



## **Concurrent design methods for energy systems**

Lappeenranta–Lahti University of Technology LUT

Bachelor's Programme in Electrical Engineering, Bachelor's thesis

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Examiner: Assistant Professor, Niko Nevaranta

## ABSTRACT

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As society's demand for sustainable energy continues to grow, the design of energy systems is becoming more complex and diverse. The introduction and development of the concurrent design (co-design) concepts allow for easy assessment of the impact and propagation of design decisions made on subsystems across the entire system. Co-design has become increasingly valuable in energy system design as a design methodology that integrates different design target for the overall system design into same framework e.g., simultaneous optimizing control law and physical system dimensions. Generally speaking, control optimization methods and system-level design-optimization have also become key factors in improving the efficiency and performance of energy systems.

In this Bachelor's thesis, first a discussion about the current situation of energy systems design complexity is given and then the development of concurrent design approaches is focused. Here a variety of case studies of systems in different energy sectors where co-design is applied are considered to analyse the practical application of concurrent design, control and optimization methods, and to illustrate the importance and impact of these methods in the design of energy systems. This study seeks to provide a comprehensive understanding and application of the co-design methodology for energy system design, by focusing on current literature and examples presented in them.

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## SYMBOLS AND ABBREVIATIONS

### Abbreviations

AEP	Annual energy generation
BIM	Bridge information modelling
CCD	Control co-design
CHP	Combined heat and power
ES	Energy storage
MG	Micro grid
TS	Thermal storage
WHR	Waste heat recovery
WF	Wind farm
WT	Wind turbines

### formula symbols

$C_t^{CHP}$ : Operating cost of the Combined Heat and Power (CHP) system

$C_t^{boil}$ : Operating cost of the boiler system

$C_t^{HRU}$ : Operating cost of the heat recovery unit (HRU)

$C_t^{TS}$ : Operating cost of the thermal storage system

$C_t^{ES}$ : Operating cost of the Energy Storage (ES) system

$C_t^{PV}$ : Operating cost of the Photovoltaic (PV) system

$C_t^{pena}$ : Other potential costs

$C_{penalty}$ : additional cost incurred due to load imbalance

$C_{inst}^i$ : the value of the installation cost of the component  $i$

$C_{inst\_ub}^{C_i}$ : upper bound value of the installation cost of the component  $i$

$C_{inst\_lb}^{C_i}$ : lower bound value of the installation cost of the component  $i$

$n_i$ : the number of design parameters for component  $i$

$v_{ij}$ : design value of the design parameter  $j$  for component  $i$

$v_{ij\_ub}$ : upper bound value of the design parameter  $j$  for component  $i$

$v_{ij\_lb}$ : lower bound value of the design parameter  $j$  for component  $i$

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# 1 Introduction

The field of energy systems has undergone significant evolution and change over the past few decades, with exponential growth in global energy demand since the end of the 20th century fuelling the development of energy technologies, policies and economic systems (Li, 2023). During this development, both energy systems and their design aspects has become more complex. The design of modern energy systems for instance involves resource management, efficiency optimisation and sustainability challenges. To be more specific, energy system design refers to a comprehensive plan and programme for meeting energy demand. An effective design processes are needed to effectively consider the optimization of production, transmission, conversion and use, improve energy efficiency, ensure the reliability and stability of energy supply, and at the same time reduce environmental impact.

For a long time, traditional approaches applied for energy system design have focused on single-domain expertise and local optimisation, often adopting a hierarchical, single-domain strategy that fails to take into account the needs of multiple engineering disciplines and the cross-cutting impacts of different domains (Robin Mutschler, 2023). This traditional, often also referred as sequential design, approach is inadequate in the face of rapidly evolving energy demands and environmental changes. Entering the era of energy transition in recent years, a dramatic shift from traditional energy source streams to renewable energy sources and from centralised to distributed systems is evident. This shift involves the upgrading and designing of the whole operation at multiple levels, and traditional design methods may not be able to effectively meet these challenges, as they may not be able to fully take into account the interests of all parties and the operation of complex subsystems in the system-of-system design process. Therefore, with the introduction and development of the integrated design approaches, also known as concurrent design (co-design), new design routines have been increasingly applied to energy systems, emphasising the collaborative participation of multiple stakeholders, e.g., focusing on several design aspect simultaneously to find out the most optimal solution.

## 1.1 Concurrent engineering

The concurrent design, or co-design, considered in this thesis is a kind of systematic working mode for the parallel and integrated design of systems and their related processes. Compared with the traditional sequential design, shown in Fig. 1 left concurrent design puts more emphasis on the early stage of product development, requiring product designers and developers to consider all aspects of the entire life cycle of the product (from product process planning, manufacturing, assembly, inspection, sales, use, maintenance to the end of the product) from the very beginning, and to establish the inheritance and constraint relationships of the performance of the product in each stage of the product life cycle, as well as the relationship between the product attributes, so as to pursue the product in the life cycle of the product (Xu, 2007). To pursue the optimal performance of the product in the whole process of the life cycle.

The concurrent design process introduces design constraints at each stage. For example, by considering control principles and functionality at the initial stages, designers can avoid imposing unnecessary or sub-optimal design constraints on the final system. (Garcia-Sanz, 2019). The traditional sequential design, where control design step is the final design step, is shown with concurrent control design (CCD) approach in Fig. 1.

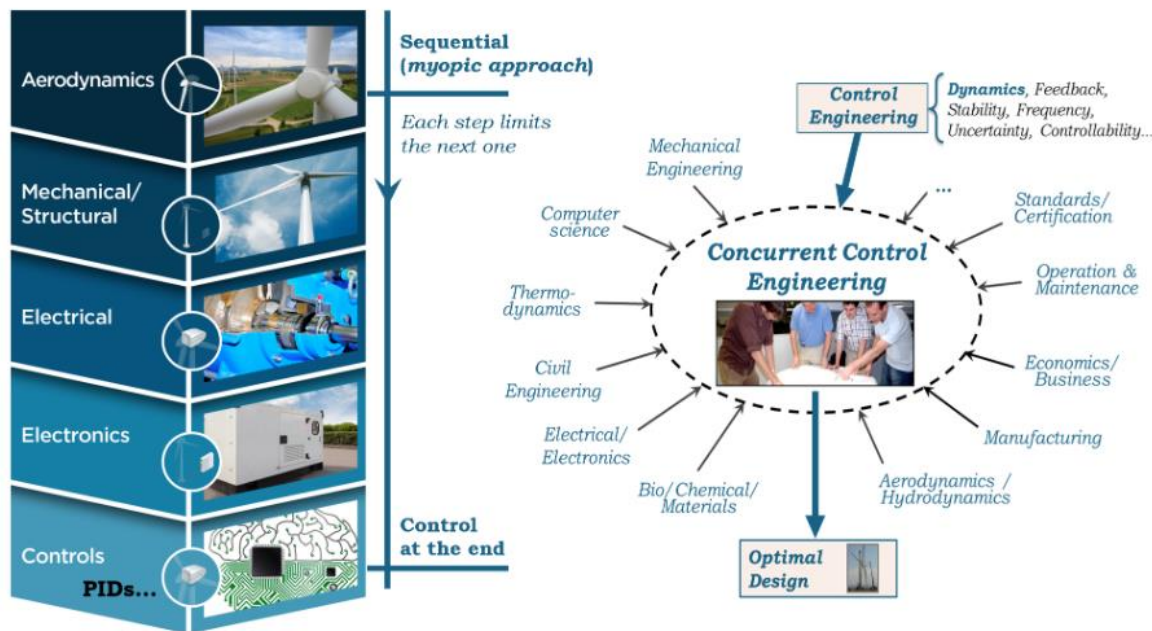


Fig. 1 Sequential and control co-design (CCD) approaches (Garcia-Sanz, 2018)



When looking the traditional sequential approach to design shown in Fig. 1, the design work is typically moved from one engineering team to another in a phase sequence, which can result in a large, inefficient design process and the potential for non-optimal system configurations. In contrast, the concurrent design method shown in Fig. 1 (on right side) simultaneously considers multiple work tasks within the same design framework, aiming to seek the optimal system configuration and allow different engineering teams to work in parallel while collaborating with each other. This work is carried out simultaneously to improve design efficiency and system optimization.

## 1.2 Objects and goals

The goal of this Bachelor's thesis is to make a literature review on the application of concurrent approaches in energy system design problems. The thesis is organized as follows; in the second Chapter of this thesis, the concurrent methodology and principles are explored, and in the third part, the importance and practical application of concurrent design in energy system design through case studies are illustrated. Research objectives include exploring state-of-the-art research results in this field through a literature review, with a particular focus on example cases of thermal and wind energy applications, to show the application of co-design method in their design. By analysing this literature in detail, it is possible to gain an insight into the current achievements of co-design methods in the field of energy systems, and to further reveal their potential value in practical applications, and to explore whether they offer a viable path for future development.

## 2 Survey of concurrent design approaches

This chapter introduces the history and development of the co-design concept, after that the emphasis is on the control co-design areas and some of the applicable methods discussed in the literature for control and optimization of energy system engineering are introduced. The chapter seeks to introduce the main concepts behind co-design approaches.

### 2.1 The history and development of co-design

Unlike the traditional design approach, the co-design approach has been widely applied in different fields like architecture, engineering, software development and product design has shown great potential to provide new ideas and opportunities for energy system design. For example, in the fields of architecture and engineering, co-design methods have been widely used in large-scale infrastructure projects such as bridge and highway design. Among them, the application of bridge information modelling (BIM) technology in bridge construction has greatly improved the efficiency and quality of design, construction and maintenance. (Meng Tao, 2019) Design teams use virtual collaboration platforms to share models, exchange ideas, and resolve design issues in a timely manner to ensure the smooth progress and final successful completion of the project.

The concept of co-design is an interdisciplinary design method whose development history can be traced back to related practices and research in different fields and different time periods. Co-design as a term and approach first emerged in the field of computer engineering and aims to consider the design of hardware and software simultaneously (Kang, 2020). As the complexity of computer systems increased in the 1960s and 1970s, people began to realize that closer collaboration between hardware and software design was needed to improve the performance and efficiency of computer systems. From the late 1970s to the early 1980s, the field of systems engineering began to emphasize the cooperation and information sharing of interdisciplinary teams to achieve comprehensive design and optimization of systems (Andres et al, 2019). Later, there were progress and developments in urban planning, manufacturing industry, industrial production and other fields. From the late 1990s to the early 21st century, design thinking emphasized multi-

party participation and interdisciplinary cooperation to solve complex problems and promote the development of user-centered design. Nowadays, with the popularization of sustainable energy and the rapid development of digital interaction, co-design has innovated, opened up new markets, and provided broader and more convenient application scenarios (Neven Duic, 2023). Nowadays, collaborative design covers a very wide range of fields. In this thesis, the application of collaborative design and system control and optimization design concepts and methods in energy systems are emphasized. The Figure 2 shows the relationship between the three within the framework of control co-design (CDD).

When considering the terms given in the Fig. 2, the co-simulation refers to multiple teams working together to simulate systems and integrate knowledge from different fields. On the contrary the co-optimization is to cooperate on multiple design variables and objectives to find the optimal solution of the system design space. The control inspired paradigms utilize control methods based on experience and heuristic algorithms to develop control strategies for the system. Both of these concepts are often related to each other. Co-simulation uses computer science and technology to provide a foundation for collaborative optimization. Co-simulation results based on mathematical operations help to better understand the design space. Co-optimization and simulation results are fed back into the control inspired paradigm combined with engineering applications to develop smarter control strategies. The input of system design includes system objectives, component pre-design, physics-based models, real data and case study.

Through a co-approach, teams work together to select and adapt design inputs to ensure that the needs of multiple disciplines are met, enabling a more comprehensive and coordinated system design. This collaboration fosters the sharing of expertise and interdisciplinary innovation, helping to identify and address potential design challenges. During the process of selecting design inputs, the team worked intensively to better understand the strengths and limitations of each discipline, responding quickly to feedback and optimising design solutions to ensure that all aspects of the system were considered holistically. This collaborative approach not only enables optimisation of the system design, but also improves the efficiency and effectiveness of teamwork, laying a solid foundation for the successful implementation of complex projects.

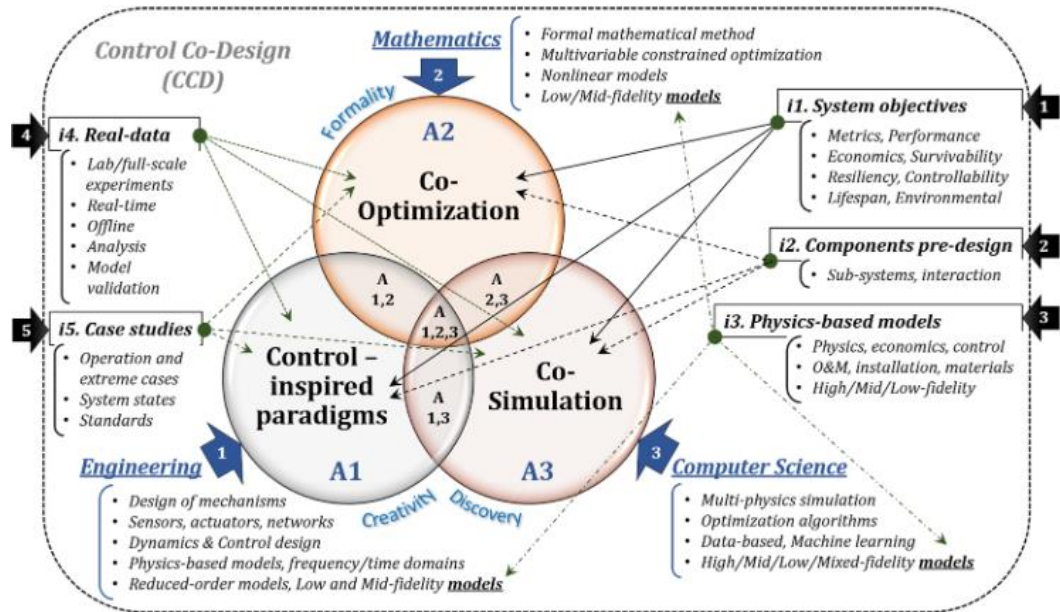


Fig. 2 Control co-design areas (Garcia-Sanz, 2019)

The industrial design problems are easier to understand by taking an illustrative example case. For instance, in the case of automobile design and manufacturing, if the traditional sequential design method is used instead of coordinated design, it may lead to severe obstacles and limitations in the design process. The main limitation would be so-called information islands between design departments: engine engineers, body designers, electronic system engineers, etc., are each responsible for the design of different parts. Due to lack of collaboration and communication, various departments may not be able to effectively share information. The next would be the outcome of incomplete system optimization. The body design may pursue the best aerodynamic performance, but this may affect the engine cooling effect, and these problems may occur in each department. Departments working independently are ignored. Next obstacle could be different type of design conflicts and duplication of work. A certain department may make changes to a specific design of the vehicle, but this change may conflict with the designs of other departments and require adjustments, adding additional time and resource costs. This in turn leads to low efficiency and lack of innovation in the design process. In contrast, the collaborative design method integrates the professional knowledge of various departments, allows joint discussion and solution of problems, and improves the overall quality and innovation of the design. This simplified example already highlights the importance

carrying out design process simultaneously in order to find out the most optimal system solution as a design outcome.

## 2.2 Control and optimal system design

Control engineering is the application of mathematics, physics, and technology to the autonomous control of dynamic systems. In the traditional system design process, control system design is usually placed as the last step in the design. This is because the performance and parameters of the control system often depend on the characteristics of the physical system, and these characteristics need to be specified in the early stages of design. Sequential design discussed above focuses on the components and structure of the physical system to ensure that they meet the requirements of the system as a whole, before considering the details of the control system. However, the concept of co-design emphasizes that the “control system” and “physical system” can be designed simultaneously without waiting for the individual components of the physical system to be determined.

Such a co-design example is discussed in (Haemers, 2019), where the control loop is designed simultaneously with a mechanical system using multi-objective optimization methods to find a balance between implementation cost and achievable performance. In the proposed framework this is achieved by changing the control architecture and finding the optimal configuration for the closed loop controlled mechanical system by evaluating Pareto front solutions. This kind of parallel co-design approach allows a preliminary framework for the control system to be established early in the design and coordinated with the design of the physical system. This greatly improves system efficiency. (Wei Sun, 2020) When considering the basic concept of the feedback controller applied for dynamic system to be controlled can be summarized based on the Fig. 3 below. In the co-design framework the control algorithm along with the physical system can be considered simultaneously.

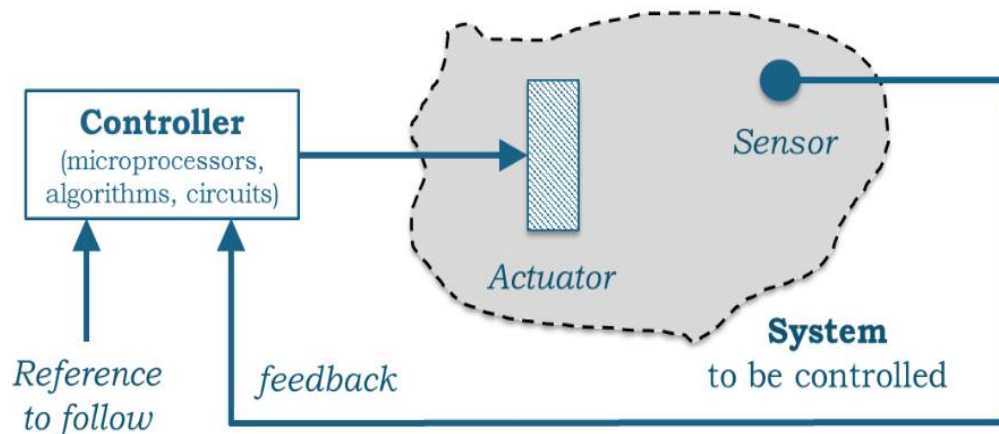


Fig. 3 Feedback control system (Garcia-Sanz, 2018)

When considering system optimal system design, the control will also have an important role in its performance. As an example, assuming that in a thermal storage plant, to maintain the reactor at a specific temperature or its product output at a target purity, a proportional integral derivative (PID) controller (Åström KJ, Hägglund T, 1995) is commonly implemented. Although these controllers have proven solutions, they cannot provide any guarantees of optics or stability because they are empirical and not model-based. Optimization is very important and an indispensable link in the entire design process and can be done for a late stage augmented control system, but often optimization by concurrent design of control and physical system will lead to better outcomes (Garcia-Sanz, 2018). In fact, the selected closed loop control methods play a crucial role in designing the inputs and outputs objectives for the overall process optimization problem. In the application of co-design in energy systems discussed in this thesis, the environment, system objectives, system requirements, and candidate components are often the input objects that need to be considered. The corresponding output results involve the optimization of the system, architecture, plant design, and control design.

Concurrent conceptual design, often mentioned in control engineering, is a sub-discipline of concurrent engineering (Salas et al, 2020). It is actually a set of extensive methodologies that refer to the integration of work in engineering activities. Numerous process systems entail the functioning of multiple parallel units or subsystems interconnected through the exchange of energy or material streams, often in the shape of shared resources (Jose & Ungar, 2000; Martí et al., 2012; Stojanovski et al., 2015; Wenzel et al., 2016). As an illustration, within extensive industrial operations, a shared power plant might supply

steam to various sub-processes (Stojanovski et al., 2015). In this case, the typical approach involves breaking down the problem into smaller parts and optimize each sub process separately for various purposes. For example, compared to large-scale centralized optimization, adopting distributed decision-making tools is usually easier to manage and sustainable (Dirza, Risvan et, 2022).

Optimal design is a systematic approach that aims to adjust various aspects of a system, product, or process to achieve optimal results or meet specific goals. System optimization is used in the cases that are later on discussed in the Chapter 3, which uses mathematical and engineering principles to improve efficiency, performance or meet specific conditions by finding the best solution. This includes clearly defining goals, building mathematical models, finding optimal solutions, evaluating results, and continuously improving the design.

The optimization process is based on the actual operation of the energy system, through adjustments and improvements, in order to achieve more efficiency, reliability or other specific goals. Energy system engineering takes mathematical optimization as its core and systematically makes decisions on the design and operation of energy systems from nanoscale to mega scale in a time range from milliseconds to months or years, and quantitative analysis (Floudas, 2016). Energy systems engineering has been successfully applied to optimize design and operation in various fields, such as the production and distribution of fuels and chemicals (Josephine A, 2012), conventional and unconventional oil production (Siddhamshetty et al., 2018), and urban energy systems (Maréchal, 2014). In the optimization process, a large amount of data analysis and the establishment of mathematical models are required, and the next step of the system is decided based on experience and actual status.

### 3 Case analysis

In this Chapter, the thesis will provide an overview of a case model of co-design methods in energy systems, focusing on mathematical and physical perspectives. At first a thermal energy example case is selected, wind energy and electric energy as representative energy forms in order to comprehensively consider the integration and optimization of multiple energy sources.

The analysis of energy systems relies on the support of mathematical models. Through parallel design, mathematical models of energy system optimisation problems can be developed at an early stage of design, covering many aspects of energy, including thermodynamics, fluid dynamics, electricity, and mathematical expressions in other related fields. The integration of concurrent design concepts enables to comprehensively consider various design aspects represented by mathematical models, thereby gaining a deeper understanding of the dynamic characteristics and performance parameters of energy systems. Through this method, system or subsystem parameters can be optimized by exploring the best solution among multiple possibilities.

From a physical perspective, the design will focus on the interactions between different energy forms in energy systems. Co-design methods allow multiple energy sources such as thermal, wind and electrical energy to be considered comprehensively within the same framework. For example, in a system that integrates thermal energy and electrical energy, the conversion efficiency of thermal energy to electrical energy can be analyzed to predict key configuration design costs. In the combination of wind energy and electrical energy, factors such as heat loss in wind power generation can be considered to achieve energy efficiency. Trying to maximize utilization and design systems for lowest cost assumptions. Under the framework of co-design method, the complementarity of different energy systems can be optimized and the efficiency of the overall energy system can be improved. Optimal system configurations can be found to meet the need for efficient and sustainable energy systems.



### 3.1 Combined heat and power hybrid energy system

A combined heat and power (CHP) hybrid energy system is an integrated energy utilization system that combines the generation of heat and electricity and meets multiple energy needs in an efficient manner. The system is often based on the principle of jointly producing heat and electricity, resulting in more efficient performance in terms of energy utilization. (Luo, 2023) Such hybrid energy systems typically include cogeneration units that can produce both heat and electricity. In cogeneration processes, waste heat is often recovered to provide additional heat energy, improving the overall energy efficiency of the system.

The co-design method can be applied to the heat and power hybrid energy system, while combining system component design and operation control optimization to consider potential destructive scenarios in advance. In the CHP model, mainly focusing on solving two sub-problems, which are interdependent. The first thing to solve is the control and optimization of the microgrid (MG) system, and then consider the key configuration components of the design system. Next, a simplified optimization example is considered, where the ultimate goal is to reduce the total system cost and improve efficiency through the collaborative design framework. The following formula can be used as a starting point to solve practical problems

$$\min C_{operation} + C_{install}, \quad (3.1)$$

where  $C_{operation}$  is the cost function describing the operation costs and  $C_{install}$  function describing the installations costs. By minimizing this total cost function, the optimal solution can be found within the framework of collaborative design.

#### 3.1.1 Control and optimization of the microgrid system

The CHP microgrid system is a comprehensive energy utilization system that organically combines the production of thermal energy and electric energy. Distributed energy

resources can include renewable energy devices such as solar panels and wind turbines, enabling the joint production of electricity and heat by combining these energy sources with traditional energy sources such as gas or biomass fuels. Waste heat recovery (WHR) devices are used to capture and reuse waste heat generated during electricity generation, converting it into useful thermal energy. The Fig. 4 details the application of energy equipment in hybrid energy systems

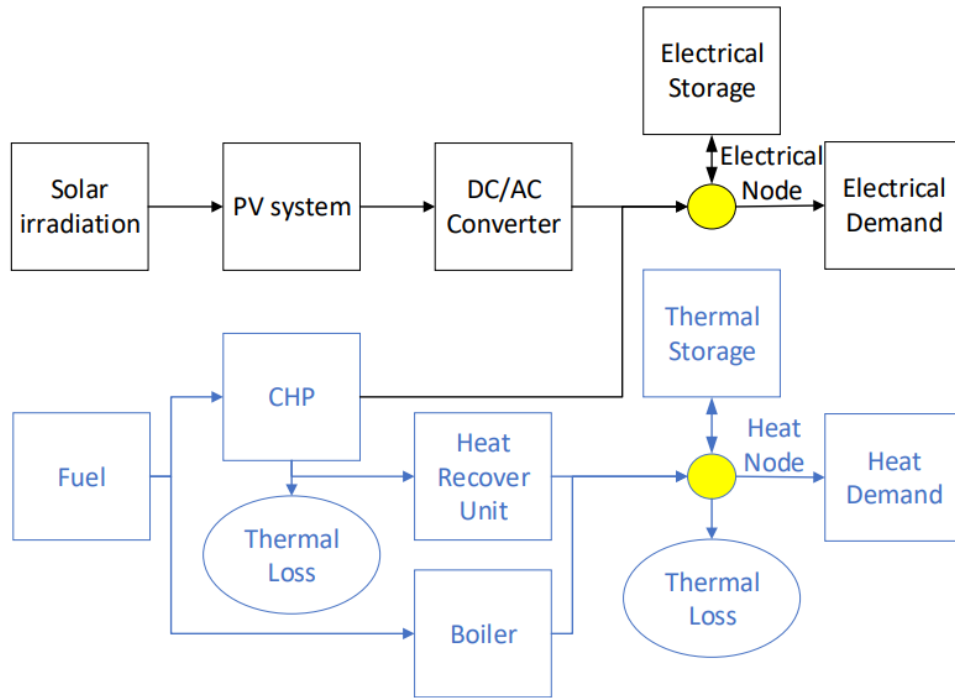


Fig. 4 Configuration of a CHP based MG model (Jiaxin,2021)

In cogeneration-based microgrid (MG) systems, finding the best combination to minimize daily production costs usually involves the optimization of an objective function. This objective function can be expressed as the sum of hourly costs. Assuming that the hourly cost is determined by factors such as power generation, heat recovery, and energy purchase, the objective function can be expressed as the following equation

$$\min C_{operation} = \sum_{t=1}^{24} (C_t^{CHP} + C_t^{boil} + C_t^{HRU} + C_t^{TS} + C_t^{ES} + C_t^{PV} + C_t^{pena}), \quad (3.2)$$

where  $C_t^{CHP}$  is the operating cost of the combined heat and power (CHP) system,  $C_t^{boil}$  is the operating cost of the boiler system,  $C_t^{HRU}$  is the operating cost of the heat recovery unit (HRU),  $C_t^{TS}$  is the operating cost of the thermal storage system,  $C_t^{ES}$  is the operating cost of the Energy Storage (ES) system,  $C_t^{PV}$  is the operating cost of the Photovoltaic (PV) system, and  $C_t^{pena}$  means Other potential costs.

To initiate the operation of the combined heat and power system, the operating status of each component is monitored according to the specified target formula. It is essential, within the framework of the concurrent design concept, to not only consider the CHP's operation but also comprehensively evaluate the on and off status of each component in the microgrid. The CHP-based MG model is composed of six key components: CHP, boiler, heat recovery unit (HRU), thermal storage (TS), energy storage (ES), and photovoltaic (PV) system. The flexibility to switch the operating status of these components in response to varying conditions is a crucial aspect of MG design. Activation of each component incurs additional operating and maintenance costs. Hence, in instances of excess power generation within the MG, strategically shutting down specific components becomes a beneficial strategy to mitigate overall costs. It's noteworthy to mention that the target formulas for monitoring the operating status are derived from a comprehensive understanding of the system and its components, ensuring a systematic approach to achieving the desired operational outcomes.

From a co-design perspective, synergies between components need to be considered to achieve more efficient energy use. For example, if at a certain point in time the PV and the boiler can be more cost-effective in meeting the power and heat demand, then consideration can be given to decommissioning the CHP to reduce the overall cost while maintaining the demand. This integrated approach to considering the state of each component helps to optimise the operation of the MG and achieve the goal of co-design.

In the co-design model, in addition to running the formulas for the above components, the heat and electricity demands in the microgrid need to be met in an optimal manner. In the microgrid, heat loads are provided by CHP, boilers and TS, and electricity loads are provided by CHP, PV and storage systems.

During the online operation of the microgrid, if the total calorific value or total power generation is insufficient to meet the needs of the MG, then load imbalance will occur,

represented by  $t$ . To alleviate the shortage, electricity needs to be purchased from the main grid, which will result in additional costs. The additional cost value can be calculated using the following expression

$$C_{penalty} = \max(0, -t) \times \text{Penalty Rate}, \quad (3.3)$$

where  $C_{penalty}$  represents the additional cost incurred due to load imbalance, and the Penalty Rate is a parameter that influences the cost calculation. The expression  $\max(0, -t)$  ensures that the penalty cost is only considered if there is a deficit ( $t < 0$ ), avoiding negative penalty costs. The operation of each component in the MG needs to be carefully managed to avoid load imbalance to the greatest extent and reduce dependence on the main grid, thereby reducing additional costs.

By considering potentially disruptive scenarios, optimal solutions for designing MGs and dispatching thermal power generation can be derived. This method helps to make the system more resilient to adapt to emergencies that may occur in actual operation and improve the system's robustness and reliability.

### 3.1.2 Components Design

In (Dongze, 2021), the second optimization subproblem of the design of a microgrid system based on CHP, involving the case with heterogeneous components, will be discussed in detail. Each component has a set of design parameters that will greatly affect its performance during the operational phase. In (Dongze, 2021), the goal is to optimize the system design parameters related to the installation costs of different systems. Calculation of the average normalized rate of change over the design parameter range for a given component  $i$ , the result of which is used to measure the relative change in component installation cost with respect to the parameter range. This can be expressed as

$$\frac{C_{inst}^{C_i} - C_{inst\_lb}^{C_i}}{C_{inst\_ub}^{C_i} - C_{inst\_lb}^{C_i}} = \frac{1}{n_i} \sum_{j=1}^{n_i} \frac{v_{ij} - v_{ij\_lb}}{v_{ij\_ub} - v_{ij\_lb}}, \quad (3.4)$$

where  $n_i$  is the number of design parameters for component  $i$ ,  $v_{ij}$ ,  $v_{ij\_ub}$ , and  $v_{ij\_lb}$  represent the design value, upper bound, and lower bound, respectively, of the design parameter  $j$  for component  $i$ . Similarly,  $C_{inst}^{C_i}$ ,  $C_{inst\_ub}^{C_i}$ , and  $C_{inst\_lb}^{C_i}$  are the value, upper bound, and lower bound of the installation cost for component  $i$ , respectively. According (3.4), the installation cost can be calculated, using the min-max normalization technique (Patro, 2015). The design parameters and the installation cost values of the components are mapped to the range of  $[0, 1]$ , ensuring that the design of each component is in the same. Under the premise of evaluating under the scale, corresponding to this formula, it is assumed that all parameters are positively correlated with the installed cost, i.e. the larger the module capacity, the higher the cost is usually. The co-design model can be optimized to obtain optimal design parameters as well as thermal/generation dispatch by minimizing the total cost shown in equation.

Mathematical computer software tools, in this case Matlab, are used to simulate and solve models. By formulating a mixed integer programming model, the system minimizes production, operation/maintenance, startup and unsatisfactory loading costs. According to the combination formula, it is found that the proposed collaborative optimization model is suitable for MG in both cases. The results show that the model can effectively solve the collaborative design problem, improve system reliability, and reduce potential risk losses while considering interruptions.

The subproblem of the first optimization and the system design parameters of the second are dependencies, which can be addressed iteratively by concurrently solving both suboptimization problems as a whole. Given that the design and operational control parameters contribute various cost items within the total cost, the objective of co-designing the model is to identify the most cost-effective solution while taking into account different design and operational constraints.

### 3.2 Wind power joint system

Due to concerns about climate change, there is an ever-increasing need to introduce abundant and free renewable energy resources into mainstream power generation systems (Vine, 2008). This plays a key role in promoting the development of global sustainable

energy, addressing climate challenges, and realizing the large-scale application of clean energy.

The booming growth of the global wind energy market provides important opportunities for reducing greenhouse gas emissions. However, the changes and intermittency of wind energy span multiple time scales, which requires careful integration of these energy resources into the power system to avoid issues of mismatch with grid demand and related grid reliability (Aziz, 2022). Social concerns about local renewable energy and energy storage systems have led to the postponement or even cessation of some planned projects. To address this challenge, a widely defined collaborative design approach is proposed to comprehensively consider various factors of wind energy at multiple levels, including society, technology, economy, and politics. This method can provide a more comprehensive and coordinated solution to the current problems. The Fig. 5 reflects well how to build a collaborative design framework to solve this kind of problem.

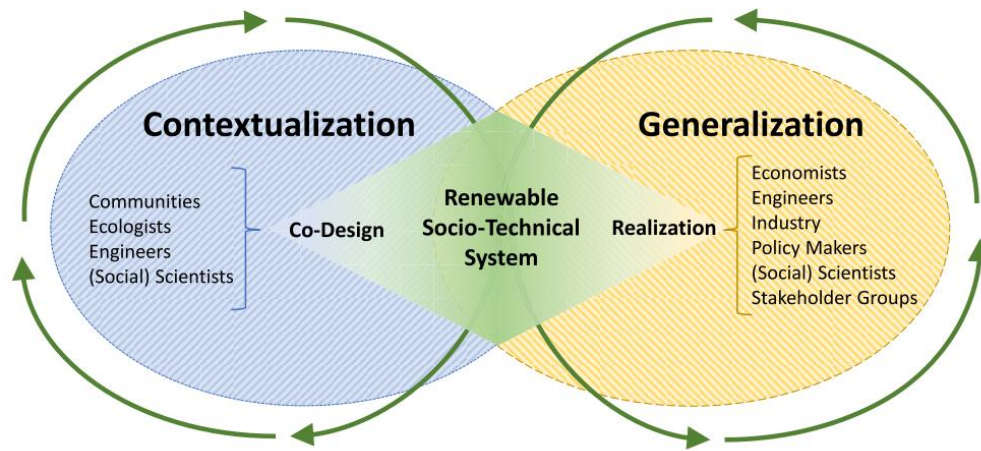


Fig. 5. Framework for renewable socio-technical system (Aziz, 2022).

This kind of multi-dimensional co-design approach can address interrelated coupling challenges, including cost, technical readiness, system integration, as well as social considerations of acceptance, adoption, and fairness.

### 3.2.1 The connection between wind energy and electricity

In wind energy storage integrated systems, there is a close correlation between wind energy and electrical energy. Firstly, wind energy is converted into electrical energy through wind turbines. However, often it is the case that the generation of wind energy is unstable and influenced by weather and climate conditions. Therefore, the variability of wind energy directly affects the performance and operation of storage systems. To overcome this variability, storage systems become a critical component, allowing excess wind energy to be stored for release when needed. An efficient energy storage system can ensure the effective release of stored electrical energy when needed. In addition, in order to balance the supply and demand of the power grid, it is necessary to dispatch and manage the system (Meliani, 2021). The correlation between wind energy and electricity requires effective system scheduling to ensure the balance of the power grid. This scheduling involves the storage system releasing or storing electrical energy at different time periods to meet the demand of the power grid load. So, wind energy and electricity form interdependent ecosystems in integrated storage systems, and various factors need to be comprehensively considered to ensure the efficient operation and sustainable development of the system.

The combination of wind and electricity physical models forms a collaborative design framework, with natural environment, wind resources, and other factors as system inputs. The sensitivity of the power grid can affect system balance, and the interference between power generation and load may cause significant fluctuations in grid frequency. Through the designed co-control framework, the system outputs optimization results, making wind power generation systems using concurrent design more practical than traditional sequential wind power generation systems (Garzia-Sanz, 2018).

According to the basic knowledge of the power system, it can be clearly analyzed that if the power grid frequency fluctuates greatly, it may lead to load shedding and power outages, which directly affects the operation of power grid customers. The power market will implement coordination based on the operation results, and ultimately ensure that interests are not compromised. In this way, compared with the first case analyzed in this thesis, the ultimate goal is to ensure the final profit and achieve a balance between the economy and the energy system.

### 3.2.2 Results of joint control optimization

Improving power production from wind farms (WF) has been a key issue. The aerodynamic interaction between WF wind turbines (WT), the wake effect is proven to be one of the main causes of energy loss in offshore WF (Boersma, 2017). To mitigate the wake effect and improve energy output, research in recent years has focused on WF layout design and collaborative control. One major approach is to place turbines further away from the prevailing wind direction. Cooperative control, on the other hand, aims to minimize wake losses by cooperatively operating turbines throughout the WF (Chen, 2021). Research on these two methods has attracted widespread attention to achieve control optimization of WF. In order to find the optimal design of the system, layout optimization should consider co-design method.

Considering the interdependence between wind energy and electrical energy, the case is examined through mathematical models in (Gao, 2016). Conventional isolation layouts or control optimizations typically employ heuristic algorithms. Nevertheless, these heuristic methods are limited by issues such as slow convergence and escalating computational burdens, leading to prolonged optimization times and increased costs. In the case of a two-stage joint optimization model, intricate factors like wind direction angle distribution must be taken into account (Bastankhah, 2016). Consequently, the algorithm's structure needs to factor in the hierarchical and decomposable nature of the problem.

The complexity of mathematical models makes the analysis results more direct towards the goal of this article. In (Chen, 2021), 180 scenarios with finer wind direction resolution and obtained different annual energy generation (AEP) results. In Table 1 the results of the studied cases are presented, showing the Annual Energy Production (AEP) for various optimization scenarios in an 80-wind turbine wind farm with 180 scenarios



Table 1: AEP Results of Various Optimization Cases for the 80-WT WF with 180 Scenarios (Yiwei, 2021)

Case	Layout	Operation	AEP(GWh)	Improvement
1	Initial	Greedy	1981.1	–
2	Initial	Optimized	1998.1	0.86%
3	Optimized	Greedy	1999.9	0.95%
4	Optimized	Optimized(sequent)	2015.2	1.72%
5	Optimized	Optimized (Joint)	2022.9	2.11%

In cases 2 and 3 presented in Table 1, the WF layout and operation were optimized separately. On the contrary, the case 4 was optimized in sequence without considering potential synergies. Sequential optimisation is a traditional optimisation approach commonly used in energy systems. In order to efficiently solve complex interrelated problems in energy systems, a sequential optimisation approach is adopted, where the subproblems are solved sequentially in a certain order. In this model, the large-scale joint optimisation problem is decomposed into many small-scale individual scenario subproblems and simple coordination problems. These subproblems are independent of each other and can therefore be solved jointly or sequentially in an efficient manner. Sequential optimisation in Case 4 refers to the incorporation of continuous feedback and iterative mechanisms between layout adjustment and operational optimisation. Specifically, in the case 4, it is first assumed that the greedy WT operation is the same as case 3, and then optimize the topology, and after that optimize the control based on this optimized layout. In addition, this sequential optimization method did not fully consider the potential synergies between layout and operation. In Case 5, joint optimization is introduced to more fully consider the interrelationship between layout and operations.

When it comes to wind farm design, jointly optimizing yaw and layout is a strategic approach that can significantly improve average annual electricity production (AEP). The results based on the Table 1 show that when evaluating 180 scenarios, the improvement in layout optimization is smaller because more power production from different wind directions is considered and balanced. Improvements in AEP are mainly achieved through

control optimization. However, the general trend across different optimization cases has not changed, that is, both layout and control optimization can improve AEP. Joint optimization still performed best, with AEP increased by 0.38% compared to sequent optimization. After the introduction of control optimization, the improvement of AEP is more significant, emphasizing that when the turbine layout is relatively reasonable, higher power generation efficiency can be achieved by more effectively adjusting the yaw direction of the turbine. In fact, the study highlights the importance of joint optimisation to obtain the WF layout, which indirectly reveals the synergistic effect of WF layout and operation, suggesting that the synergistic effect of both layout and operation can be taken into account in the design of wind farms to significantly improve the performance, and providing a useful guideline for the design of future wind farms.

When considering this case model and the co-optimization problem, the wind energy and electrical energy represent two physical models in the energy system, which are combined with each other. The wind farm data, wind turbine parameters, geographic and environmental data, and parameters of the optimisation algorithm are used as inputs to the system, and the optimal wind farm layout and the percentage of AEP improvement are used as outputs of the system, and the concurrent control design approach is used to make the optimisation model contrast with the original sequential model. The system optimisation should refer to the actual results, and the data in this case just like Table 1 can provide a good proof. These data also provide the basis for future work on how to for instance address the transport and maintenance costs of wind farms.

## 4. Conclusion

This bachelor's thesis focuses on concurrent design method applied in energy system design. With the rapid development of technology in today's society, the design of energy systems has become more and more complex. This complexity requires the system to adopt a comprehensive approach that is not limited to traditional areas of specialisation and local optimisation methods. Concurrent design approaches are one of the aspects that need to be studied in depth to be able to optimize physical system and controllers simultaneously. With the development of energy systems, the integration of renewable energy, the combination of electricity and other sustainable energy sources, etc., there is an increasing demand for flexible concurrent design approaches. The application of concurrent co-design methods in energy systems aims to solve the balance between system complexity and performance requirements.

This thesis reviews the current state of the art in this field through a literature review. Furthermore, the focus of this study revolves around two illustrative case studies; I) combined heat and power (CHP) hybrid energy system and II) wind power joint system. The first studied case of the microgrid system proves the effectiveness of the co-design model. The model optimizes six MG key components. After determining the component parameters, reduces costs to the greatest extent, improves system reliability, and also greatly reduces potential risks caused by possible losses. This demonstrates the potential of overall system optimization through concurrent design methods when facing complex energy systems.

In the case of wind energy example, the implementation of collaborative control methods has successfully solved the challenges caused by traditional sequential layout optimization, especially the wake effect, and the joint optimization method has significantly improved the average annual power generation (AEP). However, the most practical consideration for the operation of a system is cost. In the case of wind farm layout, the accompanying problems are increased transportation and maintenance costs and more complex yaw angle algorithms.

The development trend of today's energy system is to find more innovative solutions in the field of concurrent design. The increased level of (control) intelligence and automation has

put forward highly dynamic requirements for the energy production and use of electricity. The energy systems of the future will involve aerospace, automotive and other sectors, the maximising efficiency, reducing carbon emissions and achieving sustainability will require systems that can adapt quickly to change and operate efficiently. Concurrent co-design will play a key role in addressing these dynamic challenges. It will provide a solid foundation for the realisation of clean, efficient and sustainable energy.

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