APPLYING THE SMART GRID METRICS FRAMEWORK TO ASSESS DEMAND SIDE INTEGRATION IN LV GRID CONGESTION MANAGEMENT

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ABSTRACT

The enormous growth of distributed generation (DG), in particular from photovoltaic (PV) panels, drives the low voltage (LV) distribution grids to their limits and a considerable number of them are experiencing congestion issues. Demand side integration (DSI) is seen as an attractive countermeasure. DSI involves consumers into the congestion management and promotes them from passive to active. In this paper, DSI is applied to a wide range of artificial synthetic LV grids and is assessed with the help of the Smart Grid Metrics framework (SGM) [1].

INTRODUCTION

The installed renewable power capacity in Germany reached a total of 83 GW with 36 GW of PV by the end of 2013. The majority of this PV capacity consists of small scale rooftop systems. Different from ground-mounted utility-scale PV systems which are connected to the medium or high voltage level grids, most of the small scale systems directly feed into the LV grids. The traditional LV grids are built to distribute the electric power from the ring main unit to the end users. The development of small scale DG forces changes in the structure of the LV grids and the renewable feed-in from the terminal side of the feeders pushes the LV grids to their operational limits. As a consequence congestion management during system operation becomes necessary. Today, excessive voltage magnitudes can be addressed by reactive power control of PV inverters and/or by on load tap changer (OLTC) transformers at reasonable cost. However, these measures do not eliminate thermal overload situations. Overload of transformers and distribution lines may reduce their lifetime or may even cause tripping of protection devices with consequences for the quality of supply. Grid extension is the traditional approach for distribution system operators (DSO) to solve this problem. Another option already in use is the curtailment of the DGs in-feeds which causes wasting renewable energy. One not yet fully developed option is DSI. The advancements in information and communication technologies (ICT) make it possible to gather demand information from customers and develop DSI approaches. The focus of this paper is the analysis of the capability of DSI in alleviating local congestions in LV grids. For this purpose DSI is tested in a number of artificial synthetic LV Grids and the effect is evaluated by applying the SGM framework [1].

DEMAND SIDE INTEGRATION

DSI is an umbrella term for Demand Side Management (DSM) and Demand Side Response (DSR). DSM directly reshapes the electric load by technical measures while DSR indirectly influences the electric consumption by price signals [2]. DSI is formerly implemented to handle grid bottlenecks during the peak load periods and to better utilize the grid capacity. The classic description of DSI for peak load congestion is shifting parts of the peak load to fill the load valley. Different from that feed-in congestion alleviation requires the load peaking during the DG generation peak. Since the peak load typically occurs during noonday coincidentally with the DG peak, the aim of DSI changes from peak reduction to peak elevation. The power balance paradigm develops from “generation follows load” at least partly to “load follows generation”. There are various manners to affect the electricity consumption patterns. TABLE I shows the three most favorite options of DSI implementation which are investigated further in the following.

TABLE I: DSI IMPLEMENTATION OPTIONS [3]

Time-of-Use (TOU) Tariff	Rates with different unit prices for usage during different blocks of time, usually pre-defined for a 24 hour day.
Real-Time Pricing (RTP) Tariff	Rates in which the price for electricity typically fluctuates hourly reflecting changes in the wholesale price of electricity.
Direct Load Control (DLC)	A scheme by which the program operator remotely shuts down or cycles a customer's electrical equipment (e.g. air conditioner, water heater, space heating) on short notice.

APPROACHES

In order to assess the DSI options, the time series load flow simulation technique is applied. Fig. 1 illustrates the approach. Load and PV generation curves are generated in a bottom-up approach based on various determinant factors. Synthetic LV grids are developed according to a variety of settlement characteristics. With these input data congestion problems can be identified. In order to assess DSI, synthetic load curves with the above DSI options are generated and applied. The Monte Carlo method is used to generate probabilistic load curves for different households and to generate PV in-feed curves for random weather conditions. Finally, the SGM is used to compare the effectiveness of the different DSI options.

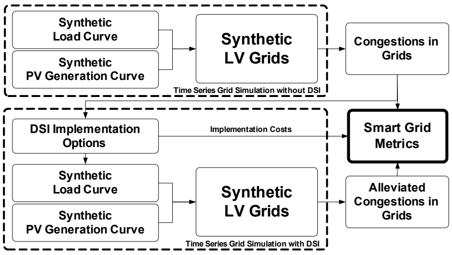

Fig. 1 Flow Chart of the Approach

MODELING THE LOADS

The synthesis of household (HH) load curves is one of the most decisive steps in assessing DSI. The bottom-up approach is widely applied to model the residential load from electricity consumption data or metering data, e.g. [4, 5]. For this paper a simplified appliance based bottom-up model with a time interval of 15 minutes is proposed. TABLE II shows the domestic appliances which are primarily used in Germany and their operational modes. These operational modes determine the appliances with DSI potential. Modifications of the time of use for semi-auto appliances are supposed to cause minimized life style changes and are assumed to have a shift potential for price signal incentives. Auto appliances have a shift potential for DLC.

TABLE II: DOMESTIC APPLIANCES

Domestic Appliances	Operational Mode
Washing machine, tumble dryer, dishwasher	Semi auto
Fridge and freezer, heating circulation pump, electric heating (storage unit), heat pump	Auto
Lighting, oven and stove, electric water heater, entertainment electronics, IT, other loads	Manual

The basic idea of the approach which can also be found in [4, 5] is to simulate the usage of domestic appliances probabilistically over time in terms of times of use per day, load curve per use and consumed energy. The load curves of individual appliances are aggregated into a single HH load curve considering the HH size and the appliance penetration. Fig. 2 shows the procedure to generate a daily appliance load curve.

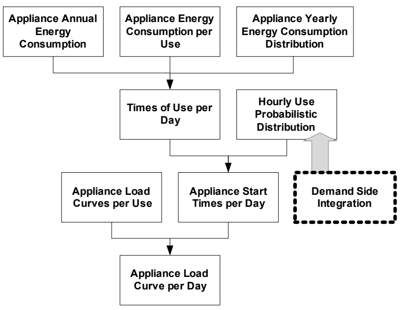

Fig. 2 Daily Appliance Load Curve Modeling Approach

The data of "Appliance Annual Energy Consumption" are obtained from surveys of customers and are categorized with HH size [6]. Most of the "Appliance Load Curves per Use" are derived from [7] and the other appliances lacking "Load Curves per Use" are simulated with constant maximum demand and use time between 15 minutes and 2 hours. Fig. 3 depicts "Load Curves per Use" for washing machines and electric water heaters.

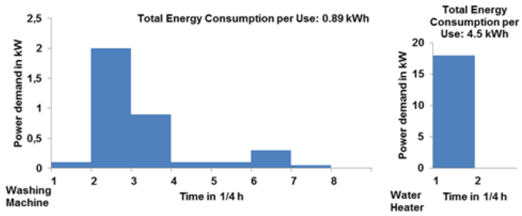

Fig. 3 Appliance Load Curve per Use [7]

The "Appliance Yearly Energy Consumption Distribution" is derived from [8] and is further developed considering the dynamic factor from the VDEW standard load profiles [9] for the whole year. With the "Appliance Annual Energy Consumption", the "Appliance Energy Consumption per Use" and the "Appliance Yearly Energy Consumption Distribution", the "Times of Use per Day" can be derived. Then with the "Hourly Use Probabilistic Distribution" the "Appliance Start Times per Day" can be determined. Finally the "Appliance Load Curve per Day" can be developed with the "Appliance Load Curves per Use". Fig. 4 shows the approach to develop the "Annual HH Load Curve". The HH size influences the annual energy consumption and the appliance penetration determines the types of appliances in a HH. All appliances are combined together to build the 365 single day curves and the annual curve is finally composed of all day curves. Fig. 5 shows a synthetic load curve for one HH for one day.

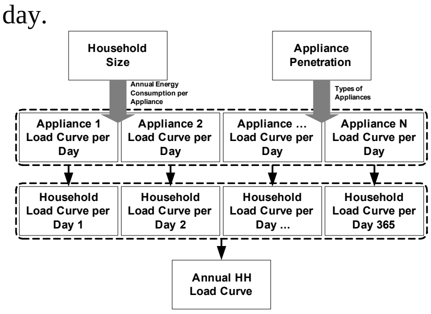

Fig. 4 Annual Household Load Curve Modeling Approach

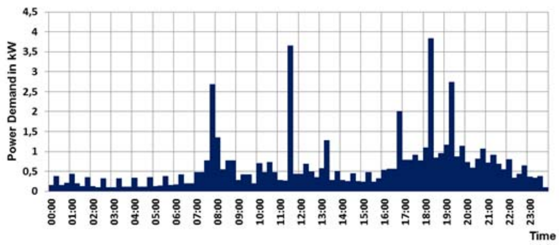

Fig. 5 Synthetic Load Curve for one HH for one day

A validation against the HH standard load profiles from E.ON Mitte AG [10] is given in Fig. 6. It is based on the VDEW load profile for an energy consumption of 100 MWh. The synthetic load curves are composed for 342 HHs to gain the same energy consumption. The HH sizes consider the common situation in Germany. The differences are not caused by modeling inaccuracies but by the randomness of the appliance use.

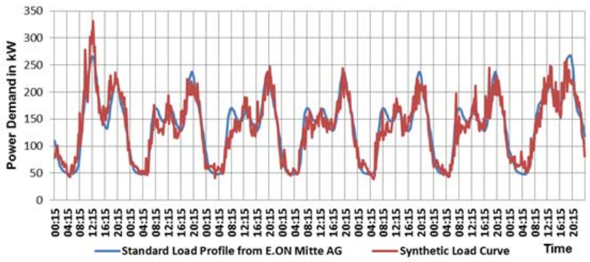

Fig. 6 Validation of the Synthetic Load Curve [10]

MODELING PV FEED-IN

The synthesis of PV feed-in curves is based on two models: the solar intensity model and the PV system model. Similar approaches can be found in [11-13]. PV systems show dominant daily generation patterns depending also on the season and short-term effects induced by clouds and other weather phenomena. The models are influenced by various factors which are displayed in Fig. 7. Compared to former modeling approaches both air mass and weather influences are considered.

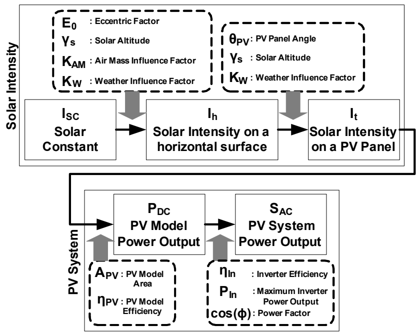

Fig. 7 PV Modeling Approach

The eccentric factor, air mass influence factor, solar altitude, and PV panel angle decide the main curve of the PV feed-in. Most factors are constant or vary regularly except the weather influence factor which varies randomly. The equations for the solar intensity calculation are taken from [13]. The air mass influence factor is introduced in [14] and the stochastic weather influence factor is similar to the cloudy index applied in [15]. Weather data from Germany are used [16]. Reactive power control is introduced in the model using the standard control curve [17].

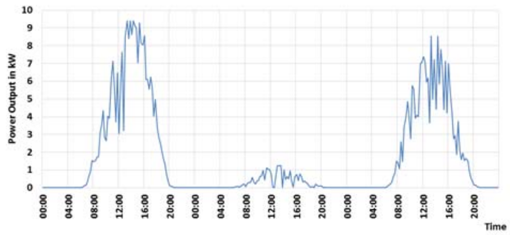

Fig. 8 Synthetic PV feed-in for May 26-27

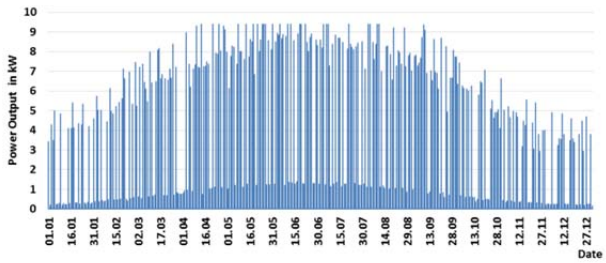

Fig. 9 Synthetic PV feed-in for One Year

Fig. 8 and 9 show an example of the generation of a PV system with 80 m^2, 30°panel angle and south orientation for several days and the whole year.

MODELING LOW VOLTAGE GRIDS

Different from grids with higher voltage levels, the LV grids are more accordant with the settlement conditions. A settlement is a community in which people live and the settlement size ranges from small hamlets to mega cities. The settlement structure (SS) has a big influence not only on the network structure but also on the parameters of the LV grids. There are sparse publications dealing with the LV grids parameterization and modeling, e.g. [11-12]. In this paper a new set of synthetic LV grids based on settlement structures are applied. The settlement data, such as building size, building type, plot size, street length, street width etc. are collected and selected from various resources [11-12, 19-20] to represent typical and extreme settlement characteristics. TABLE III shows the chosen types of LV grids and their total number of service connections (SC) and HHs. For each SS type there are three variants with different parameters for the distances between two SCs and between houses and streets. 70 mm^2 Al overhead lines are applied in rural areas while 150 mm^2 NAYY cables are utilized in urban areas. Transformers with different capacities are selected according to the power demands.

TABLE III: SYNTHETIC LV GRIDS

Region	SS	Name	SC	HH
Rural area	1a	Dispersed with individual house	18	18
	1b	Dispersed with house cluster	30	30
	2a	Linear town center	80	80
	2b	Crossed town center	100	100
Sub-urban	3a	Detached one-family house	162	162
	3b	Detached two-family house	108	216
	4a	Attached duplex house	180	180
	4b	Attached row house	162	162
Urban	5a	Ribbon building	24	240
	5b	Residential high-rise	48	288
	6a	City Block	8	256
	6b	Historic downtown	6	288

MODELING DSI

As showed in Fig. 2 the hourly use probabilistic distribution can be changed by DSI to generate the new load curves with DSI. Three different DSI options are implemented and explained as follows.

Time of Use Tariff

TOU tariffs are applied around the world to shift the peak load. Therefore high price periods are typically contemporaneous with peak load periods. Fig. 10a shows a tariff from a German pilot project from 2010 [21]. Three high price periods are arranged around 7, 13 and 19 o'clock. Considering the new situation caused by massive PV feed-in, peak load tariffs are no longer suitable during midday. Fig. 10b presents the proposed workday tariff which encourages customers to use PV feed-in energy around midday. Regarding the different load curves at working days and weekends, two separate TOU tariffs are provided. In the last three years the accelerated development of DG in Germany has caused a significant increase of the electricity price. The prices in Fig. 10b are chosen according to the average end customer price in 2013 [22].

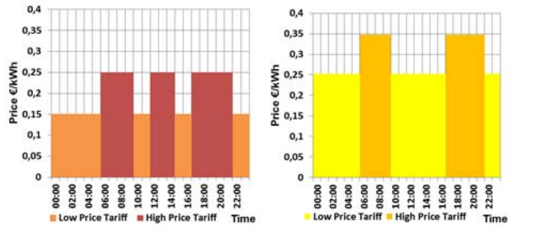

Fig. 10 a. Workday Tariff in [21] b. Applied Workday Tariff

TOU tariffs influence the appliance daily start times. Based on practical experiences [21], around 2/3 of the customers will react to high prices. Therefore in the simulation model 2/3 of the HHs avoid appliance use times during high price periods. The TOU has only effects on the hourly use probabilistic distribution in Fig. 2 whereas energy saving potentials are not considered. Fig. 11 shows an example of the TOU effect for a model with 5000 HHs and 25 % of the HHs with installed PV systems.

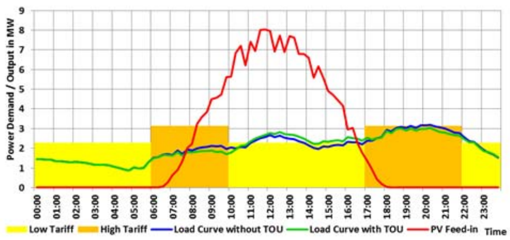

Fig. 11 TOU Effect on Load Curve (5000 HHs)

The effects are very small. The reasons is that only semi-Auto appliances are considered to respond to price signals and their probability of start time at midday is high anyway.

Real Time Price Tariff

Comparing with the TOU tariff, the RTP tariff provides price information reflecting the time-varying costs of electricity. Most implementations involve one hour time steps, with prices set one day in advance. In order to update the prices every day, ICT systems based on smart meters are necessary. In this paper a daily update cycle with 5 blocks is introduced. TABLE IV presents the tariffs based on another German pilot project [34] but update to the actual price level [22]. The prices and durations for each tariff are fixed. Only the start time of each tariff is changeable based on the 24 h forecast of DG feed-ins and loads. The customer use probabilities from [23] are applied to alter the daily start times of the appliances in cases where the use time doesn't fall into the "Low Price Tariff 1" period.

TABLE IV: RTP TARIFF BLOCKS

RTP Tariff	Period	Price (€/kWh)	Customer Use Probability
Low Price Tariff 1	6 h	0.19	0.44
Low Price Tariff 2	3 h	0.20	0.21
Main Tariff	8 h	0.25	0.29
High Price Tariff 1	4 h	0.35	0.05
High Price Tariff 2	3 h	0.40	0.01

The RTP tariff sequence changes every day according to the residual load. Fig. 12 shows the simulation results for RTP for the same 5000 HHs example and the effects are likewise limited.

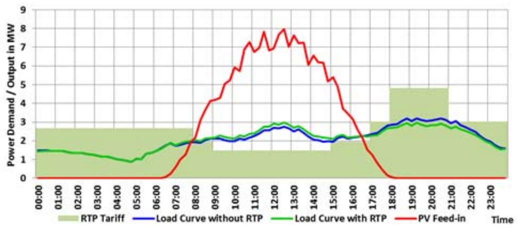

Fig. 12 RTP Effect on Load Curve (5000 HHs)

Direct Load Control

DLC refers to the scenario where third party entities outside the home as DSOs, aggregators or some control companies are responsible for deciding how and when specific customer loads will be controlled [24]. As DLC electricity prices are typical lower than the normal price, a 0.015 €/kWh discount is applied. The appliances under control include not only the semi-Auto appliances but also Auto appliances according to TABLE II. Therefore and because of the direct control DLC provides the best effects as can be seen in Fig. 14 for the same example.

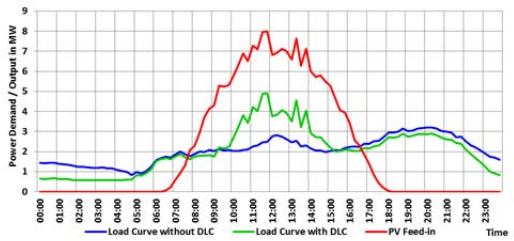

Fig. 14 DLC Effect on the daily Load Curve (5000 HHs)

GRID SIMULATIONS AND RESULTS

Worst-case load flow calculations for maximum PV feed-in at minimum load during the PV feed-in time are used to identify those synthetic test grids with possible congestion problems. Scenarios with 25 %, 50 % and

75 % of the HHs with PV are considered. No congestions were found in urban LV grids because of the low PV potential compared to the grid capacity. Different from that suburban and rural LV grids show heavy congestions when the PV share increases to 50 % and beyond. The rural and suburban synthetic LV grids with a 75 % PV share are selected to test the DSI effects for congestion alleviation by probabilistic time series load flow calculations. TABLE V presents the simulation results in terms of congestion hours per year.

TABLE V: TIME SERIES LOAD FLOW SIMULATION RESULTS
$T_{T\ overload}$-Transformer Overload Duration, $T_{L\ overload}$-Distribution Lines Overload Duration, $T_{U\ max}$-Overvoltage Duration [h/a]

Rural		w/o DSI	TOU	RTP	DLC	Suburban		w/o DSI	TOU	RTP	DLC
1a	$T_{T\ overload}$	30	26	28	12	3a	$T_{T\ overload}$	410	405	403	342
	$T_{L\ overload}$	0	0	0	0		$T_{L\ overload}$	328	326	326	285
	T_{Umax}	493	480	473	390		T_{Umax}	667	663	657	524
1b	$T_{T\ overload}$	339	335	332	286	3b	$T_{T\ overload}$	0	0	0	0
	$T_{L\ overload}$	59	57	57	43		$T_{L\ overload}$	12	8	8	2
	T_{Umax}	498	486	474	369		T_{Umax}	0	0	0	0
2a	$T_{T\ overload}$	172	165	167	128	4a	$T_{T\ overload}$	0	0	0	0
	$T_{L\ overload}$	76	72	71	53		$T_{L\ overload}$	53	49	49	27
	T_{Umax}	364	333	327	257		T_{Umax}	0	0	0	0
2b	$T_{T\ overload}$	342	339	336	276	4b	$T_{T\ overload}$	0	0	0	0
	$T_{L\ overload}$	0	0	0	0		$T_{L\ overload}$	44	37	38	21
	T_{Umax}	0	0	0	0		T_{Umax}	0	0	0	0

With the simulation results, the SGM for the congestion targets are calibrated as benefit points in TABLE VI. Their value ranges are linearly mapped to a scale from 0 to 10, where 0 marks the overload or overvoltage duration without DSI and 10 marks zero congestion hours. The three aspects of congestions are weighted equally. The costs include both capital and operating cost [25]. They can be categorized into cost for ICT systems and discounting cost for the electricity prices. For cost comparison the annual costs are calculated considering amortization for each LV grid. From the cost and benefit results, TOU and RTP have very low benefit points for LV congestion alleviation, but DLC can provide much better effects. The cost for each DSI option increases with the number of HHs and the ICT requirements. The cost of DLC is still very high, but as Fig. 14 shows it performs pretty well to follow the PV feed-in. With the raise of heat pumps and electric cars the DSI potential will certainly increase further.

TABLE VI: COST AND BENEFIT RESULTS

Cost (k €/a)	**1a**	**1b**	**2a**	**2b**	**3a**	**3b**	**4a**	**4b**
TOU	0.6	1.4	3.6	4.5	6.6	7.3	7.0	6.7
RTP	2.0	3.5	10.1	12.4	17.4	18.1	18.3	17.4
DLC	3.1	5.2	13.2	16.3	24.8	23.8	27.4	25.8
Benefit point	**1a**	**1b**	**2a**	**2b**	**3a**	**3b**	**4a**	**4b**
TOU	0.5	0.2	0.6	0.0	0.1	0.9	0.2	0.5
RTP	0.4	0.3	0.7	0.1	0.1	1.1	0.3	0.4
DLC	2.7	2.3	2.8	0.6	1.7	2.7	1.7	1.7

CONCLUSION

From the cost/benefit analysis the ability of DSI to solve congestions in LV grids is limited as shown in extensive simulations. In particular TOU and RTP show poor result. DLC is more promising but has higher cost. Therefore it is necessary to investigate other measures provided by the smart grid framework and to compare cost and benefits quantitatively against DSI.

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