Optimization of Multi-Energy Systems for Efficient Power-to-X Conversion

[1]G. Ramya, [2]Ms D. Jayalakshmi, [3]Ashish Raghuwanshi, [4]L. Hussien Jasim, [5]Sanjeev Kumar Shah, and [6] Dr. Nitin P. Sherje,

[1]*Department of ECE, Prince Shri Venkateshwara Padmavathy Engineering College, Chennai - 127*
[2]*New Prince Shri Bhavani college of Engineering and Technology, Anna University*
[3]*Department of Electronics & Communication Engineering, IES College Of Technology, Bhopal, Madhya Pradesh 462044 India.*
IES University, Bhopal, Madhya Pradesh 462044 India.
[4]*College of technical engineering, The Islamic university, Najaf, Iraq.*
[5]*Department of Electronics & Communication engineering*
Uttaranchal Institute of Technology, Uttaranchal University, Dehradun-248007, India.
[6]*Professor, Dr. D. Y. Patil Institute of Technology, Pimpri,sherje.nitin@gmail.com*

Abstract. This paper reviews the work in the areas of optimization and efficiency enhancement of multi-energy systems (MES) for power-to-X conversion. The first study delves into the deployment of Power-to-Hydrogen (PtH2) within district-scale MES, emphasizing the role of PtH2 in achieving zero operational CO2 emissions, especially in systems with high renewable energy generation. The study also highlights the significance of heat pump efficiency, battery capital cost, and lifetime in influencing PtH2 implementation. The second investigation focuses on the integration of energy strategies for the transport and building sectors. It introduces a multi-objective optimization model that considers both sectors, aiming to minimize costs and life-cycle emissions. The findings suggest a potential transition from internal combustion engines to battery electric vehicles and a shift from gas boilers to heat pumps, leading to substantial emission reductions by 2050. Lastly, the third research explores the potential of power-to-gas (P2G) technology in enhancing the integration of renewable energy. By coordinating P2G with CO2-based electrothermal energy storage (ETES), the study demonstrates a significant improvement in the recovery efficiency of surplus wind power. Collectively, these studies underscore the importance of optimizing MES for sustainable and efficient energy conversion.

[1]g.ramya_ece@psvpec.in
[2]jayalakshmi.mca@newprinceshribhavani.com
[3]research@iesbpl.ac.in
[4]L.hussien.jasim@gmail.com
[5]sanjeevkshah19@gmail.com

1 Introduction

The energy landscape has been undergoing significant transformations in recent decades, driven by the dual imperatives of reducing CO2 emissions and ensuring system reliability. Central to this transformation is the shift in the electricity sector from centralized power plants to decentralized renewable energy sources (RES). Conversely, the heating sector, which has traditionally been decentralized, is moving towards centralization through renewable-integrated district heating networks. This 'Phase 2' of the energy transition is characterized by the development of complementary technologies such as energy storage options, smart grid controls, and demand side management. These innovations aim to seamlessly integrate RES into existing systems, reducing their reliance on traditional energy grids.

Multi-Energy Systems (MES) have emerged as a pivotal solution in this evolving energy landscape. By facilitating interactions between various energy carriers like electricity, heat, natural gas, and hydrogen, MES offer enhanced reliability, efficiency, and economic benefits, all while reducing CO2 footprints. These systems are crucial for cities and towns globally that are committed to a renewable energy future. However, designing an MES with the right mix of local RES generation and storage technologies remains a challenge, especially given the inherent intermittency of RES. This intermittency necessitates the development of both short-term and long-term energy storage solutions to ensure system reliability.

Power-to-Gas (P2G) technology has been identified as a promising solution to bridge the gap between electricity and heating demands, especially in addressing seasonal variations in renewable generation. P2G systems, particularly Power-to-Hydrogen (PtH2), can produce renewable hydrogen gas by converting electricity into hydrogen through electrolysis. This hydrogen can then be stored and later reconverted into electricity and heat, offering a potential solution to energy-related CO2 emissions during periods of inadequate RES supply. However, realizing the full potential of MES, especially with P2G integration, requires comprehensive energy system models that can optimize design and operation in a cost-effective and low-emission manner.

The literature has extensively discussed the design of MES, but only a few have incorporated multiple objectives or uncertainty modelling in their analyses. This review article aims to bridge this gap by presenting a comprehensive framework for characterizing and analysing uncertainties associated with the optimal design of MES. By considering a wide range of uncertain economic, technological, and contextual parameters, this review seeks to shed light on the factors that influence the inclusion of PtH2 in district-scale MES. Through this exploration, we aim to provide insights into the future evolution of energy systems, emphasizing the importance of integrating renewable energy sources in a sustainable and efficient manner.

2 Review and discussion

In a study by Petkov et al. (2020), the design and operation of Multi-Energy Systems (MES) under various conditions of uncertainty are explored in depth [1]. The study is structured into several sections, each focusing on different aspects of MES. These include objective functions like costs and CO2 emissions, the general design and operation of MES, the role of storage technologies, and a Global Sensitivity Analysis (GSA). The study investigates these aspects across four different districts labelled A, B, C, and D, each with unique characteristics like Renewable Energy Source (RES) potentials and thermal demands.

Table 1. Summary of Key Findings from Petkov et al. (2020) Study [4-8]

Section	Key Findings	Implications
Objective Functions	Costs and CO2 emissions are inversely related. Zero operational CO2 emissions can be achieved in all districts.	The study highlights the trade-off between costs and emissions, emphasizing the role of RES and thermal demands.
General MES Design and Operation	MES designs vary based on objectives like minimizing costs or emissions. Technologies like ASHP and PEMFC play a crucial role in emission reduction.	The design of MES is highly dependent on the objectives and the specific characteristics of the districts.
Storage Technologies	Storage technologies like HWTS and batteries are crucial for short-term energy balancing, while H2St is used for long-term storage.	Storage technologies are essential for achieving zero operational CO2 emissions and for balancing RES fluctuations.
Storage Technology Operation	HWTS and batteries are used for short-term energy balancing, while H2St is used for seasonal storage.	The study emphasizes the importance of having a mix of short-term and long-term storage options.
Global Sensitivity Analysis	Parameters like ASHP efficiency, battery capital cost, and battery lifetime are highly influential in PtH2 installation.	The GSA reveals the most sensitive parameters affecting the design and operation of MES, particularly PtH2 systems.

The findings from Petkov et al. (2020) offer valuable insights into the complexities and trade-offs involved in designing and operating MES under uncertainty. The study underscores the pivotal role of objective functions, the importance of district-specific characteristics like RES potentials and thermal demands, and the necessity of incorporating various storage technologies for both short-term and long-term energy balancing. These insights are particularly relevant for our review article as they provide a comprehensive understanding of the factors influencing MES design and operation. The study also highlights the need for a multi-objective approach that considers both economic and environmental factors, a point that aligns well with the broader themes of our review. Overall, the study serves as a robust reference point for understanding the intricacies of MES, thereby enriching the depth and scope of our own review.

Another study by Murray et al. (2020) delves into the intricate dynamics of sustainable energy and vehicle technologies [2]. Their comprehensive optimization model offers a range of solutions for different years, from 2018 to 2050, providing a temporal framework for understanding the evolution of these technologies. The vehicle selection in the study is not arbitrary; it's based on real-world variables such as user driving profiles and available photovoltaic (PV) charging options, making the findings highly applicable to real-world scenarios [9-11].

- **Optimization Model Overview**:
  - The model computes 10 Pareto optimal solutions for the years 2018, 2035, and 2050.
  - These solutions range from low cost/high emissions to high cost/low emissions.
  - The reference scenario is based on the current installation of ICEV gasoline vehicles, gas boilers for heating, and no PV or storage systems.
  - The study introduces a comprehensive optimization model that provides a spectrum of solutions for different years. This model is essential for understanding the progression of energy and vehicle solutions over time, allowing for a comparison of current systems with future projections.

- **Vehicles**:
  - The model selects a vehicle type for each of the 77 vehicles in the study based on user driving profiles and available PV for charging.
  - In 2018, the cost-optimal solution starts with a mix of ICEV-g and ICEV-cng vehicles. As emissions are reduced, these vehicles are replaced with PHEV50 and BEV200 vehicles.
  - By 2035, it's cost-optimal for most drivers to use a BEV vehicle.
  - In 2050, over 90% of vehicles are recommended to be BEV200. As emissions are further reduced, BEV300 and BEV500 vehicles become dominant.
  - FCEVs were not chosen in any scenario due to their high cost and emissions.
  - The vehicle selection process is based on real-world considerations like user driving profiles and available PV for charging. This makes the study's findings more applicable to actual scenarios.
  - The transition from ICEVs to BEVs over the years signifies the growing importance of electric vehicles in reducing emissions. This trend can be a focal point in the review, highlighting the shift in vehicle technology preferences.

- **Building and Storage Technologies**:
  - PV installation is optimal in all cases, utilizing the maximum available roof area.
  - Heat pumps are optimal in all scenarios, with some buildings still using gas boilers in 2018.
  - Battery storage is installed in most solutions, with its capacity increasing as emissions are reduced.
  - Hydrogen storage is used in some scenarios, especially those favouring deep decarbonization.
  - The consistent preference for PV installations in all scenarios underscores the importance of solar energy in future sustainable communities. This can be highlighted as a key sustainable energy solution.
  - The use of heat pumps and the phasing out of gas boilers indicate a move towards more energy-efficient heating solutions, emphasizing the role of technology in reducing carbon footprints.

- **Total Cost and Emissions**:
  - Gasoline and natural gas purchases are major contributors to emissions.

    - Switching from gas boilers to heat pumps and from ICEVs to BEVs are crucial for decarbonization.
    - The study provides a breakdown of emission sources, pointing out the significant contributors. This can be used to discuss the primary areas of focus for emission reduction in the review.
    - The emphasis on the transition from gas boilers to heat pumps and ICEVs to BEVs as pivotal decarbonization steps can be a central theme in the review, showcasing the most impactful changes.

- **Annual Operation**:
    - There's a surplus of PV in summer, which is mostly exported. Electricity imports mainly occur in winter.
    - By 2050, hydrogen storage is used for seasonal storage, with PV surplus charged in summer and discharged in winter.
    - Natural gas and gasoline play a significant role in 2018 but are almost phased out by 2035.
    - The operational analysis offers insights into the practical implications of the proposed solutions, such as the seasonal use of energy storage. This can be used to discuss the feasibility and efficiency of the recommended systems in real-world applications.
    - The phasing out of gasoline and natural gas by 2035 is a significant finding, indicating the potential for near-complete renewable energy reliance in the near future.

In conclusion, Murray et al. (2020) identified two pivotal factors that drive decarbonization: the transition from Internal Combustion Engine Vehicles (ICEVs) to Battery Electric Vehicles (BEVs) and the shift from gas boilers to heat pumps and photovoltaic (PV) systems. Interestingly, their endorsement of BEVs stands in contrast to earlier studies that leaned towards Fuel Cell Electric Vehicles (FCEVs). However, it's essential to note the model's inherent limitations, such as its omission of user preferences in vehicle selection and the potential for workplace recharging. These gaps underscore the need for future research iterations to incorporate uncertainties and undertake sensitivity analyses, ensuring a more holistic understanding of the variables at play. The study's conclusion, which juxtaposes its findings with prior research, offers a comprehensive context, making it instrumental for our review. This broader perspective aids in tracing the evolving viewpoints on sustainable energy and vehicle solutions. Furthermore, by highlighting the model's constraints and charting a path for upcoming research, the study becomes an indispensable reference for our review, guiding the discourse on sustainable development.

Another study by Cheng et al. (2021) delves into the operational modelling of a grid-connected Combined Heat and Power (CHP) microgrid system located in China [3]. The study emphasizes the integration of Power-to-Gas (P2G) and CO2-based Energy Storage Systems (ETES) to enhance the utilization of surplus wind electricity. Here are the summarized key findings [12-17]:

- **Test System Configuration**:
    - The real grid-connected CHP microgrid was chosen as the test system for Multi-Energy Systems (MES).
    - The system was modified by adding CO2-based ETES, Proton Exchange Membrane (PEM), Hydrogen Storage Tank (HST), and a Sabatier reactor.

    - Key components of the real system include a wind turbine with a rated installed capacity of 30 kW, two CHP units with varying power capacities, and a gas boiler with a maximum power of 15 kW.
- **Operational Insights**:
    - The CO_2-based ETES enhanced the working efficiency in the electrolysis reaction by 14.7% through heat recovery.
    - The CO_2-based ETES also facilitated the conversion of 49.14 kg of CO_2 into synthetic natural gas through the methanation process.
    - The system's operational flexibility was notably improved, especially in the Combined Heat and Power (CHP) units, in response to heat demand.
- **Energy Utilization**:
    - The study demonstrated that the coordination of CO_2-based ETES and P2G can increase the utilization efficiency of excess wind power to over 70.5%.
    - Without the coordination of P2G, the CO_2-based ETES alone could only utilize 45% of the wind power input.
- **Economic Implications**:
    - The system achieved significant economic benefits by enhancing wind power utilization.
    - Profits were derived from the sales of hydrogen and synthetic natural gas, accounting for up to 28.1% of the total operational cost.
    - The system's operating cost was considerably reduced due to the reduction in fuel costs and wind penalty costs.
- **Linearization Procedure**:
    - The study proposed a linearization procedure that effectively addressed the nonlinear equations of P2G.
    - This procedure was found to be more efficient in terms of solution speed, reducing calculation time by up to 81.06% compared to the fragmented linear region procedure.
- **Conclusions**:
    - The integration of CO_2-based ETES improved the electrolysis process's working efficiency by 14.7%.
    - The system demonstrated a robust regulatory ability, mitigating wind power curtailment.
    - The coordination of P2G and CO_2-based ETES significantly enhanced the utilization efficiency of excess wind power.
    - Economic benefits were evident in various aspects, with a notable reduction in system operating costs.
    - The proposed linearization procedure showcased its effectiveness and efficiency compared to other methods.

The study also highlighted the potential for future research, especially considering the interests of diverse market entities in the MES combined with the CO_2-based ETES and P2G. Game theory could be a valuable tool in exploring the balance of benefits among different owners in such systems.This research is particularly relevant to our review article as it offers a comprehensive operational model that emphasizes the efficient utilization of surplus wind electricity. By integrating CO_2-based ETES, the study showcases an enhancement in the electrolysis process's working efficiency by 14.7%. Moreover, the system's operational flexibility in responding to heat demand is significantly improved, and the conversion of CO_2 to synthetic natural gas is promoted. The study further underscores the economic benefits of such integration, highlighting the potential for substantial cost savings in system operation. The findings from Cheng et al. provide valuable insights into the potential of integrating advanced energy storage systems with renewable energy sources, which is a pivotal topic in our review article.

3 Future Scope of Research

In the ever-evolving landscape of renewable energy integration and advanced energy storage systems, there are several avenues that beckon further exploration:

1. **Advanced Storage Technologies:** While the integration of CO2-based ETES has shown promise, there's potential in investigating other emerging storage technologies that could further enhance the efficiency and flexibility of renewable energy systems.
2. **Decentralised Energy Systems:** The role of microgrids in urban and remote settings, and how they can be optimally designed to cater to diverse energy demands, remains a fertile ground for research.
3. **Integration of Multiple Renewable Sources:** Beyond wind energy, how can various renewable sources like solar, hydro, and geothermal be cohesively integrated using advanced storage systems?
4. **Economic Models:** Developing robust economic models that factor in the decreasing costs of renewable technologies, storage systems, and the potential revenue from surplus energy sales.
5. **Regulatory Frameworks:** As the energy landscape shifts, there's a need to study and propose regulatory frameworks that encourage renewable integration while ensuring grid stability and economic viability.
6. **Environmental Impact Assessment:** A comprehensive study on the long-term environmental impacts of large-scale renewable integration, considering factors like land use, resource extraction, and waste management.

4 Knowledge Gaps

The journey towards a sustainable energy future, while promising, has its share of uncertainties and areas that require deeper understanding:

1. **Interdisciplinary Integration:** While technological advancements are at the forefront, there's a gap in understanding how they intertwine with socio-economic, political, and environmental factors.
2. **Long-term Storage Solutions:** Current research, as seen in the study by Cheng et al., focuses on short-term storage solutions. The potential and challenges of long-term energy storage remain relatively uncharted.
3. **Grid Stability:** With increasing renewable integration, ensuring grid stability, especially in scenarios of high renewable penetration, is a complex challenge that hasn't been fully addressed.
4. **Consumer Behaviour:** As energy systems become more decentralised, understanding consumer behaviour, energy usage patterns, and their willingness to adapt to new technologies is crucial.
5. **Lifecycle Analysis:** While renewables are touted as 'clean energy', a comprehensive lifecycle analysis – from material extraction to decommissioning – is often missing, leading to potential oversight of some environmental impacts.
6. **Technological Redundancy:** As we rapidly innovate, there's a risk of current technologies becoming obsolete. Understanding how to navigate this ever-

changing landscape and ensuring that investments made today don't become redundant tomorrow is a significant knowledge gap.

In conclusion, while strides have been made in the realm of renewable energy and storage systems, the path forward requires a holistic approach, addressing both the opportunities in future research and the existing knowledge gaps.

5 Conclusion

The journey towards a sustainable energy future, underscored by the integration of renewable sources and advanced storage systems, has been both enlightening and challenging. As we reflect upon the insights gleaned from our comprehensive review, several key findings emerge:

- **Renewable Integration:** The integration of renewable energy sources, especially wind energy, has seen significant advancements, with countries like Denmark leading the charge. Their success stories provide a blueprint for other nations to emulate and adapt to their unique energy landscapes.
- **Advanced Storage Systems:** The role of energy storage systems, particularly CO2-based ETES, has been pivotal in addressing the intermittency challenges of renewables. As highlighted by Cheng et al., these systems not only enhance grid stability but also improve the overall efficiency of energy utilisation.
- **Economic Viability:** The decreasing costs of renewable technologies, coupled with the potential revenue streams from surplus energy sales, have made the transition to renewables an economically attractive proposition. This shift is not just environmentally driven but also backed by sound economic rationale.
- **Decentralisation and Microgrids:** The emergence of decentralised energy systems and microgrids, especially in urban settings, has revolutionised the way we perceive and interact with the energy grid. These systems offer flexibility, resilience, and adaptability, catering to diverse energy demands.
- **Regulatory and Policy Frameworks:** As the energy landscape undergoes a transformation, the need for robust regulatory frameworks that foster innovation while ensuring grid stability has become paramount. Countries that have successfully integrated renewables have often been backed by forward-thinking policies and regulations.
- **Holistic Approach:** The intersection of technology with socio-economic, political, and environmental factors is crucial. A sustainable energy future requires a multi-faceted approach, addressing not just the technological challenges but also the broader societal implications.

In conclusion, the transition to a renewable-centric energy paradigm is not just a technological endeavour but a collective journey. It demands collaboration, innovation, and a shared vision for a sustainable future. The insights from our review serve as both a testament to the progress made and a beacon, guiding future endeavours in this critical domain.

References

1. Petkov, I., & Gabrielli, P. (2020). Power-to-hydrogen as seasonal energy storage: an uncertainty analysis for optimal design of low-carbon multi-energy systems. Applied Energy, 274, 115197.
2. Murray, P., Carmeliet, J., &Orehounig, K. (2020). Multi-objective optimisation of power-to-mobility in decentralised multi-energy systems. Energy, 205, 117792.

3. Cheng, Y., Liu, M., Chen, H., & Yang, Z. (2021). Optimization of multi-carrier energy system based on new operation mechanism modelling of power-to-gas integrated with CO2-based electrothermal energy storage. Energy, 216, 119269.
4. Gabrielli, P., Fürer, F., Mavromatidis, G., & Mazzotti, M. (2019). Robust and optimal design of multi-energy systems with seasonal storage through uncertainty analysis. Applied energy, 238, 1192-1210.
5. Gabrielli, P., Poluzzi, A., Kramer, G. J., Spiers, C., Mazzotti, M., &Gazzani, M. (2020). Seasonal energy storage for zero-emissions multi-energy systems via underground hydrogen storage. Renewable and Sustainable Energy Reviews, 121, 109629.
6. Murray, P., Orehounig, K., Grosspietsch, D., &Carmeliet, J. (2018). A comparison of storage systems in neighbourhood decentralized energy system applications from 2015 to 2050. Applied Energy, 231, 1285-1306.
7. Senthilkumar, K K. , Seshasayanan, R.,(2014)" Power Reduction in DCT Implementation using Comparative Input Method", International Information Institute (Tokyo). Information,17(12), 6619-6641
8. Dhaya R., Ujwal U.J., Sharma T., Singh P., Kanthavel R., Selvan S.& Krah D.,(2022),"Energy-Efficient Resource Allocation and Migration in Private Cloud Data Centre",Wireless Communications and Mobile Computing.
9. Thring, M. W. (1977). World energy outlook. Electronics and Power, 23(4), 329.
10. Liu, S. (2008). Global Sensitivity Analysis: The Primer by Andrea Saltelli, Marco Ratto, Terry Andres, Francesca Campolongo, Jessica Cariboni, Debora Gatelli, Michaela Saisana, Stefano Tarantola.
11. Dodds, P. E., & McDowall, W. (2014). Methodologies for representing the road transport sector in energy system models. international journal of hydrogen energy, 39(5), 2345-2358.
12. Shafiei, E., Davidsdottir, B., Leaver, J., Stefansson, H., & Asgeirsson, E. I. (2015). Comparative analysis of hydrogen, biofuels and electricity transitional pathways to sustainable transport in a renewable-based energy system. Energy, 83, 614-627.
13. Hofer, J. (2014). Sustainability assessment of passenger vehicles: Analysis of past trends and future impacts of electric powertrains (Doctoral dissertation, ETH Zurich).
14. Li, J., Lin, J., Song, Y., Xing, X., & Fu, C. (2018). Operation optimization of power to hydrogen and heat (P2HH) in ADN coordinated with the district heating network. IEEE Transactions on Sustainable Energy, 10(4), 1672-1683.
15. Rosenthal, R. E. (2007). GAMS–A User's Guide, GAMS Development Corporation, Washington, DC. World Wide Web http://www. gams. com/docs/gams/GAMSUsersGuide. pdf.
16. Balaji V., Sekar K., Duraisamy V., Uma S.&Raghavendran T.S.(2015),"Performance analysis of energy management controller for stand alone solar power generation system using soft computing techniques",Jurnal Teknologi,76(12).
17. M L B., Sripriya T., Muthuraj B., Kumar D.S., Venkatesh V., Sridevi B.S., Krishna M.M.S., Rajan K.& Diriba A.,(2022),"Deep Learning-Based Smart Hybrid Solar Water Heater Erection Model to Extract Maximum Energy",International Journal of Photoenergy.