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Automatic topology identification of weak low voltage networks and load management strategies for micro-mobility applications

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***Abstract*— With 55 % of the world's population residing in urban areas in 2018 and a projected rise up to 68% by 2050 [1], the challenge of integrating sustainable mobility solutions into the existing urban infrastructure is gaining worldwide attention. The new opportunities come with a challenge, which is focused on managing a dynamic combination of generations and loads on an existing infrastructure that is designed based on a set of particular standards and specification to support its static original conditions. Networks reinforcement is one solution, however this solution is expensive and typical usage times are short. An alternative is to integrate smart grid control techniques, avoiding relatively larger investments. For this purpose, an energy management system retrofitted to an existing public street lighting network can provide a more economic and reliable solution. In this work a systematic approach to optimizing the scheduling of loads and power flows in terms of maximizing load acceptance rate and the total delivered energy is presented.**

***Keywords*—Network Topology; Electro-mobility; Micro-mobility; Energy Management; Load Management Strategies, Smart Grid**

I. Introduction

A. Micro-mobility

The use of digital information and communication technologies for the sustainable development of cities characterizes the transformation to a smart city [2]. This provides a basis for solving social, political, economic and ecological challenges. Examples are concepts for the shared use of infrastructure, controlling traffic routes, improving safety and security, and increasing energy efficiency.

Alternative environmentally-friendly urban mobility solutions are expanding worldwide, as more car manufacturers are competing to add more e-vehicles in their line-up, more stricter regulations are favoring electric-mobility, and an ever-increasing number of cities around the world are optimistically experimenting with the concept of micro-mobility. According to IEA [3] shared electric foot scooters flourished very rapidly in 2018 and early 2019 in major cities around the world, operating in around 129 cities in the United States, 30 in Europe, 7 in Asia and 6 in Australia and New Zealand.

Germany's Federal Ministry for Economic Cooperation and Development (in German: Bundesministerium für wirtschaftliche Zusammenarbeit und Entwicklung - BMZ) [4] expresses that the concepts of urban mobility need to be rethought and, specifically, planned and implemented in a more sustainable, inclusive and integrated manner than has been the case until now. The German Development Cooperation is advocating for cities to move their transport systems towards sustainability in order to become more climate-friendly, healthy, inclusive, safe, prosperous and attractive [4]. With the passage of the Small Electric Vehicles Act (in German: Elektrokleinstfahrzeuge-Verordnung - eKFV), e-scooters were declared street-legal in Germany as of 15 June 2019 [5]. In drafting the eKFV, the German government specifically referenced the sustainability of e-scooters, noting their ability to increase urban mobility [5]. As micro-mobility devices

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are emerging as a new trend and popular solution for the last mile within the urban areas, the main challenge beyond improving legislation, expansion of pathways, and safety remains to be the provision of adequate charging infrastructure and load management strategies.

B. Low Voltage (LV) Distribution Network

There is a growing attention toward developing innovative service-oriented electric systems in the LV distribution network. The new trend is partly driven by the emergence of distributed generation and sector-coupling applications such as electro-mobility. The impact of expansion of electro-mobility is significant for the gird operators, who will need to provide the charging infrastructure, as there is a need to manage line congestion and voltage drops of the energy networks [6]. The new opportunities come with a challenge, which is focused on managing a dynamic combination of generations and loads (often fluctuating, unpredictable and experiencing bidirectional flows) on an existing infrastructure that is designed based on a set of particular standards and specification to support its static original conditions.

Optimal operation of the distribution networks depend on the correct estimation of its bus and node states (voltage and power consumption) and its operational radial topology. However, lines in the network still suffer from limited real time metering that hinders the network operator from learning the true topology [7]. The information of the underlying network topology is useful for efficient integration of distributed generation and efficient management of controllable loads (electro-mobility applications) in distribution networks. Further, for a reliable state estimation in a distribution network, accurate information of the network topology is essential [8].

There are several limitations which should be satisfied during the planning and operation. The DIN EN 50160 Characteristics of Voltage in Public Electricity Networks is a European Standard that defines and specifies the essential characteristics of the main voltage at the network connection point under normal operating conditions. According to this standard the grid frequency of 50 Hz has to be kept constant by balancing supply and load and the voltage changes should not exceed ±10% of the nominal voltage (230 V at low voltage network) [9].

C. Smart Poles

Public street lighting networks are conventionally designed for the specific application of illumination during certain dark intervals of the day. Figure 1 shows the illumination data and switching on and off times simulated from the weather data obtained from the university of Oldenburg weather data [10]. It is assumed that the switching on and off follow the sunrise and sunset times, the activity zone is defined as a 1-hour margin after and before these switching times, where there would be no conflict between the illumination and other applications. For simulation purposes, it is assumed that lamps are switched on, if the luminance from the sun drops below 15 lx.

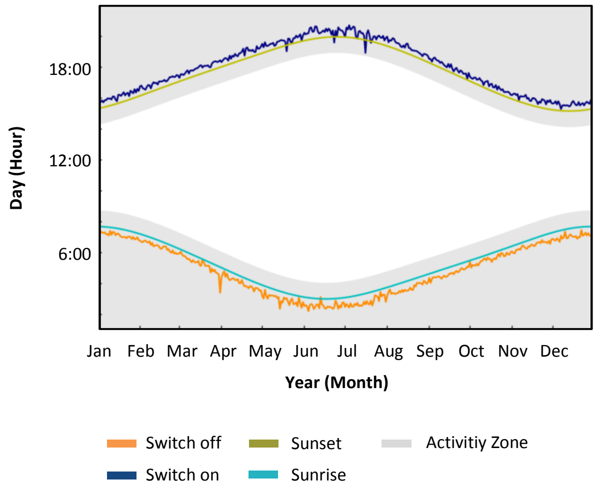


Fig. 1: Lamp switching times, sun times and activity zone for 2016

This unique behavior provides the opportunity to use the existing power grid infrastructure to provide electricity service to other urban electric applications when the lights are switched off. Potential hypothetical applications may include: micro-mobility, public USB or environmental sensors, generally speaking a public hub for energy and data.

This work was carried out as part of the project “Smart Poles” (Smarte Pfosten in German), funded by the ZIM program of the Federal Ministry for Economic Affairs and Energy (BMWi, 16KN062820) that aims to retrofit an existing street lighting network, where a smart platform of measurement, computation and communication devices will be developed and installed into the existing poles. An energy management system will be implemented to manage a variety of new energy applications. The new smart layer will enable the existing infrastructure to dynamically manage the power flow beyond its original purpose of illumination. The existing poles are spread relatively homogeneously through the urban areas and conveniently located near the micro-mobility pathways; therefore, they are the ideal candidate to be retrofitted with smart charging stations.

II. LOAD MANAGEMENT

The VDI 4602 guideline describes energy management as a coordinated, organized and systematic coordination of the procurement, conversion, distribution and use of energy to meet the requirement under ecological consideration and economic objectives described [11]. The energy management can generally be considered from both a technical and an organizational point of view [12]. In the organizational approach, the focus is on processes such as energy purchasing, energy efficiency and resource protection, whereas the technical approach looks at energy-consuming plants.

Energy management has four important functions for the safe and economical management of the distribution network, which are explained below [13].

1. The load forecast analyzes past load profiles and creates a prediction of the expected loads for the network.
2. The optimized load flow, taking into account active and reactive power flows, node voltages and equipment utilization, ensures compliance with permissible tolerances and creates timetables for producers and consumers.
3. The state estimation provides data for the assessment of the network status and enables the warning of potentially inadmissible behavior in the network.
4. The network security calculation, which is carried out before and during network faults, anticipates the failure of equipment and the effects of interferences in operation.

Energy management in the distribution network converted to a smart grid can be carried out in the sense of demand side management (DSM) or supply side management (SSM).

In the energy management of the smart lighting poles, the measurement, checking, prediction, planning and recording of the electrical consumption are to be implemented as part of a DSM. The hardware built into each pole is basically the equivalent of the ¨smart meter" installed in the smart grid at the consumer, which records and communicates performance data and issues and executes control commands. Methods such as multiple regression, exponential smoothing, stochastic time series, fuzzy logic or neural networks can be used for prediction [14]. In contrast, the prediction in the energy management of the smart poles uses a knowledge-based expert system which records device load profiles and trusts in the same course of the load when used again.

Due to the high demands on data exchange in systems with central load control, strategies with decentralized intelligence are also being pursued. So-called "agents" process data locally and carry out an independent control based on specifications and observations. This multi-agent system as a whole is geared towards a higher-level goal, with individual agents communicating with one another in a hierarchical structure [15].

The decisions about the acceptance of an application, a switching permit or a switching schedule for the smart poles are made centrally by the energy management. Smart poles still independently monitor and control the performance of connected applications and perform an emergency shutdown. A multi-agent system is therefore only partially implemented because there is no direct communication between the smart poles in this study.

In the literature, strategies and optimizations for electrical energy management in different dimensions and varying components are considered. For example, the scope of activity can include only one house or an entire settlement, whereby there can be a different composition of controllable generators, storages and consumers.

The aim of the DSM is in most of the work to reduce costs or to compensate for peak loads, which usually occur coincidently. Traditionally, the DSM can be carried out in six different ways [16] stated below and illustrated in the following figure 2.

a. *Peak shaving:* The performance of controllable loads is reduced at times of high network utilization in order to ensure the operational security of the network without having to invest in the expansion of the network.

b. *Valley Filling:* Loads are created that can be switched on at times of low network utilization.

c. *Load Shifting:* The load for the network is shifted from times of high utilization to times of low utilization, which can be implemented by energy storage.

d. *Strategic Conservation:* The consumption of loads is reduced in the long term by increasing efficiency.

e. *Strategic Load Growth:* If there is a need to increase the number of loads, planning takes place strategically and is limited by a certain limit.

f. *Flexible Load Shaping*: The consumption of individual loads by users is anticipated, after which these loads are planned under given conditions. Incentives are created for users and the interruptions of loads are also considered.

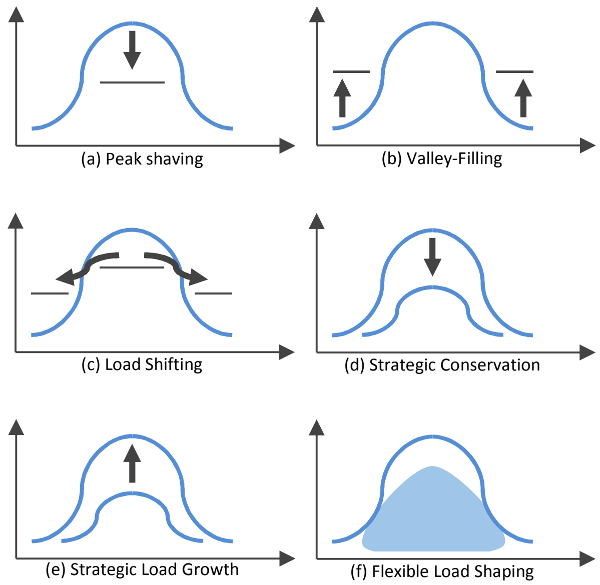


Fig. 2: Illustration of common DSM strategies

Load Shifting and Flexible Load Shaping are found suitable for the load management of the applications in this project. Application examples of related strategies are shown in the following paragraphs.

Abele et al. plans the load distribution of machine tools in two steps [17]. First, flexible switch-on times of additional loads are identified and then distributed in a suitable time, so that peak loads are reduced without reducing productivity.

Jiang and Chens describe the identification of load profiles of individual devices from a total load profile combined with a usage time analysis in order to plan loads not only cost-effectively but also user-friendly [18].

Jaiswal et al. describes the strategy in which using price signals on the mobile phone the user can actively manage the switch-on times of his devices and actively help shape the timetable [19].

Khan et al. regulates household loads through a central energy consumption planning unit in the smart meter by requesting applications and accepting or rejecting them with regard to the maximum available power in order to avoid peak loads [20]. A simulation showed a reduction of the peak load by up to 33.3% and lower electricity costs.

Agnetis et al. creates timetables for home applications [21]. In order to balance loads, an integer linear optimization and a heuristic algorithm are used to save computing power and storage space. The correct functioning was proven by simulations.

Lu et al. has linked the objective of reducing costs for planning the applications with a weighting for user friendliness in order to increase the acceptance of DSM applications [22]. Applications can be switched in intervals of one hour and partially interrupted. Through linear optimization of the target functions, incentives are used and electricity costs are reduced by 34.71%.

Li et al. shows a negotiation-based iterative approach for the planning of power-consuming applications in the home area in conjunction with photovoltaic generation and an energy storage device [23]. The applications are divided up as far as possible and scheduled according to the loading / unloading behavior of the storage. The optimal schedule is determined by dynamic programming. Electricity costs can be reduced by up to 60.95%.

Hafeez et al. compares a Genetic Algorithm (GA), Binary Particle Swarm Optimization (BPSO), Wind-driven Optimization (WDO) and Genetic Wind-Driven Optimization (GWDO) for cost reduction through load planning for scenarios with and without renewable energies and energy storage [24]. All optimization procedures delivered better results than unplanned loads, with GWDO not only showing the lowest electricity costs, but also the best load balancing.

III. Project Implementation

The focus of the main project is developing a platform to facilitate the integration of electro-mobility applications in existing and future smart city infrastructures. From the research perspective, the project consists of three consecutive phases that complement each other to produce common results. The first phase is the development of an automatic topology identification algorithm for unknown weak low voltage networks, the second phase deals with the development and analysis of load management strategies, and the third is implementation and integration of a smart pole prototype in an energetic community with high penetration of renewable energy. The last phase remains outside of the scope of this paper.

The load management module relies on the output results from three sub modules, including automatic topology identification, dynamic power calculation, and electro-mobility profile generation (figure 3).

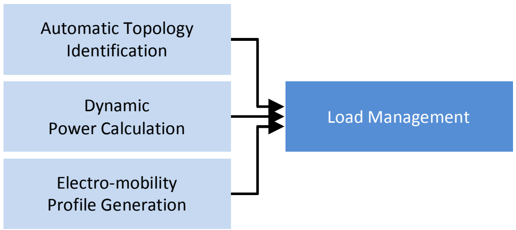


Fig. 3: The energy managemt components

A. *Automatic Topology Identification*

Growing electricity demand at the urban low voltage weak networks, suggest using the existing network in a managed way for multiple applications, including the fleet of new electric micro-mobility devices (i.e. e-scooters). When the new micro-mobility applications are connected to a weak low voltage network, it experiences higher voltage variations compared to when connected to a stronger network. This management relies on detailed knowledge of the network topology, which is defined as the arrangement of nodes and branches of a network and the impedance between them.

Figure 4 aims at explaining topology identification of a network by illustrating the difference between a known and an unknown topology. In this example, a schematic of a radial network with multiple loads (i.e. lighting poles) connected to a LV transformer is presented.

Figure 4 (left) shows a presumed LV network with an unknown topology where no information about the connection between the nodes (loads), and the impedance of lines (cables) is available.

Figure 4 (right) shows the revealed topology of the same network with known information about the node connections and line impedances.

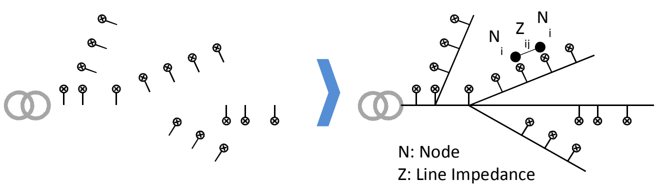


Fig. 4: Unknown (left) vs. known topology (right)

A major challenge in topology identification is having access to accurate network data. The knowledge of topology and/or impedance matrix (representing node-to-node impedance of the network) is often unavailable in LV distribution networks. Even if there is such knowledge, it may be outdated or wrong due to newly added or reconfigured partial networks and/or human interaction without information updating [25]. The information of the underlying network topology is useful for efficient integration of distributed renewable generation (PV) and efficient management of controllable loads (electro-mobility, in the case of this study) in weak LV networks. Knowing the arrangement of loads on the network is essential to make efficient scheduling of connected loads while maintaining the power quality (managing voltage drops and avoid overload of the lines), therefore the topology needs to be identified.

In the work of [26], an automatic method for identification of low voltage networks topology is presented. The method relies on measurement of voltage and power at every node of the network with the unknown topology. Therefore, the project objective is to retrofit every node (lighting pole with the connected load) with relay hardware to enable controllable loads and a measurements device that communicates with a central energy management system.

The first phase involves development of an algorithm for the identification of the topology of a modeled street lighting network. A voltage correlation method is used in this work, which uses the measured voltage data from every node in the network. Dynamic control over loads will provide the opportunity to isolate single loads (on and off) one at a time and measure the voltages at every node throughout the network. Then an algorithm based on series of data manipulation and mathematical calculations is developed to identify the network topology. Using Jenks Natural Break clustering [27], the topology becomes visible in a matrix illustration of the measured voltage drops. The proposed algorithm was further evaluated and validated by comparing the output graphical representation of topology with the model developed in a Power Factory model. The algorithm is suitable for the topology identification of single phase LV networks and can be used as a sub-module in a smart energy management system.

B. *Dynamic Power Calculation*

As a sub-module to the load management module, an algorithm to calculate the available power at any given node for a single-phase network at a steady-state operation is developed. This algorithm calculates the voltage drop at every node based on the known information about the power of each connected load and the network topology. The calculated voltage drop value is used to determine the available power at each node. This algorithm is tested and verified with a simulated model in DIgSILENT PowerFactory[1].

[1] DIgSILENT | PowerFactory: PowerFactory is a leading power system analysis software application for use in analysing generation, transmission, distribution and industrial systems. https://www.digsilent.de/en/powerfactory.html

C. *Micro-mobility Profile Generation*

One of the main inputs to the load management module is the electro-mobility profile, defined as the daily behavior of electro-mobility applications in terms of distance traveled (km) and/or energy consumed (kWh).

1) Data Set A: Electro-Mobility Profiles

Based on presence times of employees at an office building, arrival and departure times were obtained. The energy requirements were estimated by the supplied distances between home and workplace.

2) Data Set B: Enhanced Micro-mobility Profiles

Data set A is used in the first trial of this study. In order to investigate the impact of micro-mobility devices on the LV weak grids, a second set of profiles based on an average industry standard e-scooter with the specific characteristics shown in table 1 and a set of defined community users according to the information presented in table 2 is generated.

TABLE 1: MICRO-MOBILITY APPLICATION (E-SCOOTER) PROFILE

E-scooter range	48 km [28]
E-scooter average speed	9.13 km/h [29]
E-scooter consumption	633 Wh/km [30]

TABLE 2: COMMUNITY PROFILE

Community size (micro-mobility users)	100 user/residents living in Oldenburg, Germany
User types	Student, Worker, Retired
Community area/size	A round area of 5 km diameter
Points of interest	Grocery, Café, Shopping, University, Gathering, Hospital
Charging stations	4 (uniformly/equally-distance spread), reaching the charging station means complete recharge

The model is designed so that every user type, including student, worker, and retired person is associated with a set of behaviors that influence the usage of micro-mobility devices to move from home to a point of interest (Grocery, Café, Shopping, University, Gathering, Hospital). The e-scooter can charged either at home or designated charging points, with the assumption when the battery level is at zero charge. By this definition the usage of e-scooter occurs at a certain period (start and end time) of the day and for a range depending on the distance between the location of the users and points of interest. Weather patterns (i.e. rainy days of the year) are also integrated in the model, which influence the user's preference to take e-scooter over other forms of transport.

This model further analyzes the impact of distance travelled (or energy consumed) and location of charging points in the community on the network voltage drops.

D. *Development of Load Management Strategies*

The objective of this phase is to evaluate different load management strategies for weak low voltage networks with high penetration of electro-mobility applications. The strategies are intended to operate low voltage distribution networks close to their physical and operational limits, which are the current rating of the cables and the voltage level for the safe operation of the applied load.

For a safe operation, the power quality with a voltage and frequency stability needs to be provided according to the DIN EN 50160 mentioned in the previous section. Low voltage distribution networks are dimensioned based on the expected loads and their simultaneity factor. Problems will occur if the loads exceed the original specifications or operation durations. In order to avoid such operation conditions, the grid might be reinforced, or the loads might be managed to avoid the simultaneity of high loads and achieve higher utilization factors.

The operation of week grids with the example of street light power grids which are usually dimensioned for the sole operation of street lights is simulated. Due to efficiency gains provided by the LED technology, energy capacities become available which might be used for other applications [31]. In case of street light switching by dedicated signals and not by turning off the power supply, the power grid could also be used during day times [32]. Such a street lighting network was originally never intended to supply energy for electro-mobility applications; therefore it is not adequately dimensioned.

In this work different load management strategies for the operation of a street lighting network, which has to provide power for electro-mobility is analyzed on a simulation model.

Load profiles for the electro-mobility were set to simple operations with first constant power and later constant voltage, as well as first constant voltage and later constant power. The strategies were tested for two exemplary network topologies, which need to be known to the load management system.

One topology is a stab line which is most sensitive for problems with the supplied operation voltage at the last access point. The second topology is a randomly chosen topology shown in figure 5.

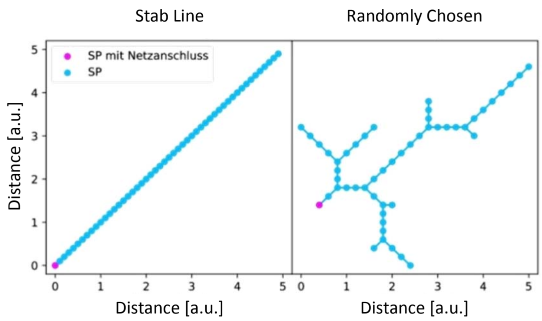
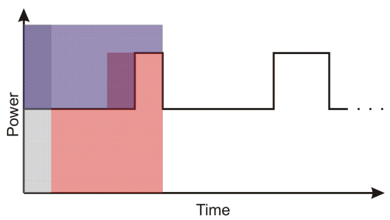


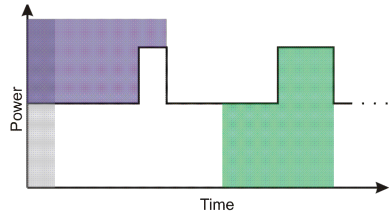
Fig. 5: Different topologies: stab line, (left) and randomly chosen (right)

Five different load management strategies were identified and simulated over the selected topologies as illustrated in figure 6.

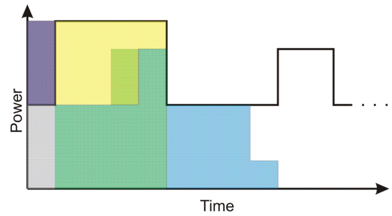
1. *Immediate Acceptance (IA):* Loads are immediately accepted unless the acceptance is causing an overload. In the latter case, loads are finally refused (red).
2. *Time Based Shift as Whole (TSW):* The new load causing an immediate overload is time shifted as a whole without interrupts until the demand can be met till the departure (green) or it is refused.
3. *Time Based Shift & Dispatching for All Remaining Loads (TSD):* All new (green) and remaining loads (yellow) are rearranged / shifted as a whole without interrupts similar to TSW. An interrupt of a running load may be introduced (blue).
4. *Time based Shift and Split (TSS):* The new load causing an immediate overload is shifted also as segments with interrupts until the demand can be met till the departure (green) or it is refused.
5. *Optimized Split (OS):* The complete schedule is rearranged, split and shifted for all load with interrupts.



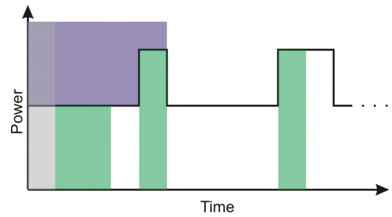
a) Immediate Acceptance (IA)



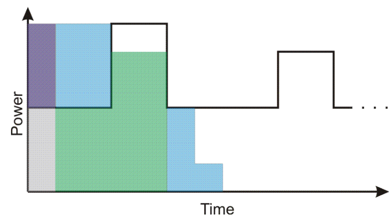
b) Time Based Shift as Whole (TSW)



c) Time Based Shift & Dispatching for All Remaining Loads (TSD)



d) Time based Shift and Split (TSS)



e) Optimized Split (OS)

Fig. 6: a) IA, b) TSW, c) TSD, d) TSS, e) OS

Maximizing the load acceptance rate (%) and the total delivered energy (MWh) are identified as the two main parameters to be calculated, optimized and compared amongst strategies.

IV. RESULTS & OUTLOOK

A. Micro-mobility Porfiles

1) Data Set A: Electro-Mobility Profiles

The average arrival and departure times with standard deviation for each employee are shown in figure 7.

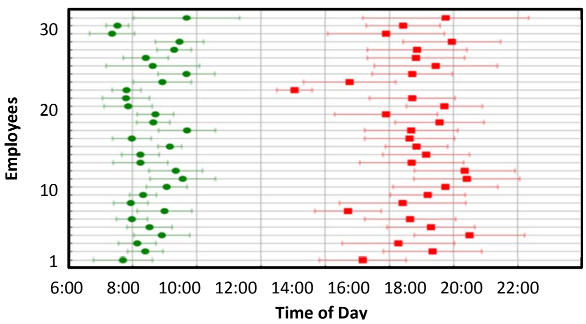


Fig 7: In and out timestamps of employees

On average, the employees start their work at 08:32 ± 01:00 a.m. and leave the workplace at 17:11 ± 01:54 hours. The average time between arrival and departure times is 8.00 ± 1.95 hours. During this time there are interruptions in working hours. The median and interquartile range of the interruption duration is shown in figure 8.

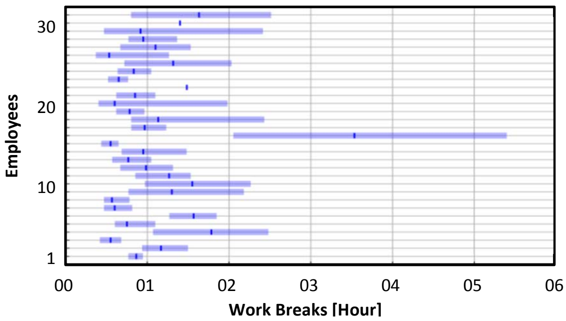


Fig 8: Work breaks of employees

With these underlying profiles a complete year of operation was simulated with the previously mentioned strategies for two network topologies at work (presence times, figure 6, top) and at home (inverted presence times, figure 6, bottom).

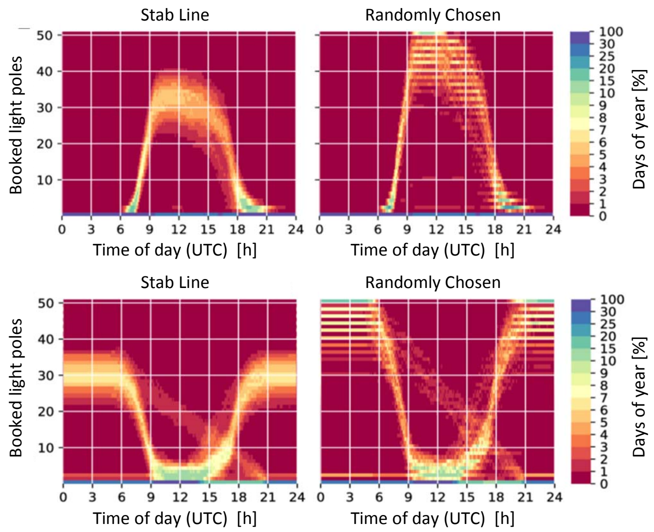


Fig. 9: Simulated profiles with presence at Work (top) and Home (bottom)

2) Data Set B: Enhanced Micro-mobility Profiles

A sample of the load profiles generated in this section is presented in this section in two formats. In the first format the Daily Average profile (figure 10) is graphed, which is defined as averaged distance travelled by each user per day over a year. In the second format the Average Day profile (figure 11) is constructed, which by definition is taking average of each minute of every day over the full year, and represent for one day.

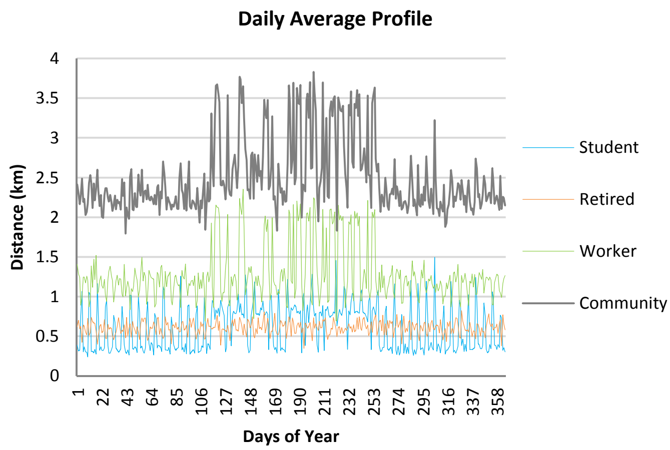


Fig 10: Daily Average profile of community travel (km)

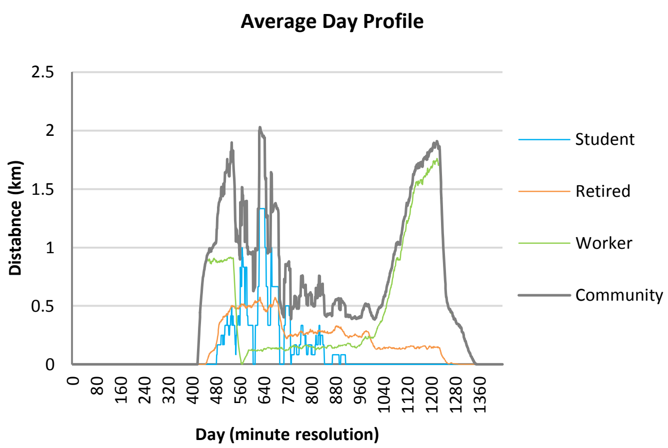


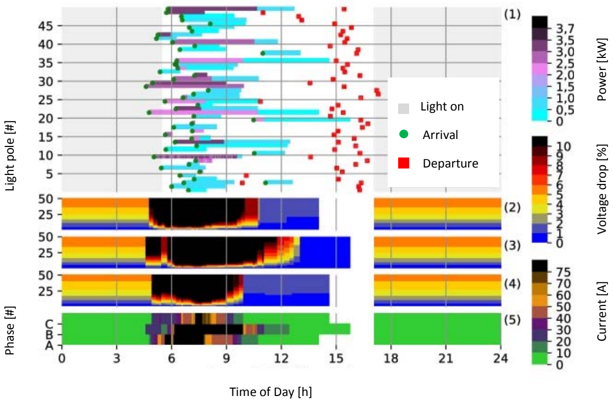
Fig 11: Average Day Profile of community travel (km)

TABLE 3: COMMUNITY CUMMULATIVE MICRO-MOBILITY PROFILE

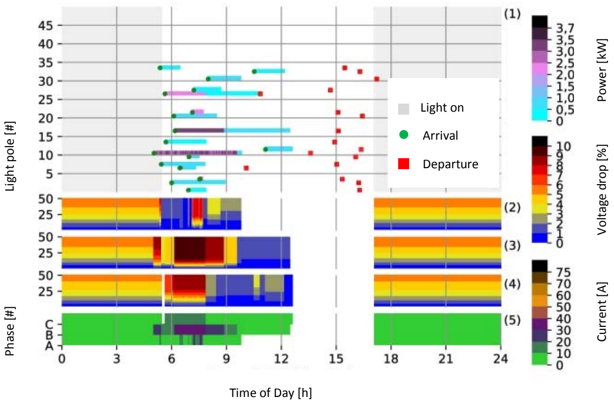
Total Distance Travelled (km/year)	910.983
Student (km/day)	0.60725
Retired (km/day)	0.60772
Worker (km/day)	1.28086

B. *Energy Management Startegies*

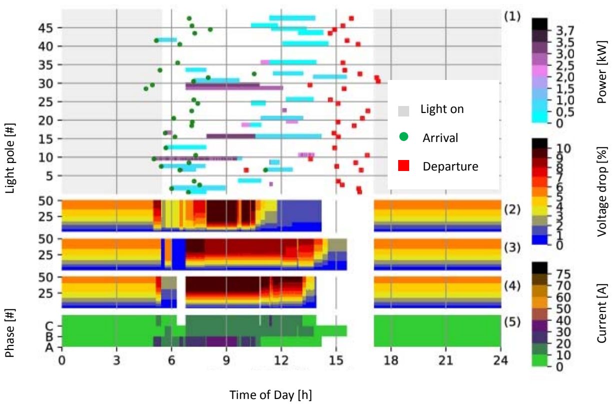
One example for the operation with time based shift and split of the loads of the street light power grid with random topology is shown in figure 12. Based on the algorithm 24 loads out of 32 load were accepted. The algorithm ensures a safe operation of the grid, as can be seen by the compliance of the operation conditions. An excess would be indicated by values illustrated in black.



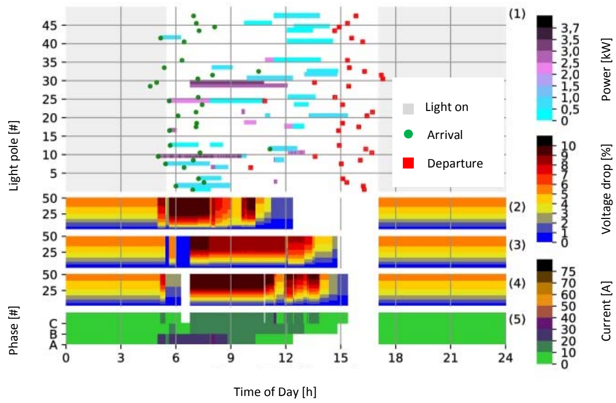
a) No management



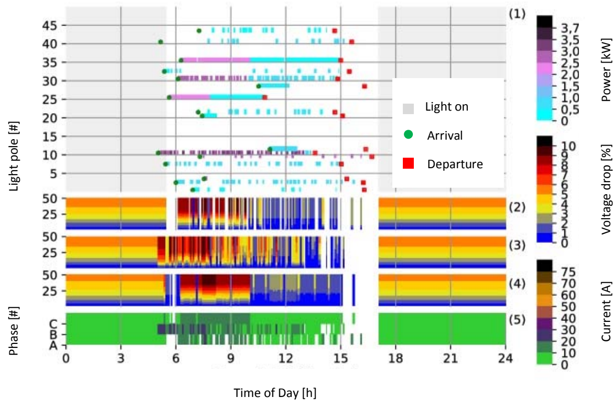
b) Immediate Acceptance (IA)



c) Time Based Shift as Whole (TSW)



d) Time based Shift and Split (TSS)



e) Optimized Split (OS)

Fig. 12: Power, voltage drop and current at the access points for one day managed with time based shift and split

The results for the immediate acceptance (IA), time based shift as whole (TSW), time based shift and dispatching for all remaining loads (TSD) and time based shift and split (TSS) are shown in table 3. The latter algorithm show higher acceptance rates and delivered energies.

TABLE 3: ACCEPTANCE RATES AND DELIVERED ENERGIES FOR THE SIMULATED SCENARIOS

		Acceptance rate [%]			
		Stab line network		Random network	
		Work	Residence	Work	Residence
Mean	IA	52,52	57,12	85,34	93,37
	TSW	79,41	75,4	98,85	99,87
	TSD	80,17	75,72	99,6	99,93
	TSS	80,2	75,54	98,9	99,88

		Delivered energy [MWh]			
		Stab line network		Random network	
		Work	Residence	Work	Residence
Mean	IA	8,15	8,16	18,39	20,07
	TSW	13,93	10,59	22,16	22,08
	TSD	14,17	10,73	22,54	22,14
	TSS	14,28	10,76	22,18	22,11

Our results showed an increased amount of acceptance of loads and increase of delivered energy for all strategies except of the complete dispatching of all loads. The decrease of the time resolution increased the delivered energy. The time based shift as a whole showed less effect, than the other strategies.

The optimized splitting showed no improvements and failed in our simulation because the large solution space with 15 minute time steps could not be solved with the chosen genetic algorithm. There are only marginal differences amongst each other, which are not consistent in correlation to the topology or location.

Due to the voltage drop of long power lines, less energy could be delivered in the stab line compared to the random network.

A future vision for the project is to implement the proposed strategy to increase the share of locally generated renewable energy from distributed PV systems by integrating a smart load management system to support micro-mobility applications (figure 13).

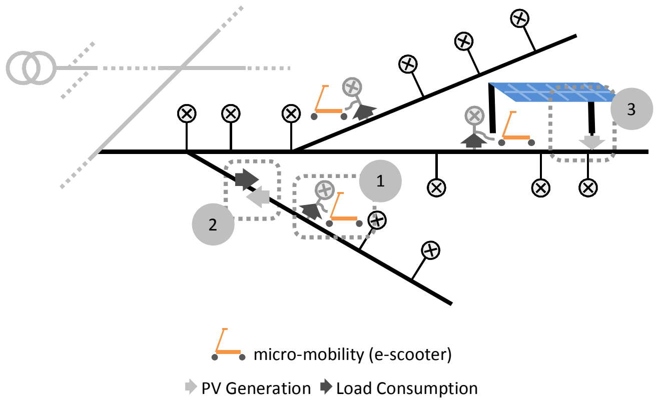


Fig. 13: Load management of micro-mobility applications with smart poles within a neighborhood with high penetration of renewable energies, 1) Charging, 2) Bi-directional Power Flow, 3) PV Feed-in

V. Conclusion

In this work a systematic approach for load management of electro-mobility application is developed. Different strategies were defined and were analyzed. Comparing the strategies, Time Based Shift of loads showed higher acceptance rates and delivered higher level of energy compared to the instantaneous acceptance of loads. Using these strategies, a safe operation of the power network could be ensured.

The approach is suitable for topology identification of LV networks and can be used as a sub-module in the intelligent energy management system for wide variety of micro-mobility charging applications, including e-scooters. If the set of information about a target community including, the size, users behavior, micro-mobility device characteristics and geo-location of points of interests is provided the load management algorithm is capable of optimizing the scheduling of loads and power flows in terms of maximizing load acceptance rate and the total delivered energy.

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