

RESEARCH

Open Access



Choosing the right model for unified flexibility modeling

Jonathan Brandt^{1*}, Emilie Frost^{2,3}, Stephan Ferenz^{2,3}, Paul Hendrik Tiemann^{2,3}, Astrid Bensmann¹, Richard Hanke-Rauschenbach¹ and Astrid Nieße^{2,3}

*Correspondence:
brandt@ifes.uni-hannover.de

¹ Institute of Electric Power Systems, Leibniz University Hannover, Appelstraße 9A, 30165 Hanover, Germany

² Department of Computer Science, Carl von Ossietzky University of Oldenburg, Ammerländer Heerstraße 114-118, 26129 Oldenburg, Germany

³ OFFIS - Institute for Information Technology, Escherweg 2, 26121 Oldenburg, Germany

Abstract

Using aggregated flexibility from distributed small-scale power devices is an extensively discussed approach to meet the challenges in modern and increasingly stochastic energy systems. It is crucial to be able to model and map the flexibility of the respective power devices in a unified form to increase the value of the cumulative flexibility from different small-scale power devices by aggregation. In order to identify the most suitable approach for unified flexibility modeling we present a framework to evaluate and compare the advantages and disadvantages of already existing modeling approaches in different levels of detail. As an introduction to flexibility modeling and as a basis for the evaluation process we initially provide a comprehensive overview of the broad range of flexibility models described in scientific literature. Subsequently, five selected modeling approaches allowing the generation of a unified flexibility representation for different power devices are presented in detail. By using an evaluation metric we assess the suitability of the selected approaches for unified flexibility modeling and their applicability. To allow a more detailed performance analysis, the best evaluated models are implemented and simulations with different small-scale devices are performed. The results shown in this paper highlight the heterogeneity of modeling concepts deriving from the various interpretations of flexibility in scientific literature. Due to the varying complexity of the modeling approaches, different flexibility potentials are identified, necessitating a combination of approaches to capture the entire spectrum of the flexibility of different small-scale power devices. Furthermore, it is demonstrated that a complex model does not necessarily lead to the discovery of higher flexibility potentials, and recommendations are given on how to choose an appropriate model.

Keywords: Flexibility modeling, Distributed energy systems, Unified flexibility representation, Evaluation of flexibility modeling approaches

Introduction

International agreements to reduce greenhouse gas emissions result in growing numbers of renewable energies in the power grid, especially in recent years (Baringo and Rahimiyan 2020). Increasing the share of renewable energies is mostly accompanied by the contribution of volatile devices, such as photovoltaic systems and wind turbines, whose

feed-in behavior is highly dependent on the weather and therefore results in an alternating supply situation (Schott et al. 2019).

Additionally, emission reduction initiatives in the mobility and heating sector lead to a growing electrical demand, by a growing number of heat pumps and electric vehicles in the lower levels of electrical energy supply systems (Valsomatzis et al. 2014; Haakana et al. 2018; Keiner et al. 2019). This expanding of electricity demand can result in consumption peaks and amplifies the renewables-based fluctuation on the generation side, leading to imbalances and congestions in power grids (Valsomatzis et al. 2015).

Advancing digitalization and the transformation to cyber-physical energy systems open up new possibilities to tackle the aforementioned challenges. More precisely, this transformation process enables energy systems to react to the increasingly fluctuating feed-in and feed-out by using the operational flexibility of its consumption and generation devices (Schott et al. 2019). This can be achieved through a coordinated and information based operation of the different devices, also known as the systems interoperability (Elloumi 2012). Interoperability and the therefore essential standardization of exchanged information can promote access to flexibility related services needed to balance the increasing volatility in consumption and generation in modern power grids and thus ensure their stability (Elloumi 2012; Schott et al. 2019). To access the benefits from interoperable flexibility usage inside cyber-physical energy systems it is crucial to describe and model the flexibility of different energy system components in a unified way (Schott et al. 2019).

In order to manage a large amount of distributed energy devices, like within virtual power plants, unified flexibility modeling can be used to generate a standardized flexibility description of the different generation and consumption devices (Wang and Wu 2020; Ulbig and Andersson 2012). The standardization enables the bundling of the flexibility through aggregation leading to an increased value of the aggregated flexibility (Wang and Wu 2020; Šikšnys et al. 2019). This increase in value allows distributed small-scale devices to participate in energy trading and in the provision of ancillary services as found in cellular energy systems where supply security and energy trading rely on the aggregation of standardized flexibility from small-scale energy devices (Neupane et al. 2017; Šikšnys et al. 2019). In addition to the described value increase, the aggregation of flexibility from distributed small-scale devices increases the total amount of usable energy and the general usefulness of the devices by making them easier to manage (Šikšnys et al. 2019).

The paradigm shift currently taking place towards decentralized supply systems necessitates a reorganisation to distributed structures. This can exemplarily be found in cellular systems, where supply security and energy trading rely on the aggregation of standardized flexibility from small-scale energy devices (Šikšnys et al. 2019).

Due to the increasing importance of flexibility from distributed small-scale devices for supply security and energy trading in modern energy systems, we aim to identify the most suitable approach for unified flexibility modeling from the broad range of flexibility modeling approaches presented in scientific literature. Thereby, in addition to the technical and methodical quality of the modeling approaches, we take the suitability for practical implementation into account in the selection.

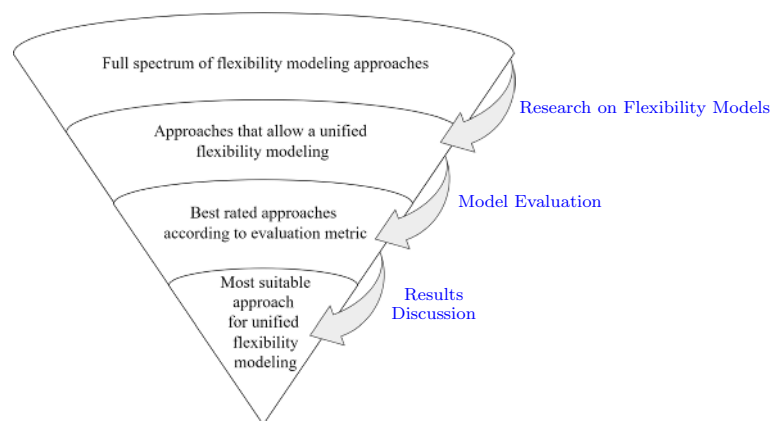


Fig. 1 Paper structure along the stepwise selection process to find the appropriate model for unified flexibility modeling

Barth et al. (2018) provide an overview of approaches for modeling demand side flexibility, evaluate the models using fourteen technical criteria to be fulfilled and present their own modeling approach for demand side flexibility that seeks to combine most of the fourteen criteria. Since the authors focus exclusively on demand side flexibility, they limit their perspective on the spectrum of energy devices considerably. This is why the work cannot be used as main support for an informed choice in the present case. Moreover, the evaluation of the modeling approaches is too theoretical and too superficial to derive a decision for a modeling approach whose quality depends not only on the mapping of technical criteria, but also on its practical performance and the required suitability for implementation.

For comparability reasons the analysis of the representation of flexibility options in energy system models, introduced by Heider et al. (2021), cannot be used as main source for decision making in this specific case. Although the authors provide a comprehensive overview of the extent to which different forms of flexibility can be represented by existing energy system models, the analysis does not address modeling aspects that are essential for making an informed decision in this particular case. The unified form of flexibility representation and the suitability of the modeling approaches for implementation and practical use are among these crucial aspects.

Therefore, to our knowledge, no overview and methodology exists in the remaining literature for evaluating, comparing and selecting flexibility modeling approaches. Due to this lack of decision support for an informed choice of a unified flexibility modeling approach, our contribution within this context comprises a comprehensive overview on flexibility modeling approaches, their stepwise evaluation by technical and practical criteria and the publication of an open source framework to support an informed choice for a unified flexibility model.

Figure 1 shows the stepwise search process for a unified modeling approach and the hyperlinks to the corresponding sections of this paper on the right. In a first step, a literature review helps to reduce the full spectrum of flexibility models to a handful of approaches, that seek to describe and model flexibility in a unified form. In this context, the following section [Research on Flexibility Models](#) provides a short impression

of the full spectrum of modeling approaches followed by a detailed presentation of the five modeling approaches that allow a unified flexibility modeling. Subsequently in section Model Evaluation, the selected models are rated regarding their advantages and disadvantages. To this end, an evaluation metric is presented that allows the selection of flexibility models to be further narrowed down. The remaining approaches are able to represent the greatest variety of devices and technical properties, while being most suitable for implementation. In a following step, described in section Implementation and Simulation, the remaining approaches are implemented and simulated with different power devices. As shown in Fig. 1, the simulation Results allow a detailed performance analysis and Discussion of the implemented approaches, leading to the lowest level in Fig. 1 and the recommendation for the most suitable model for unified flexibility modeling.

With this work, insights into the implementation and experimental phases within the Smart Grid Algorithm Engineering (SGAE) process model are given (Niese et al. 2013), by proposing a structured approach for one aspect within the development of a simulation environment for research on distributed control in cyber-physical energy systems.

Research on flexibility models

The different perspectives of relevant energy system stakeholders lead to various definitions of energy system flexibility in scientific literature (Degefa et al. 2021). Resulting from this versatile understanding of flexibility in energy systems and different modeling purposes, a diverse spectrum of flexibility modeling approaches can be found in scientific literature containing a limited number of approaches whose modeling methods allow the generation of a unified flexibility description for different power devices.

In order to meet the requirement of unification, the preselection for further analysis was based on the assumption that a suitable modeling approach should be applicable regardless of the device type and should at the same time allow a device sharp flexibility quantification and its uniform representation.

The majority of approaches reviewed focus on the modeling of specific device types as it is done by Yang et al. (2017) for battery storages and wind turbines, or by Hadi and Moeini-Aghaie (2019) for combined heat and power units. Other approaches, like the one presented by Nosair and Bouffard (2015), deal with the macroscopic modeling of the flexibility of whole electrical energy systems, also called operating reserve, that is essential to deal with the uncertainty resulting from an increasing penetration of renewable power generation. In this course the modeling approaches by Barth et al. (2018) and Petersen et al. (2013), focusing on mathematical optimization of flexible energy systems in the context of demand side management and virtual power plants, should be mentioned. Their exclusion from further evaluation is due to their holistic modeling approach allowing the optimization of whole energy systems by using the flexibility of the devices involved, but not the exclusive calculation of a unified flexibility representation for the individual devices. Furthermore, the flexibility modeling approach by Harder et al. (2020) should be mentioned in this context. Although the authors describe a method to quantify and price electrical flexibility based on steered optimization, it

Table 1 Overview of the analyzed flexibility modeling approaches

Modeling approach	Authors	Context	Modeling method	Shape of flexibility
Flexibility Trinity	Ulbig and Andersson (2012)	Operational flexibility in modern energy systems	Power node balancing	Maximal feasible power regulation from scheduled operation point
Multienergy Node	Chicco et al. (2020)	Distributed multi-energy systems	Matrix-based <i>Multienergy Node</i> balancing	Set of feasible deviations from scheduled operation point
Support Vector Data Description	Bremer and Sonnenschein (2014)	Evolutionary search methods in energy management	Meta-modeling of feasible operation regions in constrained optimization problems through a support vector decoder	Multidimensional search spaces containing all feasible operation plans
OpenTUMFlex	Zadé et al. (2020)	Provision of ancillary services through aggregation of distributed small-scale devices	Flexibility calculation based on available compensation processes in previously optimized operation plans	Flexibility offers consisting of feasible power deviations from an optimal schedule for a defined timespan
FlexOffer	Šikšnys et al. (2019)	Cellular energy systems	Device specific algorithms that allow a stepwise calculation of <i>FlexOffers</i>	<i>FlexOffers</i> : Power variable processes that can be postponed

is excluded from further evaluation. This is mainly due to its focus on flexibility from household systems rather than individual devices.

Table 1 provides an overview of five selected flexibility modeling approaches and their main attributes. The selection of these approaches for a detailed presentation and evaluation in the following sections is based on their ability to map the flexibility of different power devices in a unified form. Schott et al. (2019) and Tušar et al. (2012) also introduce modeling approaches meeting this requirement. These two are excluded from further evaluation in advance, due to their incomplete description of the applicable mathematical modeling method.

Flexibility trinity

In the context of a growing importance of operational flexibility for power system management Ulbig and Andersson (2012) present a flexibility modeling approach based on the so called *flexibility trinity*. The trinity consists of the power ramping capability ρ , the power capability π for up / down regulation and the energy storage capability ϵ of individual power system units.

In order to determine the three-dimensional flexibility of a power device, the authors present the method of *power node* balancing. Figure 2 shows the power node for a single energy device and the notation used for its mathematical balancing. The node consists of an electrical *Grid-side*, a non-electrical *Demand/Supply-side* and an energy storage that serves as a buffer between the electrical and non-electrical side.

From the mathematical balance of all in- and outgoing power, Ulbig and Andersson (2012) exemplary derive Eq. 1 to calculate the π related flexibility of a generation device, available at the analyzed point in time k . Here, the π related flexibility of a power system

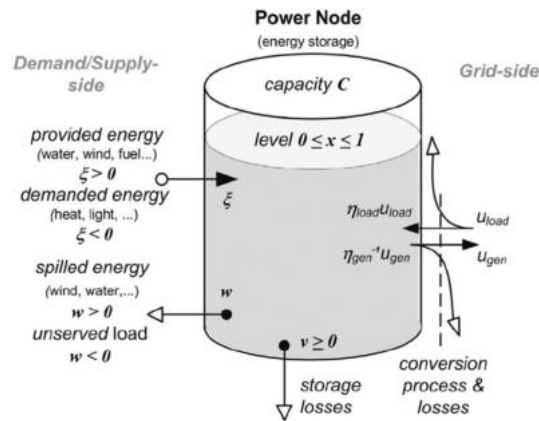


Fig. 2 Notation for a power node by Ullbig and Andersson (2012)

unit is defined as a set of all feasible power regulation points $\{\pi_i^\pm(k)\}$ forming from the difference between the set of feasible operation points $\{u_{gen,i}^{feasible}(k)\}$ and the set point of the generation unit $u_{gen,i}^0(k)$. Thereby, $\{u_{gen,i}^{feasible}(k)\}$ can be calculated by balancing the power node of the generation unit with the inclusion of the in- and outgoing power variables introduced in Fig. 2.

$$\begin{aligned} \{\pi_i^\pm(k)\} &= \{u_{gen,i}^{feasible}(k)\} - u_{gen,i}^0(k) \\ &= \left\{ \eta_{gen} \cdot \left(\xi - w_{max}^{min} - v_x - C \cdot \dot{x} \right) \right\}_{k,i} - u_{gen,i}^0(k) \end{aligned} \tag{1}$$

Due to the possibility to apply this method to all kinds of device types it is possible to generate a unified flexibility representation in the form of sets of maximal feasible power regulations from predefined operation points.

Finally, the authors point out the integral link between the flexibility key figures ρ , π and ϵ and the resulting possibility to theoretically derive the equations to calculate ρ related and ϵ related flexibility from Eq. 1.

Multienergy node

In the course of the discussion on the importance of operational flexibility to allow the decarbonization of distributed multienergy systems, Chicco et al. (2020) highlight the flexibility potentials resulting from intelligent shifting of energy across different sectors. In order to determine the flexibility of sector coupling power devices in distributed multienergy systems, the authors introduce the concept of *multienergy node*. The underlying idea is based on a combination of the *energy hub* concept introduced by Geidl et al. (2007) and the *power node* concept, presented in section Flexibility Trinity.

The resulting mathematical method for flexibility calculation is based on the understanding of a power device as a grey box whose in- and outgoing energy vectors are given by the one-dimensional arrays \mathbf{v}_i and \mathbf{v}_o , linked through a efficiency matrix \mathbf{H} as shown in Eq. 2.

$$\mathbf{v}_o = \mathbf{H}\mathbf{v}_i \tag{2}$$

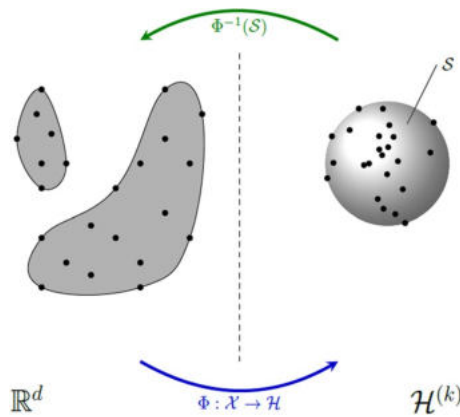


Fig. 3 Principle sketch of transforming a nonlinear flexibility space (left) into a high-dimensional sphere (right) by using Support Vector Data Description by Bremer (2015)

To be able to properly map the storage properties of a power device, Chicco et al. (2020) include the storage coupling matrix S and the array of storage energy derivatives \mathbf{P} into the equation. A more detailed breakdown of the outgoing energy array \mathbf{v}_o , composed by the array of net multienergy process demand ξ and the array of net enforced energy losses \mathbf{w} , leads to Eq. 3.

$$\begin{aligned} S\mathbf{P} &= H\mathbf{v}_i - \mathbf{v}_o \\ &= H\mathbf{v}_i - \xi - \mathbf{w} \end{aligned} \tag{3}$$

The authors describe the flexibility of a power device as the feasible up- and downward modification of the input energy array \mathbf{v}_i , that is dependent on and thereby limited by the previously presented variables and parameters, as shown in Eq. 3. Finally, Chicco et al. define a flexibility array ϕ containing all feasible positive (+) and negative (-) modifications $\Delta v_{i,k}$ of all ingoing energy vectors k in Eq. 4, that can be calculated for all kinds of devices and, therefore, understood as a unified representation of their flexibility (Chicco et al. 2020).

$$\phi = [\phi^{(+T)}, \phi^{(-T)}]^T; \quad \phi^{(+)} = \{\Delta v_{i,k}^{(+)}\}; \quad \phi^{(-)} = \{\Delta v_{i,k}^{(-)}\} \tag{4}$$

Support Vector Data Description

Bremer and Sonnenschein (2014) introduce an approach to model and map the flexibility of power devices in the context of distributed optimization for operational planning in an abstracted form. Feasible operation plans for different types of power devices are generated based on their device specific constraints by sampling the search space of the devices (Bremer and Sonnenschein 2013). In the mentioned approach by Bremer and Sonnenschein (2014), this feasible region forms a multidimensional and nonlinear search space for each device. The resulting solution spaces can be understood as a unified flexibility representation across all types of power devices. The authors describe a method to transform these highly complex flexibility spaces into easy to describe, high-dimensional spheres, by using Support Vector Data Description. Figure 3 shows a principle sketch of the described transformation process for one solution space. The

representation of possible operation plans as a high-dimensional sphere allows the classification of optimized operation plans as feasible or infeasible. This happens by using a Gaussian kernel to geometrically compare the analyzed operation plan with the support vectors of the spherical solution space. Additionally, Bremer and Sonnenschein (2014) present a decoder that makes it possible to move infeasible operation plans into the feasibility region and thus ensures the feasibility of stepwise optimized operation plans. The authors point out that the presented approach is theoretically also applicable to networks including different kinds of power devices by superpositioning the feasibility spheres of the devices.

The greatest benefit resulting from the introduced method is the possibility to run a flexibility related optimization for single power devices or power device networks without constantly checking for device-specific constraints, thus decreasing optimization complexity.

OpenTUMFlex

Zadé et al. (2020) point out the opportunities arising from the aggregation of flexibility from small-scale devices regarding the provision of ancillary services in modern power supply systems. In order to make use of the flexibility from small-scale devices the authors introduce a free accessible python-based flexibility model that allows electrical flexibility quantification and pricing for household devices.¹

The electrical devices available for flexibility modeling include electric vehicles without bi-directional charging, battery storages, photovoltaic systems, heat pumps and combined heat and power plants. The supported devices can be combined as desired to solve a predefined mixed-integer linear unit commitment problem whose solution delivers optimized operation plans for every included device needed for flexibility quantification. The following flexibility calculation is based on a compensation principle, whereby for example flexibility through unscheduled heating by a heat pump can only be provided if a subsequent and equivalent heating process can be turned off instead.

The resulting unified flexibility representation consists across all device types of a consistent positive or negative power that can be provided over a time span and the resulting flexible energy amount, together forming flexibility offers that can be used for flexibility trading in flexibility markets. The developers define positive flexibility as measures leading to a net addition of power to the grid and negative flexibility as measures resulting in withdrawal of power from the grid including curtailment of scheduled grid feed-in.

Additionally, the *OpenTUMFlex* model contains a simple aggregation of the calculated flexibility from the different devices and a pricing algorithm for the flexibility offers based on historical electricity and gas prices.

FlexOffer

In order to meet the challenges arising from the fundamental changes in power generation and energy consumption behaviour in existing energy systems, Šikšnys et al. (2019) suggest a reorganisation of system structures from centralized to cellular energy

¹ <https://github.com/tum-ewk/OpenTUMFlex>.

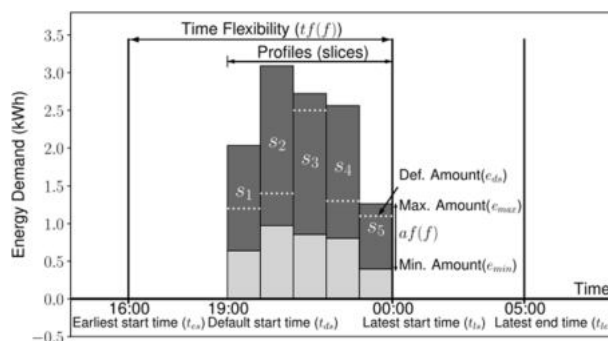


Fig. 4 Simple *FlexOffer* for a electric vehicle including the time flexibility $tf(f)$ of a charging process resulting from its time shiftability between the earliest t_{es} and latest start time t_{ls} and the energy amount flexibility $af(f)$ represented through the adaptable energy amounts in all process slices by Šikšnys et al. (2019)

systems. As core component of these cellular structures the authors propose the *FlexOffer* concept initially introduced by the European project MIRABEL (Boehm et al. 2012). A so called *FlexOffer* is a unified representation of electrical flexibility in demand and supply that is exchanged between the different layers and actors of a cellular energy system. *FlexOffers* are generated for each process of the involved electrical devices and can afterwards be aggregated to increase the *FlexOffer* value, marketed as ancillary services or power market products and finally disaggregated in order to schedule a flexibility retrieval. Neupane et al. (2017) are presenting device specific algorithms to generate *FlexOffers* for household devices, heat pumps and electric vehicles without bi-directional charging. Figure 4 shows a *FlexOffer* f consisting of the time flexibility $tf(f)$ and the energy amount flexibility $af(f)$ of a flexible process. The time flexibility $tf(f)$ results from the temporal shiftability of the process and the energy amount flexibility $af(f)$ describes the adaptable power for each process time step.

Due to the underestimation of flexibility at late process time steps in simple *FlexOffers* Šikšnys and Pedersen (2016) introduce an improved flexibility representation called dependency-based *FlexOffer*. By embedding the algorithms proposed by Neupane et al. (2017) into an optimization algorithm the developers enable the generation of energy amount flexibility lists for each process time step including flexible energy amounts in dependence of the previously retrieved energy amount. Subsequently, a diverse selection of *FlexOffers* can be composed from the resulting flexible energy lists.

Model evaluation

In order to make a profound choice of models for a more detailed analysis by implementation and simulation, the evaluation metric in Table 2 is applied to the flexibility modeling approaches presented in the previous section. The metric contains twenty-two criteria divided into two main categories: *device related criteria* and *application related criteria*. The first main category includes criteria regarding device types and technical device properties.

The selection of criteria represents an intersection between the thirteen flexibility features presented by Barth et al. (2018), the ten flexibility characteristics that are needed to assess a flexible resource according to Petersen et al. (2012) and the quantitative flexibility characteristics identified by Degefa et al. (2021). The criteria in the second main

Table 2 Evaluation criteria sorted by categories. Inspired by Petersen et al. (2012), Barth et al. (2018) and Degefa et al. (2021)

Device related criteria			Application related criteria	
Variety of devices	Technical criteria	Time related criteria	Implementation and comprehensibility	Aggregation
Generators	Efficiencies and losses	Ramping	Detailed mathematical description	Mathematically described aggregation
Loads	Load changes	Resting periods	Open source code available	Description of flexibility pricing
Storages	Available power	Device availability	Available database for simulation	Mapping of dependencies (time or technical/both)
Stochastic devices	Total amount of available energy Sector coupling	Time shiftable processes	Scientific relevance (cited/implemented) Low complexity of flexibility representation	Discrete time resolution

Table 3 Scheme for the evaluation of flexibility models

Measure	Device related criteria	Application related criteria
0	Not mappable	Not fulfilled
1	Partially or indirectly mappable	Incompletely or partially fulfilled
2	Mappable	Fulfilled

category are selected to evaluate the suitability of the models to be implemented and put into practice. Good prerequisites for this are, for example, a detailed mathematical description of the model, a scientific relevance of the model indicating its comprehensibility and a mathematically described aggregation of the respective flexibility representation indicating its suitability for aggregating small scale devices. The selection of criteria is a composition of criteria that either enable a judgement about whether a model is findable, accessible, interoperable and reusable (FAIR) (Wilkinson et al. 2016) or were additionally mentioned by Barth et al. (2018), Petersen et al. (2012), Degefa et al. (2021) or turned out to be key distinguishing features between the selected modeling approaches during the conducted literature review and more detailed study of the selected modeling approaches. To allow a more specific evaluation regarding the models different characteristics within the main categories, the criteria are additionally sorted into five subcategories.

Table 3 shows the evaluation scheme used to quantify the performance of the analyzed modeling approaches regarding the previously presented evaluation metric. The category of *device related criteria* mainly contains technical device properties which can either fully, partially or indirectly or not be mapped by the evaluated modeling approaches. As previously mentioned all additional requirements that are placed on a unified flexibility model in the evaluation can be found in the category of *application related criteria*. They are either fully, incompletely or partially or not fulfilled by the evaluated modeling approaches. A weighting of specific criteria or categories is not applied

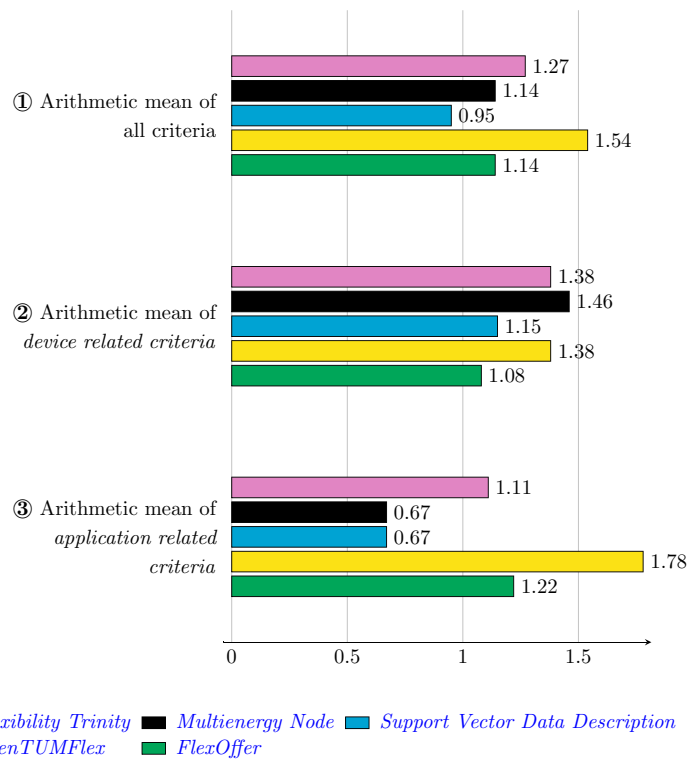


Fig. 5 Arithmetic mean values of the measures of all criteria ①, device related criteria ② and application related criteria ③ of the evaluated modeling approaches

because all introduced criteria are assumed to be equally important characteristics that an implementable and applicable unified flexibility model should have.

Evaluation results

To simplify the visualisation of the evaluation results for each modeling approach the arithmetic mean of the criteria measures of the subcategories, of the main categories and of the whole metric are calculated and visualized in Figs. 5 and 6. The detailed evaluation results can be found in Table 6 in Appendix.

Figure 5 ① shows the dominant overall performance by the OpenTUMFlex model which is only being narrowly outperformed in the main category of *device related criteria* by the Multienergy Node concept, depicted in Fig. 5 ②. The diagram in Fig. 6 additionally underlines its comparatively consistent and dominant performance across all subcategories with the exception of not being able to map a big variety of technical properties. Particularly positive to highlight is the comparatively good practical applicability, shown in Fig. 5 ③, resulting from open source code and an available database for simulation. Therefore, the model is FAIR (Wilkinson et al. 2016).

In contrast, the Flexibility Trinity concept has the ability to map a wide range of technical properties. Paired with the possibility to map a big variety of power devices, the lack of ability to map time related criteria, shown in Fig. 6, is balanced, resulting in the second best performance at the main category of *device related criteria* (see Fig. 5 ②). Due to a good description of mathematical modeling basics and its scientific relevance the modeling

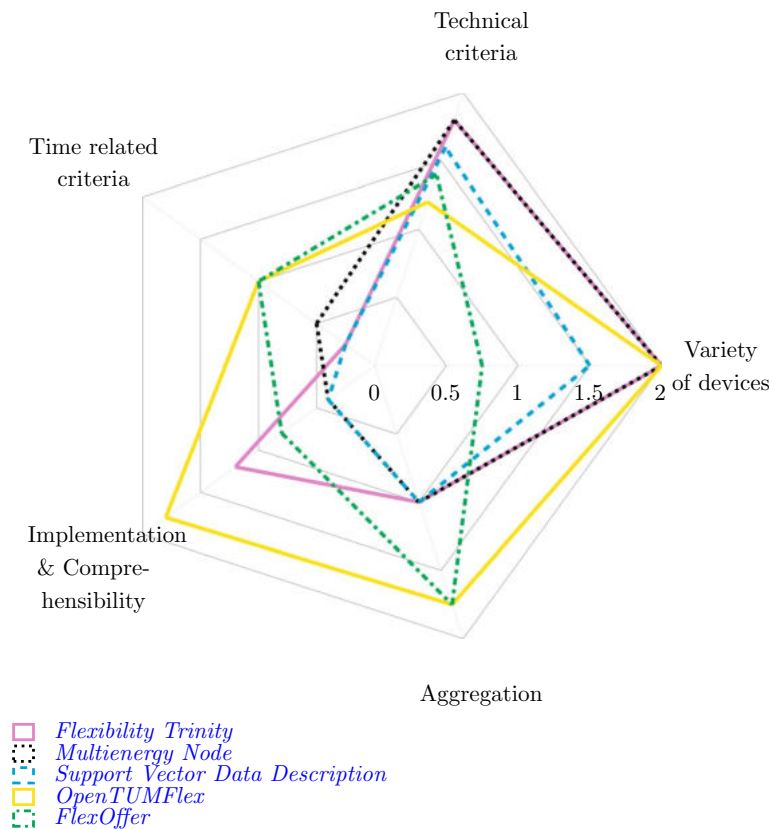


Fig. 6 Arithmetic mean values of the subcategories of the evaluated modeling approaches

approach stands out from the Multienergy Node and Support Vector Data Description concepts, leading to the second best overall performance, depicted in Fig. 5 ①.

Regarding the overall rating, the FlexOffer and the Multienergy Node approach are sharing the third place (see Fig. 5 ①). Thereby, the Multienergy Node approach is particularly characterized by its aforementioned ability to map a big variety of device types and technical properties shown in Fig. 6. A superficial mathematical description and the lack of available source code and database for simulation, which is not FAIR at all, results in a comparatively poor practical performance, as shown in Fig. 5 ③, overshadowing the aforementioned outstanding technical performance. The FlexOffer approach on the other hand has its strengths in subcategory of time related criteria thanks to the ability to map time shiftable processes and device availability depicted in Fig. 6. Additionally, the approach seems to be more suitable for practical implementation due to the available mathematical description of flexibility modeling, aggregation and pricing leading to the second best performance in the subcategory of *application related criteria*, as shown in Fig. 5 ③. The main drawback of this modeling approach is the lack of a big variety of device specific algorithms required for *FlexOffer* generation, resulting in the comparatively worst performance in the subcategory of device variety pictured in Fig. 6.

The modeling approach based on Support Vector Data Description ranks last in the overall evaluation which is mainly due to the lowest rating for its suitability for practical implementation depicted in Fig. 5 ③. Particularly noticeable in this case is the high

Table 4 Implementation and simulation overview

Modeling approach	Implemented and simulated devices	Database
Flexibility Trinity	Electric vehicle, Heat pump, Photovoltaic system, Combined heat and power plant, Battery storage	Zadé et al. (2020)
OpenTUMFlex	Electric vehicle, Heat pump, Photovoltaic system, Combined heat and power plant, Battery storage	Zadé et al. (2020)
FlexOffer	Electric vehicle, Heat pump	Neupane et al. (2017), Zadé et al. (2020)
<i>Simulation conditions</i>		
Simulation period	24 h	
Simulation resolution	15 min	
<i>Open accessible source code</i>		
Public GitLab Repository	https://gitlab.com/digitalized-energy-systems/scenarios/unified_flex_scenario/-/tree/Flexibility_Paper	

complexity of the modeled flexibility and the lack of mathematical background for the theoretically described aggregation. In contrast to the Multienergy Node concept sharing the aforementioned small suitability for implementation, this approach additionally performs comparatively bad in the main category of *device related criteria*, as shown Fig. 5 ②. Thereby, the ability to map a variety of technical criteria thanks to the flexible applicable sampling algorithm stands out as exception (see Fig. 6).

Preselection for implementation

Based on the evaluation results presented in the previous section the modeling approaches OpenTUMFlex and Flexibility Trinity are selected for implementation due to their dominant performance across the majority of criteria in the two main categories. Additionally, the FlexOffer concept is implemented because of its comparatively good suitability for implementation and the additional time related aspects distinguishing it from the equally rated Multienergy Node concept. Additional reasons for excluding the Multienergy Node concept from further evaluation through implementation are its methodical similarities with the already selected Flexibility Trinity concept, together with a comparatively worse suitability for implementation. The modeling approach based on Support Vector Data Description is excluded because of its comparatively bad performance in almost all categories, whereby the insufficient mathematical documentation is to be emphasized, which does not do justice to the high complexity of the approach.

Implementation and simulation

Table 4 provides an overview of the key characteristics of the performed implementation and simulation.

For reasons of comparability the majority of simulation data including device dimensions, operation plans and environmental constraints are extracted from the open source OpenTUMFlex flexibility model and are used as data input for the simulation of the Flexibility Trinity and the FlexOffer modeling approaches. To generate *FlexOffers* and *dependency based FlexOffers*, additional information from the simulation performed by Neupane et al. (2017) is included because of the comparatively high level of technical detail required for flexibility modeling according to the FlexOffer approach. Due to its

universal applicability all five devices supported by the OpenTUMFlex model are implemented and simulated according to the Flexibility Trinity approach. The limited number of device specific algorithms presented by the authors of the FlexOffer approach only allows the modeling of a heat pump and an electric vehicle without bi-directional charging. All simulated devices are on a domestic scale. The simulation period is 24 h with a resolution of 15 min. Due to the assumption that ramping is a negligible factor for the limiting of flexibility from small-scale devices analyzed with a resolution of 15 min, the estimation of flexibility from the power ramping capability of devices was excluded from the Flexibility Trinity implementation. The source code and more detailed information about the implementation and simulation including simulation constraints are freely accessible at GitLab.²

Results

In order to ensure the comparability of the simulation results, the following subsections exclusively focus on presenting the results of the electric vehicle and heat pump simulations. In this way, the large scope can be comprehensibly condensed into a selection that allows to show the main advantages and disadvantages of the implemented modeling approaches. A comprehensive visualisation of the results for all simulated devices can be found in the introduced GitLab Repository.²

Zadé et al. (2020) describe the possibility to offer flexibility with an electric vehicle by changing the charging process: if the charging process is stopped or the charging power is reduced, positive flexibility can be offered and if this power is increased or an unscheduled charging process takes place, negative flexibility can be provided. When determining the flexibility of a heat pump, additional environmental constraints should be considered. The flexibility can be calculated, for example, according to Neupane et al. (2017) by considering the electrical power of the heat pump and taking into account the temperature limits of a heated space where the pump is located. In the understanding of positive and negative flexibility according to Zadé et al. (2020), positive flexibility could be provided by a heat pump through curtailment of a planned heating process and negative flexibility through unplanned heating or the increase of a planned heating process. As can be seen in the following subsections, the obtained simulation results support and extend these theoretical considerations on the provision of flexibility by electric vehicles and heat pumps.

To visualize the calculated flexibility independent from the device dimensions and thus improve the visual comparability of the generated results the calculated flexible power is divided by the nominal power of the device for the presentation of the results. Furthermore, the Active Sign Convention (ASC) is used, where generated power is stated positive and drawn power is stated negative, as shown in Fig. 7 and all other figures in the following subsections Electric vehicle exibility and Heat pump exibility.

² https://gitlab.com/digitalized-energy-systems/scenarios/unified_flex_scenario/-/tree/Flexibility_Paper.

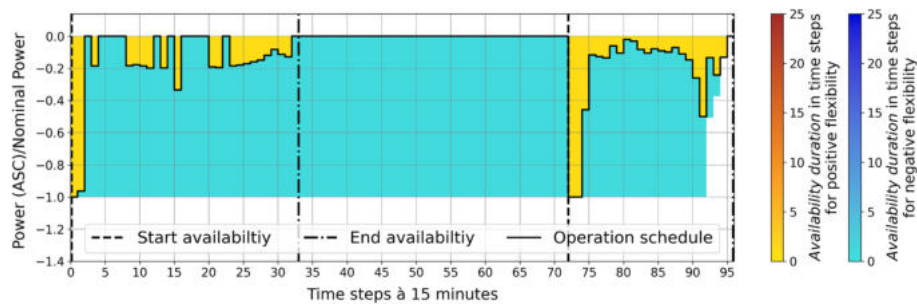


Fig. 7 Simulation results from the electric vehicle implementation according to the Flexibility Trinity approach. ASC: Active Sign Convention

Electric vehicle flexibility

Figure 7 shows the simulation results for the electric vehicle without bi-directional charging according to the Flexibility Trinity approach.

The dashed lines mark the starting points of the two periods in which the electric vehicle can be charged and the dash-dotted lines the respective end points. The solid black line shows the scheduled operation plan from which the flexibility is calculated. Positive flexibility can be provided through curtailment of scheduled charging and negative flexibility through unscheduled charging. To underline the differences between the simulation results according to the Flexibility Trinity and the OpenTUMFlex modeling approach, an underlying heat map shows for how many time steps, referred to as *availability duration* in the course of this paper, the calculated positive or negative flexible power is available for a flexibility call. By way of example, with an *availability duration* of 5 time steps at time step 35, the calculated flexible power could continuously or discontinuously be called between time step 35 and time step 40.

Looking at the pictured negative flexibility between the two periods in which the electric vehicle is available for charging in Fig. 7, it becomes clear that the Flexibility Trinity approach is not suitable to map the operation availability of devices like electric vehicles. Furthermore, Fig. 7 reveals that flexibility modeling according to the Flexibility Trinity approach limits the *availability duration* of the calculated flexible power to one time step. This is due to the time independent calculation method only taking the in- and outgoing power within the resolution period into account, which leads to the disadvantageous fact that the compliance with the storage limits of the electric vehicle is not ensured in case of a flexibility call that exceeds one time step. Additionally, because of the described time limitation in flexibility calculation, a violation of charging degree limits, that could occur after a flexibility call while executing the subsequent operation schedule, is not prevented. Another disadvantage of the Flexibility Trinity approach, becoming clear when analyzing the simulation results of the electric vehicle, is the inability to map any target charge levels, neither a fixed state of charge nor a minimum or maximum target.

In contrast to the Flexibility Trinity approach, flexibility modeling according to OpenTUMFlex allows the mapping of target charge levels, device availability for operation, storage properties and the calculation of negative or positive flexibility with a longer *availability duration* than one time step. As shown in Fig. 8, a call of negative flexibility

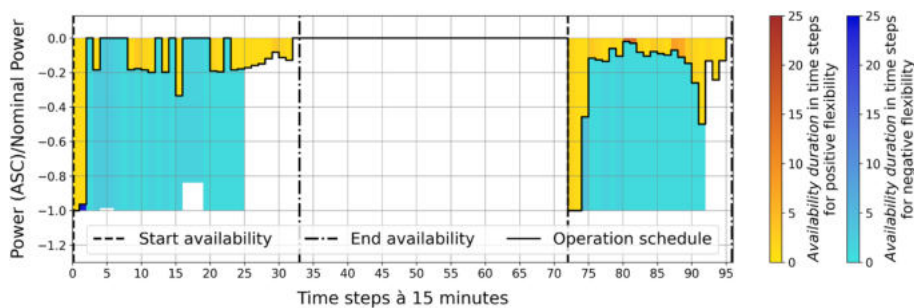


Fig. 8 Simulation results from the electric vehicle implementation according to the OpenTUMFlex approach. ASC: Active Sign Convention

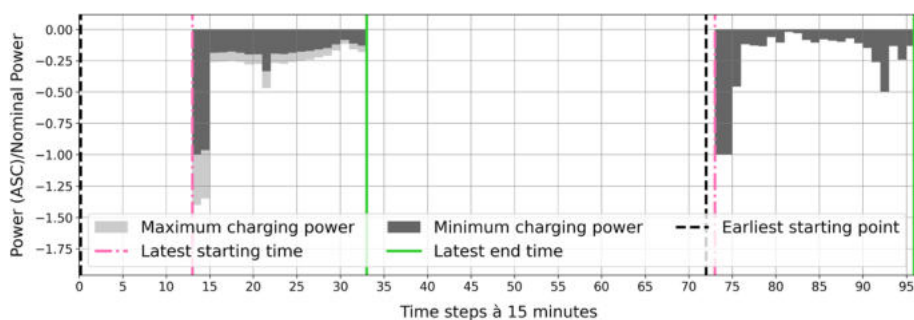


Fig. 9 FlexOffer of the electric vehicle generated according to the FlexOffer approach. ASC: Active Sign Convention

through an unscheduled charging process is not possible after time step 25 until the end of the first availability period. This is due to the concept of compensation processes requiring the presence of subsequently scheduled charging processes with an equal amount of energy to be charged. To ensure compliance of fixed target charge levels at the end of the respective availability period, an equivalent cancellation is necessary after a negative flexibility call.

The disadvantage resulting from these fixed target charge levels is the neglect of energy amount above the fixed charge levels that could also be used for a flexibility call, as long as it is not reserved for another purpose. An additional insight that can be gained from a closer look at Fig. 8 is that the generated flexibility offers have a constant power over the whole *availability duration*. This given constraint limits the *availability duration* of positive flexibility offers between time step 19 and 25 to one time step. The descending operating schedule in this time slot does not allow scheduled charging operations with a constant power over several time steps to be cancelled to provide positive flexibility.

In order to improve the visualization of the time flexibility resulting from the FlexOffer simulation, the two scheduled charging processes in the respective availability periods were compressed, as it becomes clear when comparing Figs. 8 and 9. In contrast to the visualisation of the preceding simulation results, in the FlexOffer concept the flexibility visualisation is predefined by Šikšnys et al. (2019).

Figure 9 shows the two generated FlexOffers, one for each period in which the electric vehicle is available for charging. The scheduled operation plan of the electric vehicle is displayed by the dark grey bars and defines the lower limits of the charging process for

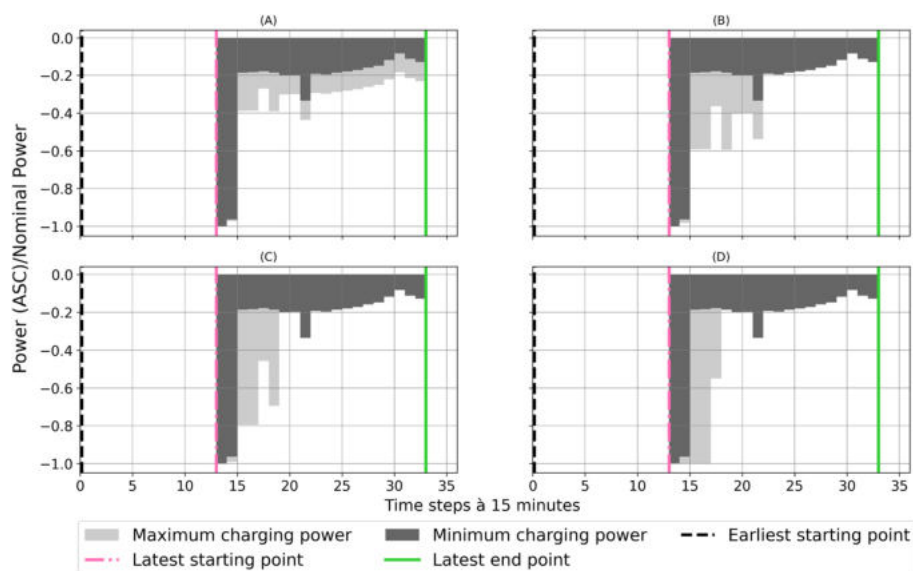


Fig. 10 A–D Four individual flexible charging processes modulated differently from a *dependency-based FlexOffer* of the electric vehicle generated according to the improved FlexOffer approach. ASC: Active Sign Convention

each *FlexOffer*. The energy related flexibility is displayed by the superimposed light grey bars representing the range in which the charging power at each time step of the charging process can be regulated. Due to the fact that the implemented algorithm sets the predefined schedule as minimum operation points in which the electric vehicle has to be operated while charging, only the energy amount above the previously scheduled end charge level of each charging process is available for the provision of flexibility.

Besides the flexibility in charging power in the first *FlexOffer*, Fig. 9 shows the time flexibility of both *FlexOffer* processes being shiftable between the respective earliest and latest starting times within the availability periods. In case of the first *FlexOffer*, a limitation of the calculation algorithm can be spotted in Fig. 9: The algorithm distributes the flexible energy amount in proportion to the scheduled energy amount over the process steps without checking the power limits of the electric vehicle. That is why the first two time steps show a violation of the maximum charging power of the electric vehicle. Using the energy amount above the respective target charge levels is in contrast to the calculation method according to OpenTUMFlex, neglecting this amount of energy for flexibility generation. The main disadvantage resulting from the FlexOffer approach can be seen when looking at the second availability period at the end where the electric vehicle is fully charged whereby no energy amount flexibility can be provided. In summary, the simulation results in Fig. 9 underline the unique feature of *FlexOffers* in contrast to the other forms of previously presented flexibility representations, which appears in the understanding of an operation plan as a power flexible and time shiftable charging process.

Due to the fact that the improved *dependency-based FlexOffer* algorithm only affects the calculation of energy amount flexibility, the algorithm was exclusively applied to the charging process in the first availability period. The resulting *dependency-based FlexOffer* enables the free distribution of the flexible energy amount over all process time steps,

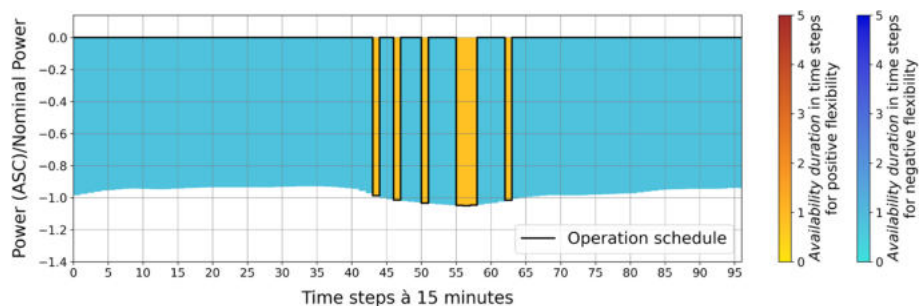


Fig. 11 Simulation results from the heat pump implementation according to the Flexibility Trinity approach. ASC: Active Sign Convention

as shown with four exemplary flexibility modulations in Fig. 10A–D. Another advantage arising from the embedding of the *FlexOffer* calculation into an optimization algorithm is the secured compliance with environmental and device boundaries. Compliance with these boundaries is not only a problem of the implemented *FlexOffer* algorithm for electric vehicles but also of the heat pump algorithm. In case of the electric vehicle, due to the optimization algorithm, the power boundaries in the first two time steps of the charging process are respected (see Fig. 10).

Heat pump flexibility

As described in the previous section Electric vehicle exibility, the time isolated calculation method according to the Flexibility Trinity approach neglects the impact of flexibility calls on the subsequent time steps while exclusively ensuring the compliance of technical boundaries within the analyzed time step. As depicted in Fig. 11, this method limits the *availability duration* of the heat pump flexibility over the whole simulation period to one time step. Due to the fact that the modeling approach does not provide any specified information about how the flexibility of a heat pump can be limited through the environmental constraints of a heated room or a coupled heat storage, the simulated heat pump can provide either maximal positive or negative flexibility at each time step of the simulation period. These results can only be reliably transferred into practice under the assumption that the heat pump is connected to a heating network which is able to compensate both negative and positive flexibility calls and thus ensure the compliance of the environmental boundaries. However, under this assumption, the *availability duration* for each analyzed time step would again have to be assumed as the difference between the end of the simulation period and the respective analyzed time step. The uneven course of the maximal electric power of the heat pump in Fig. 11 results from the changing outdoor temperature which in turn affects the optimal operation point of the heat pump.

Contrasting the previous modeling results, the flexible operation plan in Fig. 12 shows a limited number of time steps in which a flexibility call is possible with alternating *availability duration*.

The first limiting factor for a flexibility call and its *availability duration* according to the OpenTUMFlex approach is the requirement for compensation processes as described for the electric vehicle in section Electric vehicle exibility. This results in no

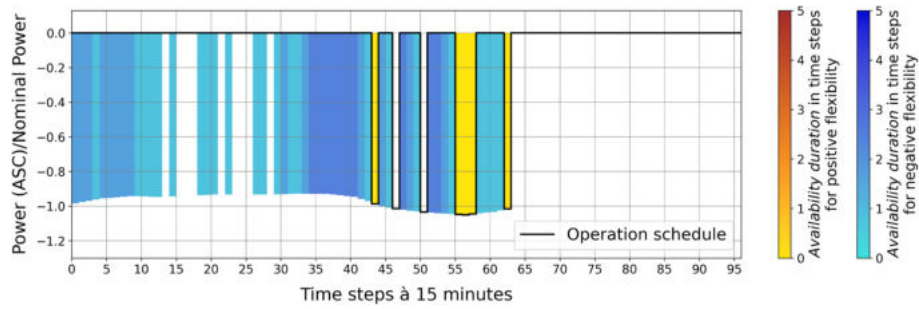


Fig. 12 Simulation results from the heat pump implementation according to the OpenTUMFlex approach. ASC: Active Sign Convention

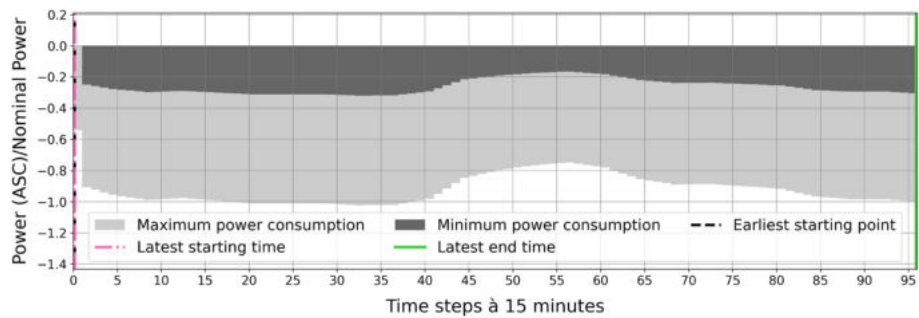


Fig. 13 Simulation results from the heat pump implementation according to the FlexOffer approach in form of a *FlexOffer*. ASC: Active Sign Convention

flexibility options after time step 63 because of the missing heating processes in the subsequent operation schedule, that could be shut down as compensation for a negative flexibility call. Due to the fact that a coupled heating storage is assumed to absorb all negative flexibility calls of the heat pump anyway, the method of compensation processes leads to an underestimation of flexibility in this case. Another limiting factor is the compliance of the charging degree limits of the coupled heating storage resulting in several time steps previous to time step 63 without flexibility options.

In contrast to the electric vehicle *FlexOffers* in Fig. 9 the *FlexOffer* in Fig. 13 resulting from the heat pump simulation of the FlexOffer approach contains no time flexibility. This is due to the calculation algorithm keeping the temperature of the heated room at its lower temperature boundary resulting in a minimum amount of heating energy being required at all time steps to compensate for heat loss due to exchange with the changing ambient temperature. The course of the alternating minimal energy amount contrasts with the previous simulation results because of the inclusion of the mentioned heat loss into the flexibility calculation. The temperature dependant amount of calculated heat loss contradicts and overlays the previously described influence of the alternating optimal operation point leading to the flexibility course. Looking at the heat pump *FlexOffer* in Fig. 13, one might assume that it is possible to freely modulate a flexibility call inside the grey area between the maximum and minimum power of the heat pump over the whole simulation period. However, comparable with the method of the Flexibility Trinity approach, the implemented algorithm only ensures compliance with the environmental boundaries, in this case the room temperature, over the course of a single time step

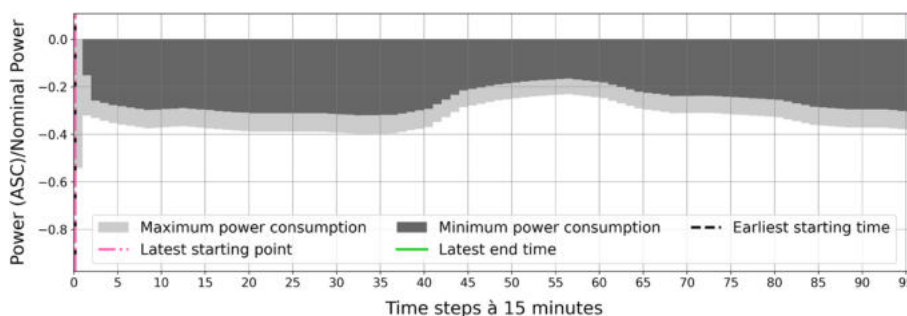


Fig. 14 Simulation results from the heat pump implementation according to the improved FlexOffer approach resulting in *dependency-based FlexOffers*. ASC: Active Sign Convention

Table 5 Summary of the advantages and disadvantages of the analyzed models revealed by implementation and simulation

	Modeling approach	Advantages	Disadvantages
Increasing modeling complexity ↓ Decreasing implementation effort	<i>Flexibility Trinity</i>	<ul style="list-style-type: none"> • Universal applicability • Low implementation effort 	<ul style="list-style-type: none"> • Limited complexity of device properties and environmental constraints • Short <i>availability duration</i>
	<i>OpenTUMFlex</i>	<ul style="list-style-type: none"> • Open source code • Comparatively good simulation results • Big device variety 	<ul style="list-style-type: none"> • Complex extension for additional devices and missing mathematical documentation • Partial flexibility underestimation
	<i>FlexOffer</i>	<ul style="list-style-type: none"> • Mapping of complex device properties and environmental constraints • Flexibility modulation 	<ul style="list-style-type: none"> • High implementation effort • Very complex extension for additional devices

in which a flexibility call occurs. The resulting overestimation of flexibility leads to the assumption that it is only possible to call the calculated flexibility over one isolated time step, if a violation of the room temperature boundaries is to be avoided.

Embedding the *FlexOffer* calculation into an optimization algorithm that generates *dependency-based FlexOffers* allows to overcome the previously described limitation of *availability duration* in case of the heat pump. Figure 14 shows an exemplary modulation of the calculated flexibility, whereby in this case the flexibility can be called continuously over the whole simulation period without violating the temperature bounds of the heated room. However, when comparing Figs. 13 and 14 it becomes clear that the long *availability duration* comes at the expense of the callable power at each time step.

Discussion

The gained knowledge from implementation and simulation is summarized in Table 5. It shows the key advantages the Flexibility Trinity approach brings to the table, including its universal applicability to any sort of power device and the comparatively low effort for implementation. Due to the time restricted power balancing method, the compliance of technical or environmental boundaries is severely restricted and the duration in which flexibility is callable is directly tied to the chosen resolution duration. Despite these severe limitations, the Flexibility Trinity modeling approach provides a solid base for flexibility modeling, covering multiple forms of cross-sector power, storage properties and additionally the aspect of power ramping flexibility not analyzed in this study due to aforementioned reasons. With the help of small algorithmic extensions, like a check for operation availability or a comprehensive compliance of loading degree boundaries, major drawbacks of the approach could be overcome.

Analyzing the OpenTUMFlex simulation results verifies the comparatively good performance of the modeling approach in the preceding metric evaluation (see Table 5). The available source code not only reduces the needed implementation effort for this approach to a minimum, but also provides a database for a comparable simulation of the three analyzed modeling approaches. Since the OpenTUMFlex approach is the only open source model among those analysed, a comparison of the number of downloads, which could give an indication of a model's popularity beyond its scientific relevance, was not included in this evaluation, but could become so in future evaluation processes by adding appropriate criteria to the evaluation metric presented in section Model Evaluation. The applied modeling method on the one hand allows the generation of easy to handle flexibility offers characterized by a constant power over a varying *availability duration*, but on the other hand leads to a partial underestimation of flexibility because of the unconditional necessity for compensation processes. Integrated in the OpenTUMFlex approach are reliably functioning flexibility algorithms for five different devices, including electrical generators, loads and storage devices. Despite the methodological similarities between the device specific algorithms, extending the OpenTUMFlex approach by including further devices is considered elaborate in comparison to the easy applicable Flexibility Trinity approach. Although the related scientific publications contributed to the understanding of the implemented computational method, the sparsely commented source code makes it difficult to understand the practical implementation and to transfer it to the implementation of additional devices.

A particularly positive feature that stands out when analyzing the simulation results of the FlexOffer approach is the possibility to modulate the calculated energy and time related flexibility (see Table 5). Thereby, the energy related modulation is enabled by embedding the *FlexOffer* calculation into an optimization algorithm entailing a significant increase of the already comparatively high implementation effort. Due to the temporal shiftability of the modeled processes, the generated *FlexOffers* provide an additional flexibility dimension usable to solve scheduling tasks like unit commitment problems. Integrating complex environmental constraints, like the thermal key figures of heated rooms is a unique feature in comparison to the other approaches and allows the modeling of isolated heating devices without a coupled storage. A disadvantage of this high degree of modeling complexity, combined with the low number of *FlexOffer*

generation algorithms, is the highly elaborate transfer of the modeling method to the implementation of additional devices.

Finally, taking all the gained knowledge into account, the OpenTUMFlex approach can be considered as the most recommendable among the analyzed approaches. The model is ready to use, functional for a relevant selection of device types and generates unified flexibility representations being easy to understand and suitable for further usage. Despite its shown disadvantages regarding complex device properties and short *availability duration*, the balancing method of the Flexibility Trinity approach provides a methodological foundation for developing a comprehensive flexibility modeling approach. By embedding the balancing method into a suitable algorithmic framework, the described disadvantages could be overcome and a model could be created that not only generates a unified flexibility representation, but also is characterized by a unified modeling method applicable to all types of power devices. Mainly due to the lack of device specific algorithms to generate *FlexOffers* and the comparatively high implementation effort for available algorithms, choosing the FlexOffer approach for practical implementation has not turned out to be recommendable, although the practicability of the generated flexibility representation is comprehensibly outlined by Šikšnys et al. (2019).

Conclusion

By reviewing flexibility modeling literature we highlighted the heterogeneity of modeling approaches in scientific literature resulting from a versatile understanding of flexibility in energy systems and different modeling purposes. We presented a metric that allows the evaluation of flexibility modeling approaches regarding their technical and methodical advantages and disadvantages and their applicability. By implementing and simulating the best performing modeling approaches we were able to make a more detailed analysis of the applicability of the previously selected models. Based on the gained knowledge we recommend the OpenTUMFlex modeling approach by Zadé et al. (2020) for anybody who is looking for an open source flexibility modeling framework that generates an easy to handle and unified representation of flexibility for domestic power devices. Furthermore, the evaluation process showed that the Flexibility Trinity concept introduced by Ulbig and Andersson (2012) deliver a strong methodological foundation on which can be built upon in the development of further approaches for unified flexibility modeling. In addition to the model specific findings the search process documented in this paper underlined the importance of detailed mathematical documentation as well as a FAIR publication of the modeling results, so that the models are comprehensible and reusable.

The presented evaluation framework and the corresponding open source code², including the implementation of selected models and a database for simulation, can be used to compare further modeling approaches regarding their suitability for unified flexibility modeling. Thereby, it is possible to evaluate the respective advantages and disadvantages in different levels of detail with the inclusion of technical, methodical and application related aspects. Accordingly, by presenting an overview of existing flexibility modeling approaches and providing an evaluation framework, we address the outlined lack of decision support to identify suitable approaches for unified flexibility modeling.

In order to use the presented framework to evaluate flexibility models with a different focus than unification and suitability for application the presented evaluation metric can be extended by additional criteria or a weighting of specific criteria or categories can be applied.

Appendix

See Table 6.

Table 6 Evaluation results: (a) Flexibility Trinity, (b) Multienergy Node, (c) Support Vector Data Description, (d) OpenTUMFlex, (e) FlexOffer; Subsections: A Variety of devices, B Technical criteria, C Time related criteria, D Implementation & Comprehensibility, E Aggregation; $\bar{z}_{m,1}$: Arithmetic mean of respective sub category of modeling approach m ; $\bar{z}_{m,2}$: Arithmetic mean of respective main category of modeling approach m ; $\bar{z}_{m,3}$: Arithmetic mean of all criteria of modeling approach m

(a)	A	B	C	D	E	(b)	A	B	C	D	E
	2	2	1	2	1		2	2	2	1	1
	2	2	0	0	0		2	2	0	0	0
	2	2	0	0	1		2	2	0	0	1
	2	2	0	2	2		2	1	0	0	2
	–	1	–	2	–		–	2	–	1	–
$\bar{z}_{a,1}$	2.00	1.80	0.25	1.20	1.00	$\bar{z}_{b,1}$	2.00	1.80	0.50	0.40	1.00
$\bar{z}_{a,2}$	1.38			1.11		$\bar{z}_{b,2}$	1.46			0.67	
$\bar{z}_{a,3}$	1.27					$\bar{z}_{b,3}$	1.14				
(c)	A	B	C	D	E	(d)	A	B	C	D	E
	2	2	1	1	0		2	0	0	2	2
	2	2	0	0	1		2	0	0	2	2
	2	2	0	0	1		2	2	2	2	1
	0	1	0	1	2		2	2	2	1	2
	–	1	–	0	–		–	2	–	2	–
$\bar{z}_{c,1}$	1.50	1.60	0.25	0.40	1.00	$\bar{z}_{d,1}$	2.00	1.20	1.00	1.80	1.75
$\bar{z}_{c,2}$	1.15			0.67		$\bar{z}_{d,2}$	1.38			1.78	
$\bar{z}_{c,3}$	0.95					$\bar{z}_{d,3}$	1.54				
(e)	A	B	C	D	E						
	0	1	0	2	2						
	2	0	0	0	2						
	1	2	2	0	1						
	0	2	2	1	2						
	–	2	–	1	–						
$\bar{z}_{e,1}$	0.75	1.40	1.00	0.80	1.75						
$\bar{z}_{e,2}$	1.08			1.22							
$\bar{z}_{e,3}$	1.14										

Abbreviations

i	Index Power node
ρ	Power ramping capability
π	Power capability
ϵ	Energy storage capability
k	Time step
π^{\pm}	Feasible power regulation point
$u_{gen}^{feasible}$	Feasible operation points of generation unit
u_{gen}^0	Set point of generation unit
η_{gen}	Generation efficiency factor
ξ	Demanded and provided external energy
w	Spilled energy and unserved load
v	Storage losses
C	Storage capacity
x	Storage level
v_i	In-going energy vector
v_o	Out-going energy vector
H	Efficiency matrix
S	Storage coupling matrix
\dot{e}	Array of storage energy derivatives
ξ	Array of net multienergy process demand
w	Array of net enforced energy losses
ϕ	Flexibility array
$\Delta v_{i,k}$	Feasible modification of input energy array
f	FlexOffer
af	Energy amount flexibility
tf	Time flexibility
$\tilde{z}_{y,z}$	Arithmetic mean of model y in category z

Acknowledgements

Not applicable.

Author contributions

JB created the simulation environment, implemented all basic concepts, performed the simulations and implemented the visualisation together with EF. They wrote the main part of the presented publication. The idea of the work presented here was developed by these two first authors in intense discussion with SF, PHT, AB, RH-R and AN. AN additionally supported the whole process as supervisor. All authors read and approved the final manuscript.

Funding

Open Access funding enabled and organized by Projekt DEAL. This work was funded by the Lower Saxony Ministry of Science and Culture under Grant Number 11–76251–13–3/19 - ZN3488 (ZLE) within the Lower Saxony “Vorab” of the Volkswagen Foundation and was supported by the Center for Digital Innovations (ZDIN).

Availability of data and materials

The software, models and datasets generated and/or analysed during the current study and the presented simulation environment are available as open source code in the GitLab repository: https://gitlab.com/digitalized-energy-systems/scenarios/unified_flex_scenario/-/tree/Flexibility_Paper.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

Received: 29 March 2022 Accepted: 3 June 2022

Published online: 11 July 2022

References

- Baringo L (2020) Virtual Power Plants and Electricity Markets. Springer, Switzerland. <https://doi.org/10.1007/978-3-030-47602-1>
- Barth L, Ludwig N, Mengelkamp E, Staudt P (2018) A comprehensive modelling framework for demand side flexibility in smart grids. *Computer Sci Res Develop* 33(1–2):13–23. <https://doi.org/10.1007/s00450-017-0343-x>

- Boehm, M., Dannecker, L., Doms, A., Dovgan, E., Filipič, B., Fischer, U., Lehner, W., Pedersen, T.B., Pitarch, Y., Šikšnyš, L., Tušar, T (2012) Data Management in the MIRABEL Smart Grid System. In: Proceedings of the 2012 Joint EDBT/CDT Workshops, EDBT-ICDT'12, pp. 95–102. ACM, Berlin, Germany . <https://doi.org/10.1145/2320765.2320797>. ACM. http://vbn.aau.dk/files/183438910/endm2012_mirabel.pdf
- Bremer J, Sonnenschein M (2014) Constraint-handling with support vector decoders. *Agents Artif Intell*. https://doi.org/10.1007/978-3-662-44440-5_14
- Bremer J, Sonnenschein M (2013) Sampling the Search Space of Energy Resources for Self-organized, Agent-based Planning of Active Power Provision. In: 27th International Conference on Environmental Informatics for Environmental Protection, *EnvirolInfo* 2013, pp 214–222
- Bremer J (2015) Constraint-Handling mit Supportvektor-Dekodern in der verteilten Optimierung. Dissertation, Carl von Ossietzky Universität Oldenburg . <https://uol.de/f/2/dept/informatik/brecon15.pdf>
- Chicco G, Riaz S, Mazza A, Mancarella P (2020) Flexibility from distributed multienergy systems. *Proc IEEE* 108(9):1496–1517. <https://doi.org/10.1109/JPROC.2020.2986378>
- Degefa MZ, Sperstad IB, Sæle H (2021) Comprehensive classifications and characterizations of power system flexibility resources. *Electric Power Syst Res* 194:2. <https://doi.org/10.1016/j.epsr.2021.107022>
- Elloumi O (2012) CEN-CENELEC-ETS: Smart Grid Coordination Group-Smart Grid Reference Architecture Report 2.0. Technical report . <https://www.researchgate.net/publication/263264218>
- Geidl M, Koeppl G, Favre-Perrod P, Klöckl B, Andersson G, Fröhlich K (2007) Energy hubs for the future. *IEEE Power Energy Magaz* 5(1):24–30. <https://doi.org/10.1109/MPAE.2007.264850>
- Haakana J, Haapaniemi J, Lassila J, Partanen J, Niska H, Rautiainen A (2018) Effects of electric vehicles and heat pumps on long-term electricity consumption scenarios for rural areas in the nordic environment. *Techn Report*. <https://doi.org/10.1109/EEM.2018.8469937>
- Hadi MB, Moeini-Aghaie M (2019) Assessing Operational Flexibility of Microgrids Considering Electrical and Thermal Energy Resources. 2019 Smart Grid Conference, SGC 2019 . <https://doi.org/10.1109/SGC49328.2019.9056588>
- Harder N, Qussous R, Weidlich A (2020) The cost of providing operational flexibility from distributed energy resources. *Appl Energy* 279:7. <https://doi.org/10.1016/j.apenergy.2020.115784>
- Heider A, Reibsch R, Blechinger P, Linke A, Hug G (2021) Flexibility options and their representation in open energy modelling tools. *Energy Strategy Rev* 38, 100737 . <https://doi.org/10.1016/j.esr.2021.100737>
- Keiner D, Ram M, Barbosa LDSNS, Bogdanov D, Breyer C (2019) Cost optimal self-consumption of PV prosumers with stationary batteries, heat pumps, thermal energy storage and electric vehicles across the world up to 2050. *Solar Energy* 185:406–423. <https://doi.org/10.1016/j.solener.2019.04.081>
- Neupane B, Šikšnyš L, Pedersen TB (2017) Generation and evaluation of flex-offers from flexible electrical devices. *e-Energy 2017 - Proceedings of the 8th International Conference on Future Energy Systems*, 143–156 . <https://doi.org/10.1145/3077839.3077850>
- Nieße A, Tröschel M, Sonnenschein M (2013) Designing dependable and sustainable Smart Grids - How to apply Algorithm Engineering to distributed control in power systems. *Environ Model Softw* 56:37–51. <https://doi.org/10.1016/j.envsoft.2013.12.003>
- Nosair H, Bouffard F (2015) Reconstructing operating reserve: flexibility for sustainable power systems. *IEEE Trans Sustain Energy* 6(4):1624–1637. <https://doi.org/10.1109/TSTE.2015.2462318>
- Petersen, M., Hansen, L.H., Mølbak, T (2012) Exploring the value of flexibility: A smart grid discussion. *IFAC Proc* 8(1), 43–48 . <https://doi.org/10.3182/20120902-4-fr-2032.00010>
- Petersen MK, Edlund K, Hansen LH, Bendtsen J, Stoustrup J (2013) A taxonomy for modeling flexibility and a computationally efficient algorithm for dispatch in Smart Grids. In: Proceedings of the American Control Conference, pp 1150–1156 . <https://doi.org/10.1109/acc.2013.6579991>
- Schott P, Sedlmeir J, Strobel N, Weber T, Fridgen G, Abele E (2019) A generic data model for describing flexibility in power markets. *Energies* 12(10):1–29. <https://doi.org/10.3390/en12101893>
- Šikšnyš L, Pedersen TB (2016) Dependency-based FlexOffers. In: *e-Energy '16: Proceedings of the Seventh International Conference on Future Energy Systems*, 1–13 . <https://doi.org/10.1145/2934328.2934339>
- Šikšnyš L, Pedersen TB, Aftab M, Neupane B (2019) Flexibility modeling, management, and trading in bottom-up cellular energy systems. *e-Energy 2019 - Proceedings of the 10th ACM International Conference on Future Energy Systems*, 170–180 . <https://doi.org/10.1145/3307772.3328296>
- Tušar T, Dovgan E, Filipič B (2012) Evolutionary scheduling of flexible offers for balancing electricity supply and demand. In: 2012 IEEE Congress on Evolutionary Computation, CEC 2012, 10–15 . <https://doi.org/10.1109/CEC.2012.6256494>
- Ulbig A, Andersson G (2012) On operational flexibility in power systems. *IEEE Power and Energy Society General Meeting*. <https://doi.org/10.1109/PESGM.2012.6344676>
- Valsomatzis E, Hose K, Pedersen T (2014) Balancing Energy Flexibilities Through Aggregation. In: Woon, W.L., Aung, Z., Madnick, S. (eds.) *Data Analytics for Renewable Energy Integration*, pp. 17–37. Springer, Switzerland 2014 . https://doi.org/10.1007/978-3-319-13290-7_2. https://vbn.aau.dk/ws/files/217297842/Balancing_20Energy_20Flexibilities_20through_20Aggregation.pdf
- Valsomatzis E, Hose K, Pedersen TB, Šikšnyš L (2015) Measuring and comparing energy flexibilities. In: *CEUR Workshop Proceedings*, vol. 1330, pp. 78–85 . <http://ceur-ws.org/Vol-1330/paper-14.pdf>
- Wang S, Wu W (2020) Stochastic flexibility evaluation for virtual power plant by aggregating distributed energy resources, 1–10
- ...Wilkinson MD, Dumontier M, Aalbersberg IJ, Appleton G, Axton M, Baak A, Blomberg N, Boiten JW, da Silva Santos LB, Bourne PE, Bouwman J, Brookes AJ, Clark T, Crosas M, Dillo I, Dumon O, Edmunds S, Evelo CT, Finkers R, Gonzalez-Beltran A, Gray AJG, Groth P, Goble C, Grethe JS, Heringa J, Hoen PAC, Hooft R, Kuhn T, Kok R, Kok J, Lusher SJ, Martone ME, Mons A, Packer AL, Persson B, Rocca-Serra P, Roos M, van Schaik R, Sansone SA, Schultes E, Sengstag T, Slater T, Strawn G, Swertz MA, Thompson M, Van Der Lei J, Van Mulligen E, Velterop J, Waagmeester A, Wittenburg P, Wolstencroft K, Zhao J, Mons B (2016) The FAIR Guiding Principles for scientific data management and stewardship. *Scientific Data* 3:1–9. <https://doi.org/10.1038/sdata.2016.18>

- Yang J, Zhang L, Han X, Wang M (2017) Evaluation of operational flexibility for power system with energy storage. In: 2016 International Conference on Smart Grid and Clean Energy Technologies, ICSGCE 2016, 187–191. <https://doi.org/10.1109/ICSGCE.2016.7876050>
- Zadé M, You Z, Kumaran Nalini B, Tzscheutschler P, Wagner U (2020) Quantifying the flexibility of electric vehicles in Germany and California-a case study. *Energies* 13(21):5617. <https://doi.org/10.3390/en13215617>
- Zadé M, You Z, Nalini BK (2020). OpenTUMFlex. <https://doi.org/10.5281/zenodo.4251512>

Publisher's Note

Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Submit your manuscript to a SpringerOpen[®] journal and benefit from:

- ▶ Convenient online submission
- ▶ Rigorous peer review
- ▶ Open access: articles freely available online
- ▶ High visibility within the field
- ▶ Retaining the copyright to your article

Submit your next manuscript at ▶ [springeropen.com](https://www.springeropen.com)
