STM JOURNALS

Journal of
Refrigeration, Air Conditioning, Heating and Ventilation

ISSN: 2394-1952
Volume 13, Issue 1, 2026
January–April
DOI (Journal): 10.37591/JoRACHV

https://journals.stmjournals.com/jorachv

Research JoRACHV

Renewable-Powered HVAC Systems: Advances in Solar, Bioenergy, and Heat Pump Technologies

G. Sujay Kumar[1,*]

Abstract

The global demand for refrigeration, air conditioning, heating, and ventilation (HVAC) systems has increased rapidly due to population growth, urbanization, industrialization, and rising expectations for indoor thermal comfort. These systems account for a substantial share of global energy consumption and greenhouse gas emissions, primarily because they rely heavily on fossil-fuel-based electricity and thermal energy. Consequently, the decarbonization of HVAC and refrigeration sectors has become a critical component of global climate mitigation strategies. Renewable energy technologies—including solar, wind, bioenergy, geothermal, and hydropower—offer viable pathways to reduce emissions while ensuring reliable and efficient heating and cooling services. This paper presents a comprehensive review of the current status, technological advancements, and sustainability aspects of renewable energy systems with specific emphasis on their application in refrigeration, air conditioning, heating, and ventilation. Recent progress in renewable-powered heat pumps, solar-assisted cooling technologies, geothermal heating systems, and district heating and cooling networks is discussed. The review also examines key challenges such as intermittency, thermal energy storage, system integration, material sustainability, and economic feasibility. Emerging solutions including advanced thermal storage, digitalized HVAC systems, and green hydrogen for heating and cooling applications are highlighted. The findings aim to support researchers, engineers, and policymakers in developing sustainable, energy-efficient HVAC systems aligned with long-term climate and energy goals.

Keywords: Renewable energy, HVAC systems, refrigeration, heating and cooling, sustainability, heat pumps, thermal energy storage, green hydrogen.

INTRODUCTION

Refrigeration, air conditioning, heating, and ventilation systems are indispensable for modern society, providing thermal comfort, food preservation, industrial process control, and indoor air quality. Collectively, heating and cooling account for nearly half of global final energy consumption, while refrigeration and air conditioning represent one of the fastest-growing sources of electricity demand worldwide. This rapid growth has been driven by increasing urbanization, climate change–induced temperature extremes, rising living standards, and expanding cold-chain infrastructure. However, the energy required to operate HVAC and refrigeration systems is predominantly derived from fossil fuels, resulting in significant greenhouse gas (GHG) emissions and environmental degradation.

In addition to indirect emissions from electricity consumption, HVAC and refrigeration systems have historically contributed to climate change through the use of high global warming potential (GWP) refrigerants. Although international

***Author for Correspondence**
G. Sujay Kumar
E-mail: gsujaykumar48@gmail.com

[1]Assistant Professor, Department of Mechanical Engineering, Yenepoya Institute of Technology, Moodbidri, Karnataka, India.

Received Date: February 05, 2026
Accepted Date: February 06, 2026
Published Date: February 21, 2026

Citation: G. Sujay Kumar. Renewable-Powered HVAC Systems: Advances in Solar, Bioenergy, and Heat Pump Technologies. Journal of Refrigeration, Air Conditioning, Heating and Ventilation. 2026; 13(1): 26–33p.

agreements such as the Montreal Protocol and Kigali Amendment have addressed refrigerant-related emissions, energy-related emissions from HVAC systems remain a major challenge. Therefore, transitioning HVAC and refrigeration systems toward renewable energy–based solutions is essential for achieving global decarbonization targets [1–3].

Renewable energy technologies provide sustainable alternatives for powering HVAC and refrigeration systems. Solar energy can be utilized directly through solar thermal collectors for space and water heating, absorption cooling, and desiccant-based air conditioning, or indirectly through photovoltaic (PV) systems supplying electricity to compressors and heat pumps. Wind and hydropower contribute low-carbon electricity for large-scale HVAC installations and district cooling systems. Biomass and bioenergy are widely applied in district heating and combined heat and power (CHP) plants, particularly in colder regions. Geothermal energy is uniquely suited for heating and cooling due to its stable subsurface temperatures, enabling highly efficient ground-source heat pump systems [4–7].

Over the past two decades, significant technological advancements have improved the performance, efficiency, and cost-effectiveness of renewable-powered HVAC systems. The levelized cost of renewable electricity has declined sharply, while innovations in heat pump design, thermal energy storage, and smart control systems have enhanced system reliability. Despite this progress, challenges such as intermittency, integration with existing infrastructure, high initial investment costs, and sustainability of materials remain barriers to widespread adoption.

This review aims to provide a comprehensive assessment of renewable energy technologies for refrigeration, air conditioning, heating, and ventilation applications. The paper evaluates current deployment trends, examines recent technological advances, analyzes sustainability dimensions, and discusses future prospects for renewable-based HVAC systems.

CURRENT STATUS OF RENEWABLE ENERGY IN HVAC APPLICATIONS

Global Overview

Renewable energy has transitioned from a supplementary energy source to a central element of modern energy systems. While renewables account for nearly 30% of global electricity generation, their penetration in heating, cooling, and refrigeration remains comparatively low. Heating and cooling applications still rely heavily on fossil fuels such as natural gas, coal, and oil, particularly in residential and industrial sectors.

Nevertheless, renewable-based HVAC technologies are gaining momentum. Electrification of heating through air-source and ground-source heat pumps has expanded rapidly, especially in Europe, North America, and parts of Asia. Heat pumps powered by renewable electricity offer efficiencies three to five times higher than conventional heating systems, making them a cornerstone of low-carbon HVAC strategies. Similarly, solar thermal systems are increasingly deployed for domestic hot water, space heating, and solar-assisted cooling applications.

District heating and cooling networks integrating renewable sources—such as biomass, geothermal energy, large-scale heat pumps, and waste heat—are also expanding. These systems enable centralized production of thermal energy with high efficiency and reduced emissions, particularly in dense urban environments [8–10].

Regional Developments

Asia leads global growth in renewable energy deployment, with China playing a dominant role. China has expanded renewable electricity generation while simultaneously promoting electric heat pumps, solar district heating, and renewable-powered cooling systems. Large-scale solar thermal installations for space heating and industrial processes have been implemented alongside rapid growth in air conditioning demand.

India has prioritized solar energy as part of its decarbonization strategy, with increasing integration of solar PV into building HVAC systems, cold storage facilities, and agricultural refrigeration. Solar-assisted cooling and solar-powered cold chains are particularly relevant in hot climatic regions where cooling demand is high.

Europe has emerged as a global leader in renewable heating and cooling integration. Policies under the European Green Deal and REPowerEU framework strongly promote heat pumps, district heating modernization, and renewable thermal energy. Countries such as Sweden, Denmark, and Germany have successfully integrated biomass, geothermal energy, and large-scale heat pumps into district heating networks. The electrification of heating using renewable electricity has significantly reduced emissions from the building sector.

In North America, the United States has accelerated renewable HVAC deployment through incentives under the Inflation Reduction Act, supporting heat pump adoption, renewable electricity generation, and grid modernization (Figures 1–3). Canada benefits from abundant hydropower, which provides low-carbon electricity for HVAC systems, while also expanding geothermal heat pump installations [11–14].

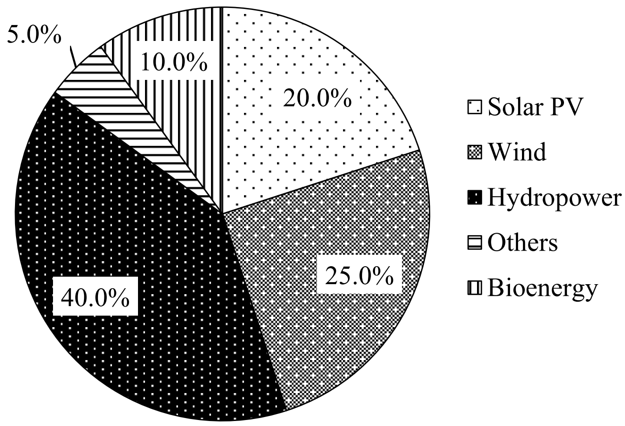

Figure 1. Global renewable energy share in electricity generation (2022)[11].

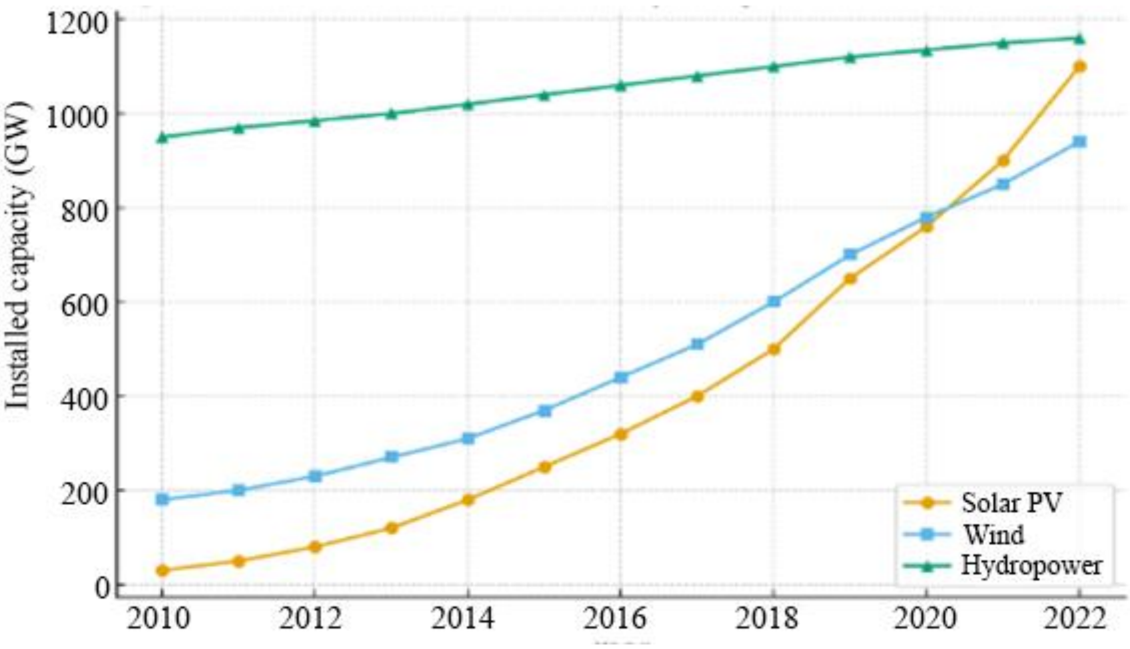

Figure 2. Installed renewable capacity trends (2010–2022)[12].

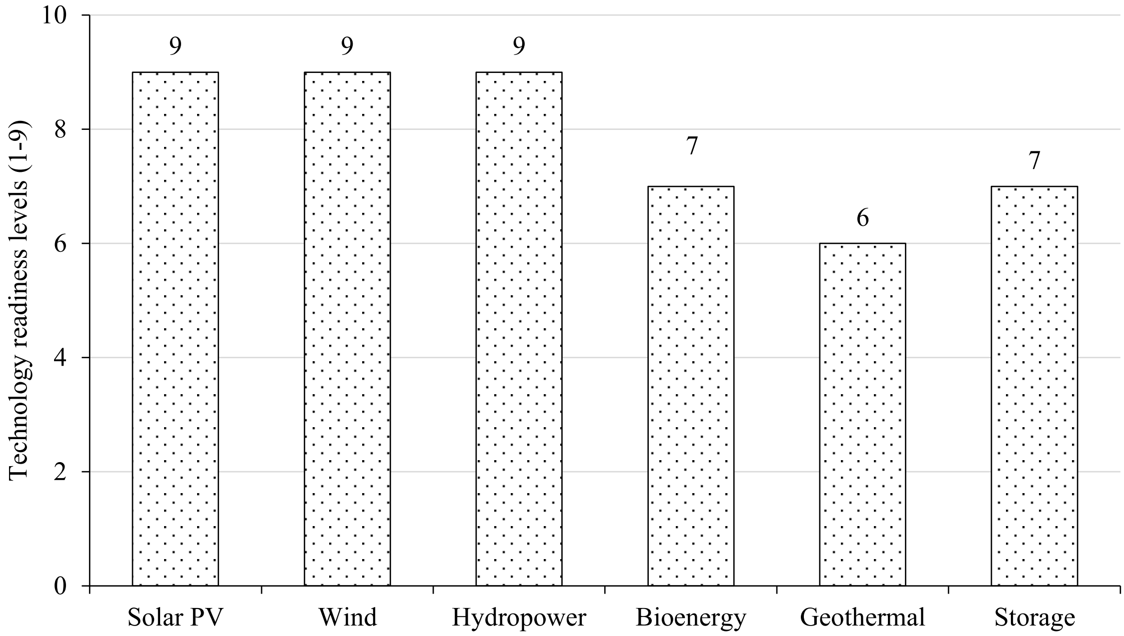

Figure 3. Technology readiness levels of renewable energy technologies [16].

TECHNOLOGICAL ADVANCES IN RENEWABLE-BASED HVAC SYSTEMS

Solar Energy for Heating and Cooling

Solar energy represents one of the most promising and versatile renewable resources for heating and cooling applications due to its wide availability, modularity, and compatibility with both thermal and electrical HVAC systems. The utilization of solar energy in HVAC applications can be broadly classified into two categories: *solar thermal systems*, which convert solar radiation directly into usable heat, and *solar photovoltaic (PV) systems*, which generate electricity to power conventional and advanced heating and cooling equipment. Both approaches have gained significant attention as effective pathways to reduce fossil fuel dependence and operational carbon emissions in residential, commercial, and industrial buildings.

Solar thermal technologies are extensively applied in space heating, domestic hot water production, and solar-assisted cooling systems. Flat-plate collectors and evacuated tube collectors are the most commonly deployed solar thermal devices, with evacuated tube collectors offering higher efficiencies at elevated operating temperatures, making them particularly suitable for space heating and absorption cooling applications. In colder climates, solar thermal systems are often integrated with auxiliary heating sources or thermal storage units to ensure reliability during periods of low solar irradiance (Tables 1–3). Large-scale solar thermal installations are increasingly being incorporated into district heating networks, where centralized solar fields supply thermal energy to multiple buildings, improving system efficiency and reducing overall emissions.[15–17].

Heat Pumps and Geothermal Systems

Heat pumps represent one of the most efficient technologies for renewable heating and cooling. Air-source heat pumps have become widely adopted due to their relatively low installation cost, while ground-source heat pumps offer higher efficiency and stable performance. Advances in compressor technology, refrigerants, and system controls have significantly improved heat pump performance across a wide range of climatic conditions.

Geothermal energy is particularly suitable for HVAC applications due to its stable thermal characteristics. Enhanced geothermal systems and shallow geothermal installations expand applicability beyond geologically active regions, enabling district heating and cooling solutions [18].

Table 1. Advantages and Limitations of Renewable Energy Technologies[14]

Technology	Advantages	Limitations
Solar PV	Abundant, scalable, rapidly falling costs, low operating emissions	Intermittent, land-intensive, resource use in PV materials
Wind	High efficiency in suitable sites, mature technology, zero emissions in operation	Intermittent, visual/noise impacts, reliance on rare earth elements
Hydropower	Reliable, large-scale baseload power, energy storage (pumped hydro)	Ecological disruption, resettlement issues, limited new sites
Bioenergy	Utilizes waste biomass, versatile (power, heat, fuels)	Food vs fuel debate, emissions if not managed sustainably
Geothermal	Continuous base-load supply, small land footprint	Limited to geologically active regions, high drilling costs
Storage (Batteries/H2)	Addresses intermittency, supports grid stability	High cost, material supply chain challenges

Table 2. Emerging Technologies and Their Potential Applications

Technology	Description	Potential Application
Perovskite Solar Cells	High efficiency (>25%), low-cost materials	Next-generation PV modules, building-integrated PV
Floating Wind Turbines	Offshore wind platforms for deep-water regions	Expansion of wind capacity in coastal and deep-water areas
Green Hydrogen	Renewable-powered electrolysis for H2 production	Industry (steel, cement), heavy transport, energy storage
Solid-State Batteries	Higher energy density, improved safety vs Li-ion	EVs, grid storage
Hybrid RE Systems	Integration of solar, wind, storage, hydropower	Grid reliability, rural electrification

Table 3. Policy Targets for Renewable Energy Adoption [5]

Country/Region	Target	Focus areas
European Union (EU)	42.5% renewable share in final energy consumption by 2030	Offshore wind, hydrogen, solar PV expansion
United States (USA)	Net-zero emissions by 2050, 100% clean electricity by 2035	Solar, wind, grid modernization, IRA incentives
China	33% renewable electricity share by 2030; carbon neutrality by 2060	Solar PV, wind, large-scale hydro, storage
India	500 GW non-fossil fuel capacity by 2030	Solar (National Solar Mission), wind, bioenergy
Japan	36–38% renewable electricity by 2030	Offshore wind, hydrogen, energy efficiency

Bioenergy and District Heating

Bioenergy plays a significant role in renewable-based heating systems, particularly within district heating and combined heat and power (CHP) applications. Unlike variable renewable sources such as solar and wind, bioenergy provides a *dispatchable and controllable* source of thermal energy, making it highly suitable for meeting continuous heating demand in residential, commercial, and industrial sectors. Biomass-based heating systems are especially prevalent in regions with cold climates and abundant forestry or agricultural resources, where they contribute substantially to space heating, domestic hot water production, and industrial process heat.

District heating systems powered by bioenergy enable centralized generation of thermal energy, which is then distributed to multiple end users through insulated pipe networks. This centralized approach allows for higher efficiency, lower emissions per unit of heat delivered, and improved integration of pollution control technologies compared to decentralized fossil-fuel-based boilers. Biomass fuels used in district heating include wood chips, wood pellets, agricultural residues, energy crops, and organic waste. When sourced sustainably, these fuels can achieve near-carbon-neutral operation, as the carbon dioxide released during combustion is offset by carbon uptake during biomass growth.

Thermal Energy Storage and Smart HVAC Systems

Thermal energy storage is essential for balancing variable renewable energy supply with heating and cooling demand. Sensible heat storage, latent heat storage using phase-change materials, and thermochemical storage systems are increasingly integrated into HVAC systems. These technologies improve system flexibility, reduce peak loads, and enhance energy efficiency.

Digitalization, artificial intelligence, and smart control systems enable optimized HVAC operation through predictive control, real-time monitoring, and demand response. Smart HVAC systems improve energy efficiency while maintaining indoor thermal comfort [19–21].

SUSTAINABILITY ASPECTS OF RENEWABLE HVAC SYSTEMS

Renewable-based HVAC systems significantly reduce operational carbon emissions compared to fossil-fuel-based alternatives. However, life-cycle assessments reveal environmental challenges related to material extraction, manufacturing, and end-of-life disposal of components such as PV panels, batteries, and heat pumps. Circular economy approaches, recycling, and sustainable material substitution are essential for improving long-term sustainability.

From a socio-economic perspective, renewable HVAC deployment generates employment in manufacturing, installation, and maintenance. However, ensuring equitable access to clean heating and cooling remains a challenge, particularly in developing regions. Policy frameworks promoting decentralized and community-based systems can enhance energy equity.

CHALLENGES AND BARRIERS

Key challenges in renewable HVAC adoption include intermittency of renewable energy sources, high upfront costs, integration with existing building infrastructure, and dependence on critical materials. Retrofitting existing buildings with renewable HVAC systems can be technically complex and financially demanding. Addressing these challenges requires supportive policies, innovative financing mechanisms, and continued technological innovation [22–27].

FUTURE PROSPECTS

The future of renewable HVAC systems is closely linked to advances in green hydrogen, hybrid renewable systems, and next-generation materials. Green hydrogen offers potential for high-temperature heating and seasonal energy storage. Hybrid systems combining solar, wind, and thermal storage can deliver reliable heating and cooling. Continued research in advanced refrigerants, smart controls, and sustainable materials will further enhance system performance.

CONCLUSION

The integration of renewable energy into refrigeration, air conditioning, heating, and ventilation systems has evolved from a conceptual sustainability goal into a practical and increasingly necessary engineering solution for modern energy systems. As global demand for thermal comfort, cold storage, and controlled indoor environments continues to rise, particularly in rapidly urbanizing and warming regions, the HVAC and refrigeration sectors have emerged as critical focal points for decarbonization efforts. This review demonstrates that renewable energy technologies—when strategically combined with advanced HVAC systems—offer a robust pathway to significantly reduce greenhouse gas emissions, enhance energy efficiency, and improve long-term energy security.

Technological advancements over the past decade have substantially strengthened the feasibility of renewable-based HVAC systems. The rapid improvements in heat pump performance, solar-assisted heating and cooling technologies, geothermal systems, and district heating and cooling networks have enabled renewable energy to meet a growing share of space conditioning and refrigeration demand. Concurrently, declining costs of renewable electricity and thermal technologies have improved economic competitiveness, making renewable HVAC solutions increasingly viable not only in new constructions but also in retrofitting existing buildings. The expanding role of thermal energy storage—through sensible, latent, and thermochemical methods—has further enhanced system flexibility by mitigating intermittency and aligning renewable energy availability with heating and cooling demand profiles.

Despite these achievements, the transition toward fully sustainable HVAC and refrigeration systems remains complex and multifaceted. Challenges persist in the form of high upfront capital costs, technical barriers in retrofitting legacy infrastructure, and material sustainability concerns associated with renewable energy components. In addition, the variability of renewable energy supply necessitates continued advancements in smart grid integration, predictive control strategies, and demand-response mechanisms. Addressing these challenges requires not only technological innovation but also coordinated policy support, standardized design practices, and capacity building among engineers, planners, and technicians.

REFERENCES

1. Apergis, N., & Payne, J. (2016). Renewable energy and economic growth. Cogent Economics & Finance, 4(1). https://www.tandfonline.com/doi/full/10.1080/23311916.2016.1167990
2. Ritchie, H., Roser, M. (2023). Renewable Energy Data. Our World in Data. https://ourworldindata.org/renewable-energy
3. REN21. (2023). Renewables Global Status Report. https://www.ren21.net/wp-content/uploads/2019/05/REN21-RESR-2023_LowRes.pdf
4. Stevovic, D. Mirjanic, N. Petrovic, Integration of solar energy by natureinspired optimization in the context of circular economy, Energy 235 (2021), 121297, https://doi.org/10.1016/J.ENERGY.2021.121297.
5. V. Turanjanin, V. Baki´c, M. Jovanovi´c, M. Pezo, Fossil fuels substitution by the solar energy utilization for the hot water production in the heating plant “Cerak” in Belgrade, Int. J. Hydrogen Energy 34 (2009) 7075–7080, https://doi.org/10.1016/J.IJHYDENE.2008.11.005.
6. V.P. Bashurin, I.N. Budnikov, V.Y. Khatunkin, V.A. Klevtsov, L.V. Ktitorov, A. S. Lazareva, E.E. Meshkov, I.A. Novikova, F.A. Pletenev, G.M. Yanbaev, Using free flow energy cumulation in wind and hydro power production, J. Sustain. Dev. Energy, Water and Environ. Syst. 4 (2016) 279–292, https://doi.org/10.13044/J.SDEWES.2016.04.0022.
7. E. Duarte, R. Fragoso, N. Smozinski, J. Tavares, Enhancing bioenergy recovery from agro-food biowastes as a strategy to promote circular bioeconomy, J. Sustain. Dev. Energy, Water and Environ. Syst. 9 (2021) 1–13, https://doi.org/10.13044/J.SDEWES.D8.0320.
8. V. Bozhikaliev, I. Sazdovski, J. Adler, N. Markovska, Techno-economic, social and environmental assessment of biomass based district heating in a bioenergy village, J. Sustain. Dev. Energy, Water and Environ. Syst. 7 (2019) 601–614, https://doi.org/10.13044/J.SDEWES.D7.0257.
9. K.L. Chan, C. Dong, M.S. Wong, L.H. Kim, S.Y. Leu, Plant chemistry associated dynamic modelling to enhance urban vegetation carbon sequestration potential via bioenergy harvesting, J. Clean. Prod. 197 (2018) 1084–1094, https://doi.org/10.1016/J.JCLEPRO.2018.06.233.
10. A. Chiodi, P. Deane, M. Gargiulo, B. Gallachoir, ´ The role of bioenergy in Ireland’s low carbon future – is it sustainable? J. Sustain. Dev. Energy, Water and Environ. Syst. 3 (2015) 196–216, https://doi.org/10.13044/J.SDEWES.2015.03.0016.
11. L.C. Kibet, H. Blanco-Canqui, R.B. Mitchell, W.H. Schacht, Root biomass and soil carbon response to growing perennial grasses for bioenergy, Energy Sustain. Soc. 6 (2016) 1, https://doi.org/10.1186/s13705-015-0065-5.

12. M. Moretti, S.N. Djomo, H. Azadi, K. May, K. De Vos, S. Van Passel, N. Witters, A systematic review of environmental and economic impacts of smart grids, Renew. Sustain. Energy Rev. 68 (2017) 888–898, https://doi.org/10.1016/J. RSER.2016.03.039.
13. H. Lund, Renewable heating strategies and their consequences for storage and grid infrastructures comparing a smart grid to a smart energy systems approach, Energy 151 (2018) 94–102, https://doi.org/10.1016/J.ENERGY.2018.03.010.
14. S.N. Khan, Intelligent algorithm for efficient use of energy using tackling the load uncertainty method in smart grid, J. Sustain. Dev. Energy, Water and Environ. Syst. 8 (2020) 547–560, https://doi.org/10.13044/J.SDEWES.D7.0308.
15. F. Calise, F.L. Cappiello, M. Dentice d'Accadia, M. Vicidomini, Smart grid energy district based on the integration of electric vehicles and combined heat and power generation, Energy Convers. Manag. 234 (2021), 113932, https://doi.org/10.1016/J.ENCONMAN.2021.113932.
16. P.A. Østergaard, N. Duic, Y. Noorollahi, H. Mikulcic, S. Kalogirou, Sustainable development using renewable energy technology, Renew. Energy 146 (2020) 2430–2437, https://doi.org/10.1016/j.renene.2019.08.094.
17. P.A. Østergaard, N. Duic, Y. Noorollahi, S. Kalogirou, Latest progress in Sustainable Development using renewable energy technology, Renew. Energy 162 (2020) 1554–1562, https://doi.org/10.1016/j.renene.2020.09.124.
18. P.A. Østergaard, N. Duic, Y. Noorollahi, S.A. Kalogirou, Recent advances in renewable energy technology for the energy transition, Renew. Energy 179 (2021) 877–884, https://doi.org/10.1016/J.RENENE.2021.07.111.
19. P.A. Østergaard, N. Duic, Y. Noorollahi, S. Kalogirou, Renewable energy for sustainable development, Renew. Energy 199 (2022) 1145–1152, https://doi.org/10.1016/j.renene.2022.09.065.
20. F. Calise, M. Vicidomini, M. Costa, Q. Wang, P.A. Østergaard, N. Dui´c, Toward an efficient and sustainable use of energy in industries and cities, Energies 12 (2019), https://doi.org/10.3390/en12163150.
21. W. Chu, F. Calise, N. Dui´c, P.A. Østergaard, M. Vicidomini, Q. Wang, Recent advances in technology, strategy and application of sustainable energy systems, Energies 13 (2020), https://doi.org/10.3390/en13195229.
22. W. Chu, M. Vicidomini, F. Calise, N. Dui´c, P.A. Østergaard, Q. Wang, M.D. G. Carvalho, Recent advances in low-carbon and sustainable, efficient technology: strategies and applications, Energies 15 (2022), https://doi.org/10.3390/en15082954.
23. W. Chu, M. Vicidomini, F. Calise, N. Dui´c, P.A. Østergaard, Q. Wang, M. da Graça Carvalho, Recent advances in technologies, methods, and economic analysis for sustainable development of energy, water, and environment systems, Energies 15 (2022), https://doi.org/10.3390/en15197129.
24. P.A. Østergaard, N. Duic, Sustainable energy, water and environmental systems, Int. J. Sustain. Energy Plan. Manag. 3 (2014), https://doi.org/10.5278/ijsepm.2014.3.1.
25. P.A. Østergaard, R.M. Johannsen, N. Duic, Sustainable development using renewable energy systems, Int. J. Sustain. Energy Plan. Manag. 29 (2020), https://doi.org/10.5278/ijsepm.4302.
26. A. Østergaard, R.M. Johannsen, N. Duic, H. Lund, Sustainable development of energy, water and environmental systems and smart energy systems, Int. J. Sustain. Energy Plan. Manag. 34 (2022), https://doi.org/10.54337/ijsepm.7269.
27. P.A. Østergaard, R.M. Johannsen, N. Duic, H. Lund, B.V. Mathiesen, I. Soares, P. Ferreira, Sustainable energy planning and management vol 38, Int. J. Sustain. Energy Plan. Manag. 38 (2023), https://doi.org/10.54337/ijsepm.7812.

