

Transition Requirements in the Need for Deep Decarbonization of Modern Energy Networks

Mohammadreza Daneshvar^{1*} and Mahdiah S. Sadabadi²

¹ Laboratory of Multi-Carrier Energy Networks Modernization, Faculty of Electrical and Computer Engineering, University of Tabriz, Tabriz, Iran

² Department of Electrical and Electronic Engineering, The University of Manchester, Manchester, UK

*Corresponding author: m.r.daneshvar@tabrizu.ac.ir

List of Acronyms

CESN	Climate–energy–sustainability nexus
EVs	Electric vehicles
MENs	Modern energy networks
RESs	Renewable energy sources

1.1 Introduction

In recent decades, industrialization has accelerated the growth of energy consumption by automating most services as well as improving the quality of life with energy-dependent devices [1]. As such changes denote the positive impacts of recent evolutions, another side of this transformation has brought tremendous challenges for the secure operation of power systems [2]. The stable and secure exploitation of the electrical power grid requires a dynamic establishment of balance in the amount of power production and consumption. The initial step for the above-mentioned balance is to ensure that the power generation matches its consumption. However, relying on fossil fuels with environmental emissions is no longer acceptable for modern societies, given advanced technologies in clean energy generation and governments' net-zero targets. As the main backbone of energy generation in modern energy networks (MENs), renewable energy sources (RESs) are considered as the overarching option

for implementing carbon-free plans in the energy world [3]. However, their impacts are not limited to delivering clean energy, and intermittencies in their outputs threaten the sustainable development of the system [4]. This is while achieving a sustainable structure for MENs is further prominent to make the system able to provide continuous energy dispatch. On the other hand, supplying energy without interruptions is a necessity for serving high-quality services for end users. RESs challenge this task by fluctuating power, which creates uncertainties in the energy generation sector. Modern management schemes and capable energy strategies are indispensable to increasing the reliability index of energy supply. Hence, in addition to the sustainability factor, different energy services should also be taken into account in manipulating modern functionalities for future energy infrastructures. Nonetheless, the world witnesses substantial changes in the climate that trace back to human activities. Herein, how energy grids need to be developed directly affects the intensification of climate change. Recent experiences have discovered the negative impacts of constructing traditional power plants with fossil fuels on climate change factors. However, new policies emphasize relying on environmentally friendly ways for procuring the energy requirements of societies. As severe changes in climate are possible due to the rapid advancements in various technologies, accounting for climate change factors in modernizing energy grids is critical for reaching a zero-emission globe. Therefore, the nexus of climate, energy, and sustainability is vital in grid modernization. For this aim, this chapter covers the different dimensions of the need for the deep decarbonization of MENs for the climate–energy–sustainability nexus (CESN). It provides a general overview of this need, concentrating on clarifying the transition requirements.

The current book focuses on bridging gaps for the deep decarbonization of MENs for the climate-energy-sustainability nexus. It consists of fourteen chapters. Chapter 1 assesses the transition requirements for deep decarbonization of MENs. It also studies how deep decarbonization can facilitate reaching a carbon-free world with zero-emission energy structures. Chapter 2 analyzes the tight nexus of climate change, energy, and sustainable development by using the key role of demand response programs. This chapter also proposes a comprehensive framework and intends to support progressive development by developing a hierarchical process of activities and strategies. Chapter 3 delves into the impact of deep decarbonization on digitalization and industrialization of modern energy societies. It also examines the effects of digitalization on enabling real-time monitoring, applying control mechanisms for emission reduction, easing incorporation of advanced systems, and increasing efficiency. Chapter 4 inspects the creative practices, changing mindsets, and interaction of developing technologies for the climate-energy-sustainability nexus. It also explores the demand-side flexibility and promotes a unified strategy for sustainable and resilient net-zero energy grids.

Chapter 5 reveals energy justice and security by assessing nexus frameworks of climate-energy-sustainability to realize low-carbon societies. It also evaluates the impacts of key strategies like smart homes, electric vehicle deployment, and renewable energy adoption on energy justice and security. Chapter 6 concentrates on investigating energy storage pathways for the nexus of climate-energy-sustainability to facilitate deep decarbonization. It also examines the decline in operational emissions under the support of storage usage in the energy grid. Chapter 7 scrutinizes practical strategies for carbon dioxide removal in line with the realization of deep decarbonization. This chapter also presents several practical and implemented examples to discuss the effectiveness of the mentioned strategies. Chapter 8 covers investigations of technological innovations in the resilient operation of decarbonized communities. It also assesses energy diversification metrics to give applicable insights for policymakers. Chapter 9 accommodates AI techniques for carbon removal of MENs. It also explores AI's role in deep decarbonization and its indirect and direct applications, as well as covers carbon sequestration, utilization, and capture. Chapter 10 analyzes intelligent cyber-physical systems in deep decarbonization of MENs. It also highlights the creation of smart decision-support units by incorporating large language models and digital twins. Chapter 11 argues how quantum-augmented and cybersecure digital twin architectures can participate in deep decarbonization by using smart cyber-physical energy systems. It also contributes to comprehensive threat analysis and mitigation, as well as secure optimization of smart grids. Chapter 12 evaluates sustainable deep decarbonization of MENs by innovating carbon capture cycles for the power system with resilient and zero-emission features. It also evaluates exergy and energy for discovering thermodynamic losses and clarifies potential improvements in energy exchangers. Chapter 13 presents policymaking models to remove carbon under the CESN structure. It also reviews the capability of various methods such as game theory, agent-based modeling, mathematical programming, data-driven approaches, and life cycle assessment for CESN in the MEN. Finally, Chapter 14 assesses real-world case studies for CESN in the deep decarbonization of the MEN. It also examines how CESN can drive sustainability and climate in low-carbon transitions.

1.2 The Necessity for Deep Decarbonization

Nowadays, decarbonization activities are more sensible in practice due to the growing trend of deploying RESs and the relevant supportive technologies [5]. However, the breadth of energy-consumed activities has highlighted the essentiality of not restricting decarbonization objectives to specific levels and sectors [6]. Such an approach drives decarbonization endeavors to much deeper

dimensions of effective parts. The deep decarbonization in the energy area forces substantial shifts of the system in both energy demand-side profiles and energy production portfolios [7]. The new policies also strengthen this shift by incentivizing RESs usage, aiming to mitigate the carbon intensity of energy generation [8]. Achieving the significant alleviation of climate change is also another key motivation for transitioning towards the deep decarbonization of MENs [9]. To reach deep decarbonization of the energy world, different solutions are widely assessed and implemented in practice, yet, which indicate multiple aspects facing this trend in the research community. The main one implies the high deployment of RESs and benefits various types of them for clean energy harvesting. However, intermittent power generation, particularly with an uncertainty feature, has made RESs as a challenging option for sensitive goals. RESs impose more operational costs on the energy system for securely integrating the grid, as energy balancing should be done in their presence [10]. Herein, RESs, such as onshore and offshore wind energy as well as solar, have a role as predominant sources for supplying carbon-free energy and play a central role in managing renewables fluctuations under different decarbonization constraints [11]. However, endeavors for decarbonization are not limited to RESs alone, and multidimensional pathways are being developed around the globe to ease the reach of deep decarbonization goals. Some of the prominent pathways are demonstrated in Figure 1.1 [12].

As shown in Figure 1.1, different urgent pathways are considered for Canada to reach deep decarbonization goals. Grid flexibility enhancement is one of the most crucial ones that concentrates on tight flexible ways, like energy storage systems, for tackling the intermittencies in renewables' outputs. However, energy storage technologies are not just intended for the grid-level applications, and their vehicle-scale versions are targeted to be developed in line with decarbonization principles. As one of the effective sectors in the grid, the transportation area is expected to undergo changes in using carbon-free fuels that mostly rely on hydrogen and advanced biofuels. In the decarbonization path, exerting low-carbon techniques should not be restricted to special parts, and advanced extraction techniques can be applied for oil sands, such as solvent extraction. These approaches can also be developed for various carbon functionalities to enable the modern grid for carbon capture, production, extraction, storage, conversion, and utilization. Given that the industry is at the point of huge energy consumption, such carbon functionalities can be adopted with other practical green technologies to reduce the portion of the industry in CO₂ release. Herein, CO₂ process sinks can be developed in a way to be optimally integrated with diverse carbon functionalities for affordably optimizing processes. A set of the mentioned tools empowered the energy network to shape zero-emission processes to harness the carbon release of various areas.

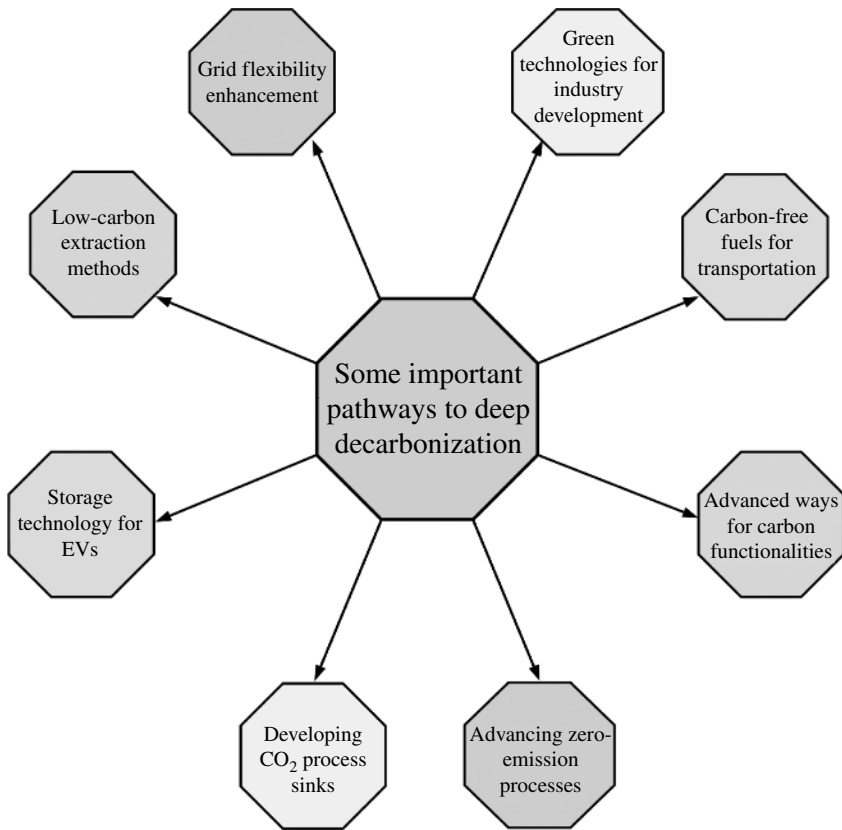


Figure 1.1 Some of the prominent pathways for deep decarbonization.

1.3 CESN Framework and Connections

Nowadays, climate change has been accelerated, particularly under human-origin activities. The increasing need for energy has been highlighted in the present style of human life that mostly depends on energy-consuming equipment. Such evolutions in the energy area have driven this sector to experience huge changes in its different parts to be able to dynamically meet the energy consumption. This transformation has occurred from energy generation to energy conversion, storage, and management. The impact of such changes in the energy landscape has not influenced the energy area alone, and one of its considerable effects has been on the climate. Indeed, growing traditional energy systems, especially fossil-fuel-based units, have substantial impacts on climate change. To mitigate

the negative consequences of the energy world development on climate change, many efforts should be coordinated to reshape energy structures by focusing on its modernization. For this purpose, RESs have been placed at the forefront of energy production, and eco-friendly technologies are also taken into account to minimize carbon release in multifarious energy processes. However, RESs bring clean energy for society with uncertain features that threaten the sustainability of the energy grid in its urgent mission to supply continuous energy. Due to the critical importance of maintaining the grid's sustainability, MENs are planned to employ reliable strategies to ensure the grid maintains its own sustainability, even equipped with a full or high range of RESs. When we reach the inevitable role of sustainability in improving social welfare after multidimensional analyses, the necessity for its realization becomes further apparent. All these facts indicate undeniable connections between climate, energy, and sustainability. Modern energy grids need to be developed in a way that effectively takes such connections into account to guarantee the success of their different plans and objectives. This can be conducted when all the aforementioned connections are considered in designing comprehensive frameworks for the CESN. Indeed, the CESN framework should simultaneously cover realistic impacts of different domains of climate change, energy, and sustainability on each other to ensure that the standards of each sector will not be violated under the operation of this framework. Such frameworks are targeted as the right option for modernizing future energy grids that are committed to deploying clean energy technologies and sources to respond to the ever-growing energy crisis.

1.4 Conclusions

Today, the world has witnessed ambitious changes in different fields that have directly affected styles of human lives and have made it dependent on various forms of energy more than ever before. Due to this, accessing clean, affordable, and sustainable energy has become a desirable and strategic request among human societies. Given the essentiality of this need, this chapter delves into assessing transition requirements for deep decarbonization of MENs. The chapter begins by discussing the urgent need for deep decarbonization of energy systems. Due to the direct impacts of decarbonization activities on climate change, energy accessibility, and the grid's sustainability, the CESN frameworks and connections are more revealed to provide the correct vision of frameworks for modernizing future MENs. By discussing such foundational concepts, the chapter prepares readers for the detailed analyses in subsequent chapters.

1.5 Future Directions and Challenges

In the modern energy landscape, deep decarbonization of MENs for CESN paves forming the set of endeavours to correctly drive the integrated system towards a net-zero emission structure. However, some critical challenges can negatively affect the complete success of the relevant plans. Technology limitation is one of the most remarkable ones that makes the smooth implementation of some beneficial and scheduled plans difficult. On the other hand, technology complexity alleviates the feasibility of developed paradigms and makes them hard to form in practice. Decarbonization-oriented plans are often hierarchical and interdependent in nature, which work coordinately with each other to achieve specific goals. Such mechanisms make the process costly, and their affordability will be questionable. This issue can lead to a significant decline in participation of different players in grid interactions. Human activities are always another effective dimension in environmental consequences and climate change. The lack of alignment of such activities typically hinders the effectiveness of deep decarbonization schemes. Another key challenge is that energy demand is dramatically surging, leading to an undeniable increase in energy generation and further challenges for the deep decarbonization of societies.

The aforementioned challenges are only some of the central difficulties ahead of employing deep decarbonization plans. From a futuristic perspective, each of them designs new roads for researchers to make them solvable by finding applicable solutions. Thus, future directions can be constructed on the described central challenges. Advancing the science of technologies can not only assist the system to address technology limitations but also can mostly ease the complexity involved in the process. Adopting emerging sciences such as multi-energy paradigms and digitalization platforms can support the integrated structure to reach the mentioned goals. On the other hand, further deploying mature technologies and nature-supported solutions can foster cost-effective mechanisms for implementing decarbonization frameworks, allowing for further reduction in energy costs. Improving human awareness of the different dimensions of decarbonization efforts and providing appropriate training for aligned actions can reduce the adverse effects of human activities to some extent. Such measures can also be expanded to the field of energy management that drives consumers to the correct energy consumption patterns, resulting in a decline in energy usage and achieving expected demand behaviors. All the mentioned items can be considered in future efforts of researchers to effectively open the ways of deep decarbonization for MENs.

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