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WaterWarmth

WORKPACKAGE 4
Smart integration of AE in the local energy system

4.1 and 4.2 Definition of system configuration (power circuit & controllers)

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ACCELERATING THE TRANSITION TOWARDS SUSTAINABLE HEATING AND COOLING BASED ON COLLECTIVE SURFACE WATER HEAT PUMP SYSTEM

Table of Contents

List of Tables

List of Figures

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Report Summary

This Deliverable 4.2 of Work Package 4 focuses on selecting appropriate energy sources based on the energy potential at each of the pilot sites in the Waterwarmth project: Middelfart (Denmark), Grieneko - Baard and Firma Van Buiten in Delft (Netherlands), Stad Mechelen (Belgium), and Le Cano in Ouistreham (France). It involves defining suitable converter topologies based on load and source requirements, optimally sizing the power circuits according to renewable energy production and consumption needs, and selecting control strategies that meet the dynamic performance requirements of the microgrid. A comparative analysis of various converter topologies and control methods is conducted to determine the most effective microgrid configuration.

Acknowledgments

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A GREEN TRANSITION

WATER = WARMTH

1. Introduction

This report presents work carried out under Work Package 4 (WP4), which aims to develop a comprehensive framework for analyzing and configuring renewable energy (RE) systems within microgrids. Specifically, Action 4.2 addresses the technical definition of system configurations, covering both power circuit design and control strategies. The work includes selecting renewable energy sources (RESs) based on the renewable potential of each pilot site, defining suitable converter topologies aligned with the characteristics of the sources and loads, and optimizing the sizing of power circuits to balance energy production with consumption. Furthermore, appropriate controller structures are chosen according to the dynamic performance requirements of the microgrid. A comparative evaluation of different converter and controller configurations is also conducted to determine the most efficient and effective system architecture for each application.

1.1. Background

Heating and cooling account for nearly 50% of Europe's total gross final energy consumption, with the residential sector alone consuming about 64% of that energy for household heating in 2021. Yet, only 27% of this demand was met by RESs, highlighting the urgent need to accelerate the adoption of low-carbon heating technologies. Globally, space heating and domestic hot water represented approximately 25% of final energy use in 2021, a share that is expected to rise—particularly in colder European regions. This trend underscores the necessity of developing sustainable heating systems that are both energy-efficient and environmentally sound.

Heat pumps (HPs) have emerged as a key solution due to their high thermodynamic efficiency and compatibility with electricity from RESs such as solar photovoltaics (PV) and wind turbines (WT). HPs transfer heat from low- to high-temperature reservoirs using a refrigeration cycle, and when powered by renewable electricity, they can operate with minimal environmental impact. The increasing penetration of PV and WT systems has further enabled the electrification of heating via HPs.

Central to this integration are power electronics converters, which match the variable outputs of the RESs to the operational requirements of the HP. These include AC-DC rectifiers, DC-DC converters (e.g., MPPT-enabled boost converters), DC-AC inverters, and bidirectional converters—each selected based on system architecture and component specifications. For example, PV-powered HP systems often require DC-DC conversion to optimize energy transfer, while WT-based systems rely on AC-DC rectification. DC operation of HP compressors can further improve efficiency by simplifying the conversion chain.

Hybrid RE systems that incorporate PV, WT, and energy storage systems (ESS) such as battery ESS (BESS) linked via a centralized DC bus have gained traction due to their modularity and improved energy management. These systems typically involve AC-DC converters for WT, DC-DC converters for PV, and bidirectional converters for ESS, with optional DC-AC inverters for AC loads. Such architectures are ideal for microgrids aiming for resilience, efficiency, and scalability.

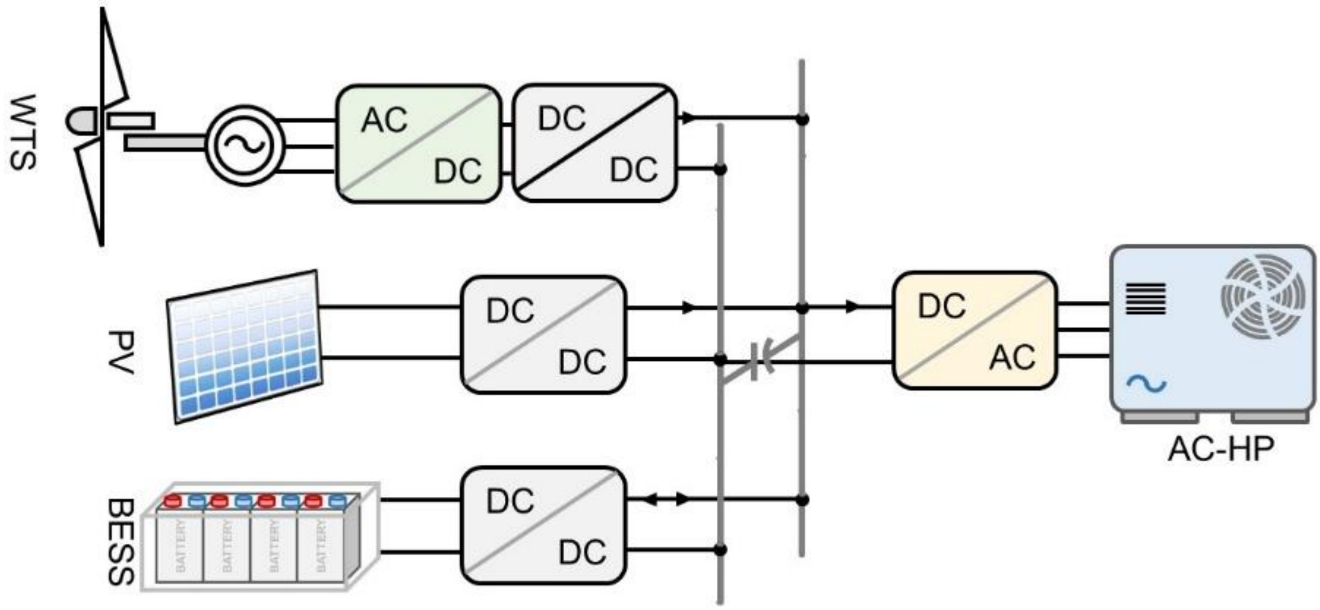

Figure 1: Hybrid system configuration

Despite growing interest, the literature lacks comprehensive studies focusing on power electronics converters specifically tailored for HPs powered by RESs. In this context, the GREAH team developed a comprehensive article [1] that addresses this gap by reviewing key converter topologies for integrating HPs into renewable microgrids. Emphasis is placed on hybrid configurations combining PV, WT, and ESS, assessing how each topology meets technical and operational requirements while supporting efficient system integration.

This work forms part of Action 4.2, which involves selecting RESs based on local potential, defining converter topologies suited to both sources and loads, and optimally sizing power circuits to balance generation and demand. It includes the evaluation of control strategies and comparative analysis of converter-controller combinations to guide the design of effective microgrid configurations.

The report investigates HPs as critical loads in microgrids, analyzing how power electronics converters influence system performance. Particular focus is given to converters on both the source side (e.g., MPPT boost for PV, AC-DC for WT) and the load side (e.g., DC-DC or DC-AC for HP compressors). Each topology is assessed for efficiency, controllability, cost, and integration potential in microgrid environments.

Finally, the report identifies current gaps in technology and research, offering future directions to enhance converter performance, improve dynamic RES-HP coupling, and ensure interoperability across hybrid energy systems.

1.2. Climate Data Collection & Analysis

As part of Activity 1, the GREAH research team has collected and analyzed climate data for five pilot sites within the Waterwarmth project: Middelfart (Denmark), Grieneko - Baard (Netherlands), Firma Van Buiten in Delft (Netherlands), Stad Mechelen (Belgium), and Le Cano in Ouistreham (France). Figures 2 to 6 illustrate the temperature, solar irradiance, and wind speed variations at the pilot sites.

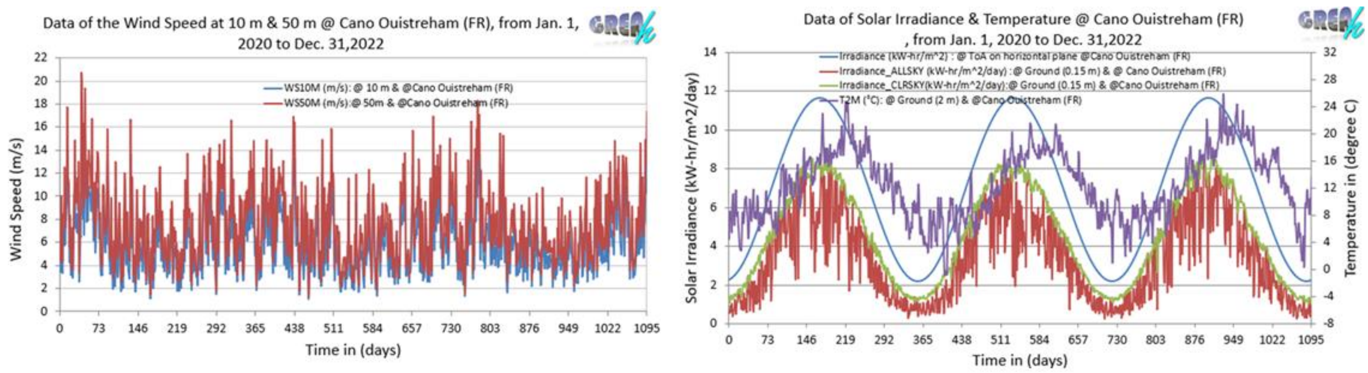

Figure 2:Wind speed, solar irradiance and temperature profiles in Le Cano Ouistreham, France.

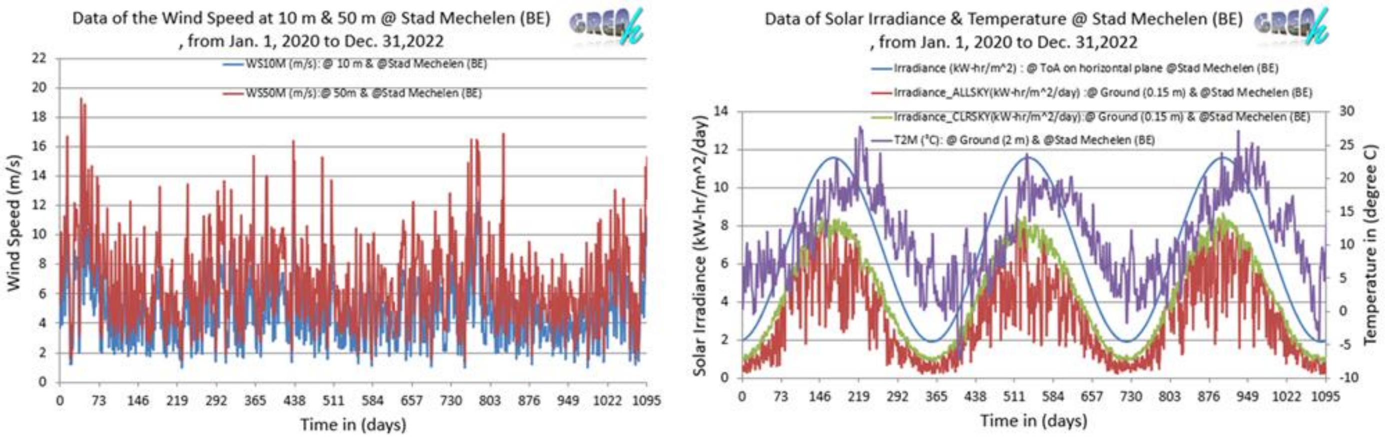

Figure 3: Wind speed, solar irradiance and temperature profiles in Stad Mechelen, Belgium.

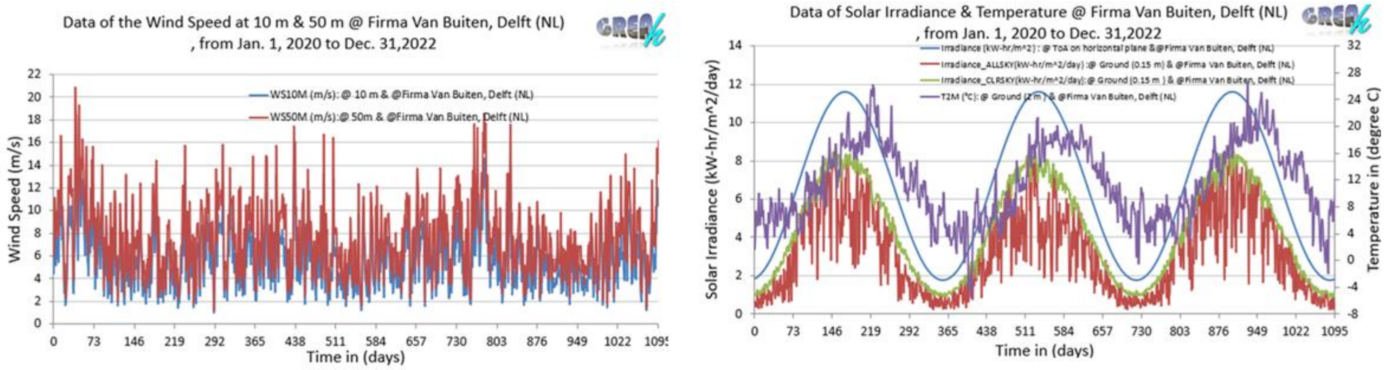

Figure 4: Wind speed, solar irradiance and temperature profiles in Firma Van Buiten, the Netherlands.

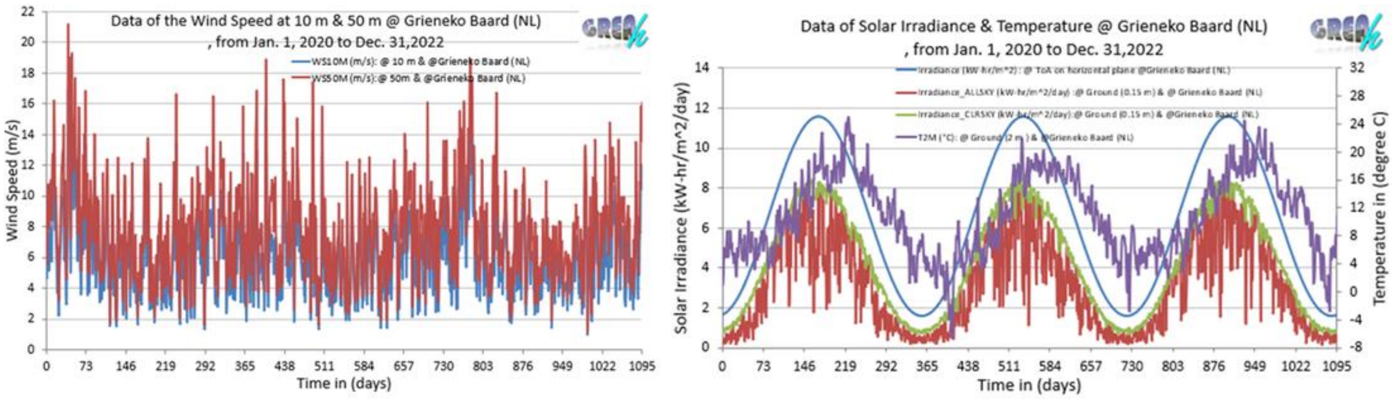

Figure 5: Wind speed, solar irradiance and temperature profiles in Grieneko Baard, The Netherlands.

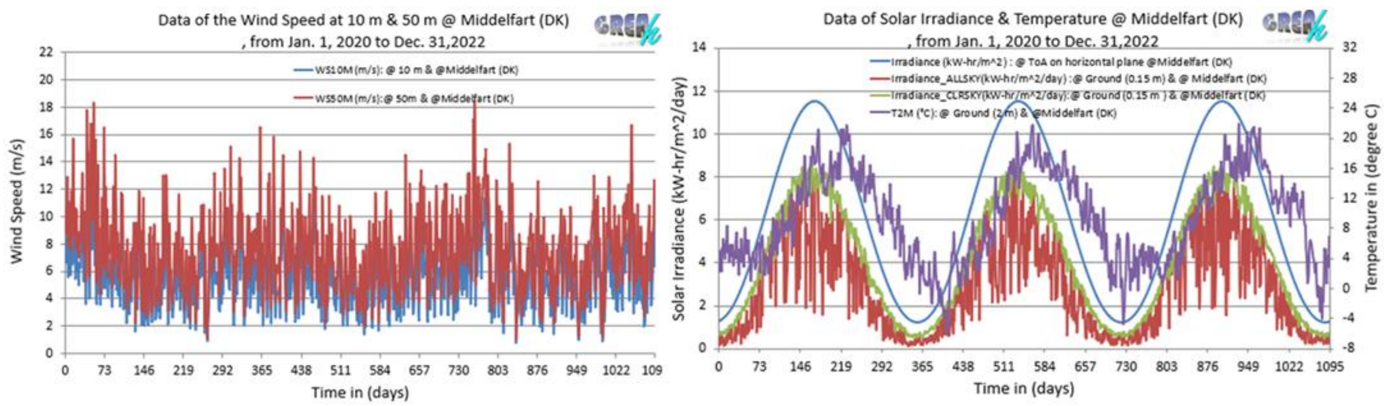

Figure 6: Wind speed, solar irradiance and temperature profiles in Middelfart, Denmark.

Based on this climate data analysis, the table below identifies the RESs most suitable for each site, taking into account local environmental conditions and resource availability.

Table 1: Comparison of pilot sites based on RES potential.

	PV	WT	BESS
Middelfart, DK	Yes	Yes	Yes
Grieneko – Baard, NL	Yes	Yes	Yes
Firma Van Buiten, NL	Yes	Yes	Yes
Stad Mechelen, BE	Yes	No	Yes
Cano Ouistreham, FR	Yes	Yes	Yes

Building on this analysis, the preliminary research focused on identifying converter topologies best suited for systems combining PV panels and WTs. To support this effort, the GREAH team developed a comprehensive article [1] that provides a structured overview of various converter topologies—including DC-DC, AC-DC, and DC-AC converters—within the context of hybrid energy systems. The study considered configurations where the energy sources include PV, WT, and/or ESS, and where the primary load is a HP.

The primary goal of this work was to determine which converter topologies are most appropriate for efficiently interfacing the RESs to be installed at the pilot sites with the HP, considering technical, economical, and operational factors. By doing so, the study aimed to provide researchers and system designers with both a solid introduction to the topic and practical guidance for selecting and implementing optimal converter solutions in future microgrid and building-scale RE systems. The article also synthesized findings and highlighted areas for further investigation to advance the integration of RE with high-efficiency thermal systems.

2. Summary of the Findings

2.1. Research Findings

As part of our work designing and modeling an energy management system comprising a hybrid setup (PV + WT + BESS), we conducted extensive research on AC-DC rectifiers and DC-DC boost converters. Our aim was to gain a comprehensive understanding of the flexibility different converter topologies could offer, particularly on the source side, once the fundamental system design was in place.

Over several months, we analyzed a wide range of converter topologies found in the literature, assessing their respective advantages and disadvantages to determine the most suitable configurations for integration into our behavioral model. The following paragraphs summarize our main findings.

2.1.1. DC-DC Converter Topologies for PV side and WT following the AC DC rectifier

As interest in DC-powered HPs grows—driven by rising DC renewable generation and the proliferation of DC residential loads—researchers have increasingly explored DC-DC converter topologies suited to PV and HP integration. DC compressors offer substantial energy savings (up to 50%) over conventional resistive heating and avoid the need for AC-DC inversion required by AC compressors.

To meet the high DC bus voltage demands (200–400 VDC) from typically low-voltage RESs (12–70 VDC), high-step-up DC-DC converters are employed. These can be non-isolated or isolated, each with distinct advantages and limitations.

Conventional non-isolated topologies like boost, buck–boost, Cuk, SEPIC, and Zeta offer simplicity but are limited in voltage gain, making them less suitable for high-power applications. To address this, advanced architectures such as multilevel converters (e.g., cascaded, interleaved) distribute voltage and current stress, enhancing reliability.

Among the various non-isolated DC-DC converter topologies we examined, the following were selected for comparison:

- Single-switch high-step-up Y-source boost converter [2]: Achieves 95% efficiency at 300 W with a 48 V input and 380 V output, balancing high voltage gain and low device stress, but requires dual control power supplies, increasing system complexity.
- High-efficiency dual coupled inductor converter for PV systems [3]: Delivers 94% efficiency at 1 kW with a 30 V input and 400 V output, featuring reduced conduction and switching losses, though its complex design with active clamp circuits and regenerative snubbers adds to the cost.
- Soft-switched converter with voltage multiplier **cells** [4]: Achieves 95% efficiency at 200 W, utilizing soft-switching techniques (ZVS and ZCS) for high voltage gains at low duty cycles, but experiences pulsating input current and lacks a common ground connection.
- Novel high-gain soft-switching converter with improved P&O MPPT [5]: Offers 96% efficiency at 200 W with a 20 V input and 200 V output, characterized by low input current ripple and simplified control, though it may be less reliable if the single power switch fails.
- Cubic high-gain converter [6]: Provides 92% efficiency at 57 W with a 12 V input and 75.5 V output, ensuring continuous input current with minimal ripples, but necessitates frequency modulation, leading to oversized components and potentially higher costs.
- Step-up LC resonant converter [7]: Achieves 95% efficiency at 1 kW with a 100 V input and 1000 V output, allowing operation at any gain value (>2) with proper control, though efficiency decreases at lower output power due to increased switching losses.
- High-gain converter with MPC-based MPPT for PV systems [8]: Delivers 93% efficiency at 150 W with a 20 V input and 100 V output, demonstrating superior performance over transformer-less counterparts, but may be unsuitable for higher voltage levels.
- Ultra-high-gain quadratic DC-DC boost converter [9]: Achieves 90% efficiency at 150 W with a 12 V input and 80 V output, offering exceptionally high voltage gain at low duty cycles, but requires two separate control power supplies, increasing system cost and complexity.

Isolated converters are preferred for their galvanic separation, essential in grid-connected or high-voltage applications. Topologies include dual-active bridge (DAB), dual-half bridge (DHB), flyback, push–pull, full-bridge, and resonant converters. Key contributions include:

- A soft-switching current-fed LCC-T resonant converter [10] that minimized switching losses and ripple at 288 W output, though oversized components due to low-frequency operation increased costs.
- A dual-flyback converter with resonant voltage multiplier [11] reduced transformer size and leakage stress, achieving 96.5% efficiency at moderate loads.
- An active-clamp flyback topology [12] improved energy recovery but was limited by 86% efficiency and a 40 W max load.
- Resonant converters like the LLC type [12] offered excellent voltage gain and low stress but were limited by discontinuous current, affecting compatibility with RESs.

Overall, researchers have introduced innovative enhancements—including soft switching, coupled inductors, voltage multipliers, and control techniques like MPC and MPPT—to improve efficiency, voltage gain, and converter compactness, while addressing challenges like component stress, pulsating currents, and system complexity.

The following two configurations [13,14] were retained to be integrated into our behavioral model:

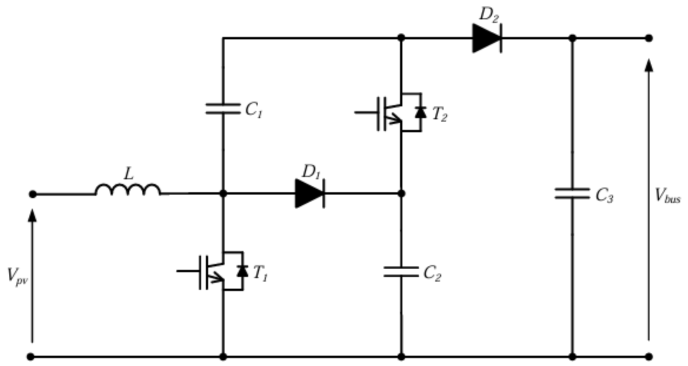

Figure 7: Retained DC-DC topologies for the PV side.

2.1.2. Bidirectional Converter Topologies for BESS side

Due to the intermittent nature of RESs like PVs and WTs, ESSs are essential for stabilizing power output and ensuring grid reliability. Fluctuations in RES output pose challenges such as power quality degradation, load imbalances, and dispatch difficulties. ESSs help mitigate these issues by regulating voltage and frequency, smoothing DC bus voltages, and enhancing system responsiveness. Among available ESS technologies, batteries and supercapacitors are most commonly used. Bidirectional DC-DC converters (BDCs) are critical in these setups, allowing two-way power flow to store surplus energy and supply it when generation is low, thus improving system stability and renewable energy utilization.

However, research on ESS use in stand-alone HP systems remains limited.

BDCs can be either isolated or non-isolated. The former is favored for low-to-medium power applications due to their compactness, simplicity, and high efficiency. Key topologies of non-isolated BDCs include:

- Buck–Boost Converters: These converters facilitate both step-up and step-down voltage operations, making them suitable for applications requiring voltage regulation in both directions.

- Ćuk and SEPIC Converters**:** These topologies offer continuous input and output currents, reducing current ripple and electromagnetic interference. However, they involve more complex control strategies and higher component counts.
- Interleaved Converters**:** By paralleling multiple converter phases, interleaved converters reduce input/output current ripple and improve thermal performance. They are particularly beneficial in high-current applications.
- Switched-Capacitor Converters**:** These converters achieve voltage conversion through capacitive charge transfer, eliminating the need for magnetic components. They are advantageous in applications where magnetic components are undesirable, though they typically handle lower power levels.

Isolated BDCs provide galvanic isolation between input and output, enhancing safety and allowing for voltage level translation. Prominent topologies include:

- Dual Active Bridge Converters**:** These converters are widely used due to their bidirectional power flow capability, high efficiency, and suitability for high-power applications. They employ phase-shift control to achieve zero-voltage switching, reducing switching losses.
- LLC and CLLC Resonant Converters**:** These converters utilize resonant tank circuits to achieve soft switching, minimizing switching losses and electromagnetic interference. The CLLC topology, in particular, offers bidirectional power flow and is suitable for wide voltage range applications.
- Flyback and Push–Pull Converters**:** These topologies are simpler and cost-effective, making them suitable for low-power applications. However, they may suffer from higher voltage stress and lower efficiency compared to other isolated topologies.

To enhance the performance and flexibility of basic converter topologies in hybrid energy systems, the following non-isolated configurations have been proposed:

- Dual input–single output converter [12]: Delivers 95% efficiency at 150 W with dual 10 V inputs and 100 V output, suitable for hybrid PV-WT systems and DC motor applications. Offers bidirectional capability and continuous input current, but requires complex control and may not scale well.
- Double-boost plus single-switch converter with voltage multiplier [15]: Operates with 12 V input, producing 480–960 V output, suitable for PV and WT setups. Offers buck-boost operation and simplified control, but suffers from output voltage drops, discontinuous input, and reduced load power delivery.
- High-gain three-port inverter with soft switching [16]: Provides 96% efficiency at 180 W using 30 V RES and 48 V ESS inputs, targeting PV and energy storage systems. Features high gain, low voltage stress on switches, and reduced switching losses, though discontinuous current flow may reduce system efficiency.

The configuration of the conventional buck-boost [17] was retained to be integrated into our behavioral model:

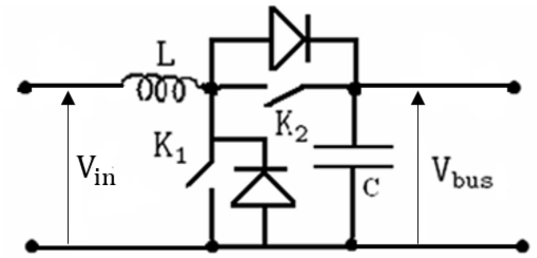

Figure 8: Retained DC-DC bidirectional topology for the BESS side.

2.1.3. AC-DC Converter Topologies for WT side

In WT systems connected to a DC-bus, rectifiers convert variable AC output into usable DC power. These rectifiers can be uncontrolled (diode-based), which are simple and low-cost but lack voltage control—unsuitable for variable-speed WTs. Controlled rectifiers (e.g., thyristor, IGBT, MOSFET) and pulse width modulation (PWM) rectifiers offer better voltage control and power factor correction. Two-stage conversions provide DC voltage gain advantages, especially when high DC voltages are needed. PWM rectifiers, often in 2-level voltage source converter (2L-VSC) form, are preferred in wind systems under 0.75 MW and can be extended to multilevel topologies like NPC, ANPC, and FC, with NPC being most common. Key evaluation criteria include cost, efficiency, and power quality (low total harmonic distortion). High-step-up DC-DC converters are sometimes used post-rectification to achieve higher DC-bus voltages.

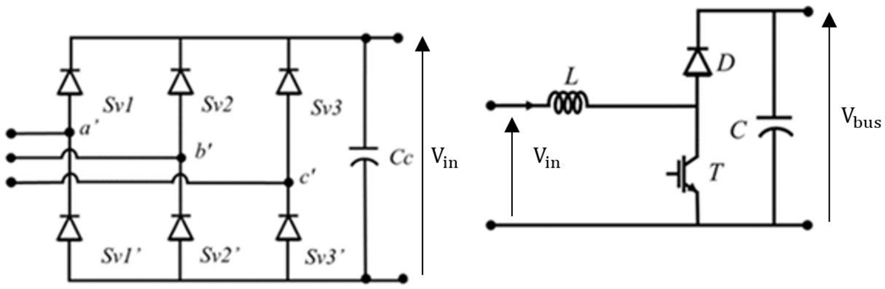

Figure 9: Retained AC-DC followed by DC-DC topologies for the WT side.

2.1.4. DC-AC Converter Topologies for AC-Powered HPs

In late 2024, our WP1 partners shared the technical datasheet of the AC-driven heat pump with us. Since our model operates with a DC bus, it became necessary to integrate a DC-AC converter on the load side to ensure compatibility.

DC-AC converters, particularly VSCs, are widely used for connecting ESSs and DC buses to AC-powered heat pumps. VSIs are categorized into two-level and multilevel inverters (MLIs). MLIs offer benefits such as reduced harmonic distortion, improved waveform quality, and better electromagnetic compatibility, making them ideal for integration with RESs like PV and WTs.

Key MLI topologies include:

- NPC (Neutral-Point Clamped): Offers scalability but faces issues with voltage imbalance and switching stress.
- CHB (Cascaded H-Bridge): Highly modular and reliable, suitable for fault-tolerant control, but requires multiple isolated DC sources, which complicates integration in common DC bus systems.
- Flying Capacitor (FC): Good voltage balancing but involves a large number of capacitors.

Hybrid MLIs integrate benefits of multiple converter types. For instance:

- Modified switched-capacitor MLI [18] Achieves 96% efficiency at 500 W with a 183 V DC input and 220 V AC output. Eliminates leakage current and removes the need for a separate boost stage, but requires complex control for voltage balancing and is costly due to the high number of switches.
- Switched-capacitor single-source cascaded MLI [19]: Delivers 275 W with an 80 V DC input and 311 V AC output. Reduces inrush current, boosts input voltage, and lowers cost, while eliminating leakage current. However, it suffers from discontinuous input current and lacks a common ground.
- Five-level transformer-less inverter with self-voltage balancing [20]: Provides 98% efficiency at 1 kW using a 100 V DC input and delivering 200 V AC. Naturally balances capacitor voltages without extra sensors or control loops but involves complex control strategies.

The configuration of [20] was retained to be integrated into our behavioral model:

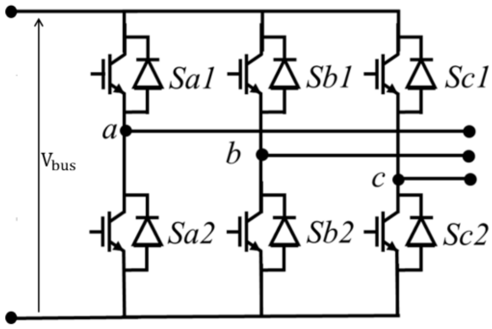

Figure 10: Retained DC-AC topology for the HP side.

2.2. Research Gaps

Research on RE-powered HPs is growing but still lacks detailed focus on converter topologies. Most existing studies involve grid-connected or stand-alone photovoltaic PV-HP systems, often based on simulations without specifying the converters used. Some notable efforts include systems combining PV, WTs, and BESS, showing promising synergy between energy production and cooling/heating demands.

Experimental studies have explored AC-driven and DC-driven HPs, with varying system sizes and configurations, including smart-grid-ready systems and direct DC integration.

However, even in promising cases, converter designs are rarely detailed. One exception is a study presenting a high-voltage-gain DC-DC converter for a 76 kW PV–55 kW HP setup [13] which was made by the GREAH team in the context of Waterwarmth project, funded by the European Union.

Overall, significant gaps remain in identifying and optimizing converter topologies to improve efficiency, reliability, and renewable energy utilization in HP systems.

3. Results & Conclusion

HPs have emerged as a cornerstone technology in the transition to sustainable heating and cooling, particularly when integrated with RE systems. Their ability to operate efficiently across various energy sources makes them a key asset in reducing carbon emissions and enhancing energy resilience. This report has provided a comprehensive review of power electronic converter topologies suitable for interfacing HPs with RESs, including DC-DC and DC-AC stages, as well as relevant modulation and control strategies. It is evident that while significant advancements have been made—especially in the development of MLIs, BDCs, and advanced control techniques—challenges remain in optimizing cost, efficiency, and system compatibility.

We concluded that future research should focus on improving converter modularity, dynamic performance, and fault tolerance to better suit the operational profiles of HPs.

To establish a robust and efficient simulation framework for the proposed hybrid RE system, a preliminary model will first be developed using fundamental power electronic topologies. This initial reference model will serve as the validation platform for operational feasibility and system behavior under varying load and source conditions. Once validated, it will be progressively optimized by integrating more advanced converter configurations tailored to each subsystem's requirements.

Given that our hybrid system connects RESs — namely, a 30 kW PV system and a 35 kW WT — to an AC-powered HP [21] via a centralized DC bus, specific converter stages are required for proper energy conversion and conditioning.

- To supply the AC-powered heat pump from the DC bus, a DC-AC inverter is required. For this, a five-level transformer-less inverter with self-voltage balancing and boosting capability [20] will be initially selected. This topology offers a compelling trade-off between cost, efficiency, and voltage boosting ability. It minimizes component count by eliminating the need for transformers and features natural voltage balancing across capacitors, which reduces complexity compared to traditional FC or NPC inverters. However, this advantage comes with increased control complexity, requiring sophisticated modulation techniques such as multi-carrier PWM or space vector modulation.
- The PV system produces DC power at a lower voltage than the DC-bus. Therefore, a DC-DC boost converter is necessary to step up the voltage to match the DC voltage of the bus. For this purpose, two topologies will be examined [14] and [22].
- The WT generates three-phase AC power, which requires an AC-DC rectification stage followed by DC-DC voltage boosting. The 2L-VSC, which is widely adopted (over 90%) in WT systems with ratings below 750 kW [23], will be selected for the purpose of this study. Its advantages include mature control methods, reliability, and compatibility with PWM-based rectification.

- The BESS, composed of a battery bank rated at 250 V and 120 Ah, is interfaced to the DC bus using a bidirectional buck-boost converter. This topology facilitates charging and discharging depending on the state of charge and power demand of the HP or RES availability. The converter will initially employ a basic PI-based control strategy, which will later be compared with advanced control methods such as Model Predictive Control to assess improvements in dynamic response, efficiency, and overall system energy management.

Acts 4.1 and 4.2 have successfully concluded with the selection of suitable RESs for each pilot sites as well as the identification of efficient, DC-DC, AC-DC and DC-AC converter topologies tailored for hybrid systems integrating these technologies on the source side and HPs on the load side. This selection forms the technical foundation for building a robust and flexible hybrid energy architecture.

With these components established, the project now progresses to Act 4.3, which focuses on developing a modeling tool for decentralized energy systems that incorporate both renewable generation and storage. A reference model is currently being created to represent the core system configuration.

This model will be generalized for application across all pilot sites and can subsequently be adapted—either scaled up or down—to meet the specific conditions and requirements of each location.

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