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TECHNICAL AND COMMERCIAL COMPARISON OF AC- AND DC-COUPLED BATTERY ENERGY STORAGE SYSTEMS

Master of Science Thesis
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ABSTRACT

Konsta Matikainen: Technical and Commercial Comparison of AC- and DC-Coupled Battery Energy Storage Systems
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The integration of renewable energy sources (RESs) and the retirement of conventional power plants have increased the importance of battery energy storage systems (BESSs) for stabilizing the grid and managing the intermittent nature of RESs. BESS configurations can be categorized into AC-coupled and DC-coupled, depending on whether the BESS is connected to other systems on the AC (alternating current) or the DC side (direct current).

AC-coupled BESSs can function as standalone systems to provide grid services like frequency regulation or be co-located with RESs to support both the power plant and the grid, with options for shared or separate grid connections. DC-coupled BESSs are always connected to another system on the DC-side, sharing components such as the DC/AC converter, transformer, and interconnection with that system.

The thesis presents the power train configurations and components of BESSs, in addition to applications and key differences between AC- and DC-coupled BESSs. To provide a basic understanding of the subject, different battery technologies and general system architecture of BESSs are reviewed. It further evaluates the economic and technical considerations of AC- and DC-coupled BESSs through comparative analysis, presenting real-world examples of operational systems and commercial products.

Key findings revealed significant differences between AC- and DC-coupled BESSs in terms of installation layout, hardware sharing and costs. AC-coupled systems are found to have typically simpler design with separate components and lower operational costs due to component centralization. In contrast, DC-coupled systems, typically integrated with photovoltaic (PV) power plants, offer more efficient solar energy capture but have higher operational costs because of decentralized layout and more complex design caused by shared converters.

The thesis concludes that the choice between AC- and DC-coupled configurations depends on specific project needs, market conditions and regulatory frameworks, highlighting the importance of system design specific to the application. Future technological advancements and cost reductions are expected to balance the commercial attractiveness of these configurations.

Keywords: Battery energy storage system, AC-coupling, DC-coupling, Power conversion system, Hybrid power plant

TIIVISTELMÄ

Konsta Matikainen: Vaihto- ja tasajännitekytkettyjen akkuenergiavarastojen tekninen ja kaupallinen vertailu
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Uusiutuvien energialähteiden käyttöönotto ja perinteisten voimalaitosten käytöstä poistaminen ovat kasvattaneet akkuenergiavarastojen merkitystä sähköverkon vakauden ylläpidossa ja uusiutuvien energialähteiden epäsäännöllisen energiantuotannon tukemisessa. Akkuenergiavarastojen eri konfiguraatiot voidaan luokitella vaihto- tai tasajännitekytketyiksi sen mukaan, onko ne kytketty muihin järjestelmiin vaihto- vai tasajännitepuolella.

Vaihtojännitekytketyt akkuenergiavarastot voivat toimia itsenäisinä järjestelminä, tarjoten erilaisia palveluja verkon vakauden ylläpitoa varten, kuten taajuuden säätelyä. Ne voivat myös olla sijoitettuina uusiutuvien energialähteiden yhteyteen tukemaan sekä voimalaitoksen että verkon toimintaa. Vaihtojännitekytketyt akkuenergiavarastot voivat jakaa saman verkkoliitynnän uusiutuvien energialähteiden kanssa tai olla kytkettyinä verkkoon oman liitynnän kautta. Tasajännitekytketyt akkuenergiavarastot ovat aina kytkettyinä toiseen järjestelmään tasajännitepuolella, jakaen yhteisiä komponentteja, kuten DC/AC-muuntimet, muuntajat ja verkkoliitynnän kyseisen järjestelmän kanssa.

Tämä diplomityö tutkii akkuenergiavarastojen tehonmuunnosjärjestelmien erilaisia konfiguraatioita ja komponentteja, sekä tasa- ja vaihtojännitekytkettyjen akkuenergiavarastojen sovelluksia ja keskeisiä eroja. Perustietämyksen takaamiseksi tarkastellaan myös erilaisia akkuteknologioita ja akkuenergiavaraston yleistä järjestelmäarkkitehtuuria. Lisäksi arvioidaan tasa- ja vaihtojännitekytkettyjen akkuenergiavarastojen taloudellisia ja teknisiä ominaisuuksia vertailevan analyysin avulla, esitellen myös esimerkkejä toiminnassa olevista järjestelmistä ja kaupallisista ratkaisuista.

Keskeiset havainnot paljastivat merkittäviä eroja tasa- ja vaihtojännitekytkettyjen akkuenergiavarastojen välillä asennustavan, laitteistojen jakamisen ja kustannusten osalta. Vaihtojännitekytkettyjen akkuenergiavarastojen suunnittelu on yksinkertaisempaa ja käyttö- ja ylläpitokustannukset ovat tyypillisesti alhaisemmat laitteiden keskittämisen vuoksi. Sen sijaan tasajännitekytketyt akkuenergiavarastot, jotka ovat tyypillisesti kytkettyinä aurinkosähkövoimaloiden yhteyteen, tarjoavat tehokkaampaa aurinkoenergian talteenottoa, mutta niiden sunnittelu on monimutkaisempaa jaettujen DC/AC-muuntimien vuoksi. Niillä on myös laitteiden hajautuksesta johtuen korkeammat käyttö- ja ylläpitokustannukset.

Diplomityö päätyy siihen, että valinta tasa- ja vaihtojännitekytkettyjen konfiguraatioiden välillä riippuu aina kyseisen projektin tarpeista, markkinaolosuhteista ja sääntelykehyksistä, korostaen järjestelmän suunnittelun tärkeyttä sovelluksen mukaan. Akkuenergiavarastojen teknologian kehittyessä ja kustannusten laskiessa näiden konfiguraatioiden kaupallisen houkuttelevuuden uskotaan tasoittuvan.

Avainsanat: Akkuenergiavarasto, Vaihtojännitekytkentä, Tasajännitekytkentä, Tehonmuunnosjärjestelmä, Hybridivoimalaitos

Tämän julkaisun alkuperäisyys on tarkastettu Turnitin OriginalityCheck -ohjelmalla.

PREFACE

This work was carried out at Merus Power, Ylöjärvi from December 2023 to August 2024.

First I want to thank Merus Power and all my colleagues there for making this master's thesis possible. Working in this company has been great, and I am glad I had a chance to write my master's thesis here too. Special thanks to Markus Ovaskainen for proposing this interesting subject and guiding me through the work, his ideas on the subject were invaluable. Thanks to my thesis supervisor and examiner Kari Lappalainen, I was able to put together a well structured thesis according to the original schedule.

The greatest thanks goes to my family and especially parents for always supporting me and encouraging me during my studies. I would not have made it here without them. Same goes for my girlfriend for being at my side at every step of the way, she has been my rock and patiently pushed me forward, especially through the hardest parts.

Tampere, 28th August 2024

Konsta Matikainen

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ABBREVIATIONS AND NOTATIONS

A_t	Total annual cost of operation in year t
$CF_{\text{BESS, AC}}$	Capacity factor of AC-coupled battery energy storage system
$CF_{\text{BESS, DC}}$	Capacity factor of DC-coupled battery energy storage system
CF_{PV}	Capacity factor of photovoltaic power plant
$E_{\text{BESS-to-grid, AC}}$	Energy fed from battery energy storage to grid in AC-coupled configuration
$E_{\text{BESS-to-grid, DC}}$	Energy fed from battery energy storage to grid in DC-coupled configuration
E_{BESS}	Energy capacity of battery energy storage system
$E_{\text{PV, AC}}$	Energy fed from photovoltaic power plant to grid in AC-coupled configuration
$E_{\text{PV, DC}}$	Energy fed from photovoltaic power plant to grid in DC-coupled configuration
$E_{\text{out, AC}}$	Net energy production of AC-coupled hybrid power plant
$E_{\text{out, DC}}$	Net energy production of DC-coupled hybrid power plant
E_t	Total energy produced in year t
I_0	Installed cost of hybrid power plant
$P_{\text{BESS DC/AC converter}}$	Power of battery energy storage system DC/AC converter in AC-coupled system
P_{BESS}	Power of battery energy storage system
$P_{\text{PV inverter}}$	Power of photovoltaic inverter
$P_{\text{common DC/AC converter}}$	Power of grid-facing bidirectional DC/AC converter in DC-coupled system
η_{AC}	Power train efficiency of AC-coupled configuration from point of BESS and PV connection to batteries to grid
$\eta_{\text{BESS transformer}}$	Efficiency of battery energy storage system transformer in AC-coupled configuration
$\eta_{\text{DC/AC}}$	Efficiency of bidirectional DC/AC converter
$\eta_{\text{DC/DC}}$	Efficiency of bidirectional DC/DC converter

η_{DC}	Power train efficiency of DC-coupled configuration from point of BESS and PV connection to batteries to grid
$\eta_{\text{battery RTE}}$	Battery round trip efficiency
$\eta_{\text{common transformer}}$	Efficiency of shared transformer in DC-coupled configuration
i	Interest rate
n	Hybrid power plant lifetime
t	Year of operation
AC	Alternating Current
AGC	Automatic Generation Control
BCR	Benefit/Cost Ratio
BESS	Battery Energy Storage System
BMS	Battery Management System
BOS	Balance of System
CHB	Cascaded H-Bridge
CIG	Converter-Interfaced Generation
DC	Direct Current
DP	Dynamic Programming
DSO	Distribution System Operator
EES	Electrical Energy Storage
EMA	Exponential Moving Average
EMS	Energy Management System
EPC	Engineering, Procurement and Construction
ERHA	Strategic Project for Renewable Energy, Renewable Hydrogen and Storage
HPP	Hybrid Power Plant
HV	High Voltage
HVAC	Heating, Ventilation and Air Conditioning
IBG	Inverter Based Generator
IBR	Inverter Based Resource
IDAE	Spanish Institution for the Diversification and Energy Savings
ILR	Inverter Loading Ratio
IRA	Inflation Reduction Act

IRR	Internal Rate of Return
ITC	Investment Tax Credit
LCOE	Levelized Cost Of Electricity
LPF	Low-Pass Filter
LV	Low Voltage
MA	Moving Average
MIC	Monitoring, Information exchange and Control system
MIMO	Multiple Input Multiple Output
MITECO	Spanish Ministry for the Ecological Transition and the Demographic Challenge
MMC	Modular Multilevel Converter
MPC	Model Predictive Control
MPPT	Maximum Power Point Tracking
MV	Medium Voltage
NPV	Net Present Value
O&M	Operation and Maintenance
PCC	Point of Common Coupling
PCS	Power Conversion System
PERTE	Strategic Projects for Economic Recovery and Transformation
PFR	Primary Frequency Response
PoC	Point of Connection
PSO	Particle Swarm Optimization
RES	Renewable Energy Source
RfG	Requirements for Generators
ROCOF	Rate of Change of Frequency
SBESS	Stationary Battery Energy Storage System
SCADA	Supervisory Control and Data Acquisition
SoC	State-of-Charge
SoH	State-of-Health
SVG	Static Var Generator
TSO	Transmission System Operator
UHV	Ultra-High-Voltage

VAC	Volts Alternating Current
VDC	Volts Direct Current
WTG	Wind Turbine Generator

1. INTRODUCTION

The integration of renewable energy sources (RESs) into power systems and the resulting retirements of conventional power plants have significantly increased the importance and deployment of battery energy storage systems (BESSs). They play a crucial role in addressing the intermittent nature of RESs and in stabilizing the grid. The need for flexible and highly controllable energy sources has led to development of different configurations of BESSs, which are roughly categorized to alternate current (AC) and direct current (DC) coupled. BESSs include batteries that are used to store the energy, transformers to connect the BESS to the grid, power electronic converters to control and enable the transfer of energy to the grid and auxiliary systems for safe and correct operation.

AC-coupled BESSs can be connected to the grid as stand-alone systems, when their purpose is to provide different services to the grid, such as frequency regulation. They can also be co-located with RESs, in which case they can support the operation of the power plant, in addition to providing grid services. The BESS and RES can be connected to the grid using the same interconnection or they can be connected to the grid separately, as they do not share any components. DC-coupled BESSs differentiate from AC-coupled in a way that they are always connected to some other system on the DC-side and share a grid-facing DC/AC converter, transformer and interconnection with that other system.

Most of the research on this subject has been done by comparing these configurations with photovoltaic (PV) power plants, with focus on efficiency [1], costs [2] and dispatch [3], for example. The research on this subject is relatively new, as are the DC-coupled BESSs in general. The thesis presents a detailed technical and commercial comparison of these two coupling methods, exploring their respective advantages, applications, economic implications and the status of research on the subject. It provides an overview of these systems from several perspectives and explores how they relate to each other.

The thesis is structured as follows. The second chapter provides an overview of BESSs, beginning with a discussion of their critical role in modern power systems. It briefly presents various battery technologies and examines the general system architecture of BESSs. This provides the reader with a basic understanding for subsequent technical discussions. The third chapter shifts the focus to the power train components of BESSs. It discusses important aspects of BESS grid coupling and presents the power train configurations unique to AC-coupled and DC-coupled systems. The chapter also addresses the role of power electronic converters, which are integral to the operation of BESSs. The fourth chapter discusses the potential applications of both AC- and DC-coupled BESSs, highlighting their respective benefits and suitability for different scenarios. It also examines co-location incentives, providing insights into the governmental programs aimed at increasing the deployment of BESSs. The fifth chapter presents a comparative analysis of AC- and DC-coupled systems, evaluating both economic and technical considerations. This analysis includes a review of existing implementations, offering a practical perspective on the adoption of these systems. The sixth chapter presents a case study comparing AC- and DC-coupled BESSs integrated with a PV power plant. It provides a concrete example of how the economic viability of these systems can be evaluated, discussing the results and their implications in detail. The thesis concludes by synthesizing the findings from the technical and commercial comparisons.

2. OVERVIEW OF BATTERY ENERGY STORAGE SYSTEMS

This chapter explores the general importance of BESSs in power systems, briefly discusses different battery technologies and their key performance metrics and presents the basic system architecture of BESSs.

2.1 Importance of Battery Energy Storage in Power Systems

The demand for energy storage solutions in modern power systems is driven by the need to integrate increasing amounts of RESs into the grid. The increase of RESs, primarily solar and wind power, is crucial for the sustainable future of electricity production. However, this transition introduces significant challenges for power systems, primarily due to the intermittent nature of these energy sources.

Renewable energy sources like solar and wind are variable, producing power that fluctuates with weather conditions and time of day. In addition to seasonal variablity, this can lead to mismatches between energy supply and demand, creating instability in the power grid. For instance, solar power generation peaks during the day, which will not always align with peak electricity demand periods [4]. Such is the case during winter, when solar irradiance is the lowest and heating drives up the electricity demand. Similarly, wind power production is subject to wind conditions and will not always coincide with consumption patterns. The intermittent nature of RESs can also aggravate grid congestion and create bottlenecks, especially in areas with insufficient transmission infrastructure [5]. This can happen when generation or demand exceeds the capacity of the local grid.

To address these challenges, increasing the flexibility of electric power systems is essential. Voropai and Rehtanz presented a following definition for electric power system flexibility in [6]: "The flexibility of the electric power system is its ability to maintain normal state when exposed to internal (sudden changes and fluctuations of load, power flows through the lines and generation) and external (sudden disturbances) random (undetermined, uncertain) factors." BESSs are viable tools for enhancing electric power system flexibility, because of their ability to rapidly respond to load fluctuations, external disturbances and to the variability of renewable energy sources.

In [7], flexibility is visualized by four different dimensions; time, control functions, uncertainty and cost. Time is related to the speed of the system to react to deviations and return to its initial state, control functions to the corrective measures taken in certain processes over a responding time interval, uncertainty to the lack of information of the future state of the system and cost to the the dynamic expenditures associated with adapting controlling processes to maintain system flexibility, influenced by the trade-off between economic efficiency and risk management.

The technical abilities of BESSs align with those dimensions of electric power system flexibility: it can offer a rapid response by fast charging or discharging, enables precise control by performing various functions based on the state of the grid (e.g., frequency regulation), compensates the power supply and demand mismatch caused by RESs (uncertainty) and can lower costs by optimizing electricity generation, transmission and usage and by providing security against unforeseen power outages or supply shortages. These capabilities make BESSs valuable tools in enhancing grid flexibility.

As the electricity production moves from centralized production and conventional energy sources to distributed generation and RESs, the use of converter-interfaced generation (CIG) also increases. This presents a challenge for the grid stability, as the share of natural inertia from the rotating mass of large synchronous generators in the grid will continue to decrease. Inertia, in this context, refers to the ability of large rotating synchronous generators to resist the grid frequency fluctuations with their own kinetic energies. As the frequency changes, the kinetic energy of the generators also changes, leading to continuous power exchanges between the grid and the generators. This power exchange slows down the rate of change of frequency (ROCOF) of the grid [8]. The ROCOF needs to be kept slow enough to ensure frequency stability. CIGs are decoupled from the grid, so they do not increase the inertia just with their own physical properties. But even when CIGs are unable to provide natural inertia to the power system, they can contribute to the controlling of power system frequency. This is especially the case with BESSs. [9]

BESSs are equipped for a pivotal role in the frequency regulation, providing rapid-response capabilities to stabilize the grid. Power system frequency is constantly fluctuating around its nominal frequency (50 Hz or 60 Hz [10]). When electricity production falls below the demand, the frequency reduces and when generation exceeds electricity demand, it is increased. During these sudden imbalances between electricity demand and supply, BESSs can inject or absorb power almost instantaneously, helping to maintain the frequency within acceptable limits. The short response time is especially what makes them very suitable for frequency regulation [11]. The ability to offer these ancillary services can also become a source of revenue for BESS operators, as they can be compensated for providing these services.

From Figure 2.1, which illustrates the required power capacities and discharge durations

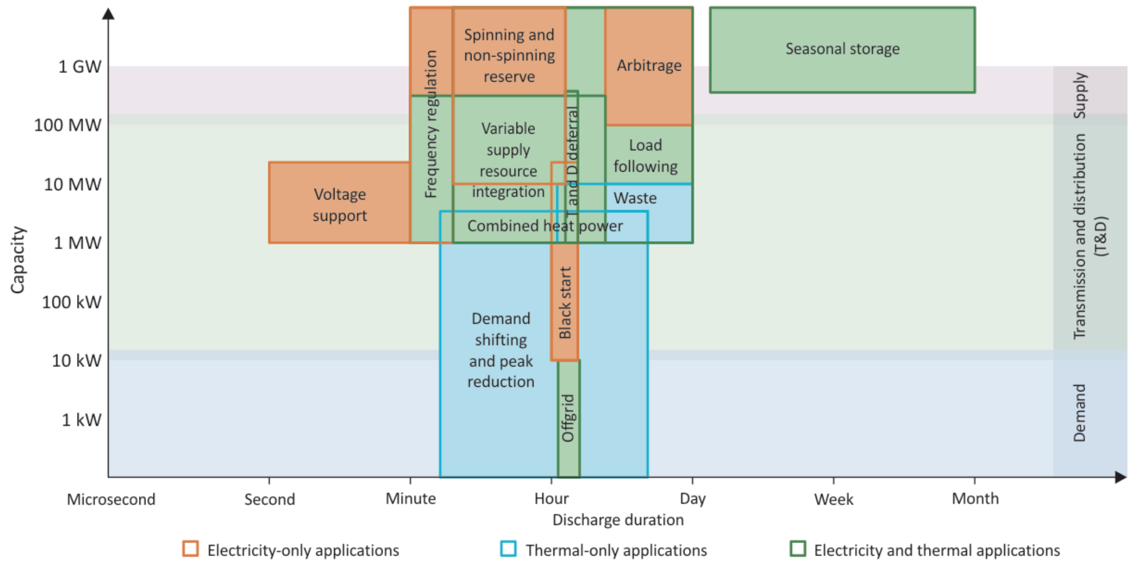

Figure 2.1. *Discharge duration and power capacity requirements for energy storages in different applications. Reprinted from [12].*

of different grid applications for energy storages, it can be seen that frequency regulation and voltage support are applications that need high power in seconds to minutes timescale. These are very interesting applications for battery energy storages, as the required response times and discharge durations are short. However, it must be noted, that the practical utilization of batteries at grid-level is always about balancing between fulfilling the transmission system operators (TSOs) requirements, minimizing battery lifetime degradation and finding economically most feasible applications [13].

BESSs can offer a versatile set of functionalities to support the operation of the power system. On a large scale, they strengthen the power grid by managing voltage fluctuations, providing short-circuit current contribution and supporting grid recovery efforts. Notably, BESSs play a critical role in mitigating challenges arising from synchronous generation retirements, providing support for grid stability [14].

Murarka et al. have listed different advantages and constraints of BESSs based on the integration site in [15]. Integration of BESSs on the generation side allows for more flexibility in how energy is supplied, based on what is financially the most feasible strategy, but is currently constrained by inefficient energy storage usage and the lack of skill or willingness of those involved with renewable energy (companies, governments) to adopt business models that would make the use of BESSs economically more viable. On transmission side, it enables lower system costs and infrastructure optimization (e.g., by allowing transmission line investment deferral), but is constrained by the lack of frameworks or strategies used to incorporate BESS into the existing transmission system in a way that effectively involves and aligns with the interests and operations of various stakeholders (utility companies, regulatory bodies, consumers). Another limitation is the difficulty in creating supply profiles that serve the specific needs of individual procurers. In order to increase the utilization of BESSs on even larger scale, further efforts in these topics are needed.

2.2 Battery Technologies

Batteries utilize chemical compounds as a storage medium to store energy. During discharge, chemical processes generate the energy, which is obtained from the batteries as current at certain voltage. Charging and discharging cycle can be repeated with secondary batteries, but primary batteries are designed to go through this only once. The main components of both primary and secondary batteries are positive electrode, negative electrode, electrolyte and separator. The energy is stored in electrochemically active materials in the positive and negative electrodes. The electrode that is gaining electrons (negative charge carriers) is called cathode and the one losing electrons is called anode. This means that, when discharging, positive electrode is the cathode and negative is the anode (usually they are referred with these terms regardless of the charging/discharging process). The flow of electrons happens in an external circuit between the positive and negative electrode, which have a potential difference between them. [16]

Every battery system is composed of individual cells, that are enclosed anode-cathode pairs. In large-scale systems, the cells are usually connected in parallel to form a block. The blocks are then further connected in series to form a battery module and the battery modules are connected in series and/or parallel to form a battery pack [17]. Battery energy storage systems utilize different battery cell technologies, characterized with their own features for specific applications. Batteries have evolved significantly in the recent years, offering a wide range of solutions for energy storages with various purposes. Following is a brief overview of some common battery technologies for stationary large-scale applications, with main disadvantages and advantages of each technology summarized in more detail in Table 2.1.

Lithium-ion batteries are the most popular choice for grid-level applications due to their long cycle and calendar life, high energy density, efficiency and decreasing costs [11]. Recent advancements in lithium-ion battery technology have been crucial in enhancing the proliferation of battery energy storage systems.

Lead-acid batteries have a lower energy density, lower specific power and a lower cycle life compared to lithium-ion, but their low cost has made them the chosen technology for some large-scale systems [18]. Due to the short cycle life (500–1000 cycles) [19], their usage is focused particularly on backup and emergency power applications.

Sodium based batteries are increasingly used in grid storage due to their high rated energy capacity and ability to provide long-duration storage. **Sodium-sulfur batteries** are

Table 2.1. Comparison of battery technologies for large-scale applications. Information gathered from [11, 14, 19, 20].

Technology	Advantages	Disadvantages
Lithium-ion	High power and energy densities, high efficiency	High production cost, requires special charging circuit
Lead-acid	Low manufacturing cost, uncomplicated technology	Slow to charge, limited charge/discharge cycles, toxic materials
Sodium-sulfur	High energy density, high efficiency, promising for large-scale stationary applications	High annual operating cost, high initial capital cost, safety problems at high temperatures
Sodium nickel chloride	Better safety and less corrosive than sodium-sulfur batteries, good pulse power, maintenance-free, low self-discharge, high cycle life	Low energy density, low power density
Flow batteries	Flexible layout, long cycle life, quick response times, no need for equalization charging	High investment cost, technical development issues
Nickel-cadmium	Used in harsh conditions, high temperature tolerance	Toxic heavy metals, environmental harm, high cost, memory effect
Nickel–metal hydride	More environmentally benign than nickel-cadmium batteries	Low energy efficiency

mostly used in large-scale applications rather than mobile applications, due to their high operating temperature and the corrosiveness of sodium polysulfide discharge products [20]. **Sodium nickel chloride batteries** have a higher cell voltage and better safety features, but have lower power and energy density than sodium-sulfur batteries [11].

While less common than the other types, **flow batteries** are gaining traction in grid-level applications due to their scalability and long cycle life. Flow batteries store energy in electrolyte solutions that are stored in tanks and the electrode and electrolyte are separated, which differs them from conventional batteries [19]. They are especially suitable for long-duration energy storage, which is increasingly valuable for integrating renewable energy sources into the power system.

Nickel cadmium batteries were considered promising technology due to their temperature resistance and high energy density, but their use has declined due to environmental concerns related to cadmium. However, they are still used in some niche applications where their temperature tolerance and durability are beneficial [20]. **Nickel-metal hy-**

dride batteries are equipped with similar features, but are more environmentally friendly than their predecessor, due to the absence of cadmium [11].

The field of battery technology is undergoing a rapid transformation, driven by advancements in battery chemistry and changes in economic factors [21, 22]. Innovations in battery chemistry are leading to the development of more efficient, durable and safer batteries. This evolution is significantly influencing the preferences and applications of batteries in grid-level energy storage systems.

2.3 System Architecture

While the primary energy-storing component of a battery energy storage system is the battery itself, BESS also requires additional systems for control, monitoring and connection to the grid. A typical large-scale BESS comprises of multiple battery packs, a battery management system (BMS), a supervisory control and data acquisition (SCADA) system, a power conversion system (PCS), an energy management system (EMS) and other systems, such as a fire suppression system [23]. EMS and SCADA are integrated, at least through communication network, with the monitoring, information exchange and control system (MIC) [24], which is also referred to as system control and monitoring [23] or simply monitoring system [25]. SCADA and EMS can be centralized (overseeing multiple energy storage assets) or decentralized (overseeing a single energy storage asset) [26].

The BMS controls the batteries, the SCADA serves as the general control and monitoring system, the PCS manages the power flow and conversion between the batteries and the grid, while the EMS controls the power flow and facilitates communication between the BESS and external systems [26]. The batteries and power electronics have their own specific thermal management systems, controlled by the BMS and PCS control units [23].

The BMS, which is used for controlling and monitoring the performance and state of the whole battery system, is crucial for ensuring its safe and optimal operation [27]. Caused by small differences in battery cell properties, the cell voltages might also have slight variation between them during the cycling process. The BMS makes sure that each cell is charged and discharged in a way that their temperature stays in safe limits and cells are burdened according to their estimated State-of-Health (SoH) [25]. This is done by cell balancing during charge, load balancing of cells during discharge and with charging cycle control [28]. Cell balancing prevents damage to the cells, uneven degradation and ensures safe and optimal operation of the battery system [29].

According to Tan et al. [29], the BMS in battery energy storage systems offers multiple benefits, such as increased battery lifetime, efficiency, safety and reliability. These advantages are achieved through a series of critical functions. The article discusses how controlling the charging and discharging cycles, maintaining an appropriate State-of-Charge

(SoC) operating range, balancing cell voltages and SoCs and controlling the temperature of the battery packs are among the key functions of BMS.

Further elaborating on these functions, Tan et al. explain that controlling the charge/discharge cycle is essential to prevent deep discharging and overcharging. Ensuring the correct SoC operation range is vital for maintaining sufficient coulombic efficiency, which is the ratio of discharge capacity after full charge to the charging capacity of the same cycle [30]. Essentially, this means that ensuring the battery operates within the right SoC range is crucial for maximizing the amount of usable energy a battery can provide relative to the energy it takes to charge it. Additionally, balancing cell voltages and SoCs is crucial for increasing the operating range. Thermal control is necessary to maintain the correct temperature range of the battery pack, as described in detail in [29].

According to a study on energy management and optimization methods for grid energy storage systems [26] by Byrne et al., EMSs are specifically designed to ensure the optimal and safe operation of ESSs. In battery-based storages, EMS is integrated with the BMS, along with the PCS and external systems, which is crucial for continuous monitoring and optimal functioning of the BESS. Data from the external systems (information from system operators, historical data, weather forecasts, energy markets) and BMS, measurements from the PCS output (e.g., PCC measurements, voltage, DC link voltage, current) are carried to the EMS, which then decides parameter limits, correct operation modes (BMS) and executes conversion control (PCS) actions by using voltage and current set points [31].

A significant engineering challenge highlighted in [26] is the responsibility of the EMS for optimal scheduling of grid-connected BESSs, which means that it has to balance between maintaining safe operational state and maximizing benefits. The architecture and interfacing of the EMS are influenced by several factors, including the BESS ownership model and prevailing regulatory frameworks. The article [26] emphasizes that these factors significantly influence the design and operation of the EMS. The interfaces of the EMS, which vary depending on the application and associated stakeholders (e.g., customers and utilities), are also a point of focus in the articles discussion. The EMS architecture can be highly centralized, providing specific operational parameters to each system, or decentralized, with most computational processes happening locally at the storage system level. These architecture models are used when one EMS is responsible for overseeing multiple energy storage assets. When considering a single BESS, the EMS can be viewed as a part of the MIC, as illustrated in Figure 2.2.

The power conversion system in BESSs is an important component, serving as the core electricity conversion system [32]. Its primary role is to carry out the power exchange between the energy storage batteries and the electrical grid, which is a critical function for the effective performance of the BESS. The PCS converts DC from the batteries into

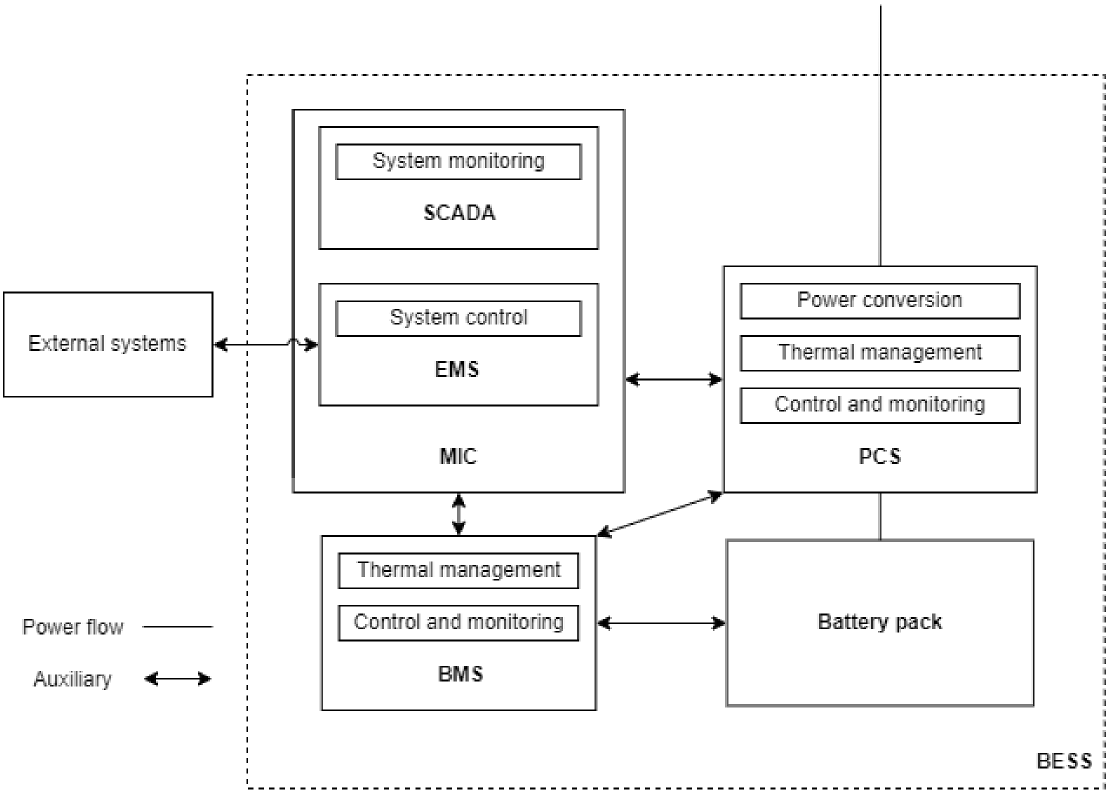

Figure 2.2. *BESS architecture.*

AC for the grid during discharge and inversely, it transforms AC from the grid into DC for charging the batteries [33].

Role of the PCS in a BESS is to carry out the current conversion and ensure that it is carried out efficiently and reliably, adapting to the needs of both the battery energy storage system and the grid which it is connected to. The requirements for grid operation can include, e.g., ROCOF withstand, fault recovery and fault-ride-through capability, fault current injection, active power and frequency control, reactive power capacity requirements, voltage and reactive power control, black start capability and island operation [34]. Choice of topology and optimized control of the PCS are key aspects for the correct operation of the BESS, affecting both the systems suitability to different applications [25], ability to store energy efficiently and provide quality power to the grid.

Based on this section, it is necessary to further clarify the relationships and interaction of these BESS sub-systems. The BMS and PCS serve foundational and intermediary roles, respectively. The BMS ensures safe and optimal performance of the batteries by managing charging, discharging and temperature, while the PCS executes the conversion of power between the batteries and the grid. These systems provide operational data to the EMS and SCADA.

The EMS, positioned at the system-level, utilizes data from the BMS and PCS to optimize the overall operation of the BESS, making decisions on power flow and operational modes. It balances between system safety, efficiency and maximizing benefits through strategic scheduling and optimization. The EMS provides a broader control capability and facilitates the exchange of information and control actions between the BESS and external systems, including grid operations and energy markets.

The relationship between the individual control and monitoring functions of the BMS and PCS and the system-level control and monitoring executed by the EMS and SCADA is synergistic. The BMS and PCS feed real-time operational data to the EMS and SCADA, enabling higher-level monitoring and informed decision making that aligns with safety standards, operational efficiency and market opportunities. This hierarchical control structure ensures that the BESS operates optimally within its internal constraints and external demands.

3. POWER TRAIN OF BATTERY ENERGY STORAGE SYSTEMS

This section delves into the technical aspects of power train setups for AC-coupled and DC-coupled BESSs. It compares the methods of connecting these systems to the grid and discusses their technical features. It also details the essential devices and requirements for both AC-coupled and DC-coupled systems, emphasizing the specific components and compatibility necessary for each connection topology.

3.1 Grid Coupling of Battery Energy Storage Systems

Integration of the battery energy storage system to the power grid is a critical part of every BESS-project. This is emphasized with large-scale storage solutions, as the power losses and performance requirements of electrical components are increased with higher power. In BESSs, the main component of the electrical power train between the batteries and the grid is the power conversion system. The most important features of PCS power converters in large-scale BESSs are bi-directional power flow, high efficiency, rated power and peak power, in addition to fast response time [35, 36]. Bi-directional power flow enables the charging and discharging of the batteries, high efficiency, rated power and peak power minimize power losses and the number of required converters, while fast response time ensures BESS suitability to most demanding grid applications.

Another important function is four-quadrant control. The four-quadrant control capability of the PCS DC/AC converter allows it to independently regulate both active and reactive power. This means that the converter can precisely manage the injection of power to the grid or absorption of power from the grid, adjusting real and reactive power flows based on the DC voltage of the battery output terminals and within the current limitations of the converter [37].

Based on the PCS-topology, different battery energy storage systems can be categorized to AC- and DC-coupled systems. In DC-coupled systems, the batteries are connected to a DC link of a common DC/AC converter, which is connected to a grid transformer. In AC-coupled systems, the connection between the batteries and the grid is done with a dedicated DC/AC converter, allowing the BESS to operate independently from other sources or loads. Depending on the PCS topology, there can also be a DC/DC conversion stage between the batteries and the DC link [24]. The key differentiating factor between DC- and AC-coupled BESSs is the output voltage type at their connection points to other systems: DC-coupled BESSs output is VDC (volts direct current), whereas the output of the AC-coupled BESSs is VAC (volts alternating current) [38].

Within AC-coupled architectures, there are variations in the design of the converter stage. Some systems employ a two-stage (also called multi-stage) PCS, incorporating a DC/DC conversion stage between the batteries and the DC/AC converter DC link. Alternatively, single-stage PCS directly connects the batteries to the DC/AC converter, bypassing the DC/DC conversion stage. Simple illustrations of AC- and DC-coupled battery energy storage system power trains are shown in Figure 3.1. The following sections will present alternative topologies for these power train setups.

The *IEEE Std 2030.2.1-2019* [24] defines a set of guidelines for design, operation and

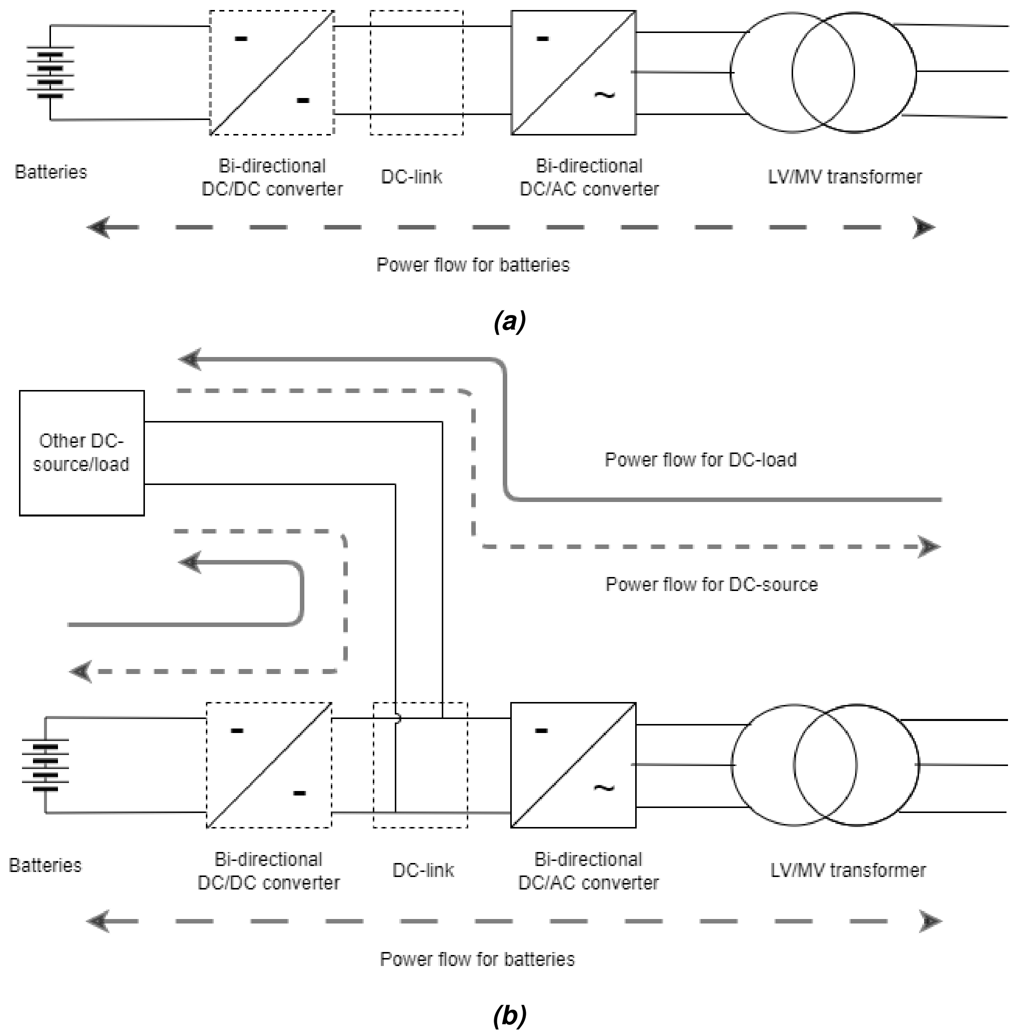

Figure 3.1. *AC-* ***(a)*** *and DC-coupled* ***(b)*** *BESS power trains with optional DC/DC conversion stage and power flow illustration.*

maintenance of battery energy storage systems. The guide includes design considerations for BESS PCS, including active and reactive power regulation capability, PCS topology adaptability with battery packs and DC link voltage range. Other design considerations mentioned in [24] include PCS AC-side voltage regulation, frequency, harmonics and flicker rules and voltage fluctuation, output voltage DC component, earthing type and synchronization requirements. These guidelines by IEEE were made to help manufacturers and system integrators to ensure power system, communication technology and information technology interoperability when working with BESSs [24]. *IEEE Std 2030.3-2016* [39] provides guidelines for type tests, production tests, installation evaluation and commissioning and periodic tests for electric energy storages (EES) used in power system applications. These guidelines were made for storage operators, manufacturers, users and grid operators for performance and quality evaluation [39].

The international standards for BESS grid connection are defined by International Electrotechnical Commission (IEC). *IEC TS 62786-3:2023* [40] provides principles and technical requirements for design, connection, operation and testing of stationary battery energy storage systems (SBESSs) connected to distribution network. The *IEC 62933* series [41] provides comprehensive guidelines for EES, covering terminology, performance parameters, testing methods, environmental impacts and safety considerations. It outlines the integration and operation of EES systems in grid-connected settings, including specific applications like frequency regulation, renewable energy integration and backup power supply. The series also addresses environmental concerns related to EES and reused batteries, offering strategies for minimizing environmental impacts. Safety standards for grid-integrated EES and modifications to BESSs are detailed, emphasizing hazard identification, risk assessment and mitigation. It must be noted, that these standards are not legally binding, unless they are adopted as national standards by a regulatory authority [42].

BESSs are classified as CIG units, also referred as inverter based resource (IBR) and inverter based generator (IBG), so they have to comply with the local grid code requirements for CIGs, which are defined by TSOs in different countries. In Germany, battery energy storages are included in the *Network Code Requirements for Generators* (RfG) [43]. In UK, a grid code modification proposal *GC0096* was accepted by Grid Code Review Panel (GCRP) in 2019 to include technical definitions for energy storage [44, 45]. The decision concluded that EES systems are treated as generator units or generator modules, in terms of minimum technical requirements, in UK's grid code.

Some European TSOs have also developed specific grid code requirements for grid-connected energy storage systems. Finnish TSO Fingrid has defined the requirements in *Grid Code Specifications for Grid Energy Storage Systems SJV2019* [34]. Danish TSO Energinet Elsystemansvar has defined the technical and functional minimum requirements for battery plants (BESS) in *TECHNICAL REGULATION 3.3.1 REQUIRE-*

MENTS FOR ENERGY STORAGE FACILITIES [46]. Both Energinet and Fingrid require also simulation models for the grid-connected energy storage systems with rated supply power of 10 MW or higher.

3.2 Power Train in AC-Coupled Battery Energy Storage Systems

As discussed in the previous section, the configuration of the PCS of an AC-coupled BESS can be either single-stage or two-stage, which are both illustrated in Figure 3.2. The single-stage PCS is directly connected to the battery, providing simplicity, high efficiency and savings in hardware costs, as there is only one bidirectional DC/AC converter needed. However, the absence of a DC/DC conversion stage means that the battery output voltage must be greater than in a corresponding two-stage system. In practise, this is solved by overdimensioning the batteries [47], so that the DC link voltage remains within the correct operation range throughout the charge/discharge-cycle.

Two-stage PCS incorporates a DC/DC conversion stage between the DC/AC converter DC link and the batteries. The DC/DC conversion allows a voltage step-up/step-down to accommodate a wider voltage range in the battery pack output terminals and acts as a charge controller, while the DC/AC converter is used to interface with the grid [48]. The main disadvantages of this PCS-topology are increased hardware costs and conversion losses due to the larger number of switching devices, in addition to decreased system-level reliability caused by two series connected converter devices [49].

The PCS-topologies that were discussed above cannot, as standalone systems, practically achieve sufficient power and energy capacities required for large-scale systems, due to the constrains in the number of series and parallel connected battery modules in

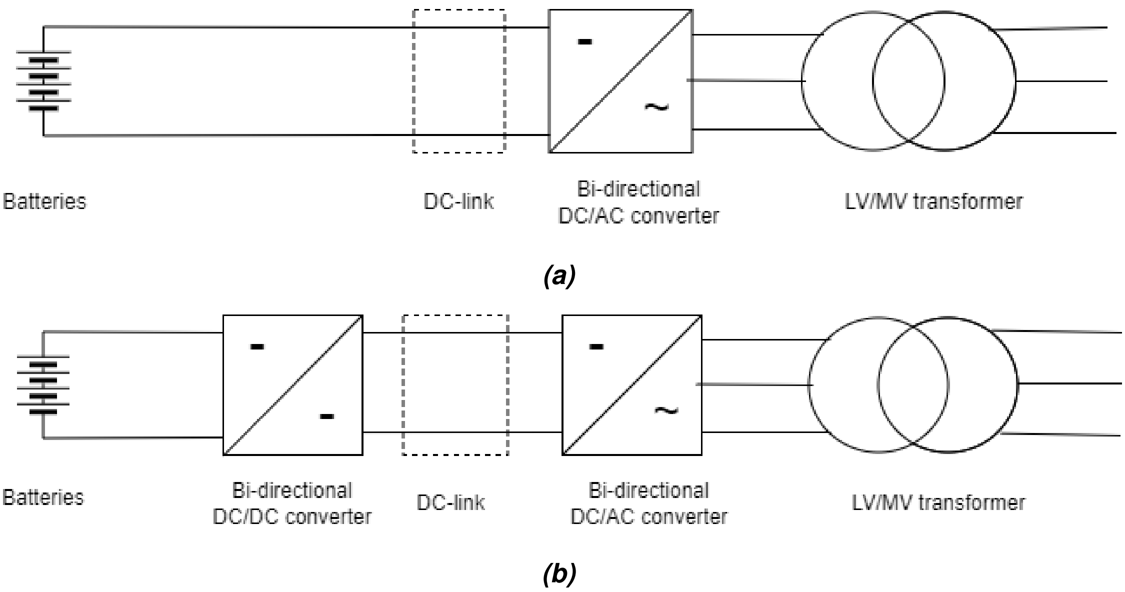

Figure 3.2. *Single-stage* ***(a)*** *and two-stage* ***(b)*** *AC-coupled PCS.*

the battery pack and the power ratings of the converters. Sufficient energy and power capacity, along with increased system level reliability, can be achieved by increasing the number of batteries and converters in the system. This can be done by utilizing series and parallel connected converters with individual battery packs connected to the DC-side of PCS. These PCS configurations are more redundant than the before mentioned systems, as there are multiple battery packs and parallel converters. These configurations can be categorized to dedicated and parallel topologies, depending on if there is a common DC link between different battery and converter strings. Some variations of these topologies are illustrated in Figure 3.3.

Dedicated PCS (Figure 3.3c) has parallel single-stage or two-stage converters connected to the low-voltage side of the line-frequency transformer. This connection topology has a clear advantage in terms of control capabilities, as each battery pack can be controlled individually and utilized for different grid applications [23]. With parallel configurations, the common DC link allows partial loading of the DC/AC converters when all of the BESS capacity is not needed.

The configuration with common DC link and parallel DC/AC converters (Figure 3.3a) also enables additional paths for battery discharging and charging if one of the DC/AC converters fail, in expense of high technical requirements for minimum impedance variations between the batteries [23]. The problem with impedance variations arises with the parallel single-stage configurations, as the impedance variations cause circulating currents between the batteries, if there are no dedicated DC/DC converters between the batteries

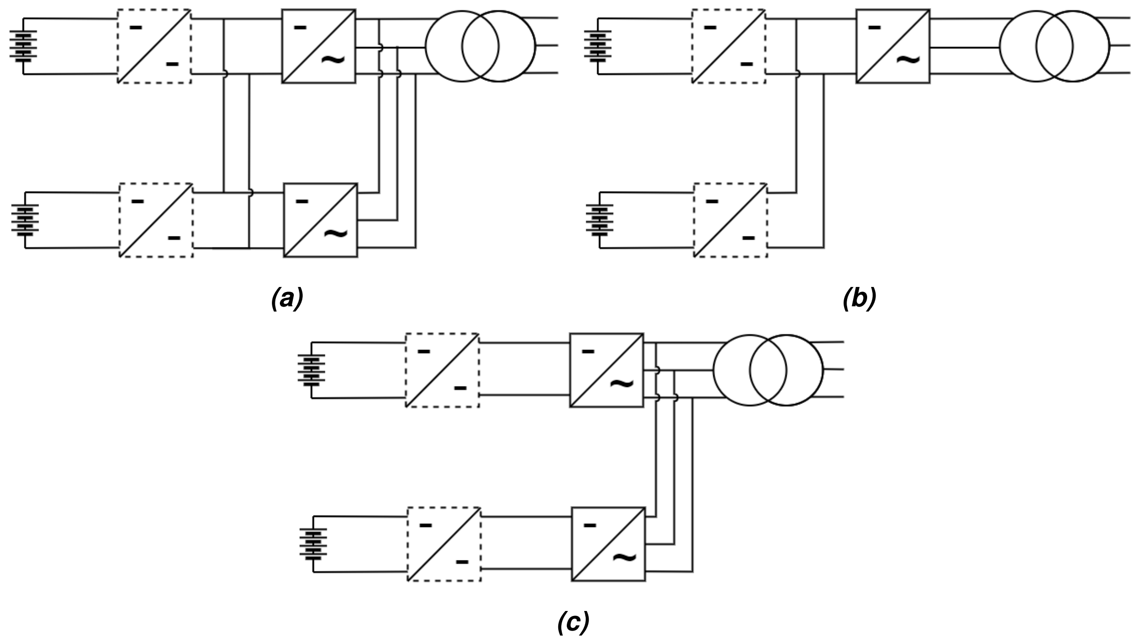

Figure 3.3. *Parallel* ***(a) (b)*** *and dedicated* ***(c)*** *AC-coupled PCS-topologies. Dotted lines around the DC/DC converters highlight that the PCS configuration can be either single-stage or two-stage.*

and the DC link. The configuration with one DC/AC converter and multiple parallel DC/DC converters (Figure 3.3b) allows an independent operation of the different battery packs, because the output voltages of the DC/DC converters are equal but currents can be different [49]. On the other hand, the common DC/AC converter needs to be larger in terms of power rating, compared to the other configurations.

Other PCS topologies that have sparked interest especially in research, are multilevel topologies. The main reason for growing interest in multilevel topologies is that they enable the BESS to be connected directly to the MV grid, eliminating the need for large, lossy and expensive line-frequency transformer. Two of the most prominent topologies are based on cascaded H-bridge (CHB) and modular multilevel converters (MMC). They are built from multiple sub-modules (also called cells or bridges) that contain a battery and a single-stage or two-stage, single-phase DC/AC converter. With this definition, the systems that were shown previously in Figure 3.2, can be viewed in this context as sub-modules with three-phase AC-outputs (excluding the transformer). The single-phase AC-output sub-modules are connected in series and the series connected strings are further connected in different ways to achieve the required voltage level for MV grids. Star-connected CHB-BESS and MMC-BESS with distributed batteries are illustrated in Figure A.1 in Appendix A. Other variations of these topologies include delta-connected CHB-BESS and MMC-BESS with centralized batteries [50].

Literature on different AC-coupled PCS topologies are listed in Table 3.1. The most interesting studies are the bolded ones, which have reported field experience. The BESS constructed in M5BAT project [51] is a 5.6 MW / 5.5 MWh system, which was built by connecting ten battery packs with two-stage PCSs to a 10 kV network with five multi-winding line-frequency transformer. The system incorporates five different battery technologies, two of which are lead-acid batteries and three lithium-ion batteries. It is used to test the operation and profitability of large-scale BESSs and there have been numerous publications since 2017 [52].

Another interesting project is a 2 MW / 2 MWh CHB-BESS implemented by Cai et al. [53], which was the first demonstration of a transformerless large-scale grid-connected CHB-BESS. It was connected to a 10 kV network and used for energy time-shift for the local grid, reporting measured PCS efficiency of over 98 % [54]. A 250 kW prototype of a MMC-BESS was built by Hillers et al. [55], which was connected to a 9 kV grid without a line-frequency transformer. The system was studied and compared with CHB-BESS. These demonstrations of multilevel PCS topologies show that as the power electronics and control systems develop, BESSs could be connected to the grid without line-frequency transformers, achieving substantial cost savings and reduced losses. However, the cost of insulation with these topologies is generally higher than with LV (low voltage) topologies. Proper insulation can be achieved, e.g. by placing the battery cells in a metal box that is installed to a highly insulating bracket, so that the discharge between the bracket and the

Table 3.1. *Literature on different AC-coupled PCS topologies [49, 54, 68]. Literature with field experience are bolded.*

Topology	**Literature**
Single stage	[47] [56] [57]
Two-stage	[56] [58]
Dedicated single-stage	[59]
Dedicated two-stage	**[51]**[1]
Parallel two-stage with a common DC/AC converter	[60][1] [61][2] [62] [63]
Parallel with common AC-link	[64][3]
CHB-BESS	**[53]** [65] [66]
MMC-BESS	**[55]**[4] [65] [66] [67]

[1] Incorporating batteries with different chemistries.
[2] System based on flow batteries.
[3] Efficiency comparison of multiple different topologies.
[4] Prototype in lab environment.

ground can happen only in extreme situations, similarly to high-voltage SVGs (static var compensators) and valves at UHV (ultra-high-voltage) potential [25].

In real-world applications, single-stage systems that incorporate line-frequency transformers are the most popular topologies [14, 69]. These systems can be standalone, dedicated or connected to the grid through several transformers, depending on the size of the BESS. The dominance of this topology can be attributed to several key advantages it holds over its counterparts. As stated before, the primary benefits include simplicity, lower hardware costs and higher efficiency. The simplicity of the single-stage system is a significant factor, as it reduces complexity in design and operation, making it more straightforward to implement. Two-stage systems incorporating only batteries have been proposed in the literature for microgrid applications [58, 63] and for connecting the BESS to an LV grid without a transformer [56]. In addition to the reasons outlined in this section, this information implies that the DC/DC conversion step is generally unnecessary in conventional large-scale systems. This is because BESSs require transformers due to their connection to medium voltage (MV) or high voltage (HV) grids. Furthermore, modern DC/AC converters are well-equipped to manage the minor voltage fluctuations at the battery terminals, so there is no need for additional conversion step if the batteries in the same system are not different in technology or ratings from each other. Regarding other topologies, such as CHB and MMC, the absence of available commercial solutions suggests that the technological maturity and economic benefits have not reached a level where manufacturers see sufficient potential to invest money and resources in developing these systems into commercial products. These distinctions are important in recognizing the differences between systems proposed in research and systems that are currently implemented in practice.

3.3 Power Train in DC-Coupled Battery Energy Storage Systems

In DC-coupled BESSs, the PCS typically includes an optional DC/DC converter, a shared DC link connecting the BESS with other DC sources or loads and a shared DC/AC converter. Sometimes, in the case of DC-coupled BESS, the PCS might only include the DC/DC converter, treating the other components as part of different systems. However, for the purposes of this study, which aims to examine the entire power train from the batteries to the grid, both the DC link and the shared DC/AC converter are also considered integral parts of the BESS PCS.

As illustrated in Figure 3.1b, the batteries within a DC-coupled BESS can be connected to the common DC link either through a DC/DC converter or directly, without any conversion. This setup is similar to the configuration seen in single-stage AC-coupled systems, as shown in Figure 3.2a. However, a notable distinction in the DC-coupled configuration without a DC/DC converter is the presence of an additional DC source or load connected to the DC link. In this configuration, the output voltages of the batteries and the other systems have to be equal to avoid circulating currents, similarly to batteries of the parallel connected single-stage AC-coupled systems. This leads to a limitation on the range of power taken from the batteries and the other systems connected to the DC link, as the power taken from one source is limited by the voltage swing of the other [36]. When the voltage on the terminal of one the sources changes, the voltages on the terminals of the other parallel connected sources have to change to the same level, so that the current does not start circulating between them. This will force a change in the power output of all sources, which are relative to the voltage change. This essentially restricts the direct connection of different battery types in the same DC link.

Similar to the two-stage AC-coupled PCS (Figure 3.2b), the DC-coupled PCS with a dedicated DC/DC converter manages the voltage step-up/step-down between the batteries and the DC link. This dedicated DC/DC converter allows the battery to operate independently of other systems connected to the DC link. This is beneficial because it allows output current conditioning of the batteries, prolonging the battery lifetime [36]. It also introduces an additional layer of redundancy to the overall system comprising of battery energy storage and other devices. This redundancy is important for several reasons. It enhances system reliability by ensuring that the failure or sub-optimal performance of one component does not immediately compromise the functionality of the entire system. For example, if another system connected to the DC link fails, the DC/DC converter can adjust the battery output to maintain a stable voltage level in the DC link, ensuring continuous operation. The ability of the DC/DC converter to manage the output of the batteries allows for more flexible system design and operation.

In scenarios involving a DC-source and batteries connected to a common DC link via dedicated DC/DC converters, as depicted in Figure 3.4, the DC link voltage is kept at a steady level. This strategy enables the DC-source to deliver maximum power to the grid, a process known as maximum power point tracking (MPPT), which is commonly used in PV power plants. According to Barcellona et al. [70], MPPT in this case is achieved by regulating the output current of the DC/AC converter to ensure the DC link voltage remains constant. This approach also includes the integration of a voltage-controlled capacitor to the the DC link. Barcellona et al. also noted that in a configuration where the DC-source is connected through a DC/DC converter to the DC link and the batteries are directly connected, the DC link voltage fluctuates in response to changes in the battery SoC. In this case, the DC/AC converter has to withstand the DC link voltage fluctuation, instead of trying to keep it constant.

Whenever batteries are directly connected, the resulting system is characterized by a variable voltage DC link. This configuration prohibits the direct connection of additional DC-sources that also have a variable output voltage to the DC link, due to isolation requirements. Consequently, this leads to the need to use isolated DC/DC converters for connecting these additional sources. In systems equipped with a variable voltage DC link, the DC/DC converters must support wider input and output voltage ranges, compared to systems with constant voltage DC link. This requirement tends to reduce their efficiency and complicate the design process [71]. Isolated converters with wide voltage ranges are also physically larger and have higher hardware costs than non-isolated DC/DC converters [72]. On the other hand, systems designed with a constant voltage DC link need DC/DC converters for all different DC-sources connected to the common DC link, regardless of whether these sources are batteries or others with variable output voltages.

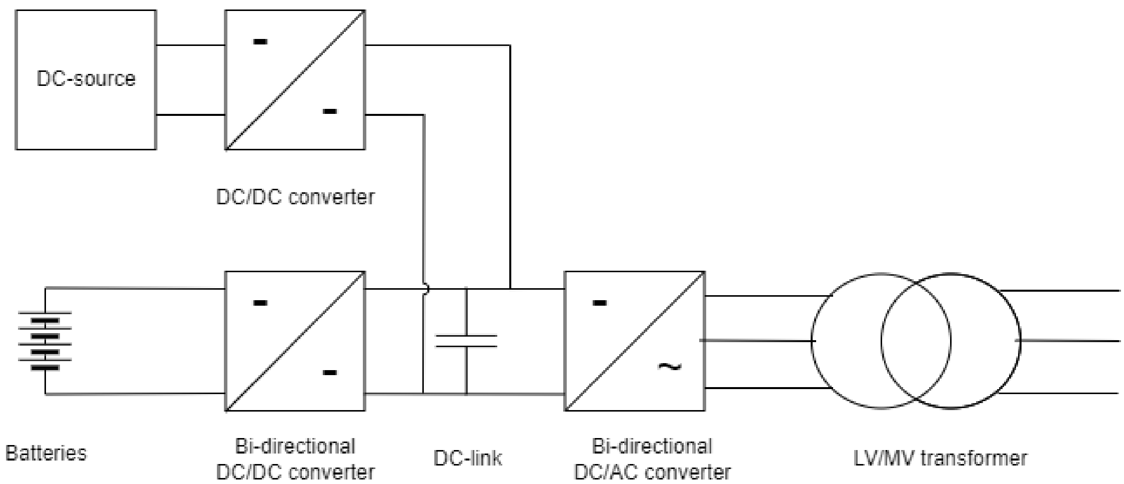

Figure 3.4. *DC-source and batteries connected in parallel to a common DC link through DC/DC converters.*

Literature on DC-coupled BESSs is heavily focused on hybrid power plants (HPPs) combining BESS and RES, especially PV plants, so the literature review on DC-coupled BESSs is covered in Chapter 4.

3.4 Power Electronics Converters in Battery Energy Storage Systems

The power electronic converters (PEC) that are used in BESS PCSs are bidirectional DC/AC and DC/DC converters, as mentioned earlier. The correct converter types are chosen based on the voltage of the used batteries, requirements of the application and the PCS topology of the BESS. Recent studies have also proposed multi-port converter technologies, (also called multiple input multiple output, or MIMO, converters) [2, 73]. Detailed categorization of some common converter types used in BESS PCSs is shown in Figure B.1. The study of individual converter types is not in the scope of this thesis, but the converters will be discussed in a more general level in this section.

DC/AC converters are used to control and execute the conversion of DC from the PCS DC link to AC that can be fed to the grid. The most common types of DC/AC converters in BESS applications are two-level and three-level converters [50, 74]. Two-level converters are the simplest type, switching the output between two states (positive and negative voltage levels) to create a sinusoidal AC waveform. They are widely used due to their simplicity, reliability and cost-effectiveness for a broad range of applications. Three-level converters add an intermediate voltage level, which allows a closer approximation of a true sinusoidal waveform. This results in reduced harmonic distortion, lower switching losses and consequently in the ability to handle higher power levels and voltages more efficiently [32]. Three-level converters are preferred in applications requiring higher efficiency, power quality and power density.

Khalid et al. [31] categorize DC/AC converters used in BESSs into four types: grid-following, grid-forming, grid-supporting and grid-feeding, each defined by its purpose and the services it provides. Grid-supporting converters are adaptable, offering ancillary services to the grid, while grid-following converters adjust their output with grid voltage and frequency to control the BESS current injection/absorption. Grid-feeding converters are a specialized form of grid-following converters that control their output independently of grid conditions. Grid-forming converters, capable of bidirectional energy flow, function similarly to synchronous generators when paired with BESS. This feature makes them a key focus in research and industry for enhancing BESS power conversion, in addition to their ability to maintain grid stability and support both islanded and grid-connected modes.

DC/DC converters can be broadly categorized to isolated and non-isolated converters, depending on the presence of galvanic isolation between the converter input and output [38]. Non-isolated converters directly connect the input and output sides, making them simpler, more compact and cost-effective. They are suitable for applications where galvanic isolation is not necessary at the LV level. This is the case when a BESS is connected to a line-frequency transformer, because it provides isolation between the BESS and the MV grid. Isolated converters incorporate a high-frequency transformer to provide galvanic isolation between the converter input and output.

Isolated converters are essential in applications requiring electrical isolation for safety or functional reasons, as they protect the LV system from higher upstream voltages [31] and provide higher voltage gain [75] than non-isolated converters. The choice between them depends on several factors, including the application safety requirements, efficiency needs and cost constraints. Isolated converters are generally preferred for high-power applications or where electrical isolation is a critical safety requirement, in expense of increased size and hardware costs, as stated in the previous section. This means that non-isolated converter is generally the preferred option, if isolation or high voltage gain are not required. The need for isolated converter mainly arises in DC-coupled BESSs, because there are other devices connected to the DC link. Standalone BESSs are usually ungrounded (floating) and the line-frequency transformer provides a galvanic isolation between the BESS and the rest of the grid. If there are grounded devices connected to the same DC link as the batteries, the batteries and other devices have different ground potentials. This problem can be solved with galvanic isolation (isolated DC/DC converters) between the DC-sources with different ground potentials.

4. APPLICATIONS OF AC- AND DC-COUPLED BATTERY ENERGY STORAGE SYSTEMS

This chapter explores potential use cases and applications for both AC-coupled and DC-coupled BESSs, analyzing the specific advantages and reasons for considering these connections in various scenarios. Section 4.1 studies some of the common applications, most of which are technically also suitable for DC-coupled BESSs, while section 4.2 presents the applications that are possible solely for DC-coupled BESSs and distinguishes the main features that set these configurations apart from each other. An in-depth analysis of the technical and commercial implications of these features is presented in Chapter 5. Section 4.3 studies a few examples of governmental incentive programs, that promote the deployment of some of these applications.

4.1 Potential Applications for AC-Coupled Systems

As discussed in Chapter 2, among the most compelling applications for large-scale BESSs are the frequency services, which include frequency regulation and frequency response. Frequency regulation involves the TSO sending an automatic generation control signal (AGC) to the BESS. This signal directs the BESS to either charge or discharge, depending on whether there is an under-frequency or over-frequency condition in the grid [76]. In contrast, frequency response is an automatic function within the BESS control system, which activates charging or discharging based on the frequency detected from the grid. This distinction leads to variations in response speed between the two methods; the latter is an inherent feature of each individual BESS, enabling a faster response, while the former relies on grid operator interventions. The quicker response time of frequency response makes BESSs particularly well-suited for this application, as opposed to frequency regulation, which can be managed using slower and less expensive assets.

The characteristics of BESS frequency response are illustrated in Figure 4.1. When the line frequency significantly deviates from the target and crosses the threshold of the preset deadband, the BESS will start to either charge or discharge. The power at which this occurs is determined by the slope at which the BESS increases its charging/discharging power relative to the line frequency. If the frequency deviation increases further, the BESS will operate at its maximum power for as long as the abnormal frequency condition

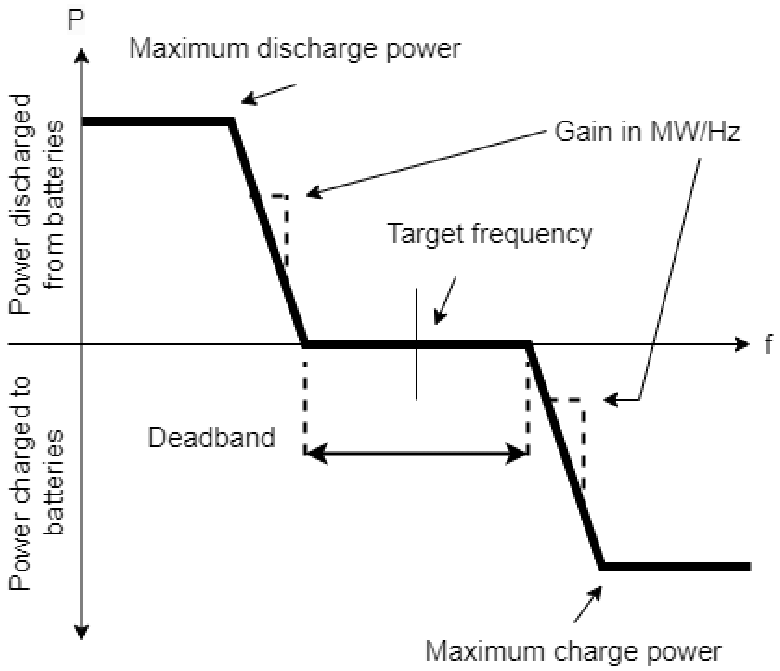

Figure 4.1. *BESS frequency response characteristics. Adapted from [76, 77].*

lasts or it has sufficient amount of energy left. This type of response capability, known as primary frequency response (PFR), allows the BESS to almost instantaneously either inject or absorb power for short durations to help recover the line frequency back to safe limits after over- or under-frequency situations [76]. In contrast, secondary and tertiary frequency responses involve longer activation periods and slower response rates, where power is only injected into the grid. These are generally better suited to the capabilities of slower and cheaper response assets.

As discussed in Chapter 3, the BESS PCS converters are able to independently control their active and reactive power output (four-quadrant control), within the converter current limits. This feature enables BESSs to provide voltage support through coordinated reactive power injection and absorption. This type of service is usually not the primary purpose of large standalone BESSs connected to MV or HV grid, as country-specific regulations do not usually offer direct benefits for it [23]. It might be more interesting for distribution system operators (DSOs) to install a BESS as an alternative for distribution grid investment deferrals, as they have to ensure a stable voltage throughout their grid [78]. Similar to the frequency control characteristics, an example of a BESS reactive power-voltage droop control algorithm to control voltage magnitude is illustrated Figure 4.2. The maximum reactive power depends on the converter power transfer limit [79].

Beyond the grid-supporting capabilities of BESSs discussed so far, there are also significant opportunities to integrate these systems with RESs, such as wind and solar power. This integration not only enhances the reliability and efficiency of renewable energy generation but also maximizes the utilization of BESSs in providing different types of ser-

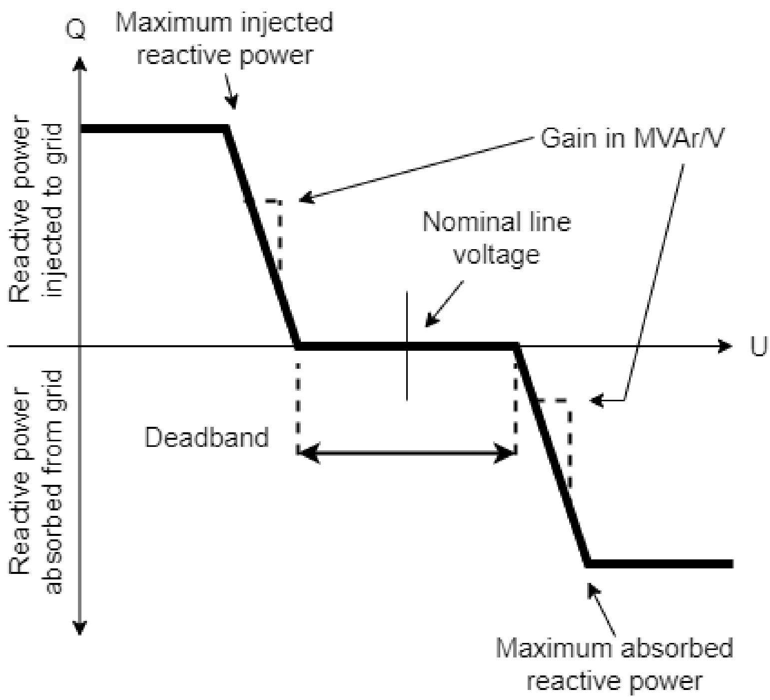

Figure 4.2. *Example of a BESS Q-U droop control. Adapted from [80].*

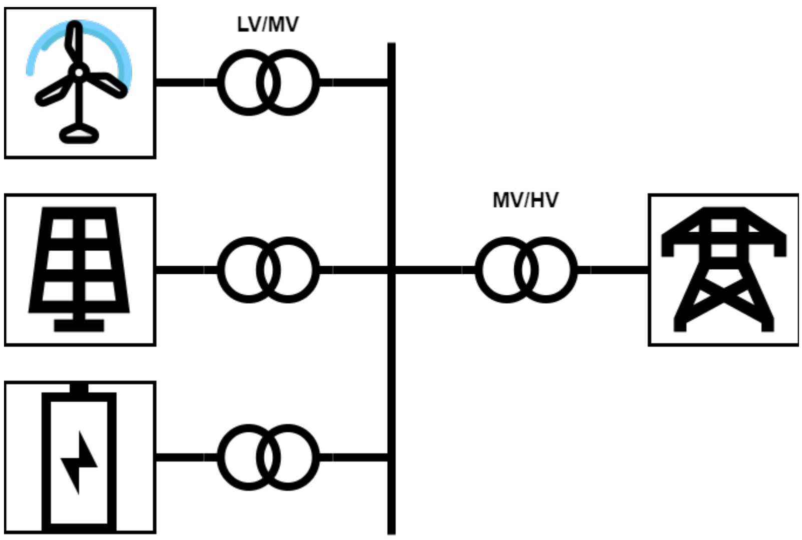

Figure 4.3. *Simple illustration of a HPP consisting of co-located wind, solar and BESS. Adapted from [82].*

vices. When a BESS has a shared grid connection with a RES plant, they are co-located. Simple illustration of a co-located HPP with wind power, PV power and an AC-coupled BESS is shown in Figure 4.3. In addition to before mentioned, the main applications of co-located AC-coupled BESSs are ramp rate control, capacity firming and time-shifting (energy-shifting) [76, 81].

Ramp rate refers to the rate at which the power of a generation unit can be increased or decreased within a specified time frame. It is a crucial parameter in electricity production management, particularly with RES, due to their natural variability and unpredictability.

Ramp rate limits are set by grid operators to ensure stability and reliable operation of the power grid. These limits dictate how quickly the output from a power generation unit can change over time [83]. Exceeding these ramp rate limits can lead to penalties for renewable energy producers or other actions like curtailing production, which can have financial and operational impacts, as the full potential capacity of the plant can not be utilized. Curtailment assists only in situations when the plant has a sudden surge of production, so there is a need for solutions that can provide ramp rate control also during sudden loss of production [84].

There are various ramp rate control methods for BESSs to manage power fluctuations of RESs. Some of these methods were studied in an article [85] by Martins et al. It discussed the moving average (MA) method, which smooths the output by averaging power values over a set period and the exponential moving average (EMA), which is similar to MA, but gives more weight to recent data for responsive adjustments. Low-pass filters (LPFs), both first and second-order, attenuate higher frequency fluctuations, smoothing rapid changes in power output and potentially extending battery life by reducing energy exchanges. Gradient control adjusts the charging or discharging rate of the battery based on the rate of change of power output, maintaining a steady power ramp without relying on previous output levels, helping to adhere to grid stability requirements. In an article [83] by Tadie et al., the ramp rate control method employed involved a hybrid optimization strategy that combined dynamic smoothing techniques and particle swarm optimization (PSO). This approach was used to optimally size and control the BESS to enhance ramp rate control and frequency regulation performance in wind energy systems.

Other possible issues caused by output power variability of RES are related to voltage stability, frequency fluctuations and even power outages [86]. These can be addressed to some extent with proper ramp rate control, but other measures are also needed to level the output power over a longer period of time. An article [87] by Zareifard and Savkin proposed a method for wind power output smoothing, using a model predictive control (MPC) strategy with co-located wind power plant and BESS. Their approach utilized a nonlinear battery model and dynamic programming algorithm to optimize battery charging and discharging processes. The system dynamically adjusted to the wind power output and electricity price forecasts to control the power delivered to the grid.

Zhang et al. proposed a state exchange strategy in [88], which was utilized to manage the operation of a BESS integrated with a wind power plant to track generation schedules accurately. The BESS was divided to two independently controlled parts, which enabled each part to respond to different output power deviations more efficiently. The strategies outlined in the article were asynchronous and simultaneous state exchanging. With the asynchronous strategy, if one part of the BESS reaches its full state (either fully charged or discharged), it switches states (from charging to discharging or vice versa) independently of the other part. This strategy prevents both parts from being in the same state (both charging or both discharging) simultaneously. In the simultaneous state exchange strategy, both parts exchange states together, regardless of their individual SoCs. This ensures that one part is always charging while the other is discharging, allowing for continuous adjustment to the power supply and more stable generation schedule tracking, as both negative and positive power deviations can compensated without changing the states of the different parts of the BESS. On the contrary, it increases operational costs by causing under-utilization of that part of the BESS which state is changed only according to the SoC of the other part, as the charging or discharging cycles will not always be fully completed.

The essence of capacity firming is the same as output power smoothing, but with more focus on enabling the HPP to provide firm hourly energy production, avoiding penalties issued for differences between contracted and produced amount of electrical energy [81]. There are several capacity firming methods presented in the literature. [89] integrated short-term wind power forecast and energy price forecast with dynamic programming (DP) tool and used optimal power dispatch strategy to adjust the amount of power either generated by wind turbines or released from the batteries of a HPP consisting of wind power and BESS. In [90], capacity firming was achieved with a DP-based optimization algorithm that managed a BESS to stabilize the output of a PV plant based on real-time weather conditions and forecasts. Other methods are also described in [91, 92].

Electrical energy time-shifting is designed to redirect surplus energy production to periods of low production and higher demand [81]. However, RESs alone cannot achieve this due to their variability, which complicates coordinated production shifts. BESSs are crucial for enabling time-shifting of wind and PV energy production, as they can be charged when production is high and demand is lower, and discharged later when demand exceeds RES output. This is particularly relevant for PV and BESS HPPs, where PV production typically decreases while demand rises during evening hours.

In [93], time-shifting was evaluated with a 10 MW wind power park and a 1 MW/2 MWh BESS. The system was designed to time-shift wind energy to peak load periods and respond to AGC signals. The study concluded that limiting charging to periods when wind power was available, reduced the extent of time-shifting and AGC services provided. [91] focused on designing control algorithms and optimization routine for a HPP, consisting of PV and BESS, which were meant to enable PV capacity firming and time-shifting. The study utilized MA method with variable intervals to predict peak-load magnitude and time to schedule BESS discharging.

The presented methods for ramp rate control, output power smoothing, capacity firming and time-shifting are meant to guide the reader towards this subject. These applications and methods are merely a scratch to the surface, as the research on this subject is highly mature. In addition to before mentioned, typical applications presented in literature are

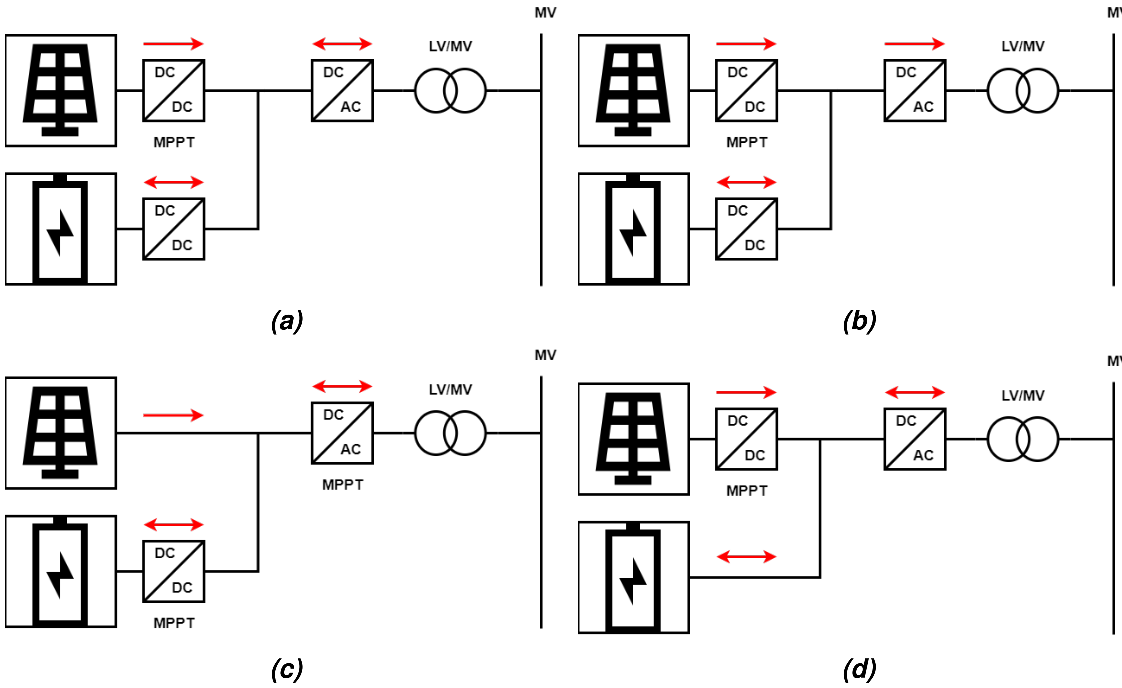

Figure 4.4. ***(a)*** *Loosely DC-coupled,* ***(b)*** *tightly DC-coupled,* ***(c)****, BESS-side DC-coupled and* ***(d)*** *PV-side (reverse) DC-coupled HPPs. Red arrows illustrate the possible power flow directions and "MPPT" marks the converter that can be used for maximum power point tracking. Adapted from [1, 23, 73, 95]*

also transmission & distribution upgrade deferral and congestion relief, energy arbitrage, harmonics suppression, peak shaving, black start and load following, among many others [35, 94].

4.2 Potential Applications for DC-Coupled Systems

The integration of a BESS with a PV plant to form a DC-coupled HPP can be achieved through various configurations, each offering distinct operational characteristics. In loosely coupled configuration (Figure 4.4a), both the batteries and the PV array are connected to a common DC-link via individual DC/DC converters. This setup includes a bidirectional DC/AC converter that enables power flow from PV array to grid and batteries, and from batteries to grid and vice versa. The primary advantages of this configuration are bidirectional power flow between the batteries and the grid, and controllable DC-link voltage, which enables MPPT (Section 3.3). These are achieved with an expense of needing individual DC/DC converters for both the batteries and the PV array. Tightly coupled configuration (Figure 4.4b) resembles the loosely coupled setup, with the significant difference being the DC/AC converter, which is not bidirectional. This limitation means that power can not flow from the grid to the HPP. While this simplifies the system design and potentially reduces costs, it restricts operational flexibility, as BESS can only be charged by the PV array.

In BESS-side DC-coupled configuration (Figure 4.4c), the PV array is directly connected to the DC-link without a DC/DC converter, whereas the batteries still have a converter. This approach reduces the number of components involved, lowering capital costs and losses associated with conversion processes. In this configuration, MPPT can be done by controlling the output voltage of the BESS DC/DC converter or controlling the output current of the common DC/AC converter. Conversely, the PV-side DC-coupled, also called reverse DC-coupled, configuration (Figure 4.4d) features the batteries directly connected to the DC-link, eliminating the DC/DC converter between the batteries and the DC-link. The direct connection poses challenges in managing the DC-link voltage (Section 3.3).

The differences in the power train of AC- and DC-coupled BESSs leads to differences in their respective efficiencies. With DC-coupled HPPs combining PV and BESS, when the batteries are charged from PV, the efficiency is slightly higher than that of AC-coupled systems due to the direct connection in the DC link and reduced conversion steps [3]. DC coupling allows for more efficient capture and storage of PV energy, minimizing losses that occur during the conversion from DC to AC and back to DC in AC-coupled systems. Because the DC-coupled configurations enable the battery to be charged directly from the PV without going through the AC conversion, it is also possible for the DC-coupled systems to fully capture the generated energy from the PVs throughout the day without incurring clipping losses (also called overload losses) due to inverter capacity limitations [96].

While the applications of AC-coupled BESSs co-located with RESs, discussed in Section 4.1, are also possible for DC-coupled HPPs, clipping loss minimization is a notable application that is only possible for DC-coupled BESSs. The captured energy, that would be clipped without a DC-coupled BESS, can also be discharged from the batteries to the grid when energy production from PV is lower and demand is high, combining clipping loss minimization with time-shifting. This enables efficient stacking of various applications, utilizing the HPP assets to their full potential.

Inverter loading ratio (ILR) is the ratio of DC power capacity (from PV modules) to AC power capacity (from the plant DC/AC converter), expressed in percentage. According to Deschamps and Rüther [97], the optimal ILR for a PV plant is identified by evaluating the balance between the marginal energy gain from higher DC capacities and the associated marginal cost increase. They also specified that higher ILRs lead to increased energy capture but also to higher clipping losses, which must be balanced for optimal system performance. When a PV plant is integrated with a DC-coupled BESS, the ILR can be increased without increasing the clipping losses, because the batteries can be charged when the generation exceeds the conversion capacity of the DC/AC converter, given that the BESS capacity is sufficient. This means that the conversion capacity can be reduced, or the number of PV panels increased, compared to a PV plant without a BESS.

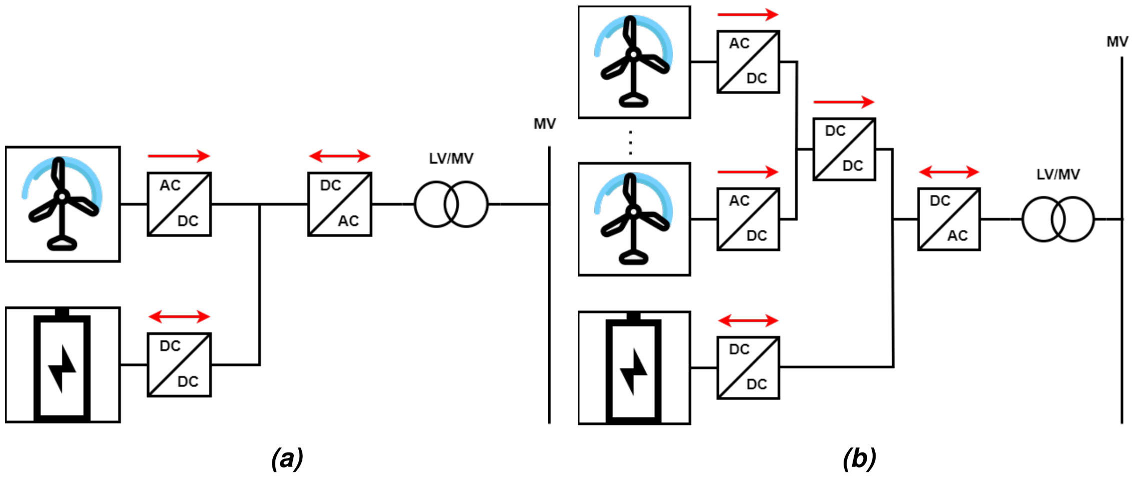

Figure 4.5. ***(a)*** *WTG-side DC-coupled* ***(b)*** *and DC collector DC-coupled HPPs. Adapted from [98, 100]*

Figure 4.5a shows a DC-coupled BESS integrated to a DC link of a type 4 variable speed wind turbine generator (WTG). In this configuration, proposed in [98, 99], the DC link voltage control is done by the BESS DC/DC converter, instead of by the grid-side DC/AC converter, as discussed in Section 3.3. In Figure 4.5b, the BESS is connected to the wind power plant DC collector. A simulation model with this configuration was presented in [100], where the batteries were connected to the DC collector through a flyback DC/DC converter to control the DC-link voltage and the wind power plant output voltage and power at PCC (point of common coupling). Out of these configurations, the WTG-side DC-coupled has clear benefits due to the lower number of conversion steps. Both of these configurations enable similar applications as discussed in Section 4.1, with an added capability of clipping loss minimization. The amount of literature found on the DC-coupled HPPs consisting of WTGs and BESSs is notably smaller and more focused in microgrid applications, in comparison to DC-coupled PV and BESS, which indicates that the level of interest and technological maturity is higher with the latter systems. A brief overview on the literature of DC-coupled BESS is presented in Appendix C, Table C.1.

4.3 Co-location Incentives

In recent years, governing bodies have played an important role in the acceleration of BESS installations through targeted incentives, particularly those designed to be integrated with a RES. These policy-driven incentives are not merely financial catalysts but strategic mechanisms that guide the development and integration of BESSs with RESs. The structured incentives are often crafted to demand that storage assets are co-located and, in case of BESS, primarily charged using the co-located RES rather than charged from the grid. This approach encourages the deployment of BESS configurations that optimize them especially as parts of HPPs. These incentives act as drivers for ambitious energy policy objectives, not only stimulating technological innovation but also scaling up the adoption of BESSs, making these systems more viable and attractive for wider implementation. It is important to understand the steering role of these incentives for certain BESS applications, as they can increase revenue from applications that would otherwise not be profitable. This section presents few examples of these types of incentives from different countries.

Federal ITC (investment tax credit) in USA is a tax return based on federal income tax benefits that can be obtained from tax equity investments. These tax returns were previously obtained for new HPPs, where the storage assets were charged directly from PV for at least 70 % of hours in the year [101, 102]. However, from deployment of Inflation Reduction Act (IRA) in January 2023, ITC has been available also for standalone ESSs [103]. This increased the economic feasibility of standalone BESSs in the US, as ITC can now be utilized to achieve reduction in CAPEX (capital expenditures) of the new HPP or standalone BESS and the batteries can be charged freely from the grid, opposed to being forced to co-locate with PV and tied to charge only from PV for 70 % of the time. Due to the differences in regulation between the states, there are also many different incentives obtainable at state-level, some of which have been summarized in an article [104] by Filho et al.

German Innovation Tender is a strategic initiative by the Bundesnetzagentur, Germany's federal network agency, aimed at promoting the integration of PV with other RESs. This tender is granted only for co-located PV HPPs, with majority of the winning projects including storage assets. This has also sparked criticism towards it, as it excludes standalone ESSs [105, 106]. However, the results from previous auction rounds demonstrate a significant interest in such combined projects [107]. For instance, one of the auctions closed with a total volume of bids substantially exceeding the available capacity, indicating strong competitive interest and the sectors momentum towards renewable integration with ESSs. The awarded projects receive financial support in the form of market premiums, which are added to the revenues the projects earn from selling electricity, creating an incentive to produce solar energy at lower costs and higher efficiency [108].

Spanish Institution for the diversification and energy savings (IDAE in Spanish) has launched strategic projects for economic recovery and transformation (PERTE), one of them being a project for renewable energy, renewable hydrogen and storage (ERHA) [109]. PERTE ERHA awards tenders for co-located ESSs and RESs, with 880 MW / 1.809 MWh awarded in the first tender [110]. The tenders were awarded based on economic viability, degree of innovation or environmental protection, scalability and market potential, project viability and externalities [111]. PERTE ERHA is an example of the Spanish government's efforts to promote the transition of energy production to RES and the desire to solve the challenges brought by the transition. Such projects significantly promote the installation of BESSs to support renewable energy production. An example of the tenders published in this project is the call for aid from the Spanish Ministry for the ecological transition and the demographic challenge (MITECO) for HPPs, which awards €150 million for ESSs integrated with new or existing RES plants [112].

In December 2023, European Commission approved a €17.7 billion Italian aid scheme under EU State aid rules to support the development of centralized electricity storage systems [113]. This initiative alignes with the European Green Deal and the 'Fit for 55' package, aiming to facilitate the integration of RESs into Italys power grid. The scheme assists in building storage facilities with a total capacity exceeding 9 GW/71 GWh and will run until December 31, 2033. The primary purpose of the aid is to balance the mismatch between renewable energy production and high electricity demand times by time-shifting. Funding is provided through annual payments covering both investment and operational costs of ESS projects. Beneficiaries will be selected via a competitive, transparent and non-discriminatory bidding process based on the lowest aid amount requested per offered capacity. Eligible technologies currently include lithium-ion BESSs and pumped hydro storages, with the list updated biennially to incorporate technological advancements. The scheme targets storage assets with long duration and it also includes the creation of a "time-shifting trading platform" to optimize the use of storage assets, allowing renewable energy producers to shift their electricity output according to demand fluctuations. The scheme has been deemed necessary, appropriate and proportionate by the European Commission, ensuring that the benefits outweigh potential competition distortions within the EU.

These incentives are primarily deployed to enhance energy security and reliability, facilitating a smoother transition from fossil fuels to renewable energy. BESSs help mitigate the intermittency of renewable sources, ensuring a more reliable and continuous energy supply. These policies serve as economic stimuli that reduce costs and encourage technological innovation within the energy sector, while adapting regulatory frameworks to support new technologies and address both environmental and economic externalities by promoting job creation and energy independence. Strategically, these incentives reflect tailored responses to national and regional energy challenges, emphasizing the importance of long-duration storage to balance supply and demand as the proportion of renewables in the grid increases. They also demonstrate a strategic directive towards promoting specific types of energy storage technologies, particularly long-duration storages. Since the incentives are mainly directed at ESSs integrated with RESs, this could also increase the deployment of DC-coupled BESSs, as they are designed and used mainly for these purposes. As different nations employ these varied strategic initiatives — from tax incentives in the USA to innovation tenders in Germany and large-scale funding in Italy — each approach reflects a unique response to the specific energy challenges and policy landscapes of these countries. These incentives not only foster technological innovation but also align with broader environmental goals, highlighting the role of government policy in shaping the future of energy infrastructure as the world continues to face urgent energy and environmental challenges.

5. COMPARATIVE ANALYSIS OF SOLUTIONS

This chapter conducts a comparative analysis of the benefits and challenges presented by AC-coupled and DC-coupled BESSs. It also showcases real-world technical solutions and operational systems, providing examples that illustrate how BESSs are implemented in practice.

5.1 Economic Considerations

The key difference of AC- and DC-coupled systems is their compatibility with existing infrastructures. DC-coupled BESSs, by connecting directly to a common DC link, enable efficient integration with other DC-sources or -loads. In contrast, AC-coupled systems offer adaptability, enabling easier integration into existing electrical infrastructure and providing a versatile solution for retrofitting without significant modifications to existing systems.

A study [114] by Bahloul et al. focused into the economic aspects of deploying a tightly DC-coupled BESS for clipping loss minimization in a 5 MW PV plant. Clipping loss minimization and energy shifting were discussed in Chapter 4. By examining a BESS with various battery technologies in a real-life case study of a PV power plant under construction in Ireland, the study assessed the economic viability of such systems. Despite the potential technical benefits of BESS in reducing clipping losses and enhancing PV power plant efficiency, the findings suggested that the economic viability of deploying a 1 MW / 1 MWh ESS under prevailing cost scenarios at the time and with the specific project parameters was not favorable. The economic analysis took into account the cost per cycle, annual operation and maintenance costs and the potential revenue from BESS, finding that none of the evaluated battery technologies offered a positive return on investment for solely clipping loss minimization purposes.

According to Schleifer et al. [115], the increase of PV-plus-BESS plant ILRs will be economically more viable in the future. Higher ILRs can be economically advantageous, particularly in locations with lower solar insolation, as they allow for more energy generation per unit of inverter capacity, despite potential losses from energy clipping and curtailment. The future viability of higher ILRs also depends on the rates of cost reduction in PV technologies versus the decreasing value and increased curtailment as PV deployment expands. Additionally, higher ILRs are more beneficial as the solar generation share increases, suggesting that optimal system configurations with higher ILRs may become more common as technology costs decrease and grid conditions evolve.

Regardless of the increased energy harvesting potential of DC-coupled PV-plus-BESS HPPs, the common DC/AC converter can be a limiting factor for the plant power dispatch despite having batteries connected to the common DC-link. As stated before, these converters have a maximum power capacity they can convert at any given time. During moments of peak solar production, the PV system can generate a substantial amount of power, potentially maxing out the converter capacity. In such scenarios, the capacity of the BESS cannot be utilized because the DC/AC converter is already operating at full capacity with the power from the PV panels. Essentially, the battery is sidelined because the bottleneck created by the converter capacity prevents additional power from the batteries being fed into the grid and therefore, utilized in different markets. This limitation impacts the operational flexibility and economic performance of the HPP. During peak demand periods, when the grid could benefit from the additional power of the battery, the plant is unable to respond due to the constrained converter capacity [3]. This inability to fully exploit all of the plant assets can lead to missed opportunities for revenue generation.

On the other hand, AC-coupled PV-plus-BESS HPPs avoid this bottleneck by the nature of their configuration. As the PV arrays and the BESS are connected to the grid through their own dedicated DC/AC converters, their design allows both the PV system and the battery to operate independently and simultaneously. Even if the PV panels are producing at full converter capacity, the battery can still charge or discharge as needed, depending on the demand and market utilization, without being restricted by the capacity of shared converters. This ensures that the capacity of all assets can be utilized, effectively leveraging the combined resources of solar generation and batteries even during peak production periods.

A study [3] by DiOrio et al. indicated that large-scale PV-plus-BESS HPPs are economically viable under certain market conditions, highlighting the importance of system configuration on flexibility and performance. It demonstrated that DC-coupled systems can slightly increase the internal rate of return (IRR) or benefit/cost ratio by about 2 percent compared to AC-coupled systems, mainly due to reduced clipping and the ability to capture otherwise clipped energy. The study was conducted in a way that the batteries can be charged either from both the grid and the PV or just from PV. There were notable differences in Net Present Value (NPV), IRR and benefit/cost ratio (BCR) of both configurations depending on if they were charged from PV only or from the grid and PV. The key results are summarized in Table 5.1.

The results from Table 5.1 demonstrate the effect of ITC on the economic feasibility of HPPs built in the United States. The scenario where the BESSs were charged only from PV, included 30 % ITC in the calculations, while the other scenario did not consider ITC

Table 5.1. *Case study results from [3].*

	Charged from PV only		Charged from PV and grid	
	DC-coupled BESS + PV	AC-coupled BESS + PV	DC-coupled BESS + PV	AC-coupled BESS + PV
NPV (M$)	8.33	7.76	-30.5	-31.0
IRR (%)	8.72	8.56	1.52	1.51
BCR	1.08	1.06	0.83	0.83

at all. The excludement of ITC brought the NPV, IRR and BCR of DC- and AC-coupled PV-plus-BESS systems significantly closer to each other. In this study, the advantage of DC-coupled system was essentially the eligibility for ITC in the case when both systems are charged only from PV. Even though the ITC improved the end results for AC-coupled BESS also, it did not benefit from it as much, as it is not designed to be charged only from PV. The excludement of ITC and allowing grid charging for both configurations in the second scenario leveled the results significantly.

As discussed previosly, in DC-coupled PV-plus-BESS HPPs, the BESS units are connected directly to the DC link between the PV array and the DC/AC converter. Large PV plants can contain hundreds of these arrays, which are all connected through their own DC/AC converters to MV transformers, from where they are connected to a single HV transformer that connects the whole plant to the grid. This configuration requires the dispersal of battery modules across various locations within the power plant premises, as the batteries must be located near the PV arrays, where their DC links and converters are also located. It leads to extended distances between individual battery modules, amplifying the complexity and costs associated with operation and maintenance (O&M) activities, which is emphasized especially in larger installations. Service personnel are required to physically access each battery module for routine inspections, maintenance or repairs. This decentralization increases the operational expenses, as it requires more workforce or time and transportation resources. Figure 5.1a shows one unit of batteries, DC- and AC-cabinets, battery and solar converters and a transformer. Large DC-coupled HPPs contain multiple units like these distributed along the PV plant field.

AC-coupled configurations, by their design, usually centralize the BESS at a single location, typically close to the PV plant substation [118] (Figure 5.1b). Centralized nature of the BESS in AC-coupled systems streamlines maintenance and operational processes. Service personnel can conduct inspections, maintenance and repairs more efficiently, without the need to move long distances to different locations within the plant. This not only lowers the operational expenses by minimizing the logistical demands on manpower and transportation but also enhances the responsiveness to maintenance needs, ensuring higher reliability and operational readiness of the storage system. If a DC-coupled

(a) *(b)*

Figure 5.1. ***(a)*** *DC-coupled and* ***(b)*** *AC-coupled PV and BESS HPPs. Reprinted from [116, 117].*

BESS would be constructed in a centralized manner, it would result in long cable runs between the BESS and the PV converters, increasing the losses, cabling costs and complexity of the system.

Some of the other costs that differ between AC-coupled and DC-coupled configurations with PV-plus-BESS HPPs include the hardware costs caused by different number and types of converters, electrical balance of system (BOS) costs from wiring of those converters, installation labor costs, engineering, procurement and construction (EPC) overhead costs and EPC/developer profit [119]. Electrical BOS costs and EPC/developer profit are generally higher with AC-coupled configurations because of greater amount of cabling needed for converters and higher total EPC costs. The difference of these costs between AC- and DC-coupled configurations is marginal, because the DC-coupled system requires additional DC/DC converters. The hardware and EPC costs are also influenced by the required enclosures, heating, ventilation and air conditioning (HVAC) systems and fire suppression systems for battery racks. As DC-coupled BESSs have smaller battery racks spread around the PV plant field, the number of these components is higher than with centralized AC-coupled BESSs, where the battery racks can be larger and inside larger individual enclosures. Installation labor and consequently EPC overhead costs are generally higher with DC-coupled configurations, due to the additional DC/DC converters and requirement for more skilled labor and more labor hours needed for DC work.

Regulatory frameworks can also significantly influence the economic differences between AC-coupled and DC-coupled configurations. The costs and delays associated with establishing new grid connections can be prohibitive, affecting the decision between AC- and DC-coupling. In some countries, the process for establishing a new grid connection can take years, depending on the voltage level. In a survey [120] conducted by SolarPower Europe in 2023, it was discovered that the average lead time for a new grid connection of a utility-scale PV plant, from permitting to final commissioning test, was around 4 years and up to 8 years at its highest in Europe. DC-coupled BESSs have an advantage here, as they could be installed using the same grid connection as an existing PV power plant, avoiding the need for an additional connection, especially if charged only from PV as the connection size does not need to be altered. This reduces costs and speeds up the deployment, making it an attractive option for projects limited by availability and costs of a new grid connection.

While BESSs present a technically feasible solution to enhance the efficiency of PV power plants, the economic viability is highly dependent on the specific project parameters, the cost of storage technologies and the operational cycle. Bahloul et al. [114] highlighted the need for further research into optimizing the sizing of BESS and the impact of technological advancements and cost reductions in energy storage on the economic outcomes of such systems. Different methods for evaluating the economic feasibility of BESSs will be presented briefly in Chapter 6.

5.2 Technical Considerations

Lo Franco et al. compared different PV-plus-BESS plant configurations in their study [1], with specific focus on the plant efficiency. They conducted a MATLAB simulation of a HPP consisting of a 288 MWp PV plant and a 92.2 MW/275.2 MWh BESS that is used for PFR and time shifting. The study considered three different configurations for the PCS; AC-coupled, DC-coupled on BESS-side and DC-coupled on PV-side (reverse DC-coupled). In the AC-coupled HPP configuration, the batteries and PV arrays were connected through their own individual DC/AC converters and transformers to a common MV bus, making the total number of converters 640 and transformers 640. In both DC-coupled configurations, the PV arrays and battery modules were distributed behind 320 common DC/AC converters that were connected to MV through 80 multi-winding transformers with four secondary windings. In the BESS-side DC-coupled configuration, the batteries were connected to the common DC link between the PV array and DC/AC converter through a DC/DC converter. In the PV-side DC-coupled configuration, the batteries were directly connected to the common DC link and the PV array was connected to the DC/AC converter through a DC/DC converter.

Transformer efficiencies were also included in the calculations for all configurations, in addition to the PCSs. The calculations were made in a way that the batteries were charged only from the PV arrays. The end results of the case study showed that the BESS-side DC-coupled configuration was the most efficient configuration with an average annual efficiency of 97.02 %. The second best was AC-coupled (96.86 %) and the worst was PV-side DC-coupled (96.34 %). The study did not consider the efficiencies of power electronic devices and transformers as a function of power flow, but as fixed values. It also excluded the losses of the batteries and PV arrays, which impacted the overall efficiency results, but did not affect the power train efficiency comparison, because the power flows were the same in all configurations. The choice to charge the batteries only from PV affected the results, as AC-coupled BESSs are mainly meant to be charged from the grid. If grid charging would have been allowed, the results could have been significantly different, as the number of power conversions during charging would have been decreased significantly.

In PV power plants, the natural variability of solar irradiance causes fluctuations in the terminal voltage of the PV panel, leading to variable voltage in the DC link. As the irradiance changes over time, the magnitude of the DC link voltage needs to be adjusted and kept steady to be able to extract the maximum power available from the PV panels. This enables MPPT in PV power plants, as discussed in Section 3.3 and 4.2. When a PV plant has batteries connected to the DC links of the PV arrays, the MPPT execution strategy requires careful designing, as the DC link voltage is also affected by the charging and discharging of the batteries. Several studies have addressed this issue by designing and simulating different control schemes to enable MPPT and DC link voltage control. Some of them have proposed loosely coupled configurations with dedicated DC/DC converters for both batteries and PV arrays to enable independent MPPT and battery charge control [121, 122], while some have proposed a BESS-side DC-coupled configuration where the BESS DC/DC converter handles the charge control and MPPT alone and DC-link voltage control in co-operation with the DC/AC converter [95].

Regardless of the configuration, the DC link voltage must be kept within the operating limits of the power electronics devices, as over-voltage can damage the power electronics and under-voltage affects the operation of the converter circuits [121]. This can be done by controlling the BESS charging and discharging, depending on the DC link voltage, so that the voltage is kept at the maximum power point of the PV array. This allows a steady operation of the PV plant and the most efficient energy production, but the biggest disadvantage of this control scheme is that the operational flexibility of the BESS is reduced, as it cannot be used for other applications when the PV panels are operational. As a result, there may be instances where the BESS cannot charge or discharge optimally according to economic or other operational considerations but must instead respond primarily to the voltage demands dictated by the PV system operating point. This dependency on solar output conditions may cause the BESS to cycle more frequently, which could shorten its lifespan and diminish its performance.

AC-coupled BESSs address these operational flexibility issues seen in DC-coupled systems through their different power train. As the PV system and the BESS are connected to the grid through separate DC/AC converters, each system is able to operate independently. Each can use its own optimized control strategy for its specific tasks. Since the BESS is connected to the AC side of the PV system, it can be operated more flexibly. It can be charged from the grid at all times and discharge power to the grid independently of the DC link voltage of the PV system. This means it can be used for a broader range of applications, without being directly tied on supporting PV system operation. Battery charging and discharging can also be scheduled based on optimal battery health management practices, enhancing the overall lifespan and efficiency of the BESS.

The topics discussed in this chapter effectively highlight the distinctive benefits and challenges associated with AC-coupled and DC-coupled BESSs, which are discussed within the context of PV power plants, since DC-coupled BESSs are mainly integrated with them. Through comparative analysis, it is clear that while DC-coupled systems can enhance efficiency by directly integrating with PV arrays, they also face limitations in flexibility due to shared converter constraints. In contrast, AC-coupled systems, with their separate converters, offer greater flexibility and operational independence, which can be crucial, especially when utilized in different applications.

5.3 Existing Implementations

Dynapower Company, an energy storage and power conversion manufacturer based in the USA, offers a range of converters for both AC-coupled and DC-coupled BESSs. Their product portfolio includes 500 kW and 1000 kW bidirectional DC/DC converters designed to integrate DC-coupled BESS with PV power plants [123, 124]. Additionally, they provide DC/AC converters for AC-coupled BESSs, with capacities ranging from 1250 kW to 3000 kW [125, 126]. These DC/DC converters are intended for connection to the DC combiners of the central inverters of PV plant.

Another similar product is offered by Ingeteam, which manufactures and sells 1700 kW bidirectional DC/DC converters for BESSs [127]. Ingeteam also has DC/AC converters directed specifically for AC-coupled BESS, with a variety of ratings [128]. Both manufacturers offer productized MV kits built from their DC/AC converters, which include the needed amount of converters and a MV transformer. The most noticeable differences between the DC/DC converters of these manufacturers are the power ratings and that the Ingeteam converter allows an optional PV input directly into the converter, as illustrated in Figure 5.2. The DC/DC converters from both manufacturers are not galvanically isolated, which means that the batteries and PV panels must have a common grounding or the PV panels have to be galvanically isolated from the rest of the system, as discussed in Section 3.4.

Some of the biggest companies that offer AC- and DC-coupled BESSs include Wärtsilä, Fluence, Sungrow and GE Vernova. Wärtsilä delivered a 40 MW / 80 MWh DC-coupled BESS to Georgia, USA in 2021 using their GridSolv Quantum BESS [117] (seen in Figure 5.1a). Their system consists of liquid-cooled battery racks delivered in enclosure(s), with outdoor-rated AC- and DC-collector cabinets [130], to be integrated with third-party converters. Because they do not use their own converters, their scope of the system can be flexibly installed to both AC- and DC-coupled configurations. Interestingly, they state that their "Renewables +" solution that combines BESS with RES allows AC- and

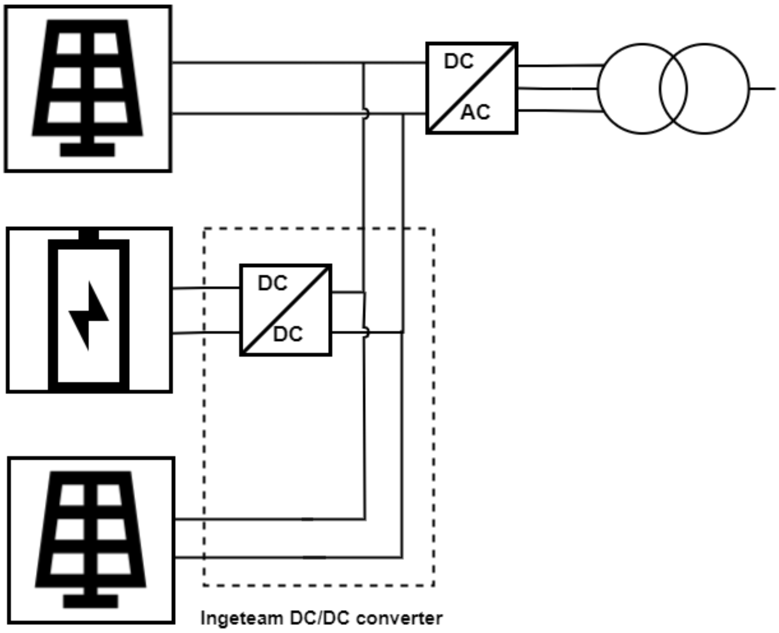

Figure 5.2. *Ingeteam DC/DC converter with PV input. Adapted from [129].*

DC-coupling, but the DC-coupled BESS is charged only from PV (tightly-coupled BESS) [131]. This could be an intentional design choice, because PV charging allows the utilization of ITC in projects based in USA, as discussed in Section 4.3.

Fluence has five different types of productized BESSs [132]. Four of them are for AC-coupled configurations and one is for a DC-coupled configuration. Their DC-coupled BESS solution is specifically designed for PV integration and is made of modular outdoor rated battery rack cabinets, 500 kW DC/DC converters and PV inverters [133]. Fluence has delivered at least one 112 MW / 560 MWh DC-coupled BESS to a PV power plant in Chile, which started operation in 2023 [134, 135]. Sungrow is developing the largest DC-coupled BESS (55 MW / 220 MWh) in Australia, scheduled to begin operation in 2024 [136]. It is built with their PowerTitan Series BESS, which can be connected in an AC-coupled or DC-coupled configuration, as it has integrated bidirectional DC/DC converters [137]. Sungrow has a large number of published DC-coupled projects, ranging from 1 MW / 1.1 MWh to 130 MW / 638 MWh [138, 139]. GE Vernova's product portfolio includes battery container units and converters that can be installed in both AC- and DC-coupled configurations [140]. In addition to their numerous AC-coupled projects, they have also delivered several DC-coupled BESSs [141, 142].

Despite the growing demand for DC-coupled BESSs, AC-coupled systems remain prevalent, as evidenced by the offerings from the companies presented in this section. These systems are versatile and easier to retrofit into existing infrastructure, making them attractive for a broader range of applications. The presence of productized medium-voltage kits, integrating DC/AC converters with transformers, indicates a market demand for solutions that simplify deployment. The examples in this section reflect the increasing trend of integrating BESS with PV. The BESS market shows a strong inclination towards modular and scalable solutions, tailored to various project requirements. The focus on both AC- and DC-coupled systems suggests that the demand for AC- and DC-coupling is beginning to balance more, with DC-coupled systems gaining traction, particularly in maximizing PV integration benefits.

6. EXAMPLE CASE STUDY: AC VERSUS DC CONNECTION

This section presents a case study calculation that compares the differences of AC- and DC-coupling in a HPP comprised of a BESS and a PV power plant. It offers a comparative evaluation of both options and demonstrates the use of a calculation model incorporating technical and commercial aspects.

6.1 Selection and Description of the Example Case

Different methods for evaluating the economic viablity of BESSs were briefly mentioned in Section 5.1, where the studied article had used NPV, IRR and BCR. The IRR method calculates the rate of return at which an investment breaks even, taking into account the time value of money [143]. If the IRR exceeds the required rate of return, the investment is considered profitable. It expresses in percentage how much return the investment generates on the capital invested.

The NPV method discounts all cash flows to a single point in time, typically the start of the investment. If the total present value of all cash flows is positive, the investment is profitable. The NPV method provides a monetary value of how much value the investment adds to the company, differing from the IRR method by presenting results in monetary terms rather than percentages [143]. In the NPV method, the net cash flows for each period — being the difference between cash inflows and outflows — are summed up and weighted by the time value of money. The BCR simply divides the overall cash inflows with the cash outflows, that are both weighted by the time value of money, for the project life-cycle.

In addition to these, levelized cost of electricity (LCOE) is also frequently used in the literature. The LCOE calculates the total life-cycle costs of a power-generating technology per unit of electricity, by spreading the net present value of costs over its generation throughout the lifespan of the system [144]. Key factors in determining LCOE for PV and BESS include capital, operations and maintenance costs and the utilization rate of the plant, representing the cost per MWh of constructing and operating a generating facility over its projected operational cycle. LCOE is used widely to compare the cost of energy between different technologies. It does not take into account any possible revenues, which makes it useful for simple preliminary studies to compare different solutions from the cost perspective.

When a BESS is integrated to a PV plant, the energy produced with PV panels can be fed to the grid or alternatively to the batteries. This enables the applications for co-located HPPs presented in Chapter 4. The energy that is charged from PV to BESS can be fed to the grid to increase the production of the PV plant during moments of low solar irradiance, which means that momentary energy production variation can be decreased and energy can be produced during mornings and evenings, when demand is high and PV production low. The amount of losses from transferring the energy from PV to batteries is different, depending on whether the BESS is AC-coupled or DC-coupled. This impacts the overall production of the HPP, which is directly affecting the revenue obtained from sold energy. The amount of energy produced by the DC-coupled system is also affected by the shared converter, which can limit the power dispatch of the BESS, as discussed in Section 5.2. The BESS is always a component that causes additional losses, compared to feeding the energy directly to the grid, so the value that it brings to the system is based on the ability to deliver the energy at a chosen time. The effects that these configuration methods have on the energy production and overall costs can be evaluated with LCOE, which is used in this chapter to compare the effects of AC- and DC-coupling in a PV-plus-BESS HPP. To enable the comparison using LCOE, this calculation assumes that the only source of revenue for both configurations is energy sale.

The chosen system for this case study is a 130 MW PV power plant (with 100 MW PV inverter in AC-coupled configuration) with a 60 MW / 240 MWh BESS. In the DC-coupled configuration, the PV power plant and BESS are connected at the DC-side of their common 100 MW DC/AC converter interfacing the grid. The BESS has its own DC/DC converter and the PV plant is directly connected without a DC/DC converter, same way as seen in Figure 4.4c. The DC-coupled system is sized based on ILR of 1.3, which was

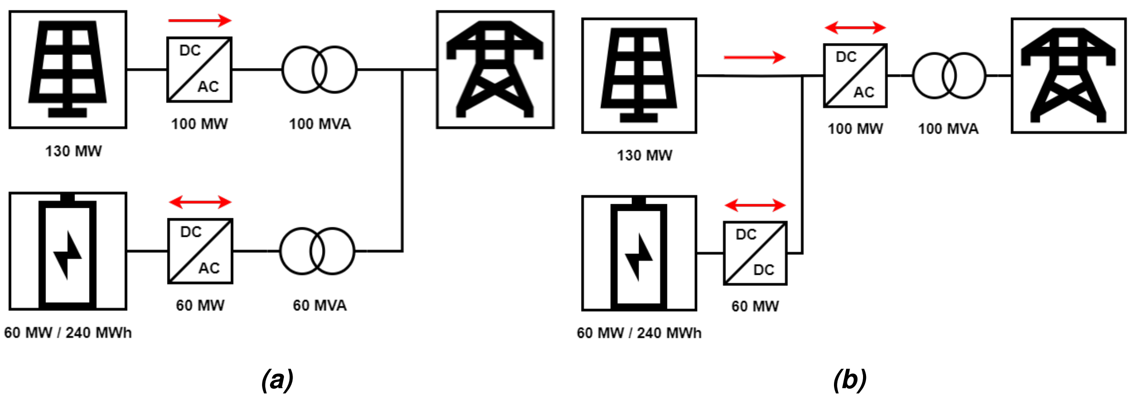

Figure 6.1. *Illustration of* ***(a)*** *AC-coupled configuration and* ***(b)*** *DC-coupled configuration for the case study.*

Table 6.1. *Parameters for the case study [1, 3, 119, 145, 146].*

	AC-coupled PV+BESS	**DC-coupled PV+BESS**
BESS power (MW)	60	60
BESS capacity (MWh)	240	240
BESS bidirectional DC/AC converter (MW)	60	-
BESS bidirectional DC/DC converter (MW)	-	60
PV power (MW)	130	130
PV inverter (MW)	100	-
PV capacity factor (%)	26.09	26.09
Common bidirectional DC/AC converter (MW)	-	100
BESS transformer (MVA)	60	-
BESS transformer efficiency (%)	98.43	-
PV transformer (MVA)	100	-
PV transformer efficiency (%)	98.68	-
Common transformer (MVA)	-	100
Common transformer efficiency (%)	-	98.68
Annual battery capacity degradation (%)	2.00	2.00
Annual PV capacity degradation (%)	0.70	0.70
Bidirectional DC/AC converter efficiency (%)	97.00	97.00
Bidirectional DC/DC converter efficiency (%)	-	98.20
PV inverter efficiency (%)	97.20	-
Round trip efficiency at battery terminals (%)	90.00	90.00
Installation cost (M€)	141.25	142.09
Levelized annual O&M expenses (M€)	4.39	6.02

the average for utility-scale PV systems installed in 2015, and inverter/BESS power ratio of 1.67, according to [147]. The AC-coupled system is sized to be comparative with the DC-coupled system. Both of these configurations are considered as aggregated models, assuming equivalent power flows through parallel components. Simple illustrations of the systems are presented in Figure 6.1 and parameters for this study in Table 6.1.

The installation costs (total costs of hardware, labor, permitting and etc. required to bring the system operational) and O&M costs take into account the cost differences that come from the hardware requirements of the coupling methods, in addition to costs that are caused by the decentralized layout of DC-coupled system, as discussed in Section 5.1. The O&M costs also consider that the battery capacity is returned back to its nominal value after 14 years of operation, assuming a 2 % degradation per year and 30 year lifetime for the system. Breakdowns of O&M costs and installation costs are shown in Table D.1 and Figure D.1 in Appendix D.

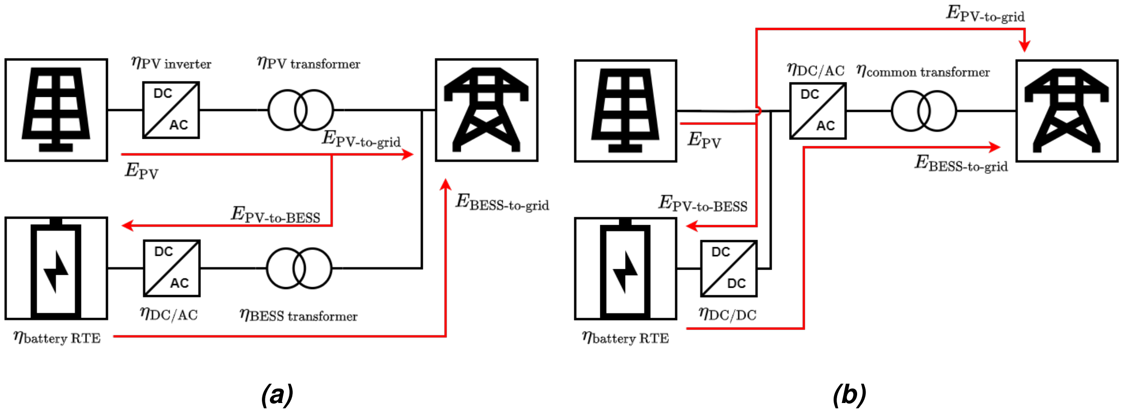

Figure 6.2. *AC-coupled **(a)** and DC-coupled **(b)** HPP power flows and component efficiencies.*

6.2 Calculation of LCOE

The power flows and the efficiencies of the components of the power train for both configurations are illustrated in Figure 6.2. E_{PV} and $E_{\text{BESS-to-grid}}$ represent the energy from PV and BESS as the values seen at grid side. The PV capacity factor CF_{PV} in Table 6.1 gives the annual average energy production seen at grid side, divided by the maximum annual production seen at grid side if run at nominal power for the whole year [148]. This calculation assumes that the batteries are charged to full capacity from PV once per day and that the batteries are discharged to the grid at a later time that day, so that PV and BESS never feed energy to the grid simultaneously. With one cycle per day, the capacity factor for AC-coupled BESS is

$$CF_{\text{BESS, AC}} = \frac{E_{\text{BESS}} * 365 \text{ days}}{P_{\text{BESS}} * 365 \text{ days} * 24 \text{ h}}, \tag{6.1}$$

where P_{BESS} is the BESS power and E_{BESS} the BESS energy capacity. For DC-coupled configuration, the BESS capacity factor is calculated with equation 6.2, which gives the annual average energy output of the battery in relation to the maximum annual production of the whole plant if run at nominal DC/AC converter power.

$$CF_{\text{BESS, DC}} = \frac{E_{\text{BESS}} * 365 \text{ days}}{P_{\text{BESS}} * 365 \text{ days} * 24 \text{ h}} * \frac{P_{\text{BESS}}}{P_{\text{common DC/AC converter}}} \tag{6.2}$$

The capacity factor of a DC-coupled BESS is restricted by the ratio of BESS power and grid-facing converter power $P_{\text{common DC/AC converter}}$. The annual energy obtained from PV and BESS at grid side for both configurations can be calculated with equations 6.3-6.6

$$E_{\text{PV, AC}} = CF_{\text{PV}} * P_{\text{PV inverter}} * 8760 \text{ h} \tag{6.3}$$

$$E_{\text{BESS-to-grid, AC}} = CF_{\text{BESS, AC}} * P_{\text{BESS DC/AC converter}} * 8760 \text{ h} \tag{6.4}$$

$$E_{\text{PV, DC}} = CF_{\text{PV}} * P_{\text{common DC/AC converter}} * 8760 \text{ h} \tag{6.5}$$

$$E_{\text{BESS-to-grid, DC}} = CF_{\text{BESS, DC}} * P_{\text{DC/DC converter}} * 8760 \text{ h}, \tag{6.6}$$

where $P_{\text{PV inverter}}$ is the power of the PV inverter, $P_{\text{BESS DC/AC converter}}$ is the power of the bidirectional BESS converter and $P_{\text{DC/DC}}$ is the efficiency of the bidirectional BESS DC/DC converter. The power train efficiencies for BESS charging and discharging can be calculated from the efficiencies listed in Table 6.1, by considering the power flows in both coupling methods. For the AC-coupled configuration, the power train efficiency from the PV and BESS point of coupling (PoC), through the batteries, to the grid is given by equation 6.7

$$\eta_{\text{AC}} = \eta^2_{\text{BESS transformer}} * \eta^2_{\text{DC/AC}} * \eta_{\text{battery RTE}}, \tag{6.7}$$

where $\eta_{\text{DC/AC}}$ is the efficiency of the bidirectional DC/AC converter, $\eta_{\text{battery RTE}}$ the battery round trip efficiency (RTE) at the battery terminals and $\eta_{\text{BESS transformer}}$ the efficiency of the BESS transformer. The BESS DC/AC converter in the AC-coupled configuration and the common DC/AC converter in the DC-coupled configuration are assumed to have the same efficiency. For DC coupled configuration, the power train efficiency from PV and BESS PoC, through the batteries, to the grid is given by equation 6.8

$$\eta_{\text{DC}} = \eta^2_{\text{DC/DC}} * \eta_{\text{battery RTE}} * \eta_{\text{DC/AC}} * \eta_{\text{common transformer}}, \tag{6.8}$$

where $\eta_{\text{DC/DC}}$ is the efficiency of the bidirectional BESS DC/DC converter and $\eta_{\text{common transformer}}$ the efficiency of the plant transformer. From the results of the equations above, the average annual net energy production for both HPPs can be obtained from equations 6.9 and 6.10 [148].

$$E_{\text{out, AC}} = E_{\text{PV, AC}} + E_{\text{BESS-to-grid, AC}} * (1 - \frac{1}{\eta_{\text{AC}}}) \tag{6.9}$$

$$E_{\text{out, DC}} = E_{\text{PV, DC}} + E_{\text{BESS-to-grid, DC}} * (1 - \frac{1}{\eta_{\text{DC}}}) \tag{6.10}$$

The summation of positive parts of both equations represent the energy obtained from the PV and BESS, without considering the energy lost in BESS operation. The negative parts of both equations represent the energy needed for the batteries to be able to provide energy $E_{\text{BESS-to-grid}}$ on the grid side, taking into account the losses occurring between the PV and BESS PoC and the grid, resulting in the value seen on the grid side. When that value is subtracted from $E_{\text{BESS-to-grid}}$, the remaining value is the total net energy lost from charging the batteries and discharging them to the grid. Now that the average annual produced energy, the installation costs in the beginning year of the project and annual O&M costs are known, the LCOE for the plant lifetime can be calculated with equation 6.11 [149].

$$LCOE = \frac{I_0 + \sum_{t=1}^{n} \frac{A_t}{(1+i)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+i)^t}} \tag{6.11}$$

In equation 6.11, I_0 is the installation cost of the system, A_t is the total annual cost of operation in year t, E_t is the total energy produced in year t, n is the system lifetime and i is the interest rate.

6.3 Results and Discussion

The parameters in Table 6.1 and results in Table 6.2 detail the base values for LCOE calculation for both AC- and DC-coupled systems. The LCOE calculation assumes a 30-year system lifetime and a 5 % interest rate. Due to the degradation of PV panels [150] and batteries, the capacity factors for PV and BESS decrease by 0.70 % and 2.00 % each year, respectively. The O&M costs include restoring battery capacity to its nominal value after year 14, resulting in the BESS capacity factor returning to its original value in year 15.

The LCOE calculations reveal that energy production costs are lower for AC-coupled HPP compared to DC-coupled HPP. Specifically, the LCOE is 69.66 €/MWh for AC-coupled HPP and 75.40 €/MWh for DC-coupled HPP. These figures, while based on assumptions and simplifications described in previous sections, provide a comparative basis for evaluating these configuration methods. The results indicate that despite DC-coupled HPP producing more energy, the cost savings with AC-coupled HPP are more significant. Fig-

Table 6.2. *Calculation results.*

	AC-Coupled PV+BESS	**DC-Coupled PV+BESS**
CF_{BESS} (%)	16.67	10.00
$E_{\text{BESS-to-grid}}$ (MWh)	87600.00	52560.00
E_{PV} (MWh)	228583.39	228583.39
η (from PV and BESS PoC to grid) (%)	82.04	83.07
Energy lost from BESS operation (MWh)	19173.42	10708.71
E_{out} (MWh)	209409.97	217874.68

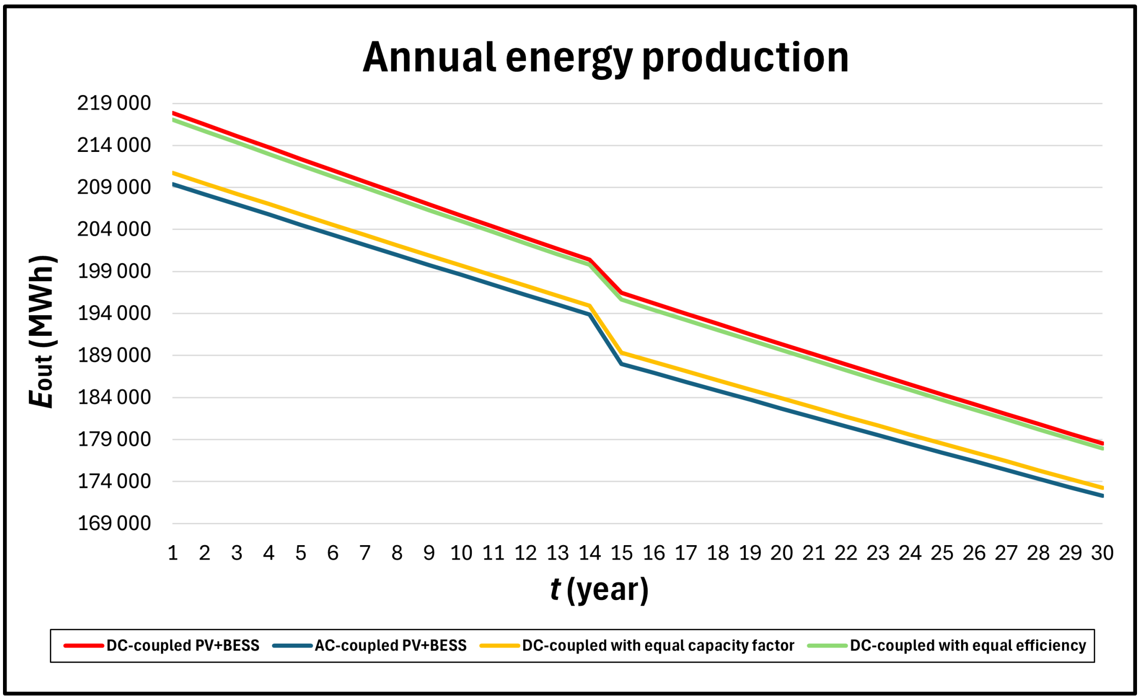

Figure 6.3. *Annual energy production of the HPP with original and varied parameters.*

ures 6.3 and 6.4 illustrate the effect of this cost difference, showing that the lower cost of the AC-coupled HPP outweighs the higher energy production of the DC-coupled HPP. Additionally, the BESS capacity factor significantly affects annual energy production. When the capacity factor of the DC-coupled BESS is aligned with the AC-coupled solution, the annual energy production of the DC-coupled HPP experiences the largest reduction. If only efficiency is matched, the reduction in energy production is much smaller, as also demonstrated by the increase of DC-coupled HPP LCOE in Figure 6.4.

From Figure 6.4 we can see that if the costs of the DC-coupled HPP are set equal with the other configuration, the LCOE decreases to 67.07 €/MWh, which is below the LCOE of AC-coupled solution. This represents the difference caused by energy production. It shows the effect of BESS capacity factor on the calculation, which is reduced in the DC-coupled configuration by the shared grid-facing converter. It must be noted that in real HPPs, this could be done by increasing the BESS energy capacity, which would also increase the costs of the plant, reducing the effect on LCOE. In the original situation, the power train efficiency is higher and the BESS capacity factor in DC-coupled configuration is smaller than in the AC-coupled HPP, which means that the annual average energy charged to and discharged from the batteries is also smaller. When less energy is cycled through the battery, more energy can be fed directly from PV to grid, making the losses also smaller. The effect of this can be seen in the rapid declines in energy production in Figure 6.3 after year 14, as the battery capacity is brought back to 100 % after year 15. If the costs and capacity factor of DC-coupled system are both set equal with the other configuration, the LCOE is 69.24 €/MWh, with the difference representing only

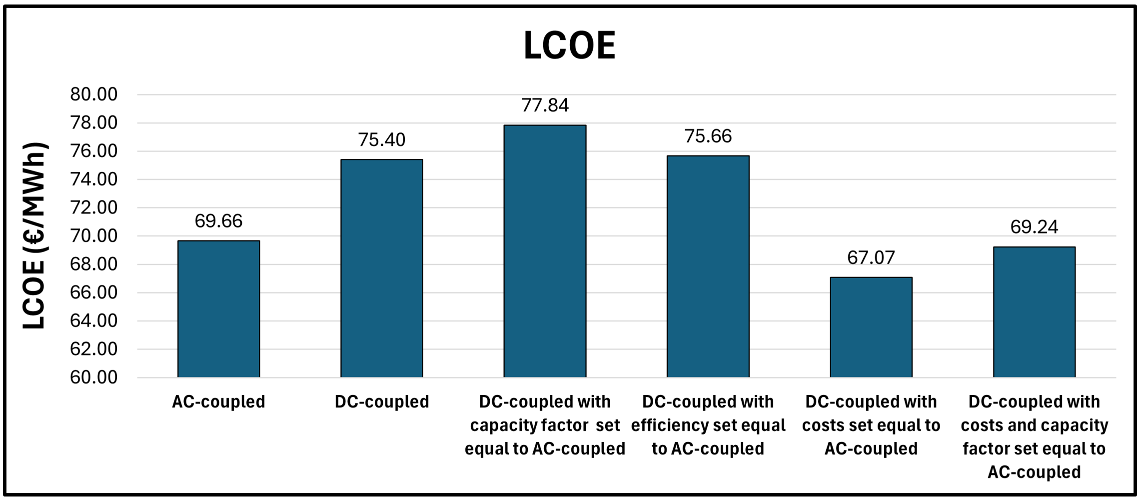

Figure 6.4. *LCOE with original and varied parameters.*

the efficiencies and now being 0.42 €/MWh in favor of the DC-coupled configuration. This sensitivity analysis is important for recognising the parameters that are critical for the calculation, because it allows the evaluation of these coupling methods without the restrictions of the assumptions and simplifications.

These results highlight the fact that the BESS is always a component that introduces additional losses to the system, which means that the value it brings to the power plant must always be greater than the lost revenue caused by its losses. If the value comes from energy sale only, it means that the revenue from selling energy from batteries must be large enough to cover the lost revenue from the energy lost during cycling energy through the batteries, which could have been fed directly from PV to the grid. Based on the calculation results presented in Table 6.2, the lost revenue from cycling energy through the BESS in first year of operation, instead of feeding it directly to the grid, is 364 295 € for AC-coupled configuration and 203 466 € for DC-coupled configuration with 19 €/MWh price for energy. These are approximately 9.2 % and 4.9 % of the total revenue that could be obtained from energy sale during the first year of operation with the same price for energy. The lost revenues are 0.26 % and 0.14 % compared to the installation costs of the systems. Even with the large difference in lost energy between these configurations, the operational costs of the DC-coupled system lead to higher cost for produced energy.

Especially with the AC-coupled system, charging the batteries only from PV would not be the optimal choice, due to the losses it causes and the variability of available PV power. When the batteries can also be charged from the grid, it can utilize the price difference between purchased energy at certain hour and sold energy at different hour, depending on which method has the potential for largest profit. This would be more beneficial with AC-coupled BESS, as it is more efficient when charged from the grid. In real HPP, the power supply of the BESS would be optimized for best possible revenue generation, taking into account the battery health management, though energy arbitrage might not be the only possible source of income. It can also be used to provide a range of ancillary services to the grid, including frequency regulation. These services are essential for maintaining grid stability and can be highly profitable in regions where the TSO has established markets for them. However, if the markets are not established and energy arbitrage is the only source of revenue, the profitability of the BESS may be lower.

DC-coupled systems suffer from the limitations caused by the shared components, which can limit their ability to provide ancillary services that require instantaneous activation when a disturbance occurs. The direct connection to the PV array means that DC-coupled systems are also more tied to the generation profile of the PV plant, which can limit their ability to utilize different markets as dynamically as AC-coupled systems. On the other hand, DC-coupled BESSs can also gain some benefit from the shared components through clipping loss minimization, which was not considered in this calculation. The potential income from clipping loss minimization depends on how large the ILR is and how much clipping actually happens, making it more lucrative in regions with high solar irradiance throughout the year. According to [148], the amount of clipped energy, for a DC-coupled HPP with same ratings as used in this calculation, is 0.0 % - 0.5 % in most parts of the United States. Even in regions with high irradiance, it is 2 % at best, indicating that the potential revenue from clipping minimization has a negligible effect on the total revenue of the plant.

The discussed potential sources of income, costs and the limitations imposed by the coupling methods suggest that even if the main purpose of the BESS is to support the operation of the PV power plant and utilize energy from it, with the cost structure presented in this case study, the AC-connected configuration is the most viable option. It also enables the use of BESS for different grid services and flexible benefit-stacking. According to the results of this case study, the situation could change if the costs of DC-coupled BESSs decrease closer to the level of AC-coupled BESS. With lower costs, the DC-coupled system could enable the HPP to produce energy with lower costs than AC-coupled HPP, utilizing the efficiency of its power train. This highlights the importance of proper economic assessments and correct system design based on the desired operational strategy.

Even when LCOE offers a solid foundation for comparing the lifetime production and costs of PV-plus-BESS HPPs with different configurations, it presents opportunities for improvements to enhance its accuracy and applicability. By incorporating detailed assessments of all potential costs, the calculation model could provide a more precise forecast. Additionally, a refined model would benefit from accounting for detailed solar irradiance specific to the installation location, thereby tailoring predictions to actual environmental conditions. The current version of the model primarily utilizes annual aggregate data, neglecting the seasonal and intraday variations which could significantly impact the accuracy of the energy output estimation. Incorporating these variations would not only refine production estimates but also allow for more dynamic financial planning and risk assessment throughout the operational life of the plant.

Furthermore, the exclusive focus of this calculation model on costs overlooks potential revenues. By integrating other financial metrics that take into account the potential revenue streams and savings, such as electricity sales, incentives, energy arbitrage, clipping loss minimization for DC-coupled BESS and different ancillary services for AC-coupled BESS, the model could offer a more comprehensive estimate of the economic potential. This inclusion could transform the model into a more robust tool for financial analysis and investment decision-making. Because this model treats BESSs as simple generating units, the main purpose of this calculation model is to study the effects that different BESS coupling methods have on the production of the PV plant. This is also the reason why it should not be used for standalone BESSs. Despite its limitations, the model can be a valuable tool for comparing different technologies, particularly in the early stages of project development where available data may be limited. To harness its full potential, it should be used together with other metrics. This multi-metric approach would provide a broader understanding of the economic viability of the project from multiple angles, enabling stakeholders to make more informed decisions based on a holistic analysis of both costs and benefits.

7. CONCLUSION

The main purpose of this thesis was to provide a comprehensive understanding of the general structure and operation of utility-scale AC- and DC-coupled BESSs, their applications, technical and commercial drivers and importance for the energy infrastructure. Different variations of these two coupling methods can be found from the literature and from the materials provided by manufacturers, but the most common ones are the AC-coupled single-stage systems and BESS-side DC-coupled systems. Even when configurations without transformers are gaining interest, the commercial systems currently utilize line-frequency transformers to enable connection to higher voltage levels.

The most significant differences between these coupling methods are the physical layout at the installation site and the sharing of hardware. AC-coupled BESSs can be centralized

Table 7.1. *PV-plus-BESS HPP differences.*

	AC-coupled PV+BESS	**DC-coupled PV+BESS**
Energy arbitrage	High potential due to grid charging capability	High potential with slightly better efficiency, if charged from PV only
Ancillary services	Broad participation in frequency regulation, etc.	Limited participation due to shared component constraints
Efficiency	Lower due to multiple conversions	Higher due to direct DC connection
Grid connection (when BESS is retrofitted)	May require new grid connection, increasing costs and deployment time	Uses existing grid connection, reducing costs and speeding up deployment
Response to demand	Can independently respond to grid demand, maximizing revenue opportunities	Limited by shared converter capacity, missing potential revenue during peak demand
Maintenance costs	Lower due to centralized BESS location	Higher due to dispersed battery modules, increasing logistical demands
Flexibility	High operational flexibility; PV and battery can operate independently	Limited flexibility; shared converter can become a bottleneck during peak production
Integration	Easier with existing AC infrastructure	Challenging, requires careful design
Benefit-stacking	Dynamic stacking of different applications	Tied more to PV generation profile, less dynamic especially regarding grid services

to a single location, where the different components can be gathered together in a compact way. They can be standalone or co-located with RESs. DC-coupled BESSs, which are mostly integrated with PV power plants, need to be distributed along the PV arrays, where they are connected to the DC-side of the central PV converters. The distribution of the components along the power plant field makes O&M activities more expensive and time-consuming and increases the costs associated with installations, EPC and hardware, like enclosures, HVAC and fire suppression systems. Shared converters decrease flexibility and application possibilities of the BESS, while enabling more efficient energy capture from the PV plant. Some of the important differences to consider for AC- and DC-coupled PV-plus-BESS HPPs are summarized in Table 7.1.

Chapter 6 reviewed different methods for evaluating the economic viability of BESSs within PV plants, focusing on profitability assessment. Additionally, the chapter discussed the impact of integrating BESS with PV on energy production, efficiency, costs and revenue generation for the entire power plant. It presented a case study using LCOE to compare the life-cycle costs of AC- and DC-coupled PV-plus-battery HPPs per unit of produced electricity. The findings indicated that the AC-coupled system has a lower LCOE due to lower installation and O&M costs, despite experiencing higher losses and lower annual energy production compared to DC-coupled systems. Even though BESSs always introduce additional costs and losses to PV power plants, they enable new possibilities for revenue generation that would not be possible without them. From the results of the case study and discussion presented in Chapter 6, the following conclusions can be made:

- The combined installation and O&M costs have the largest impact on the LCOE calculation, where the largest difference between the coupling methods is in the O&M costs.
- The power train efficiency differences between the coupling methods has a minimal impact on the LCOE calculation and total production of the HPP.
- The LCOE alone does not give a sufficient assessment of the coupling methods, but also requires other methods alongside it that take into account all possible income streams, in order to obtain a comprehensive result.

The comparison provided in this thesis demonstrates that the choice between AC- and DC-coupled configurations is not merely a technical decision but also a financial one, influenced by specific project needs, market conditions and regulatory frame works. The technical differences between the coupling methods highlight the importance of a system design specific to the application. Future advancements in technology and reductions in costs are likely to further enhance and balance the economic attractiveness of AC- and DC-coupled systems. However, the decision-making process for utilities and developers will continue to require a careful analysis of both economic feasibility and technical performance when deploying these systems.

This thesis focused on examining the fundamental system structure, power train, applications and commercial aspects of utility-scale AC- and DC-coupled BESSs. System control was addressed to the extent necessary for understanding the subject matter. Electrical protection measures were not within the thesis scope; however, they represent a critical research area that could influence the comparison of coupling methods. To the best of author's knowledge, no published articles comparing the protection of AC- and DC-coupled BESSs exist. Of particular interest are the potential differences in the complexity of protection mechanisms, which could lead to economic and operational disparities. These include increased costs associated with specialized equipment, additional maintenance and monitoring requirements, challenges in fault detection and isolation and complexities in integrating and coordinating protective measures. Understanding these constraints is crucial as they directly impact the reliability and performance of BESSs. Therefore, research efforts should focus on advanced protection strategies, cost-effective solutions and innovative fault management techniques for BESSs. Developing these aspects will not only enhance the reliability and safety of BESSs but also provide a more comprehensive comparison of AC- and DC-coupling methods. This understanding is crucial for designing, implementing and scaling utility-scale BESSs, contributing to more resilient energy storage solutions.

During the research for this thesis it was noticed that despite the widespread use of large-scale BESSs, there is a notable gap in the availability of research done on real-world systems. This significantly hinders research and development efforts aimed at optimizing the BESS technology and its applications. Constructing a large-scale BESS solely for research purposes involves prohibitive costs. The investment required for the development, installation and operation of these systems is substantial, making it financially unfeasible for most research institutions to build a large-scale BESS without commercial backing. This economic barrier limits the opportunities for hands-on experimentation and testing that could provide valuable insights and data. However, companies that have developed BESS technology may be reluctant to share operational data from their systems. This reluctance often stems from competitive and proprietary concerns, as companies may view their operational data and performance metrics as confidential information that gives them a competitive edge in the market. In addition, there may be concerns about revealing vulnerabilities or inefficiencies that could affect their reputation or market position.

The combination of these factors results in a challenging environment for researchers and developers seeking to advance BESS technology. While academic and theoretical research continues to progress, the lack of comprehensive real-world test data hinders the ability to validate models, refine systems and develop more efficient and cost-effective solutions for large-scale BESSs. Bridging this gap between theoretical research and real-world application remains a critical challenge for the energy storage industry, requiring collaboration between commercial entities and research institutions.

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APPENDIX A: CHB- AND MMC-BESSs

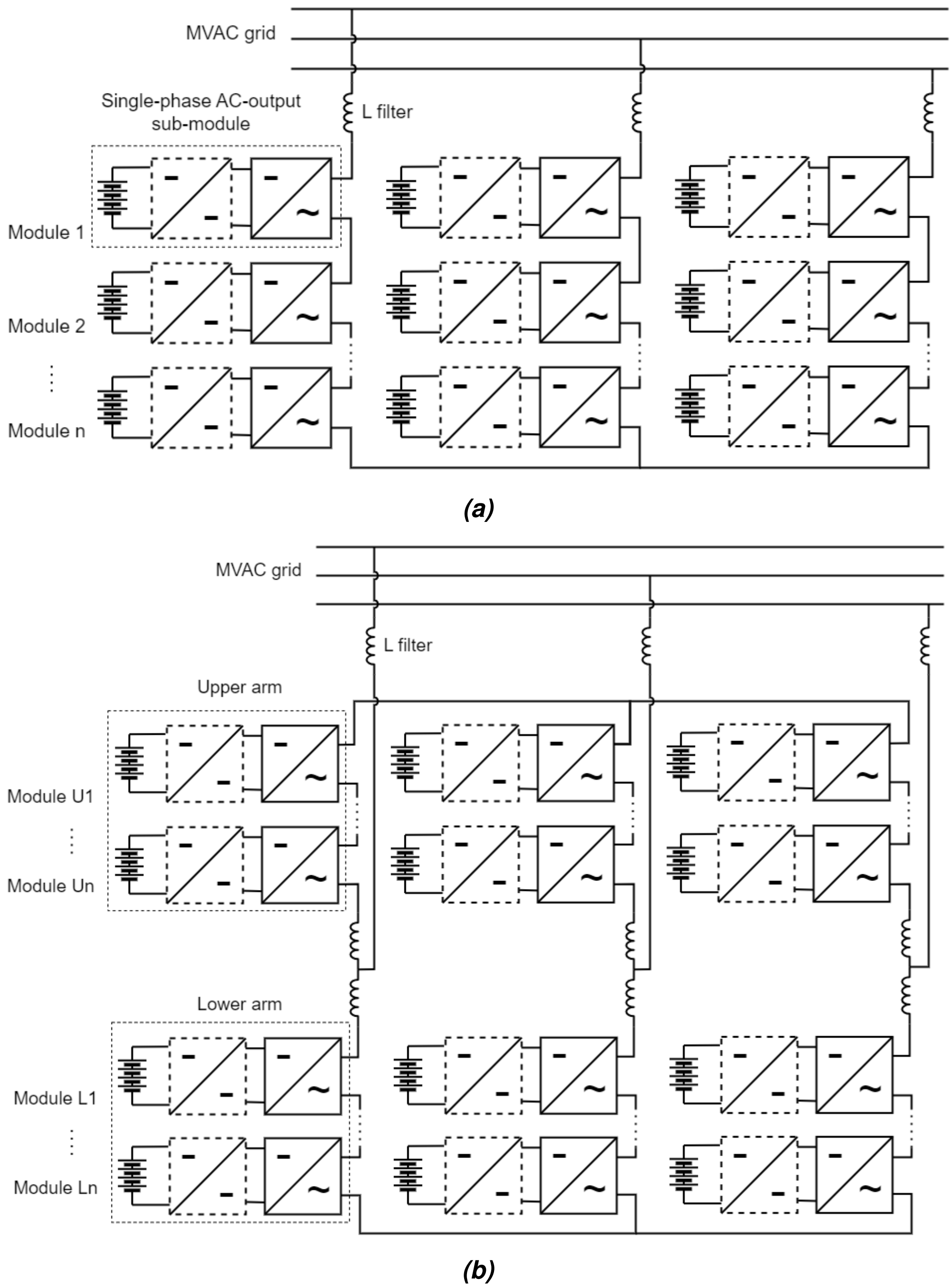

Figure A.1. *Star CHB-BESS* ***(a)*** *and MMC-BESS with distributed batteries* ***(b)****.* ***(a)*** *adapted from [54] and* ***(b)*** *from [48].*

APPENDIX B: CONVERTER TYPES USED IN BESSs

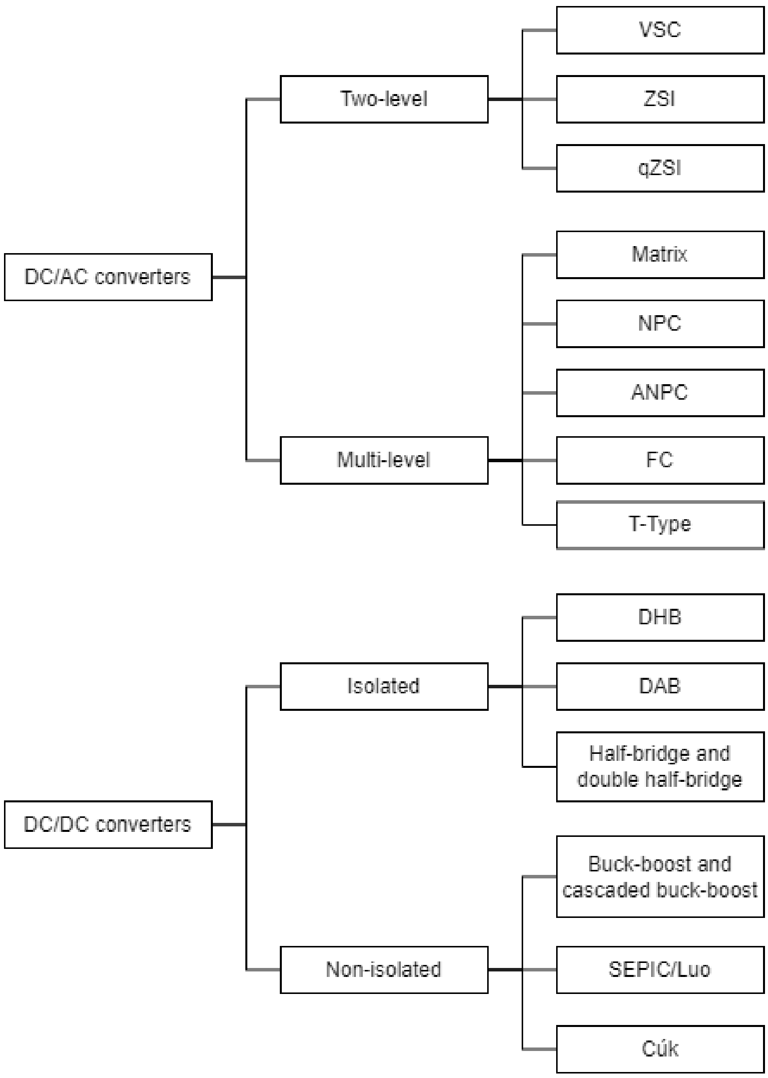

Figure B.1. *Common power electronic converters for battery energy storage systems presented in the literature [31, 32, 50].*

APPENDIX C: LITERATURE ON DC-COUPLED BESSs

Table C.1. *Literature on DC-coupled BESSs.*

Focus area	Key contributions	Source
Evaluation of PV+BESS configurations	Discusses methodologies for evaluating different configurations and dispatch strategies for photovoltaic and battery systems.	[3]
Review of energy storage technologies	Provides an overview of various energy storage technologies and their integration with large-scale PV plants.	[151]
Hierarchical control in DC Microgrids	Presents a control structure for managing distributed energy storage in DC microgrids.	[152]
PCS for multi-source systems	Describes the development and implementation of a PCS that accommodates multiple DC inputs from PVs and batteries.	[153]
Review of PCSs	Reviews current PCS technologies for ESSs, emphasizing topologies that facilitate DC coupling.	[38]
Reliability analysis of DC and AC coupling	Compares the reliability of DC- and AC-coupled configurations in 1500 V PV systems.	[154]
Cost assessment of PV+BESS configurations	Evaluates the energy unit costs of various PV+battery configurations to determine the most cost-effective approaches.	[155]
Design exploration of PV+BESS	Investigates different configurations of PV+battery systems, with an emphasis on the advantages of DC coupling under changing grid conditions.	[115]
Dynamic modelling of hybrid power plants	Discusses dynamic modelling of wind, solar, and storage hybrid power plants, including systems with DC-coupled BESS.	[156]
Efficiency comparison of coupling solutions	Compares the efficiency of DC and AC coupling solutions in large-scale PV+BESS installations.	[1]
Hybrid ESS	Explores control strategies for hybrid ESSs combining batteries and supercapacitors in AC- and DC-coupled configurations.	[157]
DC-coupled BESS with wind turbines	Investigates the integration of a BESS to the DC-link of a type IV full converter-based wind turbine, focusing on the control strategies required to achieve efficient dispatch.	[98]
Reliability of PV Systems with integrated BESS	Assesses the reliability impacts of integrating BESSs with PV systems in both DC- and AC-coupled configurations, analyzing how these integrations affect the overall system reliability and identifying the benefits and challenges of each coupling method.	[158]
Energy and capacity values in PV-plus-battery systems	Examines the changing energy and capacity values of utility-scale PV-plus-battery HPPs, focusing on how different system architectures influence these values under evolving grid conditions and market dynamics.	[159]
Large solar PV plants with DC-Connected Batteries	Analyzes the design and performance of large solar PV plant configurations that incorporate DC-connected BESSs, highlighting the advantages of DC coupling in optimizing energy storage integration and improving the overall efficiency and reliability of solar plants.	[95]

APPENDIX D: COST BREAKDOWN OF CASE STUDY HPPs

Table D.1. *Breakdown of AC- and DC-coupled HPP O&M costs [146].*

	BESS levelized O&M costs (M€)	PV levelized O&M costs (M€)	Total (M€)
AC-coupled	2.44	1.95	4.39
DC-coupled	4.07	1.95	6.02

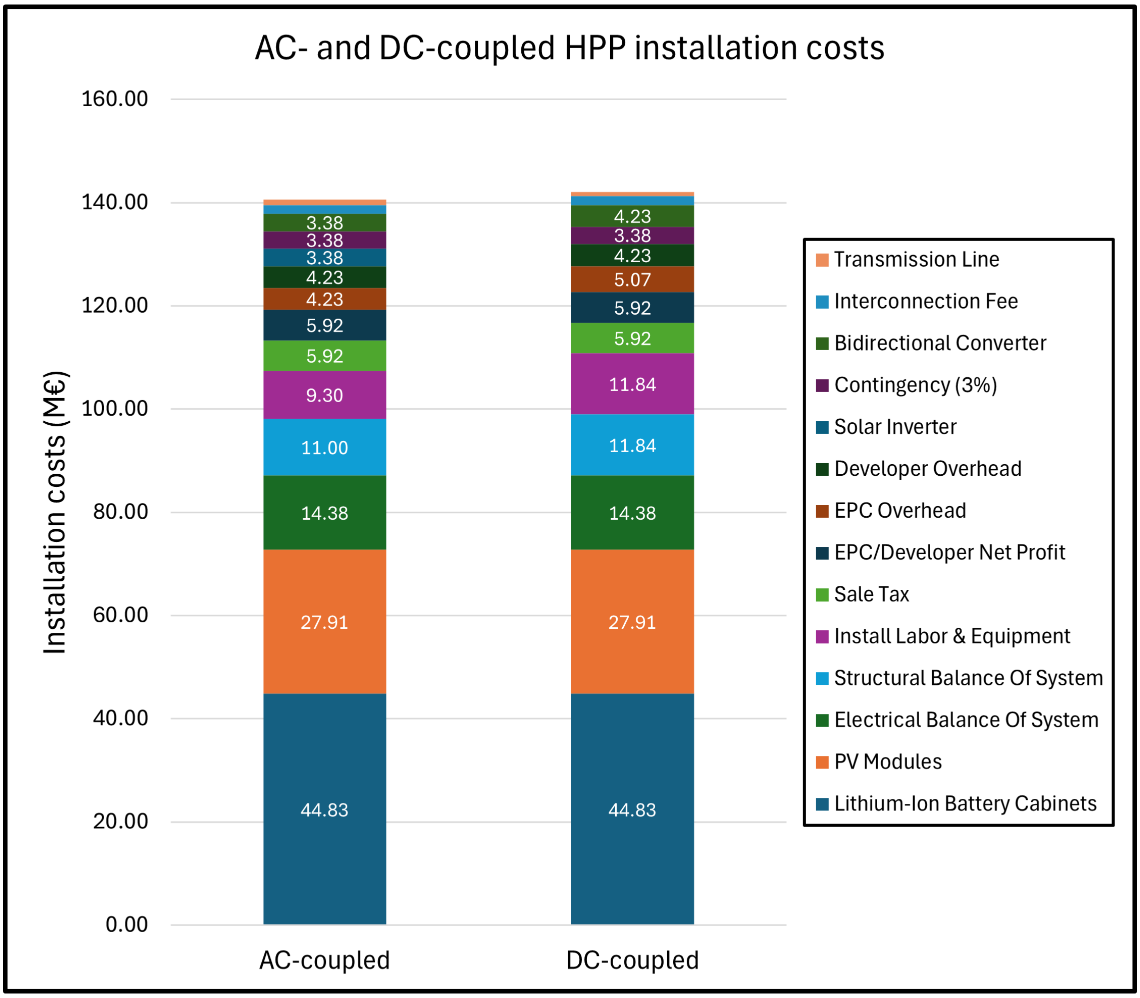

Figure D.1. *Breakdown of installation costs of the case study HPPs. Adapted from [119].*