL $V(c,t)$ differs over time t and between consumer groups c. Equation (6) 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 operational cost.

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 system operator determines the optimal dispatch of electricity generation, taking into account uncertainties about future real-time states 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 system operator 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 the same constraints of equation 6. The objective function equals:

$$\begin{aligned}\min_{a_p,a_c^s,P_{curt}^s} C_{OP}(v) = \min \Big[& C_{prev}(a_p) + \\ & \sum_{s \in S} \pi_s \cdot \left(C_{corr}(a_c^s) + P_{curt}^s(c) \cdot v\right)\Big]\end{aligned} \tag{8}$$

where π_s is the probability of occurrence of considered real-time state s. As the system operator can never take into account all possible real-time states, the set S is limited to credible real-time states (Heylen et al., 2019a).

Equation (8) shows that the cost of possible real-time curtailment actions influences operational planning decisions of forward-looking system operators. As a result, the level of VOLL detail does not only affect corrective actions and demand curtailment, but also preventive actions.

Equation (3) of our theoretical analysis is a simplified version of equation (8). While in the theoretical analysis the system operator 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.

4.2. Evaluation

The main indicator of power system performance is its yearly expected total cost (ETC). The short-term ETC consists of costs of preventive actions, costs of corrective actions and cost of load curtailment:

$$\begin{aligned}\mathrm{ETC}(v) = \sum_{t\in T}[C_{prev}(a_p(v,t)) + \sum_{rt\in RT} \pi_{rt} \cdot \big(C_{corr}(a_c^{rt}(v,t)) \\ + P_{curt}^{rt}(c,v,t) \cdot V(c,t)\big)] \quad \forall t \end{aligned} \tag{9}$$

Note that the cost of load curtailment is evaluated at the highest level of VOLL detail that is available, i.e., depending on consumer type and interruption time $V(c,t)$. The set RT considered in the evaluation should optimally consist of all possible real-time states, but is for practical purposes limited to a finite set. It is weakly 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 system operator 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 service reliability level and equity or equality between consumers. First, the service reliability level is expressed in terms of average interruption time (AIT) (Cepin, 2011):

$$AIT = (1-\rho)\cdot 8760 \cdot 60 \qquad [\text{min/year}] \tag{10}$$

Second, to evaluate inequality of the service reliability level between consumer groups and consumers at different nodes, we use the measure of Heylen et al. (2019b). This Gini-based coefficient (Atkinson, 1970) quantifies inequality based on the cumulative share of demand X and the cumulative share of curtailed load Y: (see (Heylen et al., 2019b) for more information)

$$I = |1 - (\sum_k (X_k - X_{k-1}) \cdot (Y_k + Y_{k-1})| \tag{11}$$

with k an index counting over the groups under comparison, i.e., consumer groups at nodes. The groups are ordered based on decreasing reliability values. An inequality indicator of 0 means that all consumer groups in all regions have the same reliability level. An inequality indicator closer to 1 means that all interruptions are concentrated in one or a few consumer groups or nodes.

4.3. Results for a five-node network

This numerical illustration uses a five-node test system. All relevant data can be found in Appendix A. The same analysis is repeated with VOLL data of Great Britain, Norway and the United States. In each case, we calculate the yearly expected total cost ETC, the service reliability level AIT and the inequality indicator I. We compare results for the four levels of VOLL detail that we have introduced before:

$$v \in \{V, V_t, V_n, V_c\}^{16} \tag{12}$$

Our numerical illustrations are simulated using a model developed within the Europe-wide GARPUR project [17] (Heylen et al., 2016; GARPUR consortium, 2015) and is implemented in AMPL (Fourer et al.,

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[16] Note that we have changed the notation to subscripts.

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

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 5 gives summary statistics of the detailed VOLL data used in our analysis.[18] The data differs between countries in a number of ways. First, the average VOLL V is significantly lower in Norway than in GB and the US. Second, when VOLL is constant throughout the country but differing over time (V_t), temporal variation, represented by the coefficient of variation CV, is high for Norway, average for US and low for GB. The higher temporal variability in Norway is likely due to the larger relative difference between cold winters and temperate summers. In Norway, the minimum country-wide VOLL is only 262 €/MWh (On a summer Sunday at 2 am), while it is a hundredfold in both GB and US. The country-wide maximum is between 9,645 and 120,711. This means that optimal reliability will differ substantially over time in Norway, will differ a bit in US and will not change much in GB. Third, with VOLL changing over time and differing between nodes (V_n), the minimum and maximum VOLL diverge in all three countries. Fourth, when in addition VOLL is differentiated between consumers (V_c), minimum and maximum VOLL will diverge even more in all three countries.

Table 5: Summary statistics of detailed VOLL data in Norway, Great Britain and United States.

		Norway	GB	US
V		2,145	32,400	59,353
V_t	CV	1.1898	0.088	0.4367
	min	262	28,937	28,249
	max	9,645	37,731	120,711
V_n	min	111	15,400	5,004
	max	12,592	52,530	374,676
V_c	min	85	8,278	1,232
	max	19,533	52,530	474,676

Fig. 3 presents the main results of the five-node test system. It shows how the different components of total expected operational cost (preventive redispatch cost, corrective redispatch cost and interruption cost) change if different levels of VOLL data are applied in short-term system operation. First, as expected from the theoretical analysis, considering more detailed VOLL data, i.e., moving from V towards V_t, V_n and V_c, results in total expected operational cost savings in all countries. These savings increase with a higher degree of VOLL detail, as the minimum and maximum VOLL diverge with a higher degree of differentiation. Therefore, system operators can curtail consumers with the lower minimum VOLL, resulting in less costly load curtailment. Secondly, cost savings due to the use of more detailed VOLL data are larger in Norway because its minimum VOLL is considerably lower than in the US and GB. For V_t, cost savings are substantial in Norway, low in US, and negligible in GB. The cost savings for temporal VOLL differentiation increase with the level of temporal variation, less with the absolute level of the minimum VOLL, as GB and US have a similar minimum VOLL but different temporal variability. Thirdly, also the cost savings of GB and US increase with more differentiated VOLL data V_n and V_c. In that case, it is not the temporal variability but the level of the minimum VOLL that leads to cost savings.

Fig. 3 shows that the operational cost savings with more detailed VOLL are the result of a reduction of the preventive redispatch costs in response to lower expected interruption costs. This is especially true in Norway, where the temporal variation of VOLL is highest and residential VOLL is lowest. GB and US decrease their cost of preventive actions and decrease their interruption cost when shifting to regional (V_n) and perfect curtailment (V_c).

Another important aspect to consider in the discussion is equality of the reliability level between different consumers. If more detailed VOLL data are used and system operators are able to curtail load based on

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[18] The coefficient of variation CV, the minimum and the maximum for V_t and V_n are calculated as demand-weighted average (see Table A.10) over consumer groups.

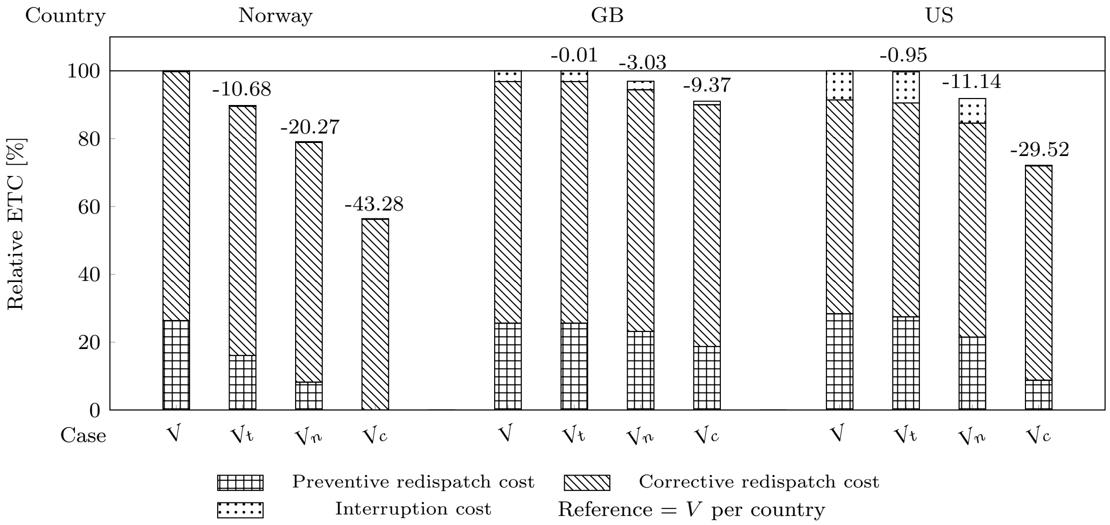

Figure 3: Evolution of cost terms in relative expected total operational cost for different levels of detail of VOLL

VOLL, particular consumer groups might experience lower reliability levels. Table 6 shows the average interruption time per node and consumer group. The penultimate column shows the inequality indicator, as defined in equation (11). Table 6 shows first that regional curtailment (V_n) considerably decreases equality. In all three countries, curtailment is almost completely limited to node 5, where low-VOLL residential consumers are located. Second, perfect curtailment (V_c) also decreases equality, but less than regional 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 equality. In Norway and US, equality slightly increases; in GB it is constant.

Note that the use of more detailed VOLL data does not necessarily change the aggregate reliability level. National AIT does not change if more detailed VOLL data are used, except when Norway uses regional 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 minimum VOLL is much lower in Norway than in GB and US, as shown in Table 5.

4.4. Results of a 118-node network

This section repeats the above analysis for the IEEE 118-node test system (see Christie (1993) for all details). The marginal generation costs are rescaled such that the average marginal generation costs of the conventional generators equal the average marginal generation costs of the conventional generators in the five-node test system. The simulations focus on a single time instant. To verify the maximum impact on the cost, reliability and inequality for each country, we use the time instant with the lowest VOLL for each country. We compare a constant single VOLL V with a VOLL V_c that is differentiated by the consumer group. As we assume a single consumer group per node, the latter also equals V_n.

Table 7 presents results for the 118-node test system. In summary, it shows that the conclusions for the small test system hold for the large system, in terms of expected total cost and average interruption time. For the large system, the maximum potential cost savings range between 2% (when using VOLL data from Norway and Great Britain) and 18% (when using US VOLL data).[19] As before, the largest share of cost savings is due to a decrease of the cost of preventive actions, by shifting some preventive actions

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[19] Note that, while the cost reduction was largest for Norway in the small test system, it is largest for the US in the large test system. The reason is that for our chosen time instant the difference between system-average VOLL and the lowest VOLL is much higher in the US than in Norway.

Table 6: Average interruption time [min/year] (per node and consumer group), consumption-weighted average AIT, inequality indicator (I) and expected total cost decrease (ΔETC) for different levels of VOLL detail and different countries.

		Nodes								Evaluation indicators		
	VOLL	2		3		4		5		AIT	I	ΔETC
Country	detail	Res	Non res	Res	Non res	Res	Non res	Res	Non res	[min/y]	[/]	[%]
Norway	V	-	1.12	0.31	0.49	1.1	0.37	3.48	16.59	1.91	0.66	0
Norway	V_t	-	1.04	0.42	0.76	0.66	0.57	3.91	13.59	1.91	0.58	-10.68
Norway	V_n	-	0.05	0	0	0.16	0.09	23.09	45.54	6.25	0.81	-20.27
Norway	V_c	-	0.06	14.16	0	127.8	0.03	109.16	0	27.86	0.75	-43.28
GB	V	-	0.8	0.31	0.31	1.01	0.39	3.5	18.11	1.91	0.7	0
GB	V_t	-	0.8	0.31	0.31	1.02	0.39	3.5	18.11	1.91	0.7	-0.01
GB	V_n	-	0	0.05	0.05	0	0	6.52	15.2	1.91	0.82	-3.03
GB	V_c	-	0.02	1.9	0.01	2.51	0	8.81	0.07	1.91	0.74	-9.37
US	V	-	1.19	0.92	0.1	0.37	0.72	3.71	15.74	1.91	0.68	0
US	V_t	-	1.19	0.3	0.49	1.06	0.51	3.94	14.78	1.91	0.64	-0.95
US	V_n	-	0.11	0.02	0.02	0.02	0.01	4.91	19.95	1.91	0.85	-11.14
US	V_c	-	0.02	2.45	0	1.87	0	8.48	0.13	1.91	0.73	-29.52

to curtailment actions. That is, as the cost of curtailment is fairly low for some consumer groups, it is not efficient to take costly actions to prevent their curtailment at all times. As a result, the reliability level decreases (i.e., AIT increases) in all three countries. Note that interruption costs even decrease if AIT increases, when using VOLL data from Norway and GB, because the higher AIT is offset by the lower VOLL of curtailed consumers.

While more detailed value of lost load data increases inequality in the small test system, inequality decreases in this case. As only a small subset of consumers is ever curtailed, inequality is high. But when AIT increases if differentiated VOLL is used, consumers in different parts of the network are curtailed in specific real-time states (like line failures in different part of the network), because the test system is much larger.

4.5. Discussion

Two issues merit more discussion. First, currently most system operators do not use even a constant VOLL in their short-term reliability management. System operators' reliability decisions are guided by the N-1 criterion, which 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 power system should still be able to accommodate all flows without load curtailment.[20] The detailed data, such as failure rates and VOLL, necessary to move beyond the N-1 criterion are not yet widely available (Heylen et al., 2019a). However, advances in communication and information technologies, like wide area management systems, facilitate gathering interruption and failure data The combination of priority service contracts and smart meters might also provide a revealed preferences estimation of interruption costs (see conclusion). With more data available, system operators 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. A low reliability level encourages local investments, e.g. in storage or local generation, to prepare for interruptions. If regional 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,

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[20] Of course, The N-1 network redundancy is not always possible at the lowest voltage levels of the network.

as people will experience lower reliability levels if exact VOLL data are taken into account in reliability management. Taking into account behavioral feedback effects of VOLL is important, but a lengthy learning process.

We have assumed that all possible real-time states s can be adequately dealt with and that curtailment is always possible to prevent a blackout. In case curtailment (or other corrective actions) increases the probability of a blackout, e.g. because it is more difficult to deal with failure of corrective and curtailment actions, the actual cost decrease of detailed VOLL data will be lower than the values we have estimated.

5. Conclusions and Policy Implications

5.1. Conclusions

Many empirical studies have recently estimated how VOLL depends on interruption characteristics – especially consumer type and time of interruption. However, few applications actually use detailed VOLL data to obtain a cost-effective power system reliability level. There is an increasing trend to use the VOLL in power system reliability incentive schemes (Ovaere, 2017), but except for the Norwegian scheme which explicitly uses the detailed VOLL data of Table 3 ((Kjolle et al., 2008)) and the Italian scheme which distinguishes between residential and non-residential consumers, these schemes only use a single constant VOLL. Such single-VOLL schemes give system operators incentives to achieve a certain average reliability level, but do not give any explicit incentive to consider the different valuations of reliability over time and between consumers. This paper theoretically and quantitatively indicates the potential decrease of total expected operational costs if consumer- and time-differentiated VOLL data are applied in short-term power system reliability management. Using detailed VOLL data from Norway, Great Britain and the United States, a numerical simulation indicates a potential operational cost decrease of up to 43% in a five-node network, and between 2% and 18% in a more realistic 118-node network.[21] These are only estimates of short-term savings. When differentiated VOLL is used in short-term operational and real-time decisions, long-term transmission and generation investment decisions might also be altered, which could lead to even larger cost savings. Moreover, 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., 2016a). 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.

A potential downside of more cost-effective regional and perfect curtailment based on detailed VOLL data is the introduction of additional inequality of reliability based on personal aspects on top of the inequality due to the nature of power systems. As equality can not be monetized, an unambiguous trade-off between cost-efficiency and equality is not possible.

5.2. Current policy and future requirements

Detailed VOLL data are essential to achieve the indicated operational cost savings. The first policy measures to support the collection of more detailed and consistent VOLL data are already taken in Europe. The European Commission's "Clean Energy for All Europeans" proposals require member states to establish a publicly-available single estimate of the VOLL for their territory, one year after the Regulation's entry into force. A different VOLL per bidding zone may be established if member states have several bidding zones (European Commission, 2016, Article 10). The ultimately chosen VOLL will serve as the upper limit on wholesale electricity prices. However, as this will require estimating detailed VOLL data for different interruption times and different consumers, these readily-available data could also be used in electricity reliability incentive schemes and the corresponding reliability management methods. To ensure the consistency

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[21] 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 3634 TWh in 2017, this amounts to potential gains between 65 million and 589 million per year in the ENTSO-E network.

Table 7: Results in terms of costs, reliability and inequality for the 118-node test system

	Norway		Great Britain		United States	
	V_c	V	V_c	V	V_c	V
Preventive cost [%]	98.01	99.57	93.05	94.06	80.30	98.87
Corrective cost [%]	0.26	0.35	0.32	0.33	0.25	0.20
Interruption cost [%]	0.060	0.079	5.52	5.61	1.44	0.93
Total cost [%]	98.33	100	98.88	100	82.00	100
Relative AIT [%]	100	61.57	100	78.61	100	8.19
Inequality I [/]	0.92	0.94	0.91	0.93	0.92	0.97

of the VOLL data, the European Regulation also requires European member states to develop a standard methodology for estimating the VOLL (European Commission, 2016, Article 19(5)). The literature review in this paper has indicated that stated-preference methods and the production function approach are most commonly used in practice nowadays. Stated-preference methods allow for a lot of detail and granularity, but are expensive and time-consuming, and may lead to skewed estimates because of strategic answering and cognitive biases. The production function approach, on the other hand, is less expensive and time-consuming, but leads to rougher estimates as they are usually based on national accounts statistics. These policy measures incentivize collecting more detailed and harmonized VOLL data. However, additional policy measures are required to facilitate the application of differentiated VOLL in power system operation.

First, future policy measures should improve transmission-distribution coordination. When implementing load curtailment based on consumer-level VOLL, a link is needed between system operation reliability decisions and the end-consumer. In non-restructured regions, a completely integrated utility, with a direct link between system operation and the end-consumer, can take consumer curtailment actions if required for reliability reasons. However, in many restructured regions, like Europe and part of the United States, where the transmission and distribution system are operationally separated, there is no direct link between consumers and the transmission system operator. As a result, distribution system operators can take reliability actions that affect end-consumers, while transmission system operators can not. If they want to do curtailment at the end-consumer level (beyond zonal or nodal curtailment), this has to go through the distribution system operator, either directly or through a load aggregator. Doing this would require national codes or European network codes to be amended to strengthen cooperation between transmission and distribution system operators (Gerard et al., 2018). For example in Europe, ENTSO-E is preparing guidelines for improving transmission-distribution cooperation. Among other things, ENTSO-E (2015); ENTSO-E and E.DSO (2019) propose coordinated access to flexibility sources (active system management) and a sharing of grid data and information. To make it possible that end-consumers are curtailed for transmission system reasons, these shared resources and data should also include transmission system reliability decisions and the load and connection status of end-consumers. As discussed by (Hadush and Meeus, 2018), the rules required for transmission-distribution cooperation on end-consumer curtailment are far from being developed, and will probably only happen after cooperation on other things like preventive or corrective redispatching.

Second, policy measures should enable the participation of all consumers in curtailment programs from a practical and legal perspective. The practical application of perfect curtailment at consumer level will be facilitated by the widespread roll-out of smart meters and smart appliances. In case electricity interruptions are needed to protect the network from a blackout, smart meters can be used to curtail or limit electricity supply to those consumer groups with the lowest VOLL at the time of interruption. The combination of smart meters and smart appliances will also make it possible to delay the activation of specific, flexible appliances, like air conditioners, washers and dryers. As the cost of delaying the activation of this shiftable load is even lower than a consumer's value of lost load (i.e. its average interruption cost), even higher efficiency gains might be possible than the ones estimated in this paper.[22] Note that a remote disconnect is an optional functionality in many smart meters. When this option is not available, voluntary load curtailment is still possible by raising the electricity price above a consumer's VOLL (i.e. demand response), but involuntary consumer-level load curtailment through the smart meter is not possible. Alternatively, direct control of smart appliances can be put into place (Strbac, 2008).

Current network codes put strict requirements on the characteristics of the load that can participate in load curtailment programs. Therefore, current load curtailment programs typically involve large consumers connected to the high-voltage grid (Smartnet Consortium, 2016) or low-voltage consumers participating via an aggregator (Elia, 2019). Future policy measures should increase the flexibility for all consumers to participate in load curtailment programs. Consumers that participate in curtailment programs could get rewarded for this through bill rebates[23] or priority service contracts that allow them to select a reliability level and an associated price for a specific period of time (Chao and Wilson, 1987; Wilson, 1989; Joskow and Tirole, 2007). A consumer will choose its reliability level based on its individual average VOLL over the contract duration and any resulting system cost increases or decreases can get transfered to the consumer, through fixed monthly compensations or usage fees (Richter and Pollitt, 2018). Especially customers with home battery systems could save considerably when selecting low-reliability-low-price priority service contracts. By linking reliability and load curtailment decisions with prices and compensations, consumer behavior in priority service contracts and load curtailment programs might also provide a revealed preferences estimation that helps to refine VOLL from stated-preference studies.

Third, to ensure the social acceptance of power system operation based on consumer-differentiated VOLL data, government or a regulator should provide policy measures that strike the balance between the opposing objectives of efficiency and equality based on society's preferences. For this reason, they have to assess public resistance to different treatment of consumer groups or regions. This 'efficiency-equality' trade-off is a fundamental economic discussion. Imposing limits on inequality (like a minimum or universal reliability level) decreases efficiency but is generally considered to be more fair (Neuteleers et al., 2017).

Acknowledgements

We are grateful for very helpful comments from Guido Pepermans and Fridrik Mar Baldursson. The research leading to these results has received funding from the European Union Seventh Framework Programme under Grant Agreement No 608540. The work of Evelyn Heylen is funded by the Research Foundation Flanders.

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[22] Dynamic models of inconvenience cost are needed to support the decision making in short-term system operation (Heylen et al., 2019c).

[23] For example, the Californian utility PG&E gives a $50 rebate to customers that install a smartAC device that directs the air conditioning to run at a lower capacity during peak hours.

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Appendix A. Data of five-node network

Appendix A.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 A.4. Generation is located in node 1 and 2; demand is located in node 2 to 5. Table A.8 shows the reactance (x), 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.

Appendix A.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 A.9 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 (A.1). Wind

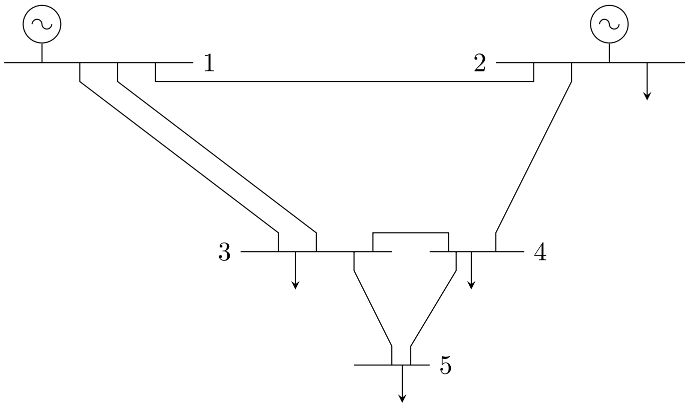

Figure A.4: Circuit diagram of the test system

Table A.8: Line data

From node	To node	x [pu]	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

generators are not available for positive redispatch.

$$\begin{aligned} c^{+}_{prev} &= 1.5 \cdot C_{marg} + 5 \\ c^{-}_{prev} &= -0.5 \cdot C_{marg} + 5 \\ c^{+}_{corr} &= 5 \cdot C^{+}_{prev} \\ c^{-}_{corr} &= -\frac{1}{5} \cdot C^{+}_{prev} \end{aligned} \tag{A.1}$$

Appendix A.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). Total system demand at each of the 72 time instants is calculated as the mean over all valid hours. Table A.10 gives the share of total demand per node that is attributed to a particular type of customer $DS(c, n)$ together with the share of the total demand at that node $DS(n)$.

The table 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

Table A.9: 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

Table A.10: Demand shares of different consumer groups at different nodes and of demand shares of different nodes in total demand

	Node	Res.	Ind.	Com.	Pub.	$DS(n)$
$DS(c,n)$	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

temporal cases. 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. By unifying the test set, we can compare the results in Norway, Great Britain and the United States, although their VOLL data have different levels of detail.

Appendix A.4. Considered real-time states

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. These realizations are determined based on a normal distribution with the forecast value of net total demand as mean and a coefficient of variation of 4%. To evaluate reliability management also in system states that are not considered in advance, 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.