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Integrating on-site renewable electricity generation into a manufacturing system with intermittent battery storage from electric vehicles

Jan Beier[a,*], Benjamin Neef[a], Sebastian Thiede[a], Christoph Herrmann[a]

[a] *Chair of Sustainable Manufacturing and Life Cycle Engineering, Institute of Machine Tools and Production Technology, Technische Universität Braunschweig, Langer Kamp 19b, 38106 Braunschweig, Germany*

[*] Corresponding author. Tel.: +49-531-391-7153; fax: +49-531-391-5842. *E-mail address:* j.beier@iwf.tu-bs.de

Abstract

Electricity storage capacity in electric vehicles (EV) can be used to compensate electricity demand/supply mismatches between (decentralized) variable renewable electricity and manufacturing. However, EVs need to be sufficiently charged for use and removing an EV results in immediate unavailability of stored energy. Effectiveness and challenges, e.g. reduced battery lifetime, for using EV batteries to increase on-site generated electricity demand from a manufacturing system is studied using a simulation approach. Results are compared to load shifting/energy flexibility options offered by the manufacturing system. A case-study based on an existing manufacturing line, on-site generation and EVs is used as application example.

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Keywords: Manufacturing system simulation; energy flexibility; electric vehicles

1. Introduction

Subsidy for electricity generated from renewable energy conversion was first introduced by the “Act on the Feeding of Electricity from Renewable Energy Conversion into the Public Grid” in Germany in the 1990s [1]. Since then, a steady increase of renewable energy (RE) conversion takes place. Although the provision of electricity by conversion of renewable energy reached a historical high of 160.6 TWh in Germany in 2014 versus an electricity demand of 578.5 TWh [2], the overall situation of the energy economy is not reproduced properly in these figures. The share of wind and solar energy (about 90.9 TWh, which corresponds to 56.6% of RE in 2014 [2]) are so-called variable renewable energy (VRE) sources. VRE is non-dispatchable and a large share of conversion is decentralized. In order to be able to obtain a realistic understanding of demand and supply matching, a time-dynamic comparison of electricity demand and variable renewable supply is recommended. The demand as well as the conversion of renewable energy is a distinct stochastic process and not congruent. Two strategies are conceivable to adjust feeding-in of electricity from renewable energy conversion and demand: reshaping of demand to match supply (demand side management) or storing electricity, e.g. in batteries. In the context of electricity storage, the use of electric vehicles (battery electric vehicles and plug-in hybrid electric vehicles) as intermittent electricity storage becomes more attractive with an increasing number of available cars. However, a central prerequisite is the ability to discharge electricity into the local grid. Without this option, EVs can be used to store (VRE) electricity for driving purposes, but not for other end-use cases. In Germany, within the third quarter of 2015, new registrations increased by 60% to 43,000 registered electric vehicles (EVs) compared to 2014. The German automotive manufacturers introduced 17 new models in the year 2014, with another twelve to follow in 2015 [3]. The potential of renewable energy conversing complemented by utilizing EVs as an intermittent electricity storage was also discovered by several enterprises. For example, LomboXnet, an internet service provider at Utrecht, Netherlands, utilizes photovoltaics to provide electricity for EVs [4]. Against this background, this paper

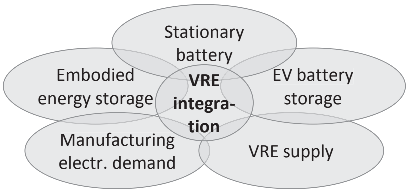

Fig. 1. Topic areas highlighted in this paper.

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presents a concept to integrate VRE into a manufacturing system with EV and stationary battery storage, supplemented by energy flexibility of the manufacturing system (figure 1). A case study is used to demonstrate the application of such a system in a simulation environment.

2. State of research

Several existing renewable energy system modeling approaches focus on hybrid renewable energy systems (HRES) stand-alone applications and/or a given demand structure. In [5], mathematical models for frequently included components (photovoltaics, wind, diesel, battery) of HRES are presented, as well as criteria for system selection and a review of modeling approaches. A comprehensive overview of optimization and simulation techniques used for design and control of stand-alone HRES, including cost objectives, can be found in [6]. On the manufacturing system energy demand and energy flexibility side, a strong focus is set on forecasting energy demand and/or adapting system energy demand to VRE by (operational) scheduling optimization. In order to analyze the impact of vehicle-to-grid (V2G) in an urban area, Drude et al. implemented a MATLAB simulation. They assumed a number of 250 EVs and a photovoltaics (PV) capacity of 7.9 MW_p on a rooftop area of 43,000 m^2. Using real solar radiation and electricity demand data they conclude that a potential for EVs exist to stabilize the grid by peak-load shaving [7]. In the domain of small micro grid implementation van der Kam and van Sark introduced an analysis to increase PV self-demand rate and peak reduction in relation to variations in EV trips using V2G strategies for an existing environment in the Netherlands [4]. López et al. present an agent based optimization model for controlled charging of EVs considering alternating selling market prices for electricity [8]. Advantages, challenges and optimization approaches for V2G applications including considerations as well as social factors and investment barriers are presented by Tan et al. [9]. The investigation on existing approaches has shown that the primary focus refers to the implementation of V2G technologies into smart grid environments. Considerations regarding an implementation within production environments do not exist so far. The method proposed in this paper presents an approach to evaluate effectiveness of V2G applications in the context of energy flexible manufacturing systems, i.e. a concept is proposed which allows to evaluate the effectiveness of V2G applications and compare V2G effectiveness to real-time demand response capability of an energy flexible manufacturing system.

3. Concept for evaluating VRE integration into manufacturing systems with EVs

In order to integrate decentralized VRE generation into an existing manufacturing system, several technical and organizational options exist. A key task is to accommodate (stochastically) fluctuating and non-dispatchable electricity generation output of VRE sources to minimize grid reliance (demand from grid and feed into the grid). Among others, additional, dispatchable supply sources can be installed (e.g. a CHP-plant or diesel generator), the electricity demand side can/needs to be adjusted to supply or surplus electricity from VRE is stored, e.g. in batteries.

3.1. VRE and EV integration concept

The following assumptions are made to limit the scope of this work:

- A manufacturing line with several processes/machines and buffers for intermediate product storage exists.
- EVs are connected to the local (company) grid, which in turn connects the manufacturing system and VRE electricity generation.
- VRE is generated on-site and economic (e.g. due to feed-in tariffs vs. grid electricity price) and environmental (e.g. lower carbon emissions) benefits exist to directly demand as much on-site generated electricity as possible.

The proposed framework for integrating VRE generation into a manufacturing system environment can be found in figure 2. It comprises six steps with the following actions and objectives:

1. A dynamic system model needs to be set-up to reflect time-dependent dynamics (material and energy flows) of all relevant system elements.
2. One or multiple hypotheses are formulated in relation to improved integration of VRE, including indicators for measuring improvement.
3. Scenarios are defined, reflected by a set of input parameters for the dynamic system model to test hypotheses. For the purpose of this approach, EV fleet changes and use case scenarios are central scenarios for evaluation, as well as energy flexibility of the manufacturing system.
4. For each scenario, model evolution is calculated and relevant indicator values obtained.
5. Based on evaluated scenarios and outcomes, conclusions on previously defined hypotheses are drawn. Dependent upon outcomes, implementation can be prepared and/or further hypotheses tested (e.g. if desired outcomes are insufficient or new, additional hypotheses towards improvement emerged).
6. Dependent upon conclusions, hypotheses are reformulated or new hypotheses are generated for testing.

In order to be applicable for multiple application cases, a generic model structure has been developed as part of step one. Its four main system model elements (manufacturing system, VRE supply, EV fleet, energy control) are described briefly in the following.

3.2. System elements

Mentioned four system elements exchange information and energy flows. Starting with VRE supply, electricity from on-site generation sources can either be directly demanded by the manufacturing system (first priority), used to charge connected EVs (second priority) or fed in to the connected power grid (third priority). The grid itself supplies electricity to the manufacturing system and EVs, if VRE supply is not sufficient to meet energy needs (see also figure 3). The manufacturing system and connected auxiliary systems' (e.g. compressed air (CA) generation) electricity demand is optionally controlled by a central electricity control which aims at matching processes total demand with VRE supply via controlling processes target states (e.g. idle/produce), similar to [10]. The EV fleet is charged with surplus VRE (if any) and can discharge VRE if required by the manufacturing system and if allowed by the EV, depen-

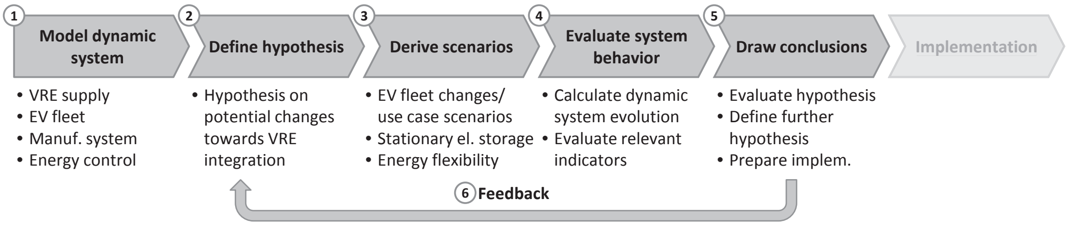


Fig. 2. Structural overview of proposed VRE integration concept.

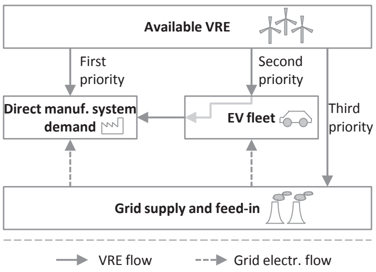


Fig. 3. VRE and grid electricity flow and VRE demand priority.

dent upon mobility requirements of the EV. Remaining required EV electricity charge is supplied by the grid.

3.2.1. *Manufacturing and auxiliary system*

Considered manufacturing system consist of a sequential production line with a number of processes, intermediate buffers with limited storage and connected CA supply system. Manufacturing process electricity and CA demand and compressor electricity demand are modeled as state-dependent (compare e.g. to [11]). Corresponding power demand is $P_{el.}$ (electric power demand) and P_{CA} (CA power demand), with additional index to differentiate between production, idle and off. Time required for switch-on and switch-off is denoted as T_{on} (switch-on) and T_{off} (switch-off). For simplicity, energy demand during switching on/off is set equal to idle demand values and to zero if a process is in off-state. Compressors are automatically switched-off after a certain idle waiting time period has passed (during which electricity demand is lower, but no CA is produced).

3.2.2. *VRE supply*

VRE supply is included as a dynamically changing time series. Either recorded data (with an adequate resolution, i.e. seconds or minutes, to reflect intermittent availability of VRE) or (physical) electricity generation models can be used to generate input for considered model.

3.2.3. *EV fleet*

The connected EV fleet is assumed to be available for charge from VRE and discharge for manufacturing system energy demand if a vehicle is available. EV batteries are (dis-)charged according to their maximum charge rates, available VRE (charge) and system electricity demand (discharge). Further, a round-trip energy efficiency parameter is included, as well as self-discharge losses and capacity degrading as a function of (dis-)charge cycles.

EV availability is subject to a weekly schedule. EVs are assumed to require scheduling before utilization, with an approximate driving distance. A control logic determines when a given vehicle is not available for discharge into the local grid, which is dependent upon the EVs current State-of-Charge (SOC), maximum charge rate and required charge as a function of desired driving distance. As soon as the logic determines that remaining time for charge (at maximum charge rate) is equal to required time to reach desired SOC from current SOC, the EV is set in charge mode and only charged from VRE (if available), but not discharged anymore. Once the scheduled trip start time has been reached, the EV is removed from the system. Upon return of the EV, the scheduled SOC reduction (in percent of the EVs capacity, derived from the trip's driving distance) is deducted from the EV's SOC at the beginning of the trip (the amount of VRE in the vehicle's battery is reduced proportional to VRE share of SOC) and connected back to the system.

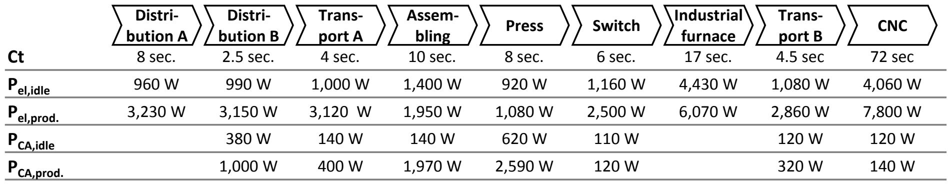
3.2.4. *Energy control*

In order to compare the effect of different energy storage and energy flexibility actions, different energy flexibility and energy efficiency control strategies are enacted. The following control strategies are investigated, they all aim at matching energy demand with supply while leaving throughput constant:

- **No control** denotes a one-piece flow strategy, i.e. a process replaces a part if withdrawn from its outgoing buffer.
- **Central energy flexibility control** determines which non-throughput critical manufacturing processes and compressor idle/produce combination yields the closest fit with available VRE and schedules processes accordingly (for further detail see [10]).
- **Switch-off** adds an energy saving, decentralized control logic: processes switch from idle/waiting to off if (a) a set wait time has been passed and (b) if upstream and downstream buffer fill levels are small (upstream) and high (downstream) enough to avoid impacting adjacent processes. Fill levels need to be in a range which allows sustaining a time period until blocking (upstream) or starving (downstream) adjacent processes (assuming maximum production) which is longer than the process' switch-off and -on time (combined). Depending on system layout, only upstream or downstream buffer fill levels might be considered (e.g. if the system bottleneck is downstream of a given process).

3.3. *Prototypical implementation*

Described system has been implemented into Anylogic$^{\circledR}$, an agent-based, mixed discrete-event and continuous time sim-



	Distribution A	Distribution B	Transport A	Assembling	Press	Switch	Industrial furnace	Transport B	CNC
Ct	8 sec.	2.5 sec.	4 sec.	10 sec.	8 sec.	6 sec.	17 sec.	4.5 sec	72 sec
$P_{el,idle}$	960 W	990 W	1,000 W	1,400 W	920 W	1,160 W	4,430 W	1,080 W	4,060 W
$P_{el,prod.}$	3,230 W	3,150 W	3,120 W	1,950 W	1,080 W	2,500 W	6,070 W	2,860 W	7,800 W
$P_{CA,idle}$		380 W	140 W	140 W	620 W	110 W		120 W	120 W
$P_{CA,prod.}$		1,000 W	400 W	1,970 W	2,590 W	120 W		320 W	140 W

Fig. 4. Case study manufacturing process chain (energy demand values scaled with a factor of 100).

Table 1. Electric vehicle parameters according to manufacturer's data.

Name	Citroen C-Zero	Mia miAmore
Capacity [kWh]	16	8
Oper. range [km]	150	80
(Dis-)charge rate [kW]	2.667	2.667
Full (dis-)charge time [h]	6	3
Electricity demand	10.67	10

Table 2. Overview of battery storage scenarios (H1-H3).

Scenario	Energy control	Bat./EVs	♯ EVs/equiv.
REF	No	No	N/A
BATa	No	Battery	4 (48 kWh)
SCH1a/2a/3a	No	EVs	4 (48 kWh)
BATb	No	Battery	8 (96 kWh)
SCH1b/2b/3b	No	EVs	8 (96 kWh)

ulation environment. Manufacturing system elements, auxiliary system, EVs and stationary batteries are interacting elements, which can be added to the simulation model as individual agents and configured according to an application case as needed. Within the following, an application case study is described.

4. Example application case study

The chosen case study to demonstrate the application of proposed VRE/EV/manufacturing system integration is based on an existing experimental manufacturing lab with connected VRE (wind and solar) generation and EV fleet.

Modeled manufacturing process can be found in figure 4. The process consists of nine individual steps, including transportation, which is modeled as individual process to be controlled separately. Further, buffers are assumed to be deployable between process steps for decoupling. In its initial configuration, maximum buffer holding size between each process is limited to five pieces, while the one-piece flow strategy is realized by keeping two pieces in each buffer (reduced inventory and system residence time).

Available electric vehicles are two Mia miAmore and two Citroen C-Zero, their relevant parameters are summarized in table 1. Both charge and discharge from/into the local grid are assumed to be feasible. Battery round-trip efficiency is set to 90%, cycle stability to resemble a case where 1,200 full charge cycles result in 20% initial capacity loss (linear decreasing with increased cycle number).

VRE generation data is used from own recorded data with a sample rate of one second and averaged (arithmetic) over one minute to manage computability. Chosen time period is 3^{rd} to 30^{th} September 2013, and supply data was scaled to match total energy demand in a no-control case (gross own supply equals total demand when not considering temporal mismatches), with an equal share between solar and wind electricity generation. Products are withdrawn from the last buffer with a cycle time of 80 seconds and thus denoting a nearly maximum possible throughput scenario, considering that CNC process has the longest cycle time with 72 seconds. Compressors are configured with similar parameters and individual control settings as in [10], while three compressors (4.2/2.8/1.4 kW energy demand during CA production) are included.

4.1. EVs and battery storage

In order to improve integration of VRE, the following initial hypothesis and related scenarios in relation to EV and battery storage are tested (step 2 and 3 from figure 2), for an overview see table 2:

H1: **Different vehicle utilization schedules** have an impact on how much electricity can be stored in EVs and fed back if demanded by the manufacturing system. Utilizing available battery storage from EVs can significantly increase VRE utilization (to be demonstrated). Based on evaluated logbook data, different example utilization schedules per vehicle can be found in figure 6 (scenario SCH1a). In addition, a high-frequency, low driving distance case (same schedule for all vehicles, scenario SCH2a, figure 6) and a heavy use-case is defined (same schedule for all vehicles, scenario SCH3a, figure 6). REF denotes a scenario without battery, i.e. pure one-piece flow strategy.

H2: **A stationary battery** with similar parameters to available EV batteries will contribute most to increased VRE utilization. The actual difference between a stationary battery and intermittent available batteries has to be investigated to compare an (additionally installed) battery to (already available) electric vehicles. Scenario BATa refers to installing a set of stationary batteries similar to the EV's batteries from table 1.

H3: **Additional EVs** are installed in the system. For simplicity, the initial vehicle fleet and their respective schedules are reproduced, resulting in four additional scenarios SCH1b, SCH2b, SCH3b and BATb (stationary battery equivalent to eight EVs).

Hypotheses H1 to H3 aim at evaluating the effect of EV and stationary battery storage to store VRE for later demand of a connected manufacturing system. Main differences between scenarios are dynamic availability of EVs/battery and the amount of energy that can be stored (four or eight EVs/battery equivalent).

The left graph of figure 5 shows the amount of on-site generated electricity which has been directly and indirectly (through battery storage) demanded by the manufacturing system, and remaining public power grid supply (external demand). As ex-

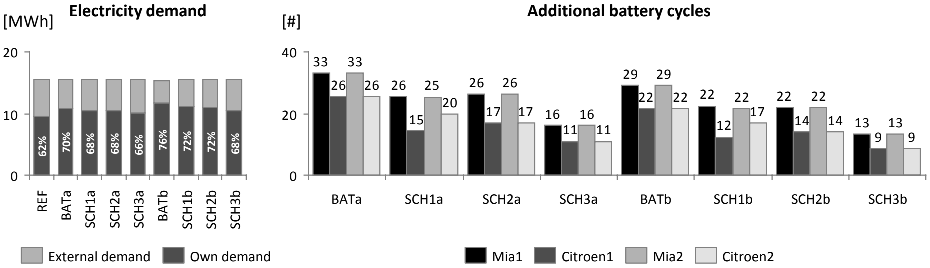


Fig. 5. Electricity demand and incurred additional battery cycles for nine scenarios (external demand refers to public power grid demand; note that scenario REF incurs no added cycles and that all *b* labeled scenarios include eight EVs with same indicator results as the shown four EVs).

Scenario	Vehicle	Time (24h)	Charge removed	Mon	Tue	Wed	Thu	Fri
SCH1	M1	10:00-13:00	50%		✓	✓	✓	✓
		15:00-18:00	40%		✓	✓	✓	
	M2	10:00-11:00	10%	✓	✓	✓	✓	✓
		13:00-15:00	30%		✓		✓	
		18:00-08:00	40%	✓	✓		✓	
	C1	08:00-16:00	80%	✓	✓	✓	✓	
	C2	09:00-12:00	30%	✓	✓	✓	✓	✓
		14:00-15:00	20%	✓	✓		✓	
SCH2	All	08:00-10:00	20%	✓	✓	✓	✓	✓
		11:00-12:00	30%	✓	✓	✓	✓	✓
		13:00-14:00	20%	✓	✓	✓	✓	
		15:00-16:00	30%	✓	✓	✓	✓	
SCH3	All	08:00-16:00	90%	✓	✓	✓	✓	✓

Fig. 6. EV utilization schedule scenarios (no utilization on weekends, M1/M2: Mia1/2, C1/C2: Citroen1/2).

pected, total electricity demand remains stable between scenarios. Second, also as expected, a stationary battery achieves the highest increase in VRE utilization compared to EV storage options. However, EV storage also yields a significant increase in VRE demand. Nonetheless, even though EVs are connected to the system for most of the time (e.g. for schedule 2 (SCH2a), EVs are only absent 22 of 144 hours/week), the requirement for being sufficiently charged before removal, using VRE for propulsion purposes and their non-availability during potential high VRE output (solar during day) reduces EV VRE integration potential overproportional (e.g. VRE use increases 8% with a stationary battery (BATa) compared to the reference case REF, but only 6% from SCH2a to REF, although EVs are available for more than 80% of total time). Looking into additional battery cycles imposed on EV batteries (right graph of figure 5), additional cycles are (a) positively correlated to increase in VRE utilization and (b) non-evenly distributed between vehicles. As additional cycles cause a battery to degrade faster, detailed economic and environmental assessment is required for further conclusions. Battery inefficiency losses (as mentioned, round-trip efficiency is set to 90%) result in less VRE grid feed-in. Losses can amount up to 3.4% of VRE generation or approx. 530 kWh compared to the reference case scenario without battery. These losses have to be accounted for in a holistic economic and ecological evaluation.

4.2. Embodied energy storage

The second set of hypothesis evaluates the impact of embodied energy storage, enabled through energy flexibility control of the system, and compares results to EV and battery storage scenarios (overview in table 3):

H4: Energy flexibility control can match electricity demand with supply by utilizing intermediate product storage capacities. Three initial reference scenarios are defined: REF1 as outlined above (same as REF, one-piece flow, no energy control, no battery or EVs), REF2 with EV battery storage and schedule according to SCH1a from figure 6 and REF3 without battery or EV storage, but with energy control of processes and compressors. The CNC-process has the longest cycle time and is also the last process of the system. In order to decouple this process, increased buffer capacities are installed in front of the process (scenarios CNC1 to CNC4, with buffer capacities of 50/100/200/500 pieces, respectively). Further, additional buffer storage between all remaining processes is investigated, labeled BUF1 to BUF3 with 50/100/200 capacity for all buffers and a scenario BUF4 with 500 capacity before CNC and 50 capacity before all other processes.

H5: Idle switch-off can be used to reduce overall energy demand and, in combination with energy flexibility control, further contribute to match electricity demand and supply by reducing idle electricity demand of processes. Idle switch-off is applied to all previously described scenarios (same scenario names, mentioned where applicable).

Table 3. Overview embodied energy scenarios (H4, H5).

Scenario	Contr.	Bat./EVs	Buffer CNC	Buffer other
REF1	No	No	5	5
REF2	No	4 EVs	5	5
REF3	Yes	No	5	5
CNC1/2/3/4	Yes	No	50/100/200/500	5
BUF1/2/3/4	Yes	No	50/100/200/500	50/100/200/50

The second set of results is presented in figure 7 and summarizes energy flexibility and energy efficiency control strategies (note that additional operational indicators are included which become relevant under energy flexibility control actions). Utilizing embodied energy as VRE integration method can increase on-site generated electricity demand. However, without switch-off, no scenario achieves a result as high as battery storage (68% with EV batteries (REF2), maximum 66% with energy control (BUF4) and 62% without control or battery (REF1)). In addition, system residence time and average inventory is increased with additional intermediate product storage, and up to 40 times higher than in the initial case. Maximum external (public power grid) demand (fifteen-minute average peak demand) is slightly reduced with energy control on. Consider-

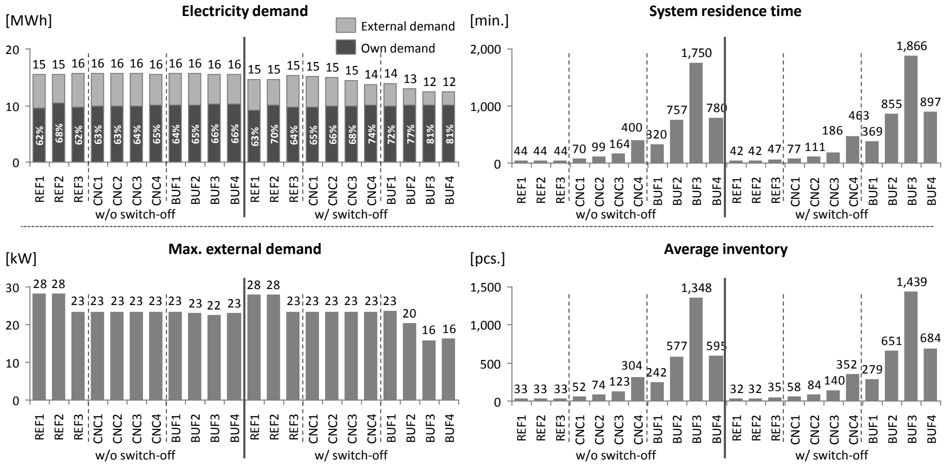


Fig. 7. Results for energy flexibility and energy efficiency control scenarios.

ing process switch-off scenario results, absolute (in MWh) VRE demand can only be slightly increased. However, external demand can be significantly reduced and thus VRE supply relative to total demand increased up to 81% (BUF4), with increasing system residence time and inventory. Switching-off not only achieves significant energy efficiency improvement, but also increases relative VRE utilization beyond battery values. This potential is enabled through increased embodied energy storage between processes. However, maximum process switch-on/off counts per hour need to be considered to avoid excessive wear on equipment; hourly counts can amount up to more than ten switches per hour for described experiments. Note that constant throughput was realized for all scenarios.

5. Discussion and conclusion

An approach to integrate decentralized VRE generation into a manufacturing system through intermittent battery storage from EVs has been presented. Competitiveness of EV battery storage is compared to stationary battery storage and energy flexibility control of manufacturing systems. A case study is used to demonstrate the effectiveness of the proposed approach.

Results indicate that intermittent EV battery storage improves integration of decentralized VRE. Stationary batteries are more effective due to uninterrupted availability. However, the benefit of EV batteries is their simultaneous utilization as traction batteries. They are available independent of VRE integration goals, while a stationary battery needs to be additionally installed. Nonetheless, increased battery cycles and thus wear-out need to be carefully evaluated under economic and environmental goals. Energy flexibility of manufacturing systems, enabled by embodied energy storage, can also improve VRE integration and be an alternative to battery storage. Especially including process switch-off using flexibility induced by product storage significantly improves VRE utilization while reducing external and total energy demand.

Further research includes a structured comparison of available energy/electricity storage options in manufacturing and connected systems, e.g. storage in compressed air, batteries and embodied electricity. Different options to match demand and dynamic supply need to be compared (economic, environmental, operational) to derive an improved solution for integrating VRE. In addition, sizing of VRE supply options (amount and wind/solar share) to improve VRE integration is pursued. Another followed lead is applying energy flexibility approaches to enable fully energy self-sufficient (autarkical) manufacturing systems and companies.

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