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The Sustainability of Integrating Contactless Occasional Charging in Electric Vehicle Material Handling

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Abstract

Electric mobility has developed itself to an option to mitigate air pollution and greenhouse gas emissions in cities same as in intralogistics material handling, while significant advances have been made in the research and development of electric vehicles (EV's). Along with the major challenge of energy storage, another important factor is the efficient design of system energy supply, transfer and consumption. This has had the effect of fundamentally changing perspectives across the mobility and transportation sector.

The overarching aim of this research is to examine the impact and potential of using contactless occasional recharging for non-road Electric Vehicles (nrEV) integrated within a manufacturing line, recognising the need to balance the (sometimes competing) demands of delivering reliable and efficient production while respecting environmental and sustainable needs. The integration of a contactless charging infrastructure targets on a reliable energy supply in process inherent break times without changing or interrupting existing production processes.

The research investigations based on the Occasional Charging Station Location Model (OCSLM) provide a set of novel results in reference to the impact from interim battery charging to system`s overall sustainability. The application demonstrated a theoretical increase in usable battery energy of 40% to 60% while realising a reduction potential in battery capacity and system cost of between 5% to 45%. However, the use of contactless power transfer based on a standard energy mix resulted in an increase in CO2 emissions of up to 6.89% revealing a negative impact to overall ecology from the use of this energy transfer system.

Keywords: contactless charging, battery electric vehicles, sustainability impact, material handling

1. Introduction

In the European Union, the transportation of goods including supply, intralogistics and distribution generates about 28% of the total CO2-emissions and consumes around 37.5% of the total European energy production (International Energy Agency, 2014), whereas the fraction of energy related cost to total transportation cost is about 7% only (Fekete et al., 2014). Only 4% of the total energy as well as of the CO2 emissions is related to pure production related material handling (Sullivan, Burnham & Wang, 2010) and by this contributes about 1,053.57 Mt of the total CO2 emissions (International Energy Agency, 2014).

At the same time, shortened product life cycles force manufacturing companies to increase their production flexibility at lower response times in order to satisfy the specific customer requirements (Hasan & Shankar, 2007; Angkiriwang, Pujawan & Sandosa, 2014). In addition to cost, quality and service level aspects, customers increasingly integrate aspects in their purchase decision-making which impact social and ecologic developments such as environmental soundness and resource conservation on product and company level (Kartnig, Grösel & Zrnic, 2012), so that industrial producers are forced to identify with the environmentally sound practices of Lean and Green production. Consequently, business units have to face this paradox and challenge between increased product and service customisation versus the demand for low product cost at sound production practices (Retief et al., 2016).

In this respect, resource consumption and the emission of pollutants are often referred to as crucial factors in an attempt to evaluate industrial manufacturers' social and environmental responsibility, whereas current discussions focus on the emission of greenhouse gases. Several approaches in logistics and material handling focus on the reduction of

CO2-emissions (Faulkner & Badurdeen, 2014; Sparks, 2014), material and energy consumption (Frade et al., 2011; Nie & Ghamami, 2013; Jin, 2016), as well as the improvement of overall system and process efficiency (Hess et al., 2012; Mueller, Krones & Hopf, 2013; Giménez-Gaydou et al., 2016). In contrast to these optimisation approaches, growth rates of society and economy balance these developments and keep the levels of emission and consumption high, so that more advanced approaches for emission reduction are required. Therefore, new technologies and manufacturing processes need further scientific investigation in order to increase overall efficiency, sustainability and ecology at increased system availability.

Addressing the named needs, battery electric vehicles (BEV) are seen to be one of the most suitable alternatives to internal combustion engine (ICE) vehicles. Fully electric vehicles do not emit tailpipe pollutants and convert about 59%–62% of the electrical energy from the grid, respectively the battery to power at the wheels, while conventional combustion engine vehicles only convert about 17%–21% (U.S Environmental Protection Agency, 2011). The most challenging aspects while using Electric Vehicles is the short mileage range compared to gasoline vehicles as well as long charging times. Therefore, the development of a dedicated energy supply infrastructure that allows the widespread realisation, implementation and usage of electric vehicles is a key element within this research environment.

Occasional charging focuses on the use of non-value adding process times, i.e. downtimes, parking times, process interruptions or similar for interim charging, so that charging systems are analysed to be implemented in process range as fast connection solutions in order to avoid process sequences and functions to experience extraordinary, additional disturbances. The cordless alternative bears several advantages, such as minimised handling efforts, fast connectivity and the opportunity for occasional, intra process charging, whereas also negative impact from decreased transmission efficiency emerge (Lee & Lorenz, 2011).

This research project is based on previous research findings (see also Fekete et al., 2016) that focused on the simulation of optimal charging infrastructure allocation in reference to the maximisation of chargeable battery energy, and further investigates the impact from sustainability factors such as transmission efficiency, energy conversion and related CO2 emissions to the design of the charging infrastructure. The investigation analyses the impact from technology implementation to economic and ecologic sustainability of the transportation system, consisting of trucks and similar non-road electric transportation vehicles, in reference to an optimised charging infrastructure allocation based on the fundamental structures of Lean and Green Manufacturing.

2. Method

2.1 Lean and Green Perspectives on Electric Vehicle Material Handling

An increasing number of business entities refers to the application of lean principles to foster productivity and efficiency, to reduce costs, waste and idle times. The primary function of Lean Management (LM) is to achieve the minimal appearance of waste and to achieve the optimal allocation of production resources with the target to create maximal value to the final consumer (Bortolini et al., 2016). Within Lean Management, the original seven types of waste such as transportation, unnecessary inventory, unnecessary motion, waiting queues, over processing, overproduction and defects have been enhanced by lost people skills being the 8th form of waste (Duees, Tan & Lim, 2012; Verrier et al., 2013).

Inspired by the Lean approach, Green Management (GM) takes this development one step further by integrating environmental thinking into production and supply chain management being based on a comprehensive investigation of all product life cycle phases including design, production and distribution as well as product use and disposal phases (Walker, Di Sisto & McBain, 2008). Green Management differentiates among seven main types of waste of external nature being excessive use of water, excessive use of energy, excessive use of resources, pollution, rubbish, greenhouse gas effects and eutrophication (Duees, Tan & Lim, 2012, Verrier et al., 2013).

Especially in the field of transportation conflicting target definitions exist between Lean and Green Management such as the target to achieve frequent replenishment and short lead-times versus the reduction of greenhouse gas emissions in reference to transportation distances (Pampanelli, Found & Bernardes, 2013; Duees et al., 2013; Bortolini et al., 2016). Referring to this, several studies highlight the potential of combined, trade-off solutions of Lean and Green methods in order to contribute to both increased efficiency and ecology (Venkat & Wakeland, 2006; Duues et al., 2013; Jabbour et al., 2013).

Lean and Green wastes are highly interconnected as shown by the complexity and the multiple, reciprocal impacts of these factors (see Figure 1.). The relations highlighted in red present the Green wastes that are likely to be connected to the liaised Lean waste, while the blue links present potential risks between these factors. As it can be seen in Figure 1., transportation causally impacts excessive resource usage, excessive power usage as well as direct emissions to the air, soil and water, so that these factors were integrated within the research investigations as well as the used research simulation model OCSLM (Occasional Charging Station Location Model).

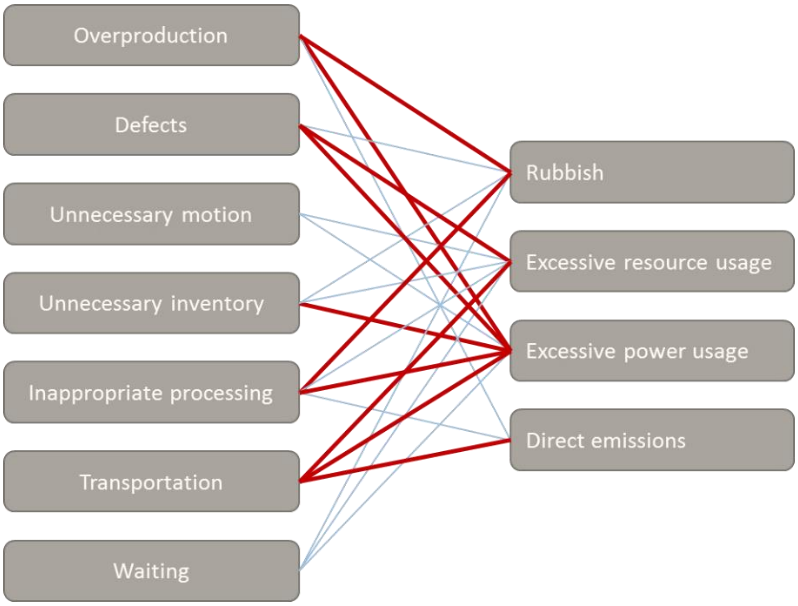

Figure 1. Causal links between Lean and Green wastes

Adapted from Verrier et al., 2016

2.2 Research Environment

Research in the field of electric vehicle material handling and transportation highlighted the major impact to a system`s energy balance and sustainability by charging infrastructure implementation to emerge from technological factors and charging station properties, process characteristics and charging station allocation determination, whereas there is a lack of models to combine economic and energetic optimisation approaches with ecologic factors.

Investigations for charging station allocation in the BEV environment noted the most suitable application to be a maximal (gradual) covering model in order to meet the requirements of BEV recharging (Frade et al., 2011; Giménez-Gaydou et al., 2014), which goes in line with the approach for optimised charging station allocation for occasional recharging in industrial applications with reference to sustainability factors (Fekete et al., 2016).

Existing research in the field of road-EV charging station allocation focuses on cost minimisation and optimisation for charging infrastructure integration (Nie & Ghamami, 2013; Mak, Rong & Shen, 2013; Chen, Kockelmann & Khan, 2013), minimisation of additional trip time (Hess et al., 2012; Sweda & Klabjan, 2011) and the reliable provision of driving range (Wang & Lin, 2009; Li et al., 2010). Only a few frameworks make the attempt to develop an integrated and holistic approach to charging station allocation, whereas metrics and frameworks are majorly based on vague, estimated or approximated figures (Berman, Drezner & Krass, 2010; Giménez-Gaydou et al., 2014; Jin, 2016).

Among a total of 30 models (see Table 1.) from the field of charging station allocation for electric vehicles, models with impact to the research target were identified and reviewed towards their applicability for occasional recharging in a non-road electric vehicle environment. The review showed most of the analysed models to contain similar factors in order to develop their model structures and frameworks, whereas the difference among the models in integrating these factors were the quality and the definition of underlying sub-elements and components. These factors are: demand definition, demand modelling, spatial representation, process sequencing, energy consumption, energy provision, covering distance. The covering distance definition plays a key role in charging station allocation and can be pre-determined by definition (exogenous covering distance) or by its expression as a function as a decision variable (endogenous covering distance) or as a mixed approach.

Table 1. Electric charging station location-allocation model

	Author(s)	**allocation model**	**car type**	**efficiency improvement**	**process data**	**energy data**	**supply data**
1	Berman, Krass & Menzenes (2007)	Median	rEV	x	x		
2	Berman et al. (2009)	Median	rEV	x	x		
3	Berman, Krass & Wang (2011)	MCLM	rEV	x	x		
4	Berman & Wang (2010)	Median	rEV		x	x	
5	**Berman, Drezner & Krass (2010)**	MCLM	rEV	x	x	x	
6	Chen, Kockelmann & Khan (2013)	Median	rEV		x		
7	Chen & Kockelmann (2014)	LSCM	rEV		x		
8	Chen,Wang & Kockelmann (2015)	LSCM	rEV		x		
9	Dashora et al. (2010)	Median	rEV		x		
10	**Frade et al. (2011)**	MCLM	rEV	x	x	x	x
11	**Giménez-Gaydou et al. (2016)**	MCLM	rEV	x	x	x	
12	Goh & Sim (2010)	LSCM	rEV		x		
13	Hanabusa & Horiguchi (2011)	Median	rEV		x		
14	He et al. (2013)	MCLM	PHEV		x		
15	Hess et al. (2012)	Median	rEV	x			x
16	Hodgson (1990)	Median	rEV	x	x		
17	Ip, Fong & Liu (2010)	Median	rEV		x		
18	Jin (2016)	MCLM	rEv			x	x
19	Kuby & Lim (2005)	MCLM	AFV	x	x		
20	Kuby & Lim (2007)	MCLM	AFV	x	x		
21	Li et al. (2010)	MCLM	rEV		x		
22	Lim & Kuby (2010)	MCLM	AFV	x	x		
23	Mak, Rong & Shen (2013)	LSCM	rEV		x		
24	Nie & Ghamami (2013)	LSCM	rEV			x	x
25	Pan et al. (2010)	LSCM	PHEV		x		
26	Sweda & Klabjan (2011)	Median	rEV		x		
27	**Upchurch, Kuby & Lim (2009)**	MCLM	AFV	x	x	x	
28	Wang & Lin (2009)	LCSM	AFV			x	
29	Wang & Wang (2010)	MCLM	rEV	x			
30	**Xi et al. (2013)**	MCLM	rEV	x	x	x	x

Source: Author

Table 2. shows the comparison of the investigated models based on the defined factors with relevance to model design as well as the target model of the executed research project. The requirements to the target model were deduced from research environment investigations as well as recommendations from previous studies.

Table 2. Comparison of available location-allocation models for charging station allocation

	FRLM[1]	**GCM**[2]	**OLSCM**[3]	**SOMCI**[4]	**CSCM**[5]	**Target Model**
Demand definition	dynamic	static	static	dynamic	static	static
Demand modelling	probabilistic	probabilistic	probabilistic	probabilistic	probabilistic	deterministic
Spatial representation	discrete	discrete	discrete	discrete	discrete	continuous
Process sequencing	none	none	none	yes	none	yes
Energy consumption	estimated	estimated	estimated	estimated	estimated	accurate
Energy provision	approx.	approx.	accurate	accurate	approx.	accurate
Covering distance	exogenous	endogenous	exogenous	exogenous	exogenous	endogenous

Source: Fekete et al., 2016

As the comparison of existing framework properties and research environment demands revealed, existing models or methods neglect investigations focussing on electrical charging station allocation for occasional recharging as well as the necessary focus on process structures and its inherent potentials. Therefore the impact from occasional charging and charging station allocation was still underdeveloped, so that the model for Occasional Charging Station Location (OCSLM) was designed in order to enable comprehensive analyses on charging system implementation, its impact to the defined sustainability factors and to identify potential areas for system improvements (see also Fekete et al., 2016).

In reference to the above explanations as well as previous research recommendations (Berman, Drezner & Krass, 2010; Giménez-Gaydou et al., 2014; Jin, 2016), the following properties were identified as essential components for realistic, comprehensive and thorough investigations in this field:

(1) Maximal Covering Location Modelling (MCLM)

(2) integration of tracked, i.e. realistic data

(3) accurate data on energy supply and consumption

(4) integration of an endogenous, i.e. function based covering radius that integrates energy consumption

(5) coverage of fractional demand

(6) sequencing of processes

The above stated aspects were taken as fundamentals to define the OCSLM model which targets to maximise the break times being usable for additional vehicle recharging by a defined number of charging stations. The reference to sustainability is implemented within the model by allowing the coverage of break times only under the premise of an eco-efficient, i.e. CO2 neutral or positive, impact. This requirement is formulated as an endogenous equation, i.e. a function based decision variable within this model.

2.3 Case Study

Relevant parameters in the field of production-related material handling with impact to process energy consumption and supply were identified as per Figure 2., so that the illustrated parameters were considered in order to analyse the influence from advanced charging system implementation to system's overall efficiency and sustainability.

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[1] Flow Refuelling Location Model - Upchurch, Kuby & Lim, 2009

[2] Gradual Cover Model – Berman, Drezner & Krass, 2010

[3] Optimal Location Charging Station Model – Frade et al., 2011

[4] Simulation-Optimisation Model for Charging Infrastructure – Xi, Sioshansi & Marano, 2013

[5] Charging Station Covering Model – Giménez-Gaydou et al., 2016

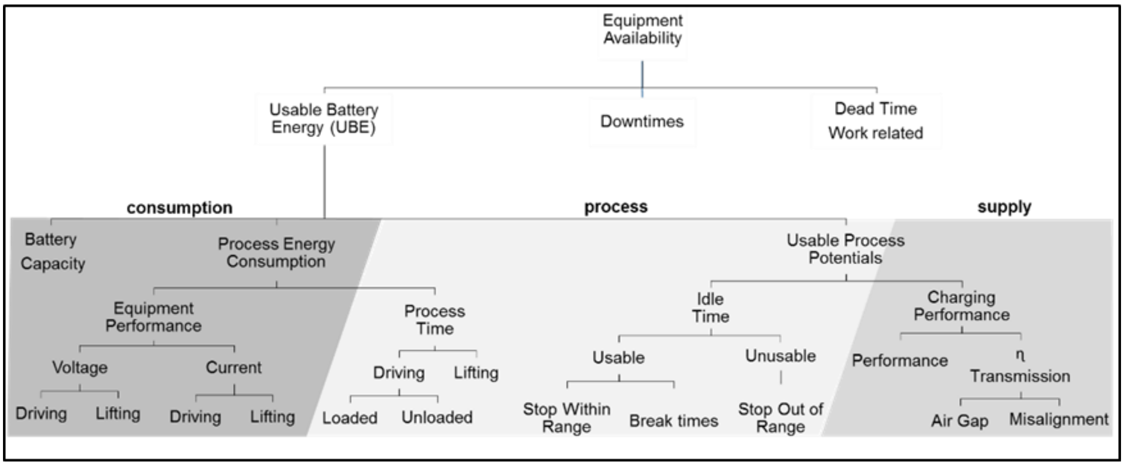

Figure 2. Performance indicators of material handling

Source: Fekete et al., 2015

The case investigations on the impact from charging system implementation to the overall system sustainability in matters of economy and ecology, analysed a total of seven related motion studies. In a first investigation, single material handling vehicles with individual process sequencing, operation characteristics and production facility affiliations were considered in isolation. In a second step these vehicles were set in context of each other in order to investigate impact factors such as synergy effects and capacity constraints. Within the investigations, identical vehicles of the type Linde E16 with a lifting capacity of 1.6tons to 2.0tons and an installed nominal battery capacity of 19.68kWh, i.e. an usable battery energy (UBE) of 16.73kWh, operated in different functions at individual process conditions and moved in partly overlapping though individual geographic surroundings. A total of 121 days with more than 1,252 hours of process data were tracked in order to back up system simulations with a reliable set of information. Several simulation runs on different sensitivities were executed in order to identify optimal system compositions.

For the determination of charging station allocation(s) and the number of charging stations to be implemented, a minimum of three charging stations being approachable by each vehicle was defined as target status.

Furthermore, some fundamental guidelines for system adaptions and improvements were defined, so that the total battery capacity could not be reduced to less than 3.3kWh even though the development of usable battery energy and state-of-charge (SOC) over the investigated operation periods allowed a further downsizing. This limitation restricts the extreme values of the developed analysis and integrated a safety value to the investigations.

Within location-allocation modelling, the covering distance is a factor that defines demand to be covered or satisfied, for the case that is lies within a pre-defined or calculated geographic distance from a point of supply, i.e. break time in this application(Berman, Drezner & Krass, 2010). In order to investigate the impact from different covering distance approaches to sustainability factors, different covering distance approaches were simulated, analysed and assessed towards their contribution to an increased availability of battery energy, the resulting possibility for battery downsizing and system adaptions and by this the impact to cost savings as well as reductions of CO2 emissions.

The results displayed under ‘S10’ are based on an exogenous, i.e. pre-defined, covering distance with a fixed covering distance being set to S = 10 meters. Referring to the covering distance definition Eij10, this determines the charging station allocation for occasional recharging under the realisation of an exogenous-endogenous covering distance. This definition allows the arithmetical relocation of possible charging times in order to identify charging infrastructure allocations under the premise of maximised system recharge energy. The target of this is to increase the recharge energy by integrating only positive potentials to charging station allocation, realised through additional charging station approaching. Furthermore, an additional limitation of the covering distance was given as 10 meters in order to limit vehicle`s additional approaching movements. This combination of an exogenous-endogenous covering distance allows charging station approaching only under the premise of a positive energy input to the system in reference to an additional quantitative system implementation requirement, so that it integrates and analyses the impact from a function-based integration same as from an exogenously determined covering distance. The values of Eij exclude the exogenous covering distance component, so that all positively contributing charging potentials are integrated by adapting the charging station allocation in order to further increase the recharge energy. This differentiation of Eij10 and Eij allows a more thorough investigation on the emission of additional greenhouse gases based on the choice of a covering distance approach.

Figure 3. illustrates the differences from the alternative covering distance definitions to the specific catchment areas. The darker the colour of the investigated squares, i.e. spots of occurring break times, the higher the potential recharge energy to the system and by this its impact to charging station allocation. The Eij covering distance shape is undefined and only exemplary illustrated as a triangle. As the illustration shows, the more flexible definition of the Eij covering distance results in an increased catchment area whereas the impact to sustainability needs a further revision.

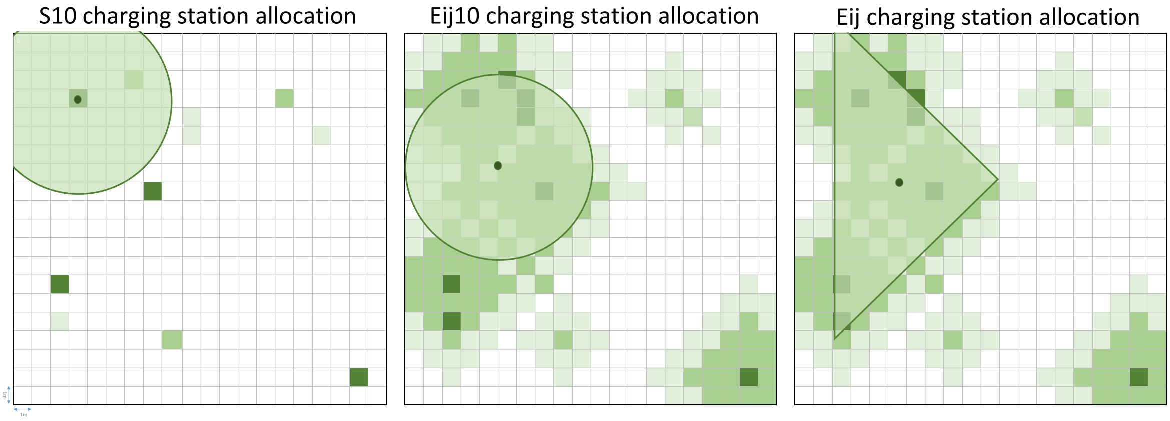

Figure 3. Research covering distance definitions

Source: Author

The results on additional usable battery energy (UBE) being realised through occasional recharging present an intermediate step towards the investigations on sustainability (see also Fekete et al., 2016). Figure 4. exemplarily illustrates the possible additional energy input to a vehicle within the executed investigations. The illustrated sample vehicle constantly operates in in a 16/6 production. The additional energy input is used to downsize the battery capacity while ensuring constant availability supported by interim, contactless energy supply. The average drive distance of this vehicle is about 15.601 meters per day at an average velocity of 1.77m/s. The Figure illustrates the arithmetic mean value (‘average’) as reference value over all investigated scenarios and sensitivities, same as case's absolute minimum and maximum values in reference to the vehicles UBE in order to determine system implementation limitations. For system design, the ‘min’ value case presents the bottle neck case in order to prevent system downtimes due to a lack of battery energy.

In line with remaining analysis results, additional UBE increases from the exogenous covering distance as used within most existing research over the mixed exogenous-endogenous to the endogenous approach. As the shown values include energy efforts for additional charging station approaching as well as charging time reductions due to additional material handling equipment movements, it can be stated at this point that occasional charging bears the potential to increase the availability of UBE, whereas advanced charging station allocation based on indeed process knowledge can increase UBE by up to 60% (see also Fekete et al., 2016).

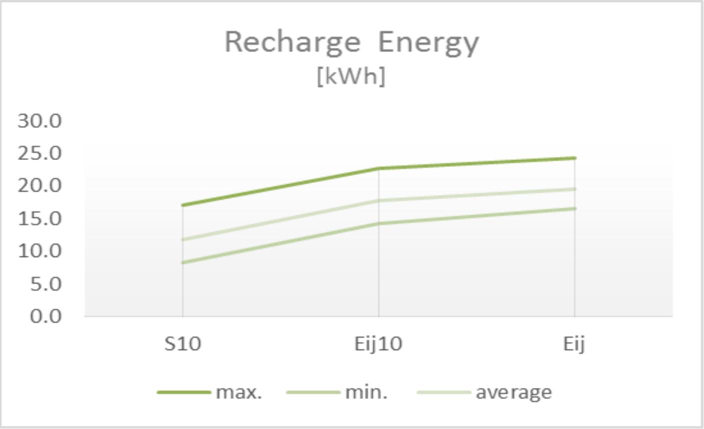

Figure 4. Result impact analysis sample vehicle

Source: Fekete et al., 2016

The executed analyses showed, that an increased value of recharge energy was not necessarily synonymous to an increased downsizing potential since other factors such as process energy consumption, additional drive distance, transmission efficiency and minimal required battery capacity influence the vehicle (component) design, so that lower additional UBE in several cases showed similar results in reference to the systems overall sustainability. As the analysis indicated, the level of recharge energy being necessary for maximum battery downsizing ranged from 6kWh to 12kWh of additional UBE, so that within some of the cases the achieved recharge energy of S10 and Eij10 was sufficient to reach the same system adaptions at lower additional energy efforts in respect to a maximisation of the overall system sustainability.

Due to additional UBE and therefore battery downsizing, these system adaptions enable additional energy savings by reduced vehicle mass in the range from 2% to 5%, which need to be evaluated in reference to the additional energy efforts for additional driving due to charging station approaching and additional transmission losses of contactless over conductive charging. In context of overall energy consumption, analyses showed these additional energy savings to range from 0.1% to 0.3% only. This low impact emerges due to the high energy density of lithium batteries which results in low weight batteries, meaning that additional battery mass reductions are of minor impact.

At this point, it can be stated that the reference to the endogenous covering distance and the developed framework in reference to charging station allocation resulted in an increased amount of recharge energy and enables improved battery sizing, whereas the results can only partially be generalised. For that reason, case adapted investigations are necessary for the integration of a charging infrastructure for occasional recharging. Furthermore, investigated cases need to be reviewed towards their consistency respectively changes of the material handling processes and structures in order to maintain the achieved level of efficiency and system availability.

3. Analysis Results

As defined by Chow (1990) and Thomopoulos (2014), equipment availability is an important factor to material handling system’s efficiency, so that the target of the research project on system integration for occasional battery electric vehicle recharging was to evaluate the potential of this charging alternative in material handling to further increase system efficiency at constant equipment availability.

In line with the description by Naef (1998), efficiency can be defined as the relation of revenue to effort, meaning that in addition to the reduced battery mass as a measure of decreased resource usage, the ratio of energy saving to additional energy effort serves as an efficiency assessment standard.

Figure 5. shows the process efficiency parameters for the investigated vehicles based on minimal recharge energy, i.e. bottle neck case examinations, which in this consideration present a first approach to the evaluation of the parameters for increased sustainability.

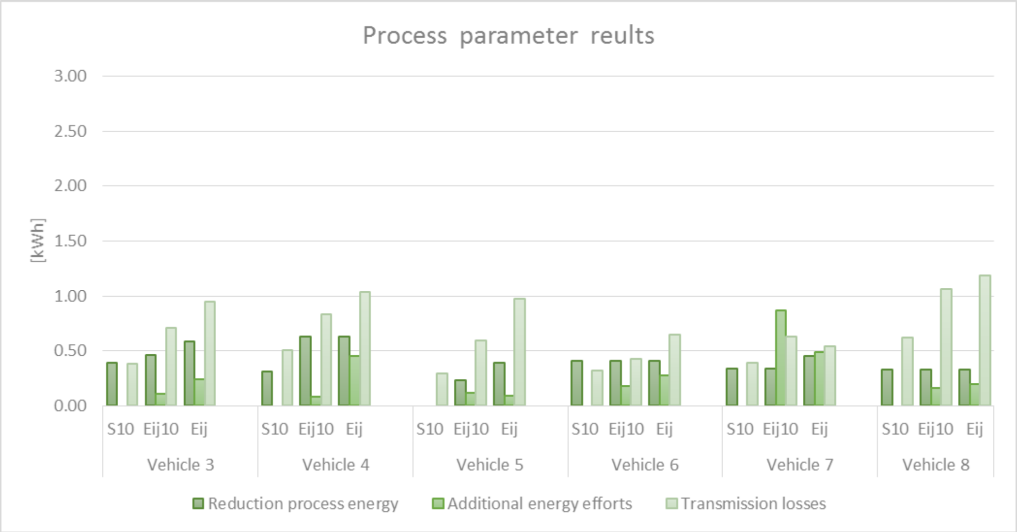

Figure 5. Process efficiency parameter

Source: Author

From Figure 5. it can be seen, that the reduction of process energy generally exceeds the additional energy efforts for additional charging station approaching, what results in a positive energy balance for five of six of the data sets. Based on decreased charging efficiency of contactless power transmission in comparison to conventional, conductive plug-in systems ($\eta \approx$ 89% vs. 96%), additional losses occur that decrease overall system efficiency. Concluding analyses showed that due to the additional energy losses at an efficiency of 89% for occasional recharging based on contactless power transfer, occasional recharging in a first consideration has no additional positive impact on the process energy consumption, whereas the investigations showed that an increase in transmission efficiency of +5.5% would be sufficient to balance this deficit and put the negative environmental impact to the same level as for conductive charging.

3.1 Efficiency Based Outcome

Figure 6. displays the cost based efficiency evaluation focussing on the comparison of a conventional lead acid battery system and an occasional charging system which includes the change to a lithium ion battery solution. The results show the system cost over the battery life-cycle for the individual vehicle investigations. The required battery capacity without a recharging system for occasional recharging was set as the standard of comparison.

General components of the efficiency evaluation consist of the fixed battery cost (see Giménez- Gaydou et al., 2016) in reference to the respective cost of process energy demand, whereas further cost for the charging stations were not included.

The values for S10 includes occasional recharging being based on the corresponding covering distance approach. The displayed values include the additional energy savings and efforts based on the simulated battery life-time in reference to process cyclation of 11.4 years.

The comparison between the results on process energy that highlighted increased energy efforts for contactless recharging and the efficiency evaluation shows the compensation of these additional variable process cost by the savings on the fixed battery cost.

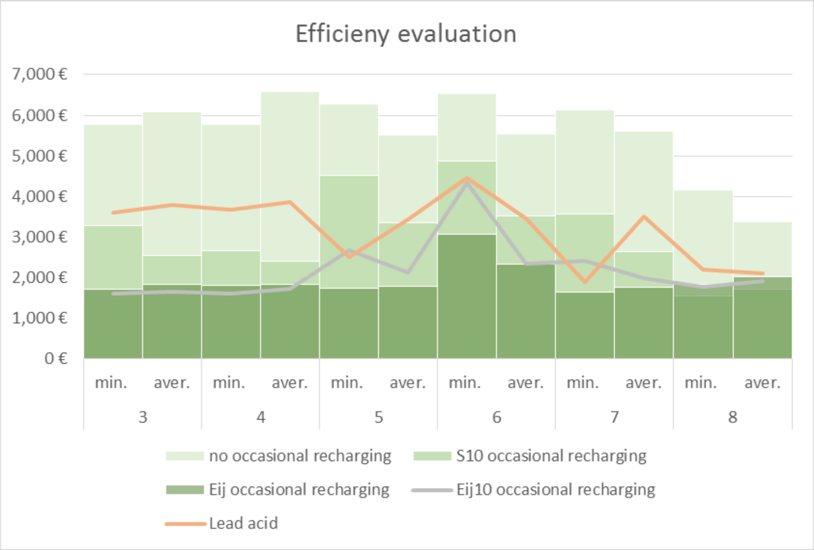

Figure 6. Cost based efficiency evaluation

Source: Author

The results display the calculated battery cost in reference to the simulated process energy demand being required for constant system availability. As illustrated, the cost of lead acid batteries, which cannot reasonably be used for occasional recharging, exceed the cost of lithium ion batteries in reference to the described battery capacity optimisations, enabled by occasional recharging and based on optimised charging station allocation. This highlights the potential of lithium ion batteries in combination with occasional recharging to contribute to increased system efficiency and fosters its use in man-guided material handling instead of lead acid technologies.

3.2 Sustainability Based Outcome

The following investigations show the impact from the integration of occasional recharging to systems CO2 emissions. Additional emissions such as greenhouse gases and nitric oxides (NO) are also emitted within the considered material handling and production processes, but were neglected as scale of ecology within this research in order to facilitate the evaluation of the results and to maintain the prevalent comparison standard.

The battery life cycle approach determines the volume of CO2 emissions, including fixed CO2 emissions for battery production, i.e. the savings on CO2 emissions by battery downsizing, and variable CO2 emission components.

The described energy consumption savings create emission savings that are compared to the additional emissions provoked by additional drive distances likewise additional transmission losses of contactless to conductive power transmission. The consumption of one kWh of electricity was therefore assumed to emit 564g of CO2 (Kranke, Schmied & Schoen, 2011) and the production of one kWh of battery capacity of lithium ion battery to generate emissions of around 75kg of CO2 (Dell'era et al., 2015).

Figure 7. shows the overall material handling process CO2 emissions as reference line for the additional emissions being generated for fixed battery production (losses of conductive charging account for 6.38% of total emissions) and the integration of an occasional recharging infrastructure over the calculated battery life time. The research project investigations showed that the reference to an S10 covering distance results in a higher energy consumption attributable to additional losses caused by the lower transmission efficiency of contactless power transfer which results in higher CO2 emissions of +0.8% (7.18% of total emissions). The reference to Eij10 and Eij show a further average increase of emission of +3.92% (11.10% of total emissions), +6.89% (14.07%of total emissions) respectively.

In reference to the existing approaches of electric vehicle operations and recharging, the implementation of a charging infrastructure for occasional recharging increases the pollutant emissions caused by electrical charging, whereas the total impact in comparison to process related CO2 emissions is comparably low. In order to address the demand for increased overall sustainability, further improvements such as contactless transmission efficiency as main contributor for the increased emission of CO2 were identified.

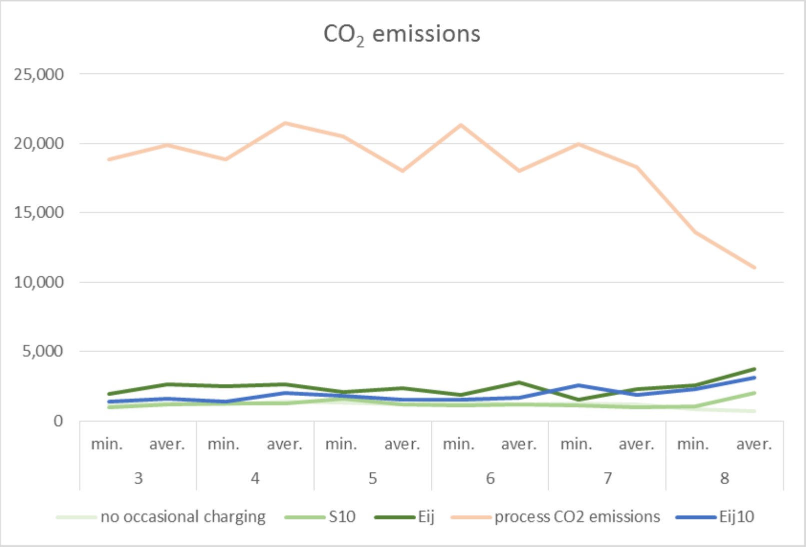

Figure 7. Case study CO_2 emissions

Source: Author

4. Conclusion

As the investigations showed, a sole reference to recharge energy maximisation does not automatically contribute to maximised system adaptions as specific system boundaries constitute adaption limitations that need to be considered within the transportation and energy supply infrastructure design. Based on these system and process specific limitations, a subsequent impact analysis has to investigate the influence on increased system efficiency and sustainability in order to achieve the optimal system component design in reference to increased system ecology and economy.

The cost based efficiency analysis generally showed the highest level of cost saving in reference to the Eij10 and Eij covering distance, which is based on the low cost of electricity in the investigated research environment. Furthermore, the high cost for lithium ion batteries fosters the profitability of resource savings. However, S10 and Eij10 showed a lower level of CO2 emissions due to the savings on additional energy efforts and losses in comparison to the Eij approach, although these savings have to be set in context of the overall system operation pollutant emissions. The results on the Eij10 covering distance highlight that this approach presents a compromise solution between cost efficiency and increased sustainability, since pollutant emissions are comparable to conventional material handling operations while enabling cost efficient battery downsizing. As further technological improvements in reference to battery cost, energy density or transmission efficiency can be expected, these factors will positively advance the outcomes in reference to cost and emissions.

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