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A Control Architecture For Energy Systems With Multiple-Energy Carrier Devices

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Abstract

As energy systems become increasingly complex with integrating multiple-energy carrier devices, there is a growing need for advanced energy management systems that can effectively coordinate and control the diverse elements within the system. This paper presents a novel architecture for energy management systems explicitly designed for energy systems with multiple-energy carrier devices. The proposed control architecture encompasses three distinct levels: the device level, the subsystem level, and the system level. Each level incorporates operation models that are the foundation for implementing use cases in operation targets. The overall concept combines a bottom-up and top-down approach, where operational goals are transferred from the upper to the lower levels and, conversely, the lower levels communicate state adjustments to their respective upper levels, enabling feedback based on the established goals. A unified input-output data exchange is introduced to increase the control architecture's applicability. The interaction between the individual levels of the control architecture makes it possible to implement use case-dependent operation targets. Their execution is carried out through dedicated operation models representing devices and logical control structures capturing state-change processes. This paper provides a comprehensive overview of the proposed control architecture by applying it to the energy system of the industrial research platform WAVE-H2, with multiple energy carriers, heat, hydrogen, and electricity. This work highlights the proposed architecture's potential for adaptability regarding complex energy systems and facilitating efficient operation.

Keywords

Hierarchical control architecture; Multiple-energy carrier devices; Complex energy systems; Logical control structures; Unified input-output

1. Introduction

The increasing energy demand and the requirement for sustainable and efficient energy systems have led to the widespread use of multiple-energy carrier devices (MEDs). These devices, such as electric heat pumps, fuel cells, electrolyzers, and energy storage systems, couple a variety of energy carriers, such as heat, hydrogen, and electricity, and allow them to be integrated into a single holistic system. This enhances the performance and flexibility of the energy supply compared to conventional single-energy carrier systems whose sectors are treated independently [1,2].

However, the integration and control of these MEDs present significant challenges due to their heterogeneous characteristics, diverse operational constraints, and complex interactions, e.g., implementing optimal energy scheduling in the presence of uncertainties, e.g., variable prices or uncontrollable energy

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demands [3].To address these challenges, the development of an effective control architecture is necessary. Such an architecture should provide an intelligent control framework that ensures the synergistic operation of the MEDs while considering the dynamic changes in energy supply and demand. Interactions with the outside world and between the various energy networks are important aspects of the multi-energy carrier system (MES). Furthermore, the system size can range from building-level to entire countries [2,4]. The interaction points between MEDs are referred to as energy hubs, where different energy carriers are transformed, converted, and stored [2,5].

Optimization objectives of MESs are typically based on reducing system operation costs or pollutant emissions, improving the stability and quality of the energy supply, increasing system reliability and minimizing outage duration, or increasing overall system efficiency [6–9].

Several topologies of control architectures are used in different contexts and applications. The most common topologies are described below, although variations or combinations of the topologies can also be found.

- Centralized control architecture: A central authority is responsible for monitoring and managing all the relevant energy data within a system in this topology. It involves centralized decision-making, control, and coordination of energy generation, distribution, and consumption. This topology lacks efficiency and flexibility, as it must be modified to integrate additional devices and has extensive computational costs [10,11].
- Decentralized control architecture: This topology distributes decision-making and control authority to multiple subsystems within a system. Each subsystem has a degree of autonomy in managing energy resources and optimizing energy consumption. A decentralized control architecture is primarily employed in distributed energy systems and microgrids [12,13], often with respect to isolated energy carriers [14].
- Hierarchical control architecture: This topology is based on a structured multi-level architecture. It divides energy management tasks and decision-making into distinct levels, each with its own set of responsibilities and objectives. This topology enables coordinated decision-making at multiple levels, from long-term strategic planning to short-term operational control. Hierarchical control architectures are commonly applied in MESs, where different energy carriers and subsystems must be coordinated [15,16].

In the context of scientific research, it is also necessary to model and simulate complex energy systems to improve their operating parameters. As the complexity increases, expertise from multiple disciplines must be combined. This paper proposes a hierarchical control architecture that facilitates a simple and flexible application across MEDs. It combines a bottom-up and top-down approach, transferring operational objectives from the upper to the lower levels and vice versa. This enables scientists and engineers to work on the same project using their preferred software, leading to efficient implementation and integration and a scalable and modular aggregation of a multitude of MEDs.

The following sections of the paper are structured as follows: Section 2 discusses the characteristics of the current developments and research results in hierarchical control architectures for MEDs. The different hierarchy levels of the control architecture are described in Section 3. Section 4 shows the conceptual application of the control architecture to an industrial research platform. Finally, Section 5 provides a conclusion and future extensions of this work.

2. Control Architectures in Literature

Coordinated the multi-energy carrier systems (MESs) offer specific opportunities to improve energy efficiency and enhance energy supply flexibility. However, operating an integrated energy system, considering all the interdependencies between the different energy supply networks, also presents various challenges in terms of modeling and planning the control architecture [17,18]. Recently, researchers have shown significant interest in optimizing the operation of MESs. The proposed control architectures vary based on energy consumption and time scale [19]. Typically, the hierarchical control architectures are developed based on a two- or three-level control architecture, depending on the system's complexity.

The two-level control architecture controls multiple-energy carriers by dividing the control tasks into two distinct levels: main or supervisory control level and a primary or unit control level [18,20,21]. Each level has specific responsibilities in managing and optimizing the usage of the energy carriers in the system. The main control is responsible for setting the overall objectives and constraints for the system, such as energy demand and cost. The main control considers the specific requirements of the system and the constraints of the energy carriers to determine the optimal energy demand. The primary control coordinates the operation of the different energy carriers to meet the energy demand set by the main control. It translates the objectives and constraints into specific control actions for individual energy carrier devices. This control architecture has been successfully applied in several studies, some of which are briefly addressed in the following.

The authors in [21] introduce a control strategy for the operation of an autonomous distributed generation system with multiple energy sources, storage devices, and wind energy based on a two-level hierarchical control architecture. The main control manages the entire system, distinguishing control actions for the electrical and heat systems, while the primary control embedded in each component ensures fast and accurate control of individual components to maintain desired set points. The results for a residential district application demonstrate stable and efficient performance of the control strategy in a 24-hour simulation. Leading to achieving the balance between demand and supply for both electricity and heat systems. The authors suggest that it can be adapted for different configurations of multiple energy carrier systems, making it a robust and applicable control solution for autonomous distributed generation systems with various energy sources.

In [18], the author designed a two-level control architecture for the application in systems with multiple-energy carriers. Here, the unit control is a local control system installed in each controllable unit, operating independently but receiving signals from the main control. Whereas the main controller oversees the entire system, monitoring parameters, allocating generation power, optimizing the use of multiple energy sources, and distributing the load among the controllable units. The control architecture was tested at the DENlab, a renewable energy laboratory located at the Power Systems Group of Delft University of Technology, on an off-grid energy system configuration, considering electricity and gas as input and electricity and heat as output. The results of the study demonstrate that the multi-carrier hierarchical control architecture is robust and stable under normal operating conditions. The control strategy successfully handles perturbations and load changes in the system, keeping main control parameters within defined boundary conditions.

The authors of [20] presented a hierarchical control architecture for a hybrid energy system built in Lambton College, Sarnia, Canada. The two-level control architecture consists of a supervisory level with long-term resource planning (hours) and a low-level control reacting to rapid dynamic system changes (seconds) for dynamic real-time optimization and ensuring that each unit operates at its set point determined by the supervisory level. The different time scales of the higher- and low-level control are buffered by a battery, serving as a dynamic energy storage. Simulation results of case studies based on average weather data for a 24-hour period in the month of June in the Ontario region and a typical load demand of the hybrid system show effective energy management with hydrogen and battery storage systems. The authors suggest that the strategy can be adapted for other standalone energy systems with multiple units, offering flexibility in integrating operational, economic, and safety objectives.

In more recent studies, a hierarchical control architecture for MES involving three levels of control have been proposed. In [22], a hierarchical control architecture for multi-source multi-product microgrids is presented. The system includes a supervisory control layer, an optimizing control layer, and an execution control layer. The proposed control architecture coordinates thermal, gas, and electrical systems and incorporates static energy hub models and dynamic characteristics of the microgrid components. Numerical studies demonstrate that the proposed system enables economically efficient operation of multi-source multi-product microgrids. The interactions among thermal, gas, and electrical systems are effectively managed, resulting in cost savings and sustainable operation. The authors suggest that developed control architecture can be implemented for microgrids with various energy sources without the need for a completely new energy management system.

The authors of [23] propose a hierarchical control architecture for multi-energy system that is divided into three levels: superior control, intermediate control and subordinate control. The superior control level serves as the management platform. It is mainly responsible for monitoring operation parameters and analyzing the centralized control strategy of the system. The intermediate control level schedules operation strategies for each subsystem, ensuring flexible and optimal scheduling within the complex energy system. It determines the cooling, heating, and power supply required by each subsystem based on forecasts, maintaining energy supply balance. The subordinate control manages local equipment operations, start-stop, temperature, and flow controls. Based on the simulation results the authors come to the conclusion that this hierarchical approach effectively considers all factors and optimizes the system control at different levels, resulting in a more efficient multi-energy system operation.

Both presented forms of control architecture offer a clear division of control tasks, facilitating the control and optimization of the system. As each level is responsible for specific functions, new elements or energy sources can be integrated without fundamental changes to the existing control architecture. The three-level approach provides a more holistic and efficient approach to managing the complex interactions and dynamic requirements of multiple energy sources. A two-stage system may lack the level of detail and flexibility required to effectively manage the complexity of a larger multi-energy system. Without the intermediate level to provide fine-tuned control, a two-level system may struggle to address the complexity of a larger multi-energy system and manage the specific needs of the various energy carriers and of their interactions. The examples of three-level control architectures presented in literature are limited in scope, as they have been developed for specific applications. The objective of the work at hand is to develop a standardized control architecture based on a three-level system. This contributes towards the applicability of the architecture for different systems and aims to maximize adaptability and extendibility after initial implementation.

3. The Proposed Control Architecture

The proposed architecture consists of three hierarchy levels: the system, the subsystem, and the device levels (Figure 1). Each level can comprise one or more operation models that form the basis for implementing the use cases into operation targets. The presented concept combines a bottom-up and top-down approach, where the data flow is bidirectional, with the purpose depending on the direction.

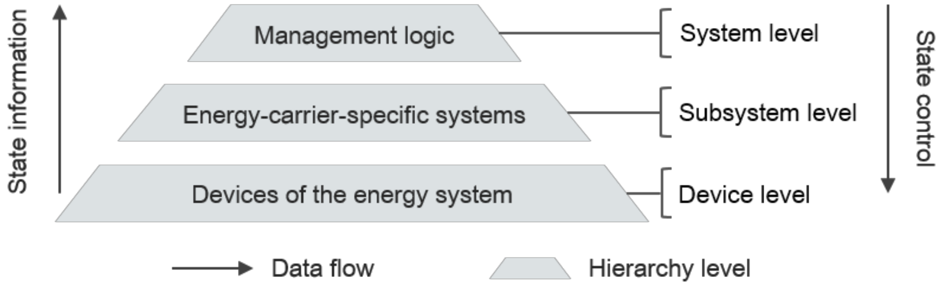

Figure 1: Hierarchy levels of the proposed control architecture.

The hierarchy levels of the control architecture serve the purpose of clearly structured distribution of function and applicability to different energy system compositions. In the following, the framework and tasks of the hierarchy levels are specified, summarized in Table 1.

The *system level* contains the management logic of the energy system. Here, use cases, e.g., market price-dependent choice of energy carriers and hydrogen production from renewable generation, are implemented through operation targets, and the allowed state changes are determined dependent on system constraints. Its task is to coordinate the overall energy system by evaluating the input from the subsystem level regarding required changes in the operational state and the input from use cases regarding the targeted operation to determine necessary adjustments.

The *subsystem level* consists of energy carrier-specific systems. Their task is the supervision of the operation point of each involved device. Here, the individual operating points are aggregated into the overall operating state of the energy carrier's respective subsystem. A continuous comparison between the targeted and the current operational state is carried out. This level optimizes the system efficiency and ensures the security of the energy supply.

The *device level* contains all devices of the examined energy system. Its task is to facilitate information exchange between the devices and the overlying subsystem level, ensuring the execution of targeted operations. From the control architecture viewpoint, these devices are black boxes connected to the subsystem level through an input and an output. The devices themselves are then operated decentral according to the parameters of their respective operation model, which also ensures the operational safety of the devices. This enables easy integration of various devices with minimal limitations to the underlying model of the respective device.

Table 1: Framework and tasks of the proposed control architecture hierarchy levels.

Hierarchy level	Framework	Task
System	Overlying management logic	Specify the operation targets and determine allowed operational state changes based on system constraints.
Subsystem	Energy carrier-specific systems	Supervise the operational point of devices and form an overall energy carrier-specific operating state.
Device	System devices (black boxes)	Enable device integration and ensure the execution of targeted operations.

The management logic at the system level evaluates the requested adjustment to the operating state of the originating energy carrier-specific subsystem and the resulting changes in other subsystems according to the implemented system constraints. If the requested state change of one subsystem is determined to result in a constrained operational state of another, the management logic calculates compensational operating states across all involved energy carrier-specific systems. After each newly determined compensational adjustment, the management logic again assesses whether or not the adjustment results in a constrained operating state for any of the involved energy carrier-specific systems. The concluded operational states are then generated as output and passed on to the subsystem level. In the case of user instructions in the form of use cases, the management logic follows the identical logical path for implementation. For the management logic, a distinction regarding the origin of input is not necessary, as the intention behind the input is always an adjustment of the operational states. The described process of input evaluation prevents undesired or critical operation states across the energy system and is generically depicted in Figure 2.

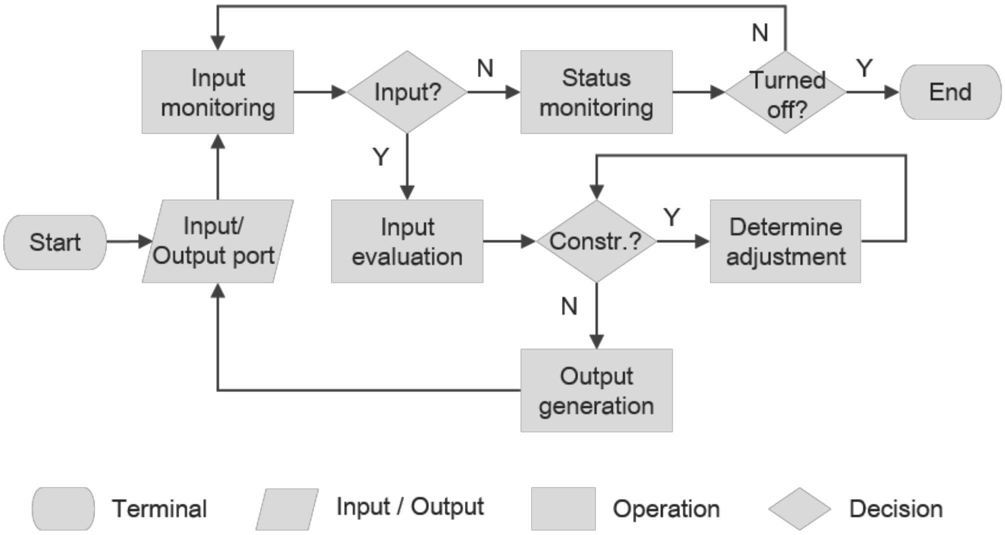

Figure 2: Generic depiction of the management logic at the system level.

The subsystem level is an information carrier between the system and device levels. After the concluded adjustment to the operational state is communicated, the subsystem level passes the resulting operating point adjustments to the device level as input. Here, the black box approach allows the input to be of the same form independent of the addressed device. Thus, the system architecture communicates solely through operating states, the only differentiation being informational and requested ones flowing upwards and directive ones downwards. This allows for easy application of the architecture to various energy carriers and devices and simplifies the integration of differing software used for modeling. This also contributes to the control complexity's scalability by unifying the data flow content between all architecture levels, independent of the energy carrier.

4. Application to the Industrial Research Platform WAVE-H2

The system architecture concept was applied to the hydrogen industrial research platform (WAVE-H2) [24]. The platform is now under construction and will be operated on an industrial scale. The ideal hydrogen value chain for different industrial applications can be tested by using different technologies. The platform offers a hydrogen-based innovation stage for a wide range of industrial applications, further driving the decentralized decarbonization of the industrial sector. The platform consists of a multitude of devices working with different energy carriers. The photovoltaic modules for on-site renewable energy generation and a battery energy storage system for buffer storage are the only devices that are exclusive to a single energy carrier system. Following devices are incorporated regarding the use of multiple energy carriers: a combined heat and power plant capable of running on a mixture of natural gas and hydrogen, two electrolyzers for hydrogen production, one a proton exchange membrane (PEM) electrolyzer and the other an alkaline electrolyzer, a PEM fuel cell, and a heat pump. Subsequently, the platform has three energy carrier systems, hydrogen, electrical and thermal. Apart from the photovoltaic modules and the battery energy storage system, the devices are at least part of two energy carrier systems. The proposed control architecture was used to model the complex interdependencies of the platform's energy system. Figure 3 depicts these interrelationships by mapping the devices' input and output sides to the control architectures' overlying levels.

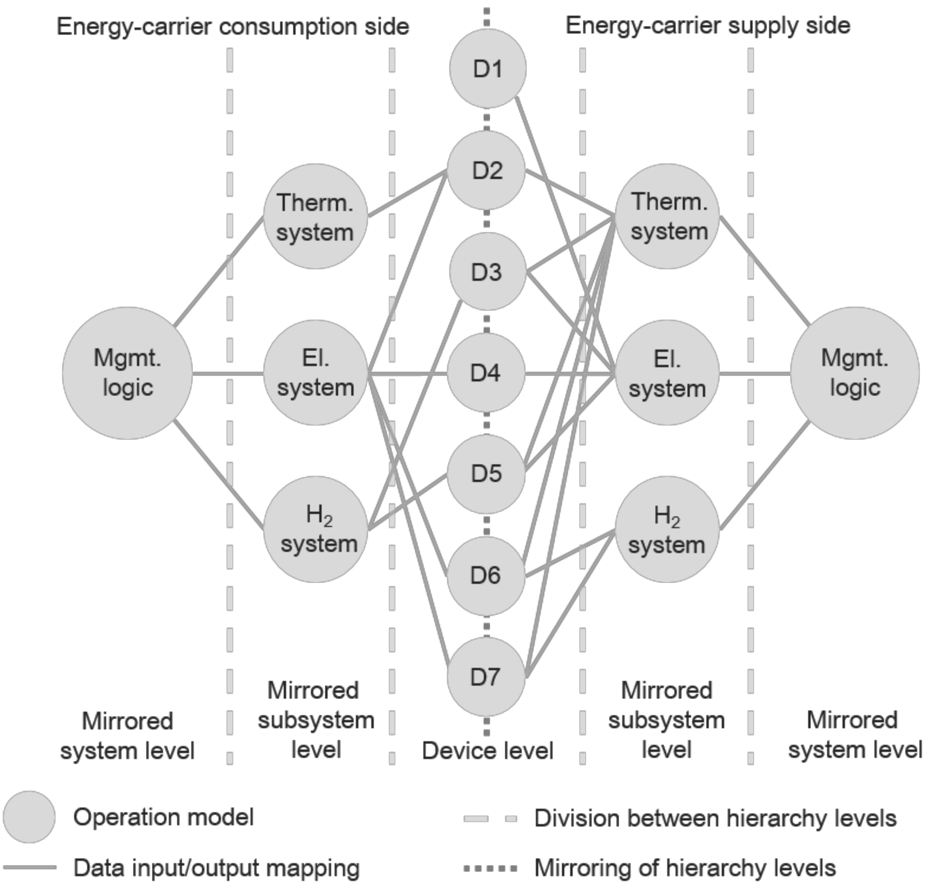

Figure 3: Map of input/output interrelationships between hierarchy levels of the control architecture, depicted by mirroring the architecture according to the device consumption and supply sides.

At the system level, the management logic has been adapted to the constraints of the respective energy carrier systems, e.g., given the research purpose of the platform, it must only act as a consumer of the connected energy grids. Thus, real-world circumstances are depicted, through which the reasonability of operation targets is evaluated before they are acted upon. The three energy carrier systems were integrated at the subsystem level and linked to their respective devices (D1 to D7) at the device level. Table 2 describes the resulting structure of the platform's control architecture and the linking of the hierarchy levels through the input and output parameters. Figure 3 depicts these interrelationships by mapping the devices' input and output sides to the control architectures' overlying levels.

Table 2: Operation models of the industrial research platform and their input and output parameters.

Hierarchy level	Framework	Purpose of Input/ Output
System	Management (Mgmt.) logic	Adjustment requirement/ Operation state adjustment
Subsystem	Thermal (Therm.) system, Electrical (El.) system, Hydrogen (H_2) system	Devices operating point and adjustment/ System operation state and adjustment requirement
Device	Photovoltaic modules (D1), Heat pump (D2), Combined heat and power plant (D3), Battery energy storage system (D4), PEM fuel cell (D5), PEM electrolyzer (D6) and Alkaline electrolyzer (D7)	Adjustment of operating point/ Current operating point

One of the main objectives of such projects as WAVE-H2 is to provide expansion opportunities, ensuring that the work remains adaptable and can grow as new ideas and technologies emerge, which is essential to the long-term success of any scientific endeavor. This paper also encourages and facilitates the development and mapping of a digital twin of the industrial research platform it was applied to. It simulates the physical system and can model, analyze, and optimize its performance. As a result, researchers can gain valuable insights into the systems' behavior and identify areas for improvement, such as enhancing the overall system efficiency, improving the integration of several of multiple-energy carrier devices (MEDs), ensuring interoperability between different MEDs, and promoting the use of low or zero-carbon energy carriers to achieve decarbonization goals.

5. Conclusion

Today, energy systems are expected to include multiple-energy carriers, such as hydrogen, natural gas, and heat, rather than being dominated by a single-energy carrier, like electricity. With an increasing number of energy carriers in one energy system, multiple-energy carrier devices (MEDs) are also becoming the standard. Managing the resulting interdependencies between MEDs and their respective energy carrier systems is challenging. The proposed control architecture addresses this need and provides adaptability by establishing a three-level hierarchical control architecture with unified data content regarding the inputs and outputs.

The hierarchy levels of the control architecture fulfill specific but not application-bound tasks. Firstly, the system level specifies the operation targets and determines allowed operational state changes based on system constraints. Secondly, the subsystem level supervises the operational points of devices and forms an overall energy carrier-specific operating state. Conclusively, the device level enables device integration and ensures the execution of targeted operations. The data flow between the hierarchy levels only contains the operational state information, informing the overlying level and instructing the level below. This allows system devices to be integrated and exchanged with relatively low effort.

Accordingly, the main contribution of this research can be considered as follows:

- Proposal of an appropriate control architecture designed for facilitated applicability to complex energy systems with MEDs.
- Simplified expandability of a multi-energy carrier system (MES) due to the flexibility of the proposed architecture.
- Facilitated development and mapping of a digital twin of a MES.

The next step in this research is the advancement of the digital twin, which implements the proposed system architecture by integrating operation models regarding the subsystem and device level. Subsequently, the aim is to optimize the operation through the proposed architecture. Therefore, a mathematical description of dependencies between the inputs and outputs can be defined mathematically, e.g., by a coupling matrix to minimize a resulting objective function oblique to the optimization objective of the system. Regarding the complexity of interrelationships between energy carrier systems, optimization is required to address multi-objective problems. For this purpose, typical use cases, e.g., peak shaving and consumption-dependent generation, must be defined and tested in combination. Thereafter, it is necessary to analyse the digital twins operational behaviour in comparison to their real-life counterparts before realizing it as the energy management system for the industrial research platform.

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Biography

Kerim Torolsan (*1992) has been working as a research associate of the Institute for Energy Efficiency in Production (EEP) at the University of Stuttgart since 2022. M. Sc. Kerim Torolsan completed his studies in the field of sustainable electrical energy supply at the University of Stuttgart in 2022 and has a B. Sc. in the field of renewable energies. His research focus is on energy management for industrial energy systems.

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