Re-Thinking the Definition of Self-Sufficiency in Systems with Energy Storage

Zepter, Jan Martin; Engelhardt, Jan; Gabderakhmanova, Tatiana; Marinelli, Mattia

Published in:
Proceedings of 2022 International Conference on Smart Energy Systems and Technologies (SEST)

Link to article, DOI:
10.1109/SEST53650.2022.9898436

Publication date:
2022

Document Version
Peer reviewed version

Re-Thinking the Definition of Self-Sufficiency in Systems with Energy Storage

Jan Martin Zepter, Jan Engelhardt, Tatiana Gabderakhmanova, Mattia Marinelli
Department of Wind and Energy Systems
Technical University of Denmark (DTU)
Roskilde, Denmark
{jmwze, janen, tatigab, matm}@dtu.dk

***Abstract*—Self-sufficiency is an important metric for various energy concepts, as it reflects what share of the local consumption is covered by local generation. However, the equation commonly used in literature cannot be applied to systems with an energy storage that actively exchanges energy with the grid. With more and more systems incorporating storage units it is therefore necessary to re-think the mathematical definition of self-sufficiency. The present paper addresses this issue by proposing an alternative equation that captures distinctive factors introduced by storage units: (i) Energy exported to the grid can originate from previously imported energy, (ii) initial and final storage energy in a given observation period can be different, (iii) the usage of storage systems entails energy losses. It is demonstrated that neglecting these factors leads to an over- or underestimation of self-sufficiency with values even reaching below 0 % or above 100 %. In contrast, the self-sufficiency calculated by the proposed definition considers the above mentioned factors and always stays within the defined range.**

***Index Terms*—battery, microgrid, photovoltaic, self-sufficiency, virtual power plant**

I. Introduction

The increase of renewable energy sources (RES) and new electric loads, such as electric vehicles (EVs) or power-to-X technologies, pose new challenges to the operation of modern power systems. As a result, several energy concepts were adopted in the past years, such as home energy management systems (HEMS) in the residential domain, microgrids (MG) in a local domain, as well as virtual power plants (VPPs) in a regional domain. All of these concepts take advantage of the joint control of units for being cost-efficient or achieving high levels of RES penetration [1]. An important metric or performance indicator in these concepts has been the *self-sufficiency* that incentivises the use of green energy. In general terms, it provides the answer to the question: "What percentage of the load energy was provided by local generation?"

Self-sufficiency has repeatedly been taken as a decisive criterion for long-lasting planning problems. For instance, Hernández et al. [2] dimension a hybrid energy storage system for prosumer households to maximise self-sufficiency, while Latinen et al. [3] used this metric to determine the cost-optimal investments into renewable energy systems for districts. For achieving complete energy self-sufficiency in residential buildings, Lokar and Virtič [4] analysed the impact of investing in hydrogen fuel cells in a Slovenian pilot site. Langer and Volling [5] as well as Zepter et al. [6] translated high self-sufficiency targets into grid minimizing objective functions for home energy managements systems and local energy communities, respectively. A common definition of self-sufficiency that many recent scientific articles refer to was introduced by Luthander et al. [1]. This definition was predominantly constructed for households with rooftop-photovoltaic (PV). The usage of storage in the equation was indicated, but not explicitly detailed. For instance, it was not specified how to factor in an active interchange with the grid besides fulfilling load demand, or to account for storage losses. This could lead to incorrect values for other system setups. In future energy systems with high shares of RES, however, storage systems will become of relentless importance. They will be actively involved in system operation through different services, e.g. for energy arbitrage [7], microgrid applications [8], frequency control [9], or as battery-buffered EV charging [10].

The present paper addresses this issue and proposes an alternative definition of the term self-sufficiency for respective systems that include at least one storage entity. We mathematically derive self-sufficiency in general terms for a system with local generation, local consumption, a storage unit and a grid connection. We then perform a sensitivity analysis by varying several key parameters to identify boundaries of the common definition when introducing energy storage.

The remainder of the paper is structured as follows. Section II reviews related literature applying self-sufficiency in various contexts. Section III mathematically derives the self-sufficiency for a system with energy storage and introduces the sensitivity study. In Section IV, the presented definition of self-sufficiency is systematically compared to the definition commonly used in the literature. Section V discusses the obtained results, while Section VI concludes the paper.

II. Related Literature

Self-sufficiency has been widely used for evaluating the operating performance of energy systems at different scales, and for sizing assets in investment planning problems. For systems without energy storage, self-sufficiency can be calculated as

This work has received funding from the European H2020 project InsulaE under the Grant Agreement No. 824433. The goal of the project is to demonstrate innovative energy solutions for decarbonising European islands. For more information, please visit http://insulae-h2020.eu.

the direct overlap of local generation and local consumption. A common equation for self-sufficiency (σ) that many recent scientific articles apply is

$$\sigma = \frac{E^{\text{gen}} - E^{\text{exp}}}{E^{\text{load}}} = \frac{E^{\text{load}} - E^{\text{imp}}}{E^{\text{load}}}, \tag{1}$$

where E^{gen} is the local generation, E^{exp} the grid export and E^{imp} the grid import, and E^{load} the local consumption. For systems without storage units, both variants given in eq. (1) are equivalent. The analysis conducted in this paper uses the first variant as reference for the following calculations.

Storage units can generally help increase the self-sufficiency of a system by storing excess generation instead of directly exporting it, and later consuming it locally. However, the active usage of the storage for economic and technical services introduces different levels of complexity that are not captured by the common definition. First, energy exported to the grid may originate from both previously imported energy. Previous studies explicitly excluded this operation in their study designs. For instance, Oliveira e Silva et al. [11] analyse the interaction of residential energy storage coupled with photovoltaics and the grid for different limits of feed-in power. Kichou et al. [12] evaluated the effect of PV and battery systems on the self-sufficiency of two residential buildings in Prague, where the active discharge of the storage into the grid is foreclosed by design. Similarly, Hassan et al. [13] analyse a PV-supercapacitor system for improving self-sufficiency, while Gudmunds et al. [14] analyse the self-sufficiency of prosumers and prosumagers when introducing an EV. For reasons of simplicity, the entailed storage entities in above-mentioned studies are used exclusively for the storage of own local generation, and hence disallowed for active grid exchange. However, in future power grids the active operation of batteries and other bidirectional storage systems is expected to take a key role as they provide flexibility for both loads and generating units. Hence, storage facilitates the aggregation of various units in virtual power plants [15], and the deployment of high power components in distribution grids [16].

Second, the initial and final energy level in the storage in a given observation period may be different, which is not reflected in the common definition of self-sufficiency. However, this energy difference must be considered to satisfy the energy balance equation of the overall system. Dong et al. [17] perform a techno-enviro-economic assessment of household and community storage in the UK and rely on the self-sufficiency metric as an important key performance indicator. In their study, the authors explicitly neglect any difference in the storage level between start and end of the simulation period, which could lead to distorted values following the common self-sufficiency definition as depicted in (1). This becomes particularly important for studies looking at limited time horizons (e.g. representative days, weeks, months) where the order of magnitude of battery cycles is low [18].

Third, the usage of storage systems entails energy losses which might need to be clearly allocated to the components making use of the storage, when estimating self-sufficiency. Li and Danzer [19] state that losses in inverters and batteries decrease self-sufficiency values. Sun et al. [20] doubt if self-sufficiency is a sufficient metric for domestic PV-battery systems as the common definition does not incorporate system complexities such as losses. However, the authors of both studies do not propose adjustments to the common definition.

Other proposed variants of self-sufficiency, as e.g. the one used in [21] where export is divided by import for a nearly zero emission building, produce values above 100 % in case export is greater than import and approaches infinity in case of no import (autarkic system). Hence, this proposition does not seem to be a valid alternative. Liu et al. [22] analyse load matching in zero energy buildings, and define the self-sufficiency as the ratio of directly used PV energy for the consumption of the buildings. However, it is unclear what role the storage in their investigation plays and how it is included in the calculation of self-sufficiency. Kobashi et al. [23] investigate the potential of combining PV systems, batteries, and electric vehicles for decarbonising the city-scale energy system of Kyoto, Japan. In their definition of self-sufficiency, it remains unclear how losses and grid exports are accounted for, since they only consider the energy sent from the PV and battery systems to the load.

The H2020 Insulae demonstration project aims at deploying innovative energy solutions to decarbonise European islands and increase their self-sufficiency. In the investigated solutions, storage plays a crucial role in various energy concepts [24]. In one of the examined use cases, we assess the value of battery storage for facilitating EV fast-charging with high shares of local RES [25]. Here, the storage is actively interacting with the grid, e.g. by exporting excessive PV generation to avoid high state of energy levels while importing energy to satisfy EV demand. Thus, the common definition given in eq. (1) constitutes no valid metric.

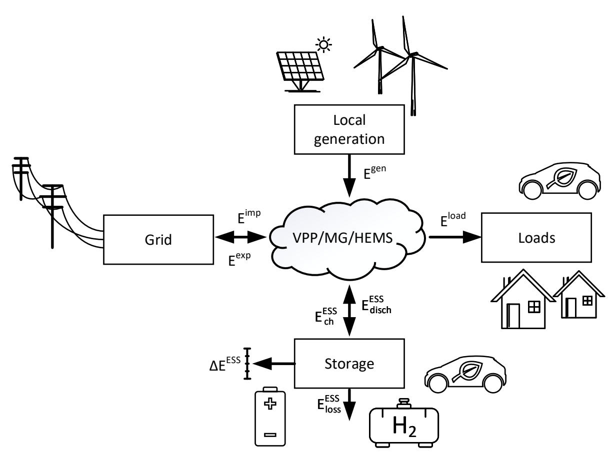


Fig. 1. Set of generation and consumption units confined in either a physical (HEMS or MG) or a virtual network (VPP).

III. Methodology

In the following, an equation for estimating self-sufficiency for systems with energy storage is derived. Subsequently, a comparative sensitivity study is introduced that aims at comparing the proposed definition to the definition commonly used in literature.

A. Derivation of self-sufficiency

For a network with generation, consumption, and storage units, the basic energy balance of the system can be formulated as

$$E^{\text{in}} - E^{\text{out}} - \Delta E^{\text{ESS}} = 0, \tag{2}$$

where E^{in} and E^{out} are absolute quantities of energy inputs and outputs, respectively, and ΔE^{ESS} is the difference between final and initial storage energy level, $E^{\text{ESS}}_{\text{end}} - E^{\text{ESS}}_{\text{init}}$, of the given observation period. Taking the setup shown in Fig. 1 as an example, the energy balance equation can be further extended to incorporate the contributions of the individual units:

$$E^{\text{gen}} + E^{\text{imp}} - E^{\text{load}} - E^{\text{exp}} - E^{\text{ESS}}_{\text{loss}} - \Delta E^{\text{ESS}} = 0, \tag{3}$$

where $E^{\text{ESS}}_{\text{loss}}$ are the associated losses with the storage composed of losses from charging and discharging as well as self-discharging effects. Since self-sufficiency is defined as the percentage of load energy met by local generation, eq. (3) is reformulated by adding and subsequently dividing the load on both sides of the equation:

$$\frac{E^{\text{gen}} + E^{\text{imp}} - E^{\text{exp}} - E^{\text{ESS}}_{\text{loss}} - \Delta E^{\text{ESS}}}{E^{\text{load}}} = 1 \tag{4}$$

For determining which percentage of the load energy is provided by the local generation or the import, eq. (4) can be separated into fractions representing the different system inputs. In this regard, both the exported energy E^{exp} and the battery variables ΔE^{ESS} and $E^{\text{ESS}}_{\text{loss}}$ can be proportionally allocated to the respective fractions of E^{gen} and E^{imp}. For this reason, a new parameter κ is introduced, representing the share of local production to the overall input as

$$\kappa = \frac{E^{\text{gen}}}{E^{\text{gen}} + E^{\text{imp}}} \in [0, 1]. \tag{5}$$

Based on this parameter, we can now split (4) into two fractions that represent the share of the consumed energy provided by local generation and grid import, respectively:

$$1 = \frac{E^{\text{gen}} - \kappa \cdot [E^{\text{exp}} + E^{\text{ESS}}_{\text{loss}} + \Delta E^{\text{ESS}}]}{E^{\text{load}}} + \frac{E^{\text{imp}} - (1-\kappa) \cdot [E^{\text{exp}} + E^{\text{ESS}}_{\text{loss}} + \Delta E^{\text{ESS}}]}{E^{\text{load}}} \tag{6}$$

The self-sufficiency represents the first part of (6), as it directly estimates what fraction of the local consumption was covered by local generation. Hence, the proposed equation for self-sufficiency is

$$\sigma = \frac{E^{\text{gen}} - \kappa \cdot [E^{\text{exp}} + E^{\text{ESS}}_{\text{loss}} + \Delta E^{\text{ESS}}]}{E^{\text{load}}} \in [0, 1]. \tag{7}$$

The aim of the following analysis is to compare the estimated self-sufficiency when applying the common definition (1) and the proposed definition (7).

B. Sensitivity study

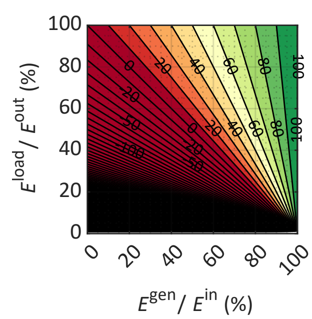
The impact of three main factors introduced by storage units are investigated: (i) exported energy can originate from both previously imported and locally generated energy, (ii) initial and final storage energy in a given observation period can be different, (iii) the usage of storage systems entails energy losses. These scenarios are constructed by utilizing the three variables E^{exp}, ΔE^{ESS}, and $E^{\text{ESS}}_{\text{loss}}$ in the energy balance equation. The analysis is divided into three parts. In each part, two of the three variables are kept constant, while the remaining one is varied. By doing so, the impact of the respective variable on self-sufficiency can be observed for both self-sufficiency equations. Subsequently, the validity of either equation is assessed and the results are compared to each other.

IV. Results

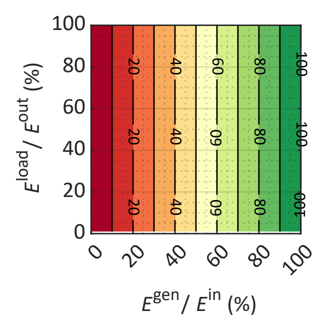
The results section is divided into three parts, each assessing the influence of a single factor on self-sufficiency. Subsection IV-A focuses on the influence of grid export, subsection IV-B on energy level differences between beginning and end of an observation period, and subsection IV-C on the impact of storage round-trip efficiency.

A. Influence of exported energy

To assess solely the influence of exported energy on the self-sufficiency, other factors were excluded by setting $\Delta E^{\text{ESS}} = 0$ and $E^{\text{ESS}}_{\text{loss}} = 0$. Hence, the only difference between (1) and (7) is the factor κ that defines what ratio of the exported energy is assigned to the local generation. A parameter sweep was performed, where the share of local generation E^{gen} was varied between 0 % and 100 % of the overall input $E^{\text{in}} = E^{\text{gen}} + E^{\text{imp}}$. Furthermore, the share of locally consumed energy E^{load} of the overall output energy $E^{\text{out}} = E^{\text{load}} + E^{\text{exp}}$ was varied in the same range. Fig. 2 shows the results of this two dimensional sensitivity analysis. It can be seen that for $E^{\text{load}}/E^{\text{in}} = 100\,\%$ both definitions lead to the same result. However, with decreasing $E^{\text{load}}/E^{\text{in}}$, thus increasing exported energy, the self-sufficiency as defined by (1) decreases, and eventually reaches negative values when the exported energy exceeds the locally produced energy. Yet, this behaviour is perfectly possible in scenarios with an active grid exchange (arbitrage, frequency



(a) Common definition



(b) Proposed definition

Fig. 2. Self-sufficiency for varying levels of locally produced and consumed energy.

control) and does not justify faulty values of self-sufficiency. In contrast, the proposed definition produces valid results for the complete domain and is generally independent of the share of exported energy.

B. Influence of storage level differences

Self-sufficiency is usually calculated for a given observation period. This time window can be limited by the availability of data, or it can be intentionally set to compare the system performance for different periods (e.g. days or months). A difference in storage energy level between end and beginning of an observation period changes the overall energy balance of the system, as seen from (2). In the proposed equation for self-sufficiency (7), this value ΔE^{ESS} is considered, while the common definition does not include this quantity. To investigate the impact of the energy difference, the other factors E^{exp} and $E^{\text{ESS}}_{\text{loss}}$ were set to zero.

Two different cases were assessed, constructing distinct shares of the local generation and grid import. In the first case, local generation and grid import were set to 95 % and 5 % of the overall input, respectively. Then, we performed a parameter sweep of the local consumption between 90 % and 110 % of the overall energy input. The mismatch between input and output energy is balanced by the storage and results in an increase or decrease of the energy level ΔE^{ESS}. If at the end of an observation period the storage energy level is higher compared to the beginning, ΔE^{ESS} is positive. Vice versa, decreasing energy levels are represented by negative values of ΔE^{ESS}. In the second case, local generation and grid import were set to 70 % and 30 % of the overall input, respectively. As previously, the local consumption was varied between 90 % and 110 % of the overall energy input, while the storage compensated any mismatch between system inputs and outputs leading to an increase or decrease of the storage energy level.

Fig. 3 compares for both cases the progressions of self-sufficiency obtained by the common and the proposed definition, as a function of ΔE^{ESS} normalized by the locally consumed energy E^{load}. While the proposed definition compensates the effect of energy storage difference and achieves constant values of self-sufficiency in both cases, the common definition shows a linear dependency on ΔE^{ESS}. In the first case, with a local production of 95%, the common definition estimates self-sufficiency values of above 100 % if the ratio $\Delta E^{\text{ESS}}/E^{\text{load}}$ exceeds 5.26 %. If the energy level is the same at the beginning and the end of the observation period ($\Delta E^{\text{ESS}} = 0$), both equations achieve the same value. The example shows that neglecting storage energy level differences can distort the estimated self-sufficiency and even push it to invalid values.

C. Influence of storage efficiency

The use of storage systems generally entails energy losses, generated during energy uptake (charging) and output (discharging), as well as when being idle due to self-discharge or leakage rates. Related losses are represented by $E^{\text{ESS}}_{\text{loss}}$ in

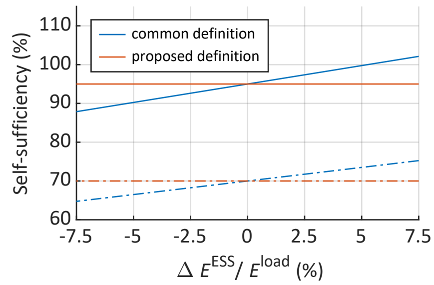
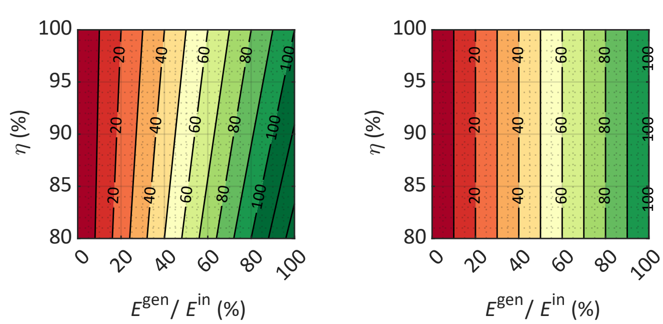


Fig. 3. Comparison of common and proposed definition of self-sufficiency as a function of storage level difference between end and start of a given observation period. The solid lines compare the definitions for a system with 95 % self-sufficiency at $\Delta E^{\text{ESS}} = 0$, while the dashed lines compare the definitions for a system with 70 % self-sufficiency at $\Delta E^{\text{ESS}} = 0$

the energy balance eq. (3). In the following, we compare the influence of storage efficiency on the self-sufficiency obtained by the common and the proposed definition. The effects of the other two factors were excluded by setting E^{exp} and ΔE^{ESS} to zero. We performed a parameter sweep of the storage roundtrip efficiency between values of 80 % and 100 %. The consumed energy was set to a fixed value and the overall energy input was varied as a function of the storage efficiency η with $E^{\text{in}} = E^{\text{load}}/\eta$, to compensate for the energy losses in the storage and satisfy the energy balance equation. Furthermore, the share of local generation was varied between 0 % and 100 % of the overall energy input, eventually forming a two-dimensional sensitivity analysis. It should be noted that information on energy losses could be obtained through the battery management system which monitors the operating states of the battery. Fig. 4 compares the results estimated with both equations. Generally, self-sufficiency improves with an increasing share of local generation. Furthermore, both definitions estimate the same values if no losses occur, i.e. for a storage roundtrip efficiency of 100 %. However, with decreasing storage efficiency the common definition consistently estimates a higher self-sufficiency than the proposed definition. For high shares of local generation this leads to values of above 100 %. However, assuming a system operates in islanded mode with zero grid exchange, the self-sufficiency is expected to be 100 %, since all local consumption is covered



(a) Common definition

(b) Proposed definition

Fig. 4. Self-sufficiency for varying levels of storage round-trip efficiency and locally produced energy.

by local generation. Yet, for $E^{\text{gen}}/E^{\text{in}}$ and storage efficiencies below 100 %, the common definition always estimates a self-sufficiency of above 100 % and even shows a positive trend with decreasing storage efficiency. This suggests that by neglecting storage losses self-sufficiency is systematically overestimated. By contrast, the definition proposed in the present paper does not violate the defined range of $\sigma \in (0, 1)$.

V. Discussion

The results show that the commonly used definition of self-sufficiency yields values outside the defined range, i.e. above 100 % or below 0 %. Furthermore, even if the obtained values are in the valid area between 0 % and 100 % (which cannot be directly argued as incorrect), they are distorted by neglecting the factors introduced by a storage unit. Hence, the commonly used definition may under- or overestimate the self-sufficiency of a system. By contrast, the definition proposed in the present paper does not violate the defined range, and the obtained results are even independent of the influencing factors introduced by storage (grid export, storage level differences, losses). For the cases where none of these factors is present, the common and the proposed definition lead to the same result.

For all studied scenarios, the obtained values represent in fact directly the κ-factor introduced in (5) when applying the proposed definition. It can also be shown mathematically that by substituting (2) and (5) in (7), the equation simplifies to $\sigma = \kappa$. Yet, this is not the case if κ was defined in a different way. To describe the system behavior more precisely, the factor could also be introduced as a multi-dimensional matrix that details the impact of each system input on each of the factors E^{exp}, ΔE^{ESS}, and $E^{\text{ESS}}_{\text{loss}}$. For instance, if one input generally causes higher energy losses due to higher power values, this can be considered accordingly. Furthermore, coincidence factors between local production and consumption should be taken into account if data with high temporal resolution are available. If only energy measurements over a longer time period are at hand, the proposed definition can be directly applied.

In many recent scientific studies, self-sufficiency is taken as an decisive criterion for evaluating operating performance. However, different studies obtain diverging self-sufficiency values in their calculations which originate from differing definitions. The diffusive use of this metric may lead to incorrect conclusions and generally makes it difficult to compare systems and control concepts from different studies. It is hence needed to rely on a general metric that addresses the differences in several setups (e.g. with or without storage) while producing valid results for all cases. The definition proposed in this paper provides a starting point in this discussion.

VI. Conclusion

Self-sufficiency is an important metric for evaluating the operating performance of energy systems at different scales, and for sizing assets in investment planning problems. The common definition of self-sufficiency was originally designed for systems without storage. However, future systems will rely strongly on storage units. Storage units can introduce new levels of complexity to the calculation of self-sufficiency, namely grid export of previously imported energy, differences in storage levels, and energy losses. Therefore, the present paper proposes an alternative formulation of self-sufficiency that takes into account the distinctive factors introduced by storage systems. The equation is mathematically derived by starting from the energy balance of a generic system. Subsequently, we separately examine the influence of the above-mentioned factors introduced by an active operation of storage that are not covered by the commonly used definition. The results demonstrate that neglecting these three factors can lead to unrealistic values above 100 % and below 0 % when applying the common definition. Furthermore, even if reasonable values are obtained, those might be distorted: An active energy exchange of the storage with the grid leads to an underestimation whereas not considering storage losses to an overestimation of self-sufficiency. By contrast, the proposed self-sufficiency definition considers these factors and yields values always within the defined range, even in extreme cases.

References

[1] R. Luthander, J. Widén, D. Nilsson, and J. Palm, "Photovoltaic self-consumption in buildings: A review," *Applied Energy*, vol. 142, pp. 80–94, 2015.

[2] J. C. Hernández, F. Sanchez-Sutil, and F. J. Muñoz-Rodríguez, "Design criteria for the optimal sizing of a hybrid energy storage system in PV household-prosumers to maximize self-consumption and self-sufficiency," *Energy*, vol. 186, p. 115827, 2019.

[3] A. Laitinen, O. Lindholm, A. Hasan, F. Reda, and A. Hedman, "A techno-economic analysis of an optimal self-sufficient district," *Energy Conversion and Management*, vol. 236, p. 114041, 2021.

[4] J. Lokar and P. Virtič, "The potential for integration of hydrogen for complete energy self-sufficiency in residential buildings with photovoltaic and battery storage systems," *International Journal of Hydrogen Energy*, vol. 45, no. 60, pp. 34 566–34 578, 2020.

[5] L. Langer and T. Volling, "An optimal home energy management system for modulating heat pumps and photovoltaic systems," *Applied Energy*, vol. 278, p. 115661, 2020.

[6] J. M. Zepter, A. Lüth, P. Crespo del Granado, and R. Egging, "Prosumer integration in wholesale electricity markets: Synergies of peer-to-peer trade and residential storage," *Energy and Buildings*, vol. 184, pp. 163–176, 2019.

[7] D. Krishnamurthy, C. Uckun, Z. Zhou, P. R. Thimmapuram, and A. Botterud, "Energy Storage Arbitrage Under Day-Ahead and Real-Time Price Uncertainty," *IEEE Transactions on Power Systems*, vol. 33, no. 1, pp. 84–93, 2018.

[8] M. H. K. Tushar, C. Assi, M. Maier, and M. F. Uddin, "Smart Microgrids: Optimal Joint Scheduling for Electric Vehicles and Home Appliances," *IEEE Transactions on Smart Grid*, vol. 5, no. 1, pp. 239–250, 2014.

[9] J. Engelhardt, A. Thingvad, J. M. Zepter, T. Gabderakhmanova, and M. Marinelli, "Energy Recovery Strategies for Batteries Providing Frequency Containment Reserve in the Nordic Power System," *SEGAN-D-22-00529*, 2022. [Online]. Available: http://dx.doi.org/10.2139/ssrn.4093894

[10] J. Engelhardt, J. M. Zepter, T. Gabderakhmanova, G. Rohde, and M. Marinelli, "Double-String Battery System with Reconfigurable Cell Topology Operated as a Fast Charging Station for Electric Vehicles," *Energies*, vol. 14, no. 9, p. 2414, 2021.

[11] G. de Oliveira e Silva and P. Hendrick, "Lead–acid batteries coupled with photovoltaics for increased electricity self-sufficiency in households," *Applied Energy*, vol. 178, pp. 856–867, 2016.

[12] S. Kichou, N. Skandalos, and P. Wolf, "Evaluation of Photovoltaic and Battery Storage Effects on the Load Matching Indicators Based on Real Monitored Data," *Energies*, vol. 13, no. 11, p. 2727, 2020.

[13] Q. Hassan, M. Jaszczur, A. M. Abdulateef, J. Abdulateef, A. Hasan, and A. Mohamad, "An analysis of photovoltaic/supercapacitor energy system for improving self-consumption and self-sufficiency," *Energy Reports*, vol. 8, pp. 680–695, 2022.
[14] D. Gudmunds, E. Nyholm, M. Taljegard, and M. Odenberger, "Self-consumption and self-sufficiency for household solar producers when introducing an electric vehicle," *Renewable Energy*, vol. 148, pp. 1200–1215, 2020.
[15] J. M. Zepter, M. Ledro, J. Engelhardt, T. Gabderakhmanova, M. Marinelli, A. S. Poulsen, H. H. Ipsen, and T. Jørgensen, "D4.9 Bornholm Lighthouse UC-5 report: WP4 – Modelling, simulation, engineering, and equipment development for the Lighthouse demonstration," 2021.
[16] J. Engelhardt, J. M. Zepter, T. Gabderakhmanova, and M. Marinelli, "Energy Management of a Multi-Battery System for Renewable-Based High Power EV Charging," *eTransportation (under review)*, 2022. [Online]. Available: arXiv.2112.00351
[17] S. Dong, E. Kremers, M. Brucoli, R. Rothman, and S. Brown, "Techno-enviro-economic assessment of household and community energy storage in the UK," *Energy Conversion and Management*, vol. 205, p. 112330, 2020.
[18] Y. Zhang, A. Lundblad, P. E. Campana, and J. Yan, "Employing Battery Storage to Increase Photovoltaic Self-sufficiency in a Residential Building of Sweden," *Energy Procedia*, vol. 88, pp. 455–461, 2016.
[19] J. Li and M. A. Danzer, "Optimal charge control strategies for stationary photovoltaic battery systems," *Journal of Power Sources*, vol. 258, pp. 365–373, 2014.
[20] S. I. Sun, M. Kiaee, S. Norman, and R. Wills, "Self-sufficiency ratio: an insufficient metric for domestic PV-battery systems?" *Energy Procedia*, vol. 151, pp. 150–157, 2018.
[21] S.-Y. Li and J.-Y. Han, "The impact of shadow covering on the rooftop solar photovoltaic system for evaluating self-sufficiency rate in the concept of nearly zero energy building," *Sustainable Cities and Society*, vol. 80, p. 103821, 2022.
[22] C. Liu, W. Xu, A. Li, D. Sun, and H. Huo, "Analysis and optimization of load matching in photovoltaic systems for zero energy buildings in different climate zones of China," *Journal of Cleaner Production*, vol. 238, p. 117914, 2019.
[23] T. Kobashi, T. Yoshida, Y. Yamagata, K. Naito, S. Pfenninger, K. Say, Y. Takeda, A. Ahl, M. Yarime, and K. Hara, "On the potential of "Photovoltaics + Electric vehicles" for deep decarbonization of Kyoto's power systems: Techno-economic-social considerations," *Applied Energy*, vol. 275, p. 115419, 2020.
[24] T. Gabderakhmanova, J. Engelhardt, J. M. Zepter, T. M. Sørensen, K. Boesgaard, H. H. Ipsen, and M. Marinelli, "Demonstrations of DC microgrid and virtual power plant technologies on the Danish island of Bornholm," in *55th International Universities Power Engineering Conference (UPEC)*. IEEE, 2020, pp. 1–6.
[25] J. Engelhardt, T. Gabderakhmanova, L. Calearo, J. M. Zepter, M. Ledro, and M. Marinelli, "D4.8 Bornholm Lighthouse UC-4 report: WP4 – Modelling, simulation, engineering, and equipment development for the Lighthouse demonstration," Technical University of Denmark (DTU), 2021.