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Life Cycle Assessment of primary control provision by battery storage systems and fossil power plants

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Abstract

Increasing renewable energy generation influences the reliability of electric power grids. Thus, there is a demand for new technical units providing ancillary grid services. Intermittent renewable energy sources can be balanced by energy storage devices, especially battery storage systems. By battery systems grid efficiency and reliability as well as power quality can be increased. A further characteristic of battery systems is the ability to respond rapidly and precisely to frequency deviations, making them technical ideal candidates for primary control provision (PCP). PCP by battery systems is applied in form of positive (discharge mode) and negative control (charge mode) and can reduce must-run capacity of fossil power plants.
In this study environmental impacts of PCP by novelLi-ion large-scale battery energy storage systems (BESSs) are compared to impacts of PCP by state-of-the-art coal power plants (CPPs) using a Life Cycle Assessment (LCA) approach. An inventory of all relevant inputs (resources, material and energy flows) and outputs (emissions, wastes and waste water) is compiled. Environmental impacts associated with these inputs and outputs are evaluated. Finally, PCP by BESSs and fossil power plants are compared in terms of environmental performance. Different scenarios are analyzed by varying sensitive parameters like efficiency loss due to PCP at fossil power plants and required must-run capacity for PCP.

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Keywords: Life Cycle Assessment; environmental impacts; battery storage systems; primary control; must-run and residual load analysis

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1. Introduction

Increasing renewable energy generation influences the reliability of electric power grids. Thus, there is as demand for new technical units providing ancillary grid services. Control power is required if the amount of generated electricity varies from current load which results in grid frequency deviations. As fastest measure of control power, primary control has to be activated entirely within 30 seconds to stabilize the frequency [1]. Up to now primary control power is primarily provided by fossil power plants. The ability to respond rapidly and precisely to frequency deviations is a main characteristic of battery systems, making them ideal candidates for primary control provision (PCP). PCP by battery systems occurs in form of positive (discharge mode) and negative control (charge mode) and can reduce must-run capacities of fossil power plants. However, environmental impact assessments of large-scale battery energy storage systems (BESSs) using Li-ion cells and especially of the comparison of PCP provided by either BESSs or by fossil power plants are missing in scientific literature. Here we present an assessment of environmental impacts of primary control provided by BESSs in comparison to state-of-the-art coal power plants (CPPs) using a Life Cycle Assessment (LCA) approach based on data from Europe's biggest commercial BESS in Schwerin, Germany. The attributable must-run electricity generation for PCP shifts as a consequence of the provided ancillary services and influences the environmental performance of CPPs. Thus, this study presents different scenario calculations of ancillary service provision by CPPs.

2. Methodology and system description

2.1. LCA method

Life Cycle Assessment (LCA) is an adequate method for a holistic evaluation of environmental effects. It is well-established, internationally acknowledged, and defined in the ISO standards 14040 [2] and 14044 [3]. Within LCA environmental impacts along the whole life cycle of products are assessed. These assessments typically include construction, operation, and end of life of technical products or systems. In this study end of life of BESSs is not taken into consideration due to existing lacks of data concerning recycling of large-scale battery systems. Data from Younicos AG from an established 5 MW/5 MWh Li-ion BESS in Schwerin, Germany [4], are applied as central database. Where data from Younicos AG or own calculations could not be used generic data were taken from the LCA databases GaBi 6.0 and ecoinvent 2.2.

2.2. Goal and scope definition

This LCA study compares the environmental performances of PCP provision by BESSs and by CPPs according to German primary control power market conditions. The control power demand of 551 MW represents the average demand in Germany for the year 2013 and is assumed to be constant in the period of 2015-2034. This period of 20 years is considered as time frame within the calculations because it represents lifetime expectations and the duration of warranties on current large-scale battery systems. Environmental impacts of BESSs and CPPs are compared by means of the functional unit (FU). In this context the FU is defined by the total primary control power demand of 551 MW which has to be provided permanently for the period of 20 years.

Fig. 1.illustrates a simplified scheme of system boundaries of BESSs and CPPs for this LCA.

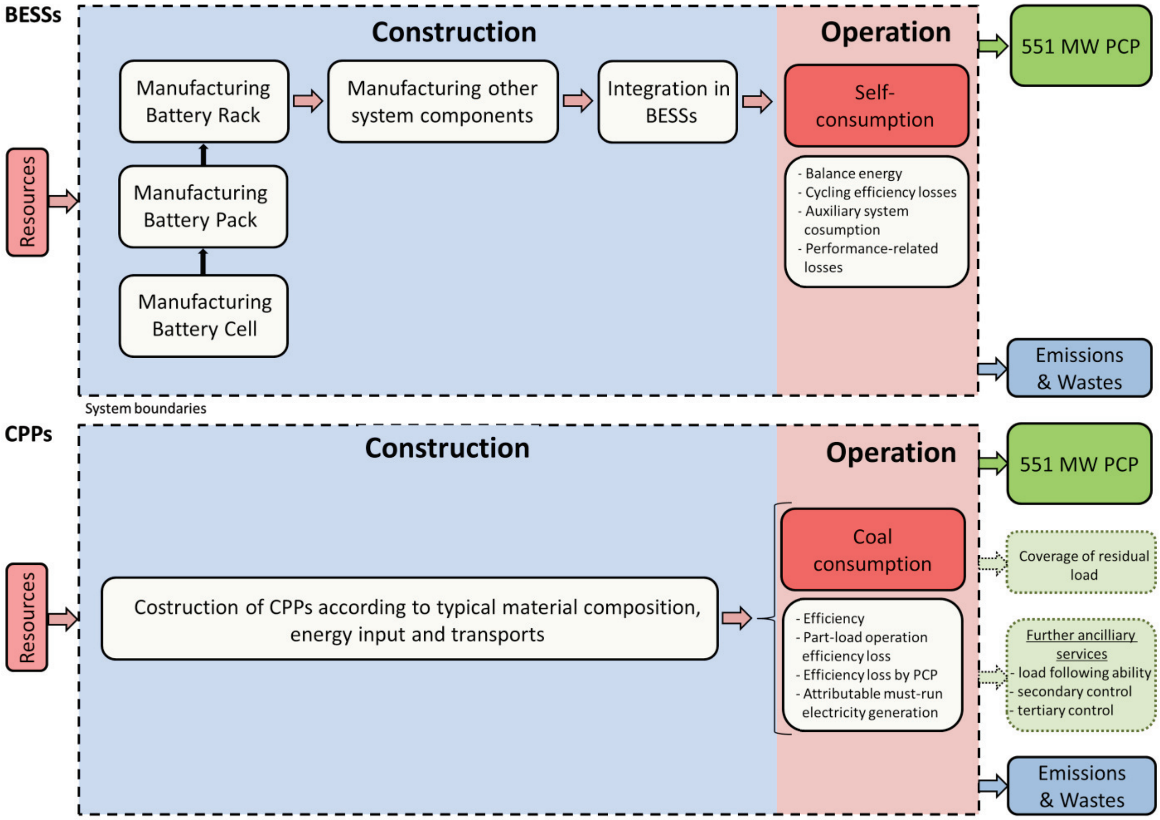


Fig. 1.System boundaries of CPPs and BESSs.

As shown in fig. 1 the considered BESSs and CPPs 551 MW provide primary control (FU) and cause emissions and wastes. Additionally, CPPs are deployed for residual load coverage and able to provide several ancillary services simultaneously. This makes an allocation of the expenditures to the different services necessary. The illustrated characteristics are explained in detail within the subsequent sections.

2.3. System description – BESSs

PCP by battery systems is provided in form of positive (discharge mode) and negative control (charge mode). For providing primary control BESSs require energy from the electricity grid which is summarized as their self-consumption of electricity. This value includes additional energy required from the grid to balance the difference between positive and negative PCP, cycling efficiency losses (charging/discharging), consumption of auxiliary systems (e.g. battery management systems, ventilation and air conditioning of the BESSs buildings), and performance-related losses by transformers etc. The self-consumption within this study is derived from the before mentioned 5 MW/5 MWh BESS. Based on simulations of BESSs operation conducted by Younicos [5] self-consumption sums up to 121.4 MWh per megawatt and year of installed and for PCP prequalified BESS power. This value is converted to 0.206 MWh per MWh provided (pos. and neg.) PCP for further calculations. Within the assessment the impacts of self-consumption during the BESSs operation has to be calculated for the period from 2015-2034 as described above. To simplify further calculations an average electricity mix is modeled for this period based on[6]and used as input parameter (Tab. 1).

Table 1.Projected share 2015 and average electricity mix (2015-2034) for Germany.

	Hydro	**Biomass gaseous**	**Biomass solid**	**Solar**	**Wind**	**Hard coal**	**Lignite**	**Natural gas**	**Oil**	**Nuclear**
2015	3.57%	5.27%	1.85%	5.44%	13.08%	20.59%	25.07%	12.29%	1.03%	11.82%
2015-2034	3.24%	6.05%	2.12%	7.79%	27.61%	19.28%	18.60%	12.52%	0.41%	2.38%

While the climate gas emission factor of the assumed electricity mix in 2015 sums up to 0.59 kg CO_{2eq}, the average emission factor for the period 2015-2034 is 0.50 kg CO_{2eq}/kWh.

To provide 551 MW primary control by BESSs in the order of magnitude 5 MW/5 MWh per BESS, in total 111 BESSs are required. The construction of the BESSs is considered based on[7].

2.4. System descriptions - CPPs

It is assumed that PCP by CPPs is realized in a homogenous power plants stock with following properties[1, 8]:

- Nominal power Pnom: 800 MW
- Minimum output Pmin: 40 % of Pnom
- Maximum share of primary control: 5.6 % of Pnom
- Dynamics: 4 % Pnom/min
- Maximum primary control power of 90 MW per power plant

As presented in Fig. 1 CPPs are operated to cover the residual load and to provide further ancillary services, while the considered BESSs only deliver PCP. To determine environmental impacts for PCP, CPPs stock operation is modeled and environmental impacts are accounted for CPPs operation with and without PCP. The differences in the balances are defined as the environmental impacts caused by PCP.

For operation of CPPs an input of coal is applied. There are two factors responsible for the related environmental impacts, the coal import mix and the coal type. The mix of different coal types and their transport from different supplying countries has essential influence on the environmental effects. In practice there are changes of the coal mix every year. An estimation for the German coal import mix in the year 2030 based on [9] and the consideration of the coal type Kleinkopje (24,991 kJ/kg) according to [10]are used as simplified calculation values. The total amount of required coal depends on the subsequent listed and explained factors:

- CPPs efficiency (affecting the amount of coal input)
- CPPs efficiency loss caused by part-load operation
- CPPs efficiency loss caused by PCP
- Attributable must-run electricity generation calculated by residual load analysis

CPPs efficiency

As base net efficiency of the power plants 46.06 % is considered. This value is based on an ASPEN modeling of an advanced supercritical 600 °C coal-fired power plant according to [10]. This CPP has been designed as a notably high-efficient power plant and represents the state of the art.

CPPs efficiency loss caused by part-load operation

Efficiency of power plants depends on the load level. CPPs providing ancillary services are operated within a defined operating range to be able to provide different ancillary services as necessary. The possible operation ranges are determined for the CPPs according to [8]. Nominal efficiency is considered to be constant for a load level of 80 % and higher. In case of lower load (< 80 %) efficiency losses are considered according to [11]. Hourly efficiency factors based on modeled CPP operation are summarized to an annual performance ratio.

CPPs efficiency loss caused by PCP

In thermal power plants a short-term adjustment (increase or decrease) of net power plant output for PCP can be achieved by utilization of heat storage vessels on the steam site (steam boiler and generator) and on the water site (e.g. pre-heater, feedwater tank) [12]. Technical options for PCP by CPPs can be applied solely or in combination. The most important options are throttling of turbine valves and pre-heaters as well as condensate build-up. The previously mentioned technical options for PCP cause effects like interruption of optimal heat integration and increased feed pump power. Consequently, PCP by CPPs provokes efficiency losses and related environmental impacts. The efficiency loss is dependent on the age of CPPs and the utilized technical options for PCP. Based on values from literature an efficiency loss of 0.35 % results [13] for older power plants. The efficiency loss of newer CPP is considerably lower. Therefore, the values 0.01 %, 0.1 % and 0.35 % are considered as parameter variation within the further assessment.

Attributable must-run electricity generation calculated by residual load analysis

The attributable must-run for electricity generation for PCP is calculated by residual load analysis. Residual load names the power demand within an electricity grid minus fluctuating feed-in of non-adjustable renewable energy sources. Thus, residual load indicates the remaining demand, which has to be covered by adjustable power plants. Data for the residual load analysis within this study contain hourly averages of vertical grid load (VGL) [14-17], onshore wind power feed-in (ONW) [18-21], and photovoltaic feed-in (PV) [22-25]. Furthermore, hourly potential offshore wind power feed-in (OFW) calculated from offshore wind velocities measured every 10 minutes [26] is considered. The gross grid load (GGL) in each hour of the base year 2011 is calculated according to equation 1:

$$GGL_{2011}(t) = VGL_{2011}(t) + ONW_{2011}(t) + PV_{2011}(t) \quad (1)$$

Offshore wind power feed-in was negligible in 2011 and therefore not considered in equation 1. Wind and PV power feed-in in each of the scenario years (YY = 2014...2034) is extrapolated from the wind and PV feed-in time series of 2011 to the wind and PV power installed in YY. Finally, the residual load (RL) in each scenario year YY is calculated based on equation 2:

$$RL_{YY}(t) = GGL_{YY}(t) - ONW_{YY}(t) - OFW_{YY}(t) - PV_{YY}(t) \quad (2)$$

The must-run capacity defines the minimum load of the CPPs stock which is required for the provision of ancillary services. This capacity is calculated for the CPPs stock with and without PCP according the methodology in [8]. CPPs stock operation is based on the residual load demand and the different must-run levels (with and without PCP). The required must-run capacity changes in considerations with and without PCP. Therefore, the resulting electricity generation difference of the consecutively explained scenarios is defined as the attributable electricity generation for PCP. This value represents the key parameter to determine the environmental impacts.

2.5. Scenario definition and calculation

Four scenarios are defined and calculated within this study to analyze different variants of ancillary service provision by the modeled CPPs stock.

Table 2. Scenarios of ancillary service provision by the modeled CPPs stock.

Scenario 1	Provision of primary, secondary and tertiary control power as well as load following ability
Scenario 2	Provision of primary and secondary control power
Scenario 3	PCP as exclusive ancillary service
Scenario 4	Provision of primary, secondary and tertiary control power as well as load following ability in latest and prospective power plants without load restrictions for PCP

Basic data of the four considered scenarios as well as results of the residual load analysis are summarized in Tab. 3. According to each scenario the required rated output of CPPs stock for the provision of ancillary services are calculated. Furthermore the CPPs contribute to the coverage of residual load. The resulting total electricity generation in Tab. 3 is calculated with and without PCP respectively under consideration of minimum and maximum power plant load and the residual load of the electricity grid.

It can be seen from the data in Tab. 3 that there is no efficiency loss caused by part load operation in both cases of scenario 1. This is due to CPPs operation at > 80 % of nominal load, which is given in both cases. Scenario 2 without PCP yields higher efficiency losses in part load operation than with PCP as a result of more frequent low part-load operation. Within the case without PCP of scenario 3 there is no must-run required. This is based on the assumption of a gradual grid connection and disconnection of CPPs from the stock as CPPs are only required to cover the residual load (no ancillary service provision) and no required minimum number of power plants. Due to the CPPs stock characteristics of scenario 4 there is also no efficiency loss caused by part load operation.

Table 3.Results of residual load and must-run analysis.

		Scenario 1		**Scenario 2**		**Scenario 3**		**Scenario 4**	
Category	**Unit**	with PCP	without PCP	with PCP	without PCP	with PCP	without PCP	with PCP	without PCP
Required rated output	[GW]	16	16	11,2	11,2	5,6	5,6	14,4	14,4
Minimum load (must-run)	[GW]	13,02	11,81	7,13	6,57	2,79	0 (0.32)	11,81	11,81
Maximum load	[GW]	13,32	13,32	8,51	8,51	5,05	5,05	12,28	12,28
Efficiency loss PCP	[%]	0.01-0.35	-	0.01-0.35	-	0.01-0.35	-	0.01-0.35	-
Efficiency loss part-load operation	[%]	0	0	0,41	0,52	0,46	0	0	0
Electricity generation (2015-2034)	[TWh]	2.319	2.262	1.444	1.427	827	770	2.130	2.130
Electricity generation difference	[TWh]	57		17		57		0	

Different stages of must-run levels for the considered scenarios and residual load, using the years 2014, 2024, and 2034 as examples, are illustrated in Fig. 2.

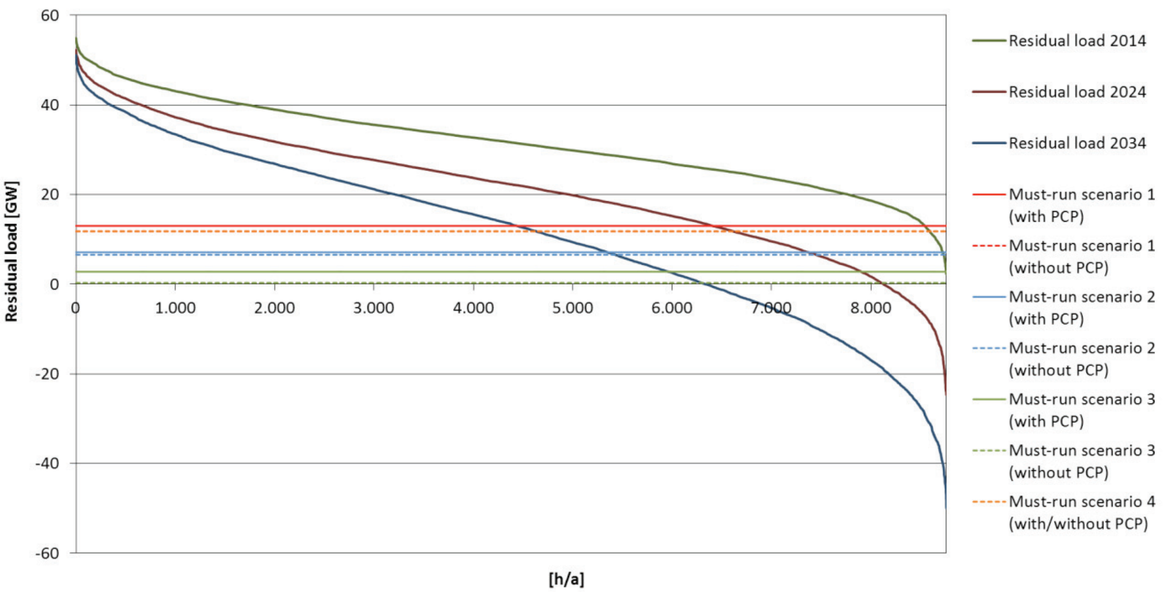


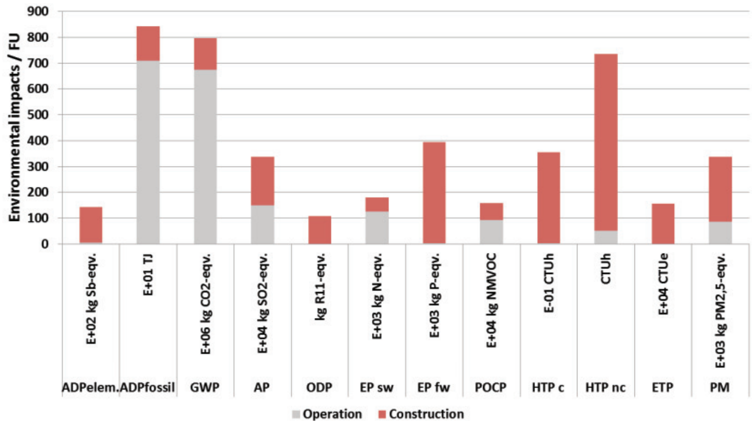
Fig. 2. Residual load and must-run scenarios of a German model CPPs stock providing ancillary services.

For the scenarios 1 to 3 Fig. 2 reveals a considerable decline of must-run in cases without PCP in comparison to the cases with PCP. Moreover, there is no must-run difference between scenario 4 with and without PCP. Furthermore, the must-run of scenario 4 is identical to the results of scenario 1 without PCP. Thus, there is a swapping of both lines in Fig. 2.

In all scenarios of this study it is assumed that a fossil back-up capacity is indispensably required to cover the residual load and to bridge periods of low renewable electricity generation. This is independent of the provision of ancillary services. In all scenarios, the maximum annual value of the residual load is considerably higher than the required must-run capacity in each case. Thus, there is no attributable CPP construction for PCP considered.

3. Results

The environmental impacts of BESSs and CPPs are selected and calculated using ILCD recommendations [27]. Impacts caused by the construction of BESSs and their operation for PCP over 20 years are shown in Fig. 3. Furthermore, this figure illustrates the share of different life cycle stages related to the functional unit (20 years of provision of 551 MW primary control power under German market conditions).



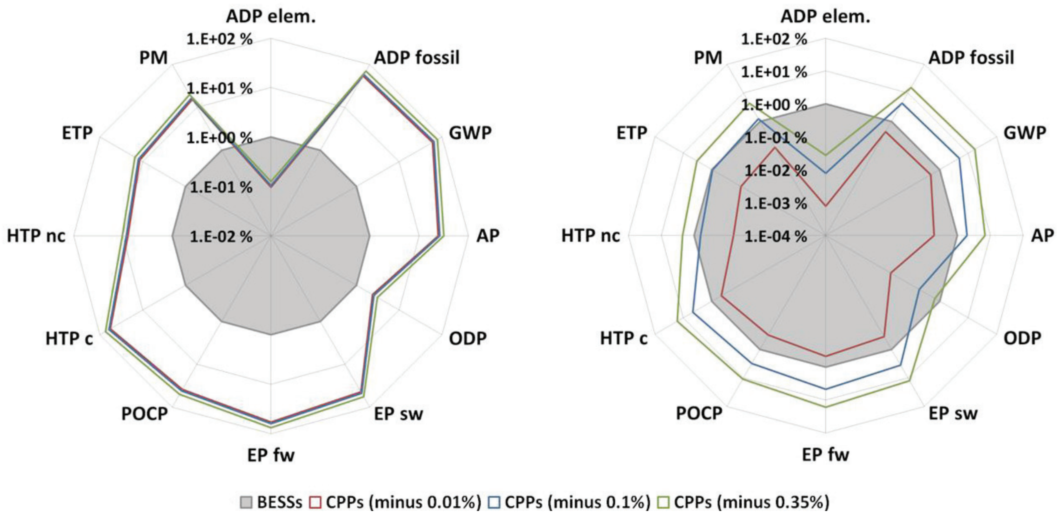
$ADP_{elem.}$	Abiotic Resource Depletion Potential (mineral)
ADP_{fossil}	Abiotic Resource Depletion Potential (fossil)
GWP	Global Warming Potential
AP	Acidification Potential
ODP	Ozone Depletion Potential
EP sw	Eutrophication Potential (saltwater)
EP fw	Eutrophication Potential (fresh water)
POCP	Photochemical Ozone Creation Potential
HTP c	Human Toxicity Potential (carcinogen)
HTP nc	Human Toxicity Potential (non carcinogen)
ETP	Ecotoxity Potential
PM	Particulate Matter

Fig. 3. Contribution of life cycle stages to environmental impacts.

As shown in Fig. 3 environmental impacts caused by BESSs are dominated by the construction in many categories. Impacts of operation are only prevailing for four impact categories. Due to a high dependence of environmental impacts on the composition of the electricity consumed by BESSs a German electricity mix with higher shares of renewable energy would intensify the contribution of construction.

Fig. 4 compares the results of environmental impacts caused by BESSs and CPPs in scenario 1 with the impact results of scenario 4.

For scenario 1 environmental impacts of the BESS, illustrated by the grey area in Fig. 4, are considerably lower than those of the CPPs in almost every category. The only exception is given by $ADP_{elem.}$ impacts. $ADP_{elem.}$ describes the scarcity of mineral resources. Examples of this resource type are metalsand inorganic material. The use of these materials within upstream processes of electricity generation, which used to cover the self-consumption of BESSs, induces the majority of the $ADP_{elem.}$ impacts. Furthermore, there is an obviously higher dependency of these results on the amount of must-run electricity generation than to efficiency losses.



a) Scenario 1 **b) Scenario 4**

Fig. 4. Comparison of environmental impacts caused by BESSs and CPPs (relative, BESSs = 100 %).

In comparison to scenario 1, scenario 4 shows significantly improved environmental performance for CPPs. CPPs with an assumed loss of efficiency of 0.01 % loss would show superior results in all categories. Whereas, CPPs with an efficiency loss of 0.1 % would be beneficial in four categories ($ADP_{elem.}$, ODP, ETP and HTP nc). The ETP and HTP nc impacts are primarily evoked by copper use and chrome long-term emissions in its copper-related upstream processes. ODP is to the largest extent affected by electronic components and their materials. The CPPs variant with 0.35 % efficiency loss would be better in only two categories ($ADP_{elem.}$, ODP). There is no electricity generation difference in scenario 4 affecting environ-mental impacts, thus this scenario shows a significant higher dependency on efficiency losses caused by PCP.

In scenario 2 there is a slight decrease of the environmental advantages of BESSs and an increase of its dependence on efficiency loss. Due to the location of scenario 2 results in between the range of results of scenarios 1 and 4 they are not presented. Furthermore, the presentation of scenario 3 is also left out. This is by reason of almost equal results to scenario 1, according to a coincidentally identical electricity generation difference (Tab. 3), which is the dominating parameter of environmental impacts.

4. Discussion

This study set out with the aim of assessing the environmental impacts of PCP either by BESSs or by CPPs. The current study shows that a superior environmental performance of BESSs is given especially in cases where BESS contributes to the reduction of fossil must-run capacities. A period under investigation longer than 20 years would change the results due to additional construction of BESSs. Comparative or even better environmental performance of CPPs compared to state-of-the-art BESSs can be achieved if power plants without load restrictions for provision of primary control (scenario 4) and with minimal efficiency losses caused by PCP (0.01 %) are used. Though, even for this special case advantages would drop out, if only primary control would be provided as ancillary service. In this case PCP would provoke an electricity generation difference and accompanying environmental impacts. On the other hand, the environmental performance of BESS can be improved likewise, especially impacts caused by BESS construction. The usage of materials like nickel or copper in the BESS construction has noticeable effects [7]. Due to possibilities of material reductions or replacements there will probably be further environmental improvements.

Additionally, broader improvements would be achieved if the self-consumption of BESSs would be covered by electricity with higher shares of renewable sources.

5. Conclusion

Findings of this assessment enhance the knowledge about environmental performance of PCP provided by BESSs or CPPs. The use of BESSs for PCP can affect a significant reduction of fossil must-run electricity generation. Different assumptions regarding the characteristics of the power plant stock could lead to higher attributable must-run electricity generation of CPPs for PCP. Hence, the environmental performance of BESSs would be further improved. Consequently, BESSs are a promising option to reduce environmental impacts of primary control provision. In the future, alternative energy technologies, like renewable energy systems, might also contribute to PCP. These technologies are not included in this assessment and subject to further research.

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