Post COVID-19 ENERGY sustainability and carbon emissions neutrality

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ABSTRACT

This review covers the recent advancements in selected emerging energy sectors, emphasising carbon emission neutrality and energy sustainability in the post-COVID-19 era. It benefited from the latest development reported in the Virtual Special Issue of ENERGY dedicated to the 6th International Conference on Low Carbon Asia and Beyond (ICLCA'20) and the 4th Sustainable Process Integration Laboratory Scientific Conference (SPIL'20). As nations bind together to tackle global climate change, one of the urgent needs is the energy sector's transition from fossil-fuel reliant to a more sustainable carbon-free solution. Recent progress shows that advancement in energy efficiency modelling of components and energy systems has greatly facilitated the development of more complex and efficient energy systems. The scope of energy system modelling can be based on temporal, spatial and technical resolutions. The emergence of novel materials such as MXene, metal-organic framework and flexible phase change materials have shown promising energy conversion efficiency. The integration of the internet of things (IoT) with an energy storage system and renewable energy supplies has led to the development of a smart energy system that effectively connects the power producer and end-users, thereby allowing more efficient management of energy flow and consumption. The future smart energy system has been redefined to include all energy sectors via a cross-sectoral integration approach, paving the way for the greater utilization of renewable energy. This review highlights that energy system efficiency and sustainability can be improved via innovations in smart energy systems, novel energy materials and low carbon technologies. Their impacts on the environment, resource availability and social well-being need to be holistically considered and supported by diverse solutions, in alignment with the sustainable development goal of Affordable and Clean Energy (SDG 7) and other related SDGs (1, 8, 9, 11,13,15 and 17), as put forth by the United Nations.

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1. Introduction

Energy is one of the keys supporting economic development and playing an essential in our daily life. It is the sector that contributes significantly to various sustainability issues, such as GHG (Greenhouse Gases) emissions [1], air pollutants [2], water use [3], and poverty [4]. At the same time, the energy sector has prevalent room for improvement and is the target solution in various sustainability-related policies. Energy sustainability is a persisting concern; however, the challenge has been impacted differently under the unexpected interruption of COVID-19. The COVID-19 impact on electricity, particularly during the implementation of lock-down measures, have been widely reported [5]. The electricity demand decreased with the confinement measures and recovered steadily with the lifted restriction. Another observation lies in the changes in electricity mix where the share of renewables is higher during the lock-down measures. A high decrease in energy generation from nuclear, fossil coal and oil is also identified [6]. The reduction in energy demand and the higher share of renewable energy contributes significantly to the short term reduction in environmental pressure; for example, cleaner air is reported [7]. Positive trends to the environment are encouraging. However, there are also reports and predictions on the negative impacts and long-term challenges, as summarised in Fig. 1.

Hosseini et al. [8] highlight the hit of COVID-19 to the renewable energy manufacturing, supply chains, and companies, slowing

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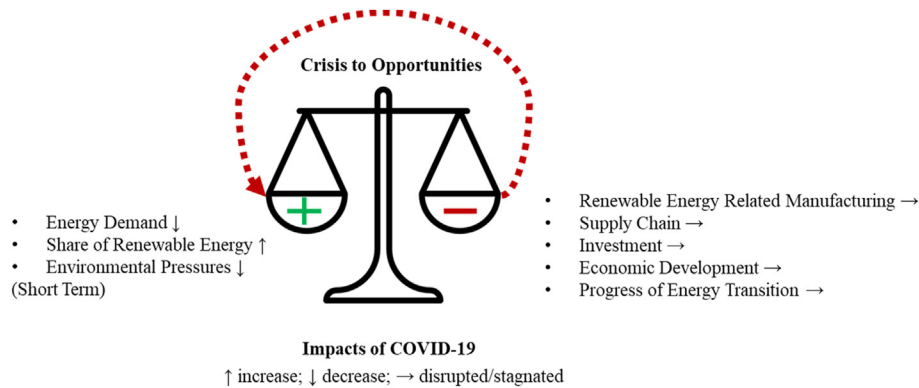*E-mail address:* ctlee@utm.my (C.T. Lee).

Fig. 1. The continuous unfold impacts of COVID-19 on sustainable energy development.

down the sustainable energy transition. The extensive economic consequences of COVID-19, expecting to have adverse influence, either directly or indirectly, on renewable energy development. The sectoral and regional shocks to the economy's structure and environmental pressures have been projected [9]. Jiang et al. [10] also suggested that despite the declines in overall energy demand, the spatial and temporal variations are complicated. Some sectors incurred additional energy, such as the manufacturing of Personal Protective Equipment [11] and vaccine rollout as estimated in Klemeš et al. [12]. The impacts of COVID-19 on the energy system will continue to unfold. Turning the crisis into an opportunity is critical for ensuring energy sustainability in the post-COVID-19 recovery. Creative destruction and wave of innovation [13] have been elaborated [14], highlighting the pandemic's e-services and renewable energy opportunity. Stakeholders' collaboration is needed to prevent the decline in energy investments, projects and redirect other priorities after the Ebola outbreak [15]. Publics and political participation have been suggested as important drivers to shape the future energy system [16]. Steffen et al. [17] suggest that the policy framework consists of three policy horizons (short-, mid-, and long-term); not overreacting in the short term and paying more focus on new policy design that can withstand future shocks.

There have been various initiatives or strategies in the attempt to improve energy sustainability. Energy transition, shifting the fossil-based system to renewable sources, is one of the significant efforts. The extent of the transition is usually associated with goals such as.

(a) 100% renewable energy [18],
(b) a carbon emission neutrality system [19],
(c) limit global warming to 1.5 °C [20] or a more localised target of
(d) reducing particulate matter [21].

The ambitious goals could serve as an effective driver for succession. However, it should be well aware that the achievements are not indisputably equivalent to a sustainable solution, especially environmental sustainability. Table 1 illustrates the Energy Return on Investment (EROI) [22], Levelised Cost of Energy (LCOE) - a measure of the average net present cost of electricity generation for a generating plant over its lifetime [23], various environmental and social performance of different energy sources. 100% renewable energy does not mean carbon emission-free energy. De Chalender and Benson [24] highlighted that 100% renewable energy is not enough. Power consumption needs to be matched with renewable generation on an hourly basis, which is currently based on annual accounting, to ensure progress in emission reduction and prevent erroneous carbon emissions accounting. A carbon emission neutrality system and limiting global warming to a 1.5 °C system are not indispensable for land use or the ecosystem. The targets focus solely on GHG, possibly causing a shift of environmental footprint from a problem (e.g. climate change) to another problem, hindering the progress towards factual sustainability. The environmental co-benefits of decarbonization strategies in the power sector has been reported by Luderer et al. [25]. However, there is adverse side effect on non-climate ecosystem damages depending on the technology choices. Transparent, precise, and comprehensive sustainability accounting, considering a wide range of sustainability indicators [26], is necessary to optimise the transition towards multiple objectives. Table 1 shows the sustainability-related performance of different energy sources, ranging from fossil fuel-based to renewable energy.

Based on Table 1, fossil fuel and nuclear energy are generally having a higher EROI. The other renewable energy sources have a comparable EROI, with the increasing trend for wind and solar technologies [39], except for comparatively modest biomass energy. In terms of LCOE, the cost of renewable energy has been decreased over the years where it has become cost-competitive, especially certain technology for solar and wind energy [23]. 100% renewable energy system is identified as feasible but incurs high cost and land use [40]. This limitation is also reflected in the efforts to tackle the considerable space requirement, high transport cost, and heavy foundations of wind energy, one of which is the kite power system [41]. Consistent with the study by Hertwich et al. [26], the environmental performance of renewable energy is lower than non-renewable energy, e.g. coal (see Table 1). However, differences exist among the renewable energy sources, where each source has different environmental challenges. McManamay et al. [42] suggested that energy transitions for climate mitigation incur trade-offs with biodiversity and the highest impacts from biomass, solar, wind and hydropower expansion. Lu et al. [43] proposed that solar farms in the Sahara Desert could boost renewable energy and contribute to vegetation recovery through shifted atmospheric circulation with a surprisingly adverse impact of increased global temperature. Material sourcing [44] and end-of-life management should also be considered in evaluating an optimal energy system. The increasing share of renewable energy and the approaching end-of-life stage raises attention to mitigate the impacts of material consumption and waste created, which could threaten the environmental friendlier status of renewable energy. Accumulation of the wind turbine blades waste and the diversity in models [45] has been raised several repurpose, and disposal options [46], including repurposing as a roof [47] are being suggested. The environmental impacts of decommissioning (end-of-life stage) should be

Table 1
The sustainability-related performance of different energy sources.

Energy	EROI [22]	LCOE [23] [USD/MWh]	Carbon Footprint [27] [kg/MWh]	Water Footprint [27] [L/MWh]	NO$_x$ [27] [kg/MWh]	SO$_2$ [27] [kg/MWh]	Land use/ biodiversity losses [28] [acres/GWh/y]	Risk [29] [death rate/TWh]	End of Life Management - reclamation
Fossil Fuel (Coal)	10.7 −39.1	65-159 (45 in average)	855	2220	2.1	3.365	11.11 (once)	24.62	
Solar (PV)	1.0 −16.1	29−227	101.5	330	0.275	0.205	8.33 (perpetual)	0.02	Electronic waste [30], Solution [31].
Wind	10.3 −32.4	26−54	22	43	0.275	0.205	26 (perpetual)	0.04	Blade waste [32], Solution [33].
Hydro	5.0 −66.4	44 (in average) [34]	11	4,961	0.032	0.016	30 (perpetual)	0.02	
Biomass	3.5 [35]	76 (in average) [34]	69.25	85,100	0.89	0.485	188 (perpetual)	4.63	
Nuclear	69.6 −96.2	129−198	19	2,290	0.025	0.021	16.66 (only once)	0.07	Radioactive waste [36] Solution: e.g. TP [37], Bio-T [38]

EROI = Energy Return on Investment, LCOE = Levelised Cost of Energy, Bio-T = Biological Treatment, TP = Thermal Plasma Technology.

encompassed in assessing and designing a sustainable energy system towards a circular economy. The importance of inclusion (end-of-life stage) is further magnified with the rapid increase of smart energy technologies [48] and digitalization, contributing to the increased generation of electronic waste, as for solar energy. The energy transition and development of smart technologies should be carefully monitored to ensure long term feasibility and environmental sustainability despite the advantages roles in general.

Williams et al. [40] stated that all carbon emission neutral scenarios required technological carbon emission capture, even for 100% renewable energy cases. A similar observation is suggested by Van Vuuren et al. [49] to the 1.5 °C target, highlighting the critical roles of negative emission technologies for this goal. Fig. 2 summarises the negative emission technology with the different storage mediums. Each negative emissions technology has different carbon storage potential and costs. Air capture is the most expensive option, and soil carbon sequestration is the cheapest [50]. Applying biochar, the by-product of bioenergy, to the soil could counteract climate change at a lower cost; however, the ecotoxicological aspects should also be evaluated [51]. There is a broad misconception that if a system is good for the climate, it should be good for the local ecosystem [42]. Lower environmental footprints [52] could be a more suitable indicator than having a 100% renewable energy system or focusing solely on carbon emission neutrality, assuming there is a co-benefit to the other sustainability

issues. There is a need for practical assessment tools for energy sustainability and considering the potential long-term impacts of COVID-19.

Apart from the aspects related to the energy transition, other issues such as energy efficiency deserve attention in establishing a sustainable energy system. Energy efficiency can be improved from materials and design, conversion technologies, distribution and storage [55], waste heat recovery [56], and integration. Materials and design are fundamental in deciding the resulting energy efficiency. For example, installing floating photovoltaic power with an inherent cooling effect from water (energy efficiency) and solving land-use problems require lightweight material, good strength and durability that is not affected by moisture [57]. Nanotechnology is fast developing for high-efficiency applications in solar energy, wind energy, batteries, and supercapacitors [58]. However, the main challenge lies in increasing production without deteriorating the environment and currently receiving high research attention (e.g. materials derived from waste). Operational research, including modelling and optimisation, plays critical roles in aiding the decision making of these complex implementation problems for efficiency enhancement. Even though there is a significant development in the modelling or optimisation methods, limitations such as lack of consideration on out of equilibrium situations [59], nonlinear feedback [59], non-harmonised datasets [60], the inclusion of key players [61], assessment scale and boundary [60] still exist for continuous improvement.
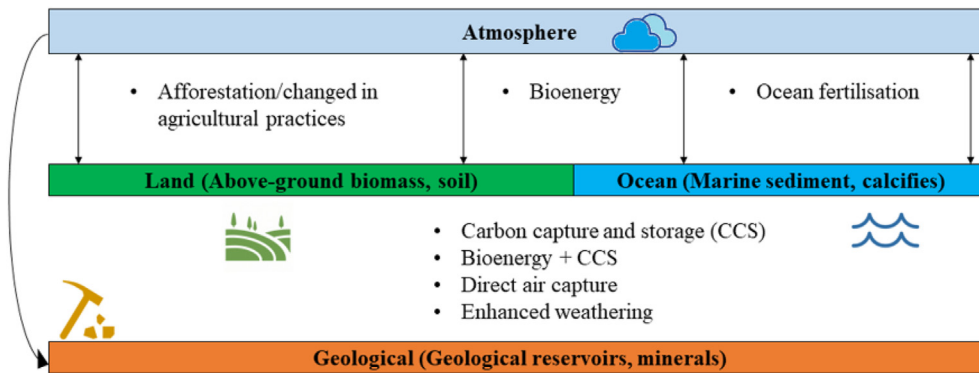
Fig. 2. The negative carbon emissions technologies − Smith et al. [53] in different storage mediums and flows - Minx et al. [54].

This study summarises the recent contribution published in a special issue with a collection of work presented in the 6th International Conference on Low Carbon Asia and beyond (ICLCA'20) and the 4th Sustainable Process Integration Laboratory Scientific Conference (SPIL'20). The studies covered sustainable energy development contributing towards the post-COVID-19 recovery. This review paper is divided into four sections, including (a) advancement in energy efficiency modelling, (b) novel materials for energy storage and conversion, (c) smart renewable energy systems, and (d) assessment of energy sustainability, with critical discussions and the possible ways forward presented.

2. Advancement in energy efficiency modelling

The advancement in the energy system relies significantly on the progress of the component technologies, system integration and implementation. The energy system's design and optimisation often require extensive analysis of various components, subsystem, and system-level parameters. Designing an optimally functional energy system leads to the progress and advancement of modelling methods. Energy modelling and implementation for buildings have become an important area of research to address climate change [62]. Adopting new technology, innovative design that leads to low energy consumption while maintaining comfort and functionality, preserving architectural values become an important research area. This section discusses some of the advanced energy efficiency modelling methods used in energy systems, processes, components, and buildings to overview the progress in energy modelling.

Component level simulation and modelling is a commonly used but essential approach to increase the system's performance. Consider the finned heat exchangers commonly used in water heaters, evaporators, and superheaters in heat recovery steam generators; the fins are attached to the tubes to facilitate heat exchange for the moving fluid [63]. The design of the fins for optimum performance requires the exact distribution of temperature along the tubes, and detailed experimentation within such confined space and complicated geometry present great difficulty [64]. In this context, modelling the components provides insight into the flow under realistic operating conditions, greatly assisting the components' design while minimising the cost and time. From the system level, Wang et al. [65] optimised the heat exchanger (HEX) network using a method based on Advanced Grid Diagram that considers the prohibited and restricted matches. Retrofitting the HEX network gained a 2.5% economic benefit rather than removing the prohibited match's heat exchanger. Optimisation of a more complex system involving heat-integrated water networks with a large number of water streams was reported by Ibric et al. [66]. The model combines water, wastewater treatment, heat integration, and HEX network synthesis models. The model enables the reduction in the number of hot and cold streams for heat integration with a manageable number of these streams, indicating the effectiveness of the model to reduce the complexity of a multi-subsystem for multiple objectives optimisation.

The use of modelling methods to improve the energy efficiency of a combustion system was demonstrated by Dere and Deniz [67]. A zero-dimensional model was utilized to simulate the energy balance and energy efficiency of the marine diesel engine. The analysis shows that heat losses to the cooling medium occurred at low engine load, resulting in reduced efficiency. Using the ethylene−glycol/water mixture as the medium in the water jacket to maintain the liner temperature, higher efficiency can be attained, which translates to lower fuel consumption and CO_2 emission saving [67]. Experimentation is needed as the liner temperatures are used in the model to adjust the cooling strategy; the modelling-experimental approach is the most effective way. Modelling the internal combustion engine with exhaust gas recirculation (EGR) shows that fuel consumption, NO_x and hydrocarbon emissions can be reduced, while hydrogen doping can extend the flame stability [68]. The operating limits of the internal combustion engine with EGR and hydrogen addition have been mapped. An industrial burner that uses biomass as feedstock can be improved by conducting a computational fluid dynamic study [69].

Optimised combustion conditions that lead to low emissions can be investigated without incurring a high cost. In solar energy utilization, the solar receiver is one of the key components in the concentrated solar power (CSP) system that works as an energy exchanger to convert solar irradiation into thermal energy. An improvement in the solar receiver presents an opportunity to increase the system's energy efficiency. Zhu et al. [70] modelled the solar receiver with metal forms for design optimisation. The proposed model accounts for the heat transfer in the form of conduction, convection and radiation. The predicted energy efficiency agrees well with the experimental data. Fig. 3a shows the actual concentrated solar power experimental setup used to validate the modelling result, while Fig. 3b shows the 3D view of the pressurised volumetric solar receiver. The result shows that a reduction of radiant loss in the solar receiver can improve energy efficiency.

The transition to industry 4.0 also presents the opportunity to reshape the operating landscape with more advanced, intelligent equipment, cleaner energy production and distribution, digitalization of energy demand, which improve energy efficiency and sustainability [71]. The opportunity for energy efficiency improvement has been extensively explored in the energy-intensive manufacturing sector via various modelling efforts. Bonilla-Campos et al. [72] modelled the process of an aluminium die-casting plant to evaluate the potential of waste heat recovery.
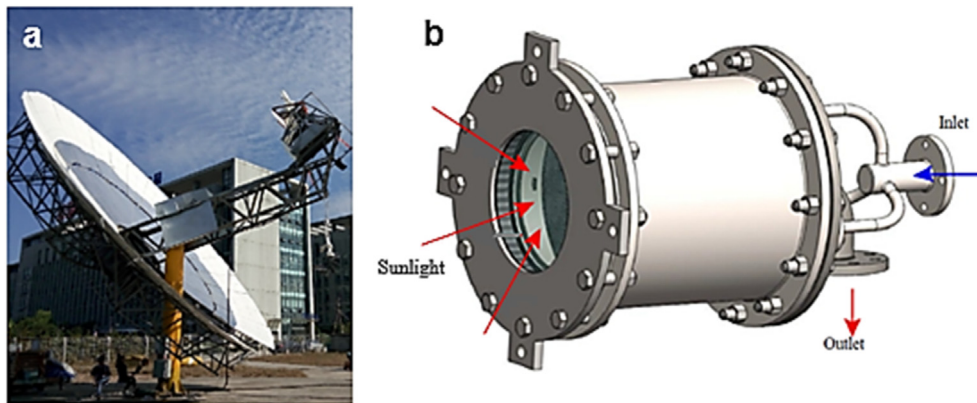
Fig. 3. (a) Actual CSP system used for experimentation; and (b) modelled part of the solar receiver Zhu et al. [70].

The modelling result shows that waste heat recovery provides up to 63% of the energy required by the furnace, reducing the consumption of natural gas. Na et al. [73] modelled the iron and steel manufacturing process's energy flow model and identified the opportunities for energy saving and consumption reduction. Strengthening the application of interface technology, optimising steel ratio, promoting waste heat recovery are among the effective ways to improve the energy efficiency of the iron and steel manufacturing process. Another approach to enhance energy efficiency via smart manufacturing is through a dynamic energy model that manages the peripheral equipment in the plant. Bermeo-Ayerbe et al. [74] proposed an adaptive predictive control mechanism that manages the devices' energy consumption profile in the industrial environment. The method reduced energy consumption by 2% and sudden power peaks of more than 11%. These approaches show that the decarbonization effort in the age of industry 4.0 can commence with the existing plant and infrastructure via advanced modelling methods. Within a realistic payback time, the modification required to enhance the energy efficiency of the existing plant is worth pursuing, given the positive impact on the environment in the long run.

Zhuang et al. [75] proposed the process of syngas-to-methanol using the Kalina cycle with waste heat recovery. Optimisation of the model enables maximised net power output from the cycle while fully utilizing the waste heat from background processes, increasing energy efficiency. The system approach modelling presents a novel method of utilizing waste heat while producing liquid fuel acts as chemical storage for energy. In the energy storage area, the energy efficiency and performance of a stationary lithium-ion battery system were evaluated via a detailed electro-thermal model [76]. The model calculates the conversion losses and auxiliary power consumption, providing a good basis for engineering improvement of the design. The complexity of the model is enhanced with the addition of more sub-models that account for other parts such as power electronics, thermal management, control and monitoring. Advancement in modelling is important to catalyse the development of energy storage systems. Modelling the risk associated with the energy system is useful for the implementation and decision-making process. Tapia [77] developed a neutrosophic optimisation model to manage the risks for a polygeneration plant and integrated biorefinery. The model involves multi-product, such as the product demands, waste targets, economic benefits, and the user's risk perception, to create the risk profile of the energy system.

Legislation plays an important role in driving the development of low energy building. The EU commissions have passed the 2010

Energy Performance of Buildings Directive and the 2012 Energy Efficiency Directive in the European Union, aiming to reduce energy consumption [78]. An effective method to increase the energy efficiency of the existing building is via retrofitting with energy-efficient facilities. Fan and Xia [79] modelled a rooftop retrofit with a solar panel, considering the degradation performance and corresponding maintenance to estimate the energy savings and economic benefits. The optimisation model can be applied to identify the investment opportunity in building envelope retrofitting projects. Wu et al. [80] proposed a time-building-technology framework to maximise energy savings and net present value during large-scale building retrofitting. Sandvall et al. [78] modelled the heat supply of a low energy building at three scales, i.e. individual, on-site and large network supply, to assess the system cost. The district heating system modelled the annual heat demand, heat duration curve, technologies, fuel input, capacities, and efficiency. The result shows that the large heat network option has the lowest system cost. The climate is of high stable temperature and high humidity level in the tropical region; these factors should be considered when designing a smart energy system. On a smaller scale, the energy efficiency of the classroom can be modelled based on the building information modelling method by considering the daylight, thermal condition, energy consumption and natural ventilation. The proposed daylight strategy reduced energy by 7−12% [81]. Effective energy management for smart buildings requires the consideration of real-time demand response.

Integrating renewable energy sources into an existing building is an attractive option, given the potential to reduce operating costs via self-generated electricity. Sharma et al. [82] proposed a centralized energy management system framework that enables off-grid operation and optimal energy usage of a residential building. The system can promote the use of renewable energy while maintaining the comfort level of residents, thereby optimising the energy usage and controllable loads. Dadashi-Rad et al. [83] modelled the energy management of a smart building equipped with responsive and non-responsive devices and renewable photovoltaic resources. The battery was used as energy storage for charging during a low load period. The proposed model was able to reduce network losses and energy consumption while improving the voltaic profile of the building. The cost of operation can be significantly lowered by controlling the charging and discharging of the batteries and solar cells. Yang et al. [84] developed a model predictive control (MPC) system with an adaptive machine-learning-based building model for building automation and control applications. The dynamic modelling scheme is based on an artificial neural network with a nonlinear autoregressive

exogenous structure that updates the building model regularly using online building operation data. Fig. 4 shows the approach of the MPC system with an adaptive machine learning-based building model. The system reduces 58.5% cooling thermal energy consumption and 36.7% cooling electricity consumption. A more intelligent and advanced model will be adopted to model energy efficiency in smart energy building, in tandem with the adoption of advanced renewable energy technology to meet the zero energy building target [85].

There are various tools and models developed for the modelling of the energy systems focusing on integrating various renewable energy resources. Lund et al. [86] identified and compared the optimal solutions and the analytical simulation approach commonly adopted by researchers in energy system modelling. The optimisation approach typically set an objective function to identify the optimal solution. The choice of objective could include, for instance, energy consumption or environmental consequences in economic terms. Such models typically have a current system as a starting point for the algorithms to identify the optimal way, using linear, non-linear or mixed integer linear programming methods to express the problems mathematically. On the other hand, the simulation approach lacks a well-defined system to start with, rather, guided by a set of established priorities and the appropriate system response is searched. Such simulation provides details about the future technologies rather than details in the existing system. An example of such a model is the use of the EnergyPLAN model to simulate the national level district heating sector to identify the costs, emissions, energy supply and etc. [87]. Cross-sector energy integration modelling is also important as it facilitates the wider inclusion of renewable energy shares in the system [88]. From the standpoint of the system designer and programmer, the scope of energy system modelling can broadly be performed based on temporal, spatial and technical resolutions, depending on the modelling objectives [89]. For example, modelling the temporal resolution of renewable into the energy system allows capturing the actual dynamics of a modelled system and adequacy in balancing supply and demand. Deane et al. [90] reported that system modelling with higher temporal resolutions could better capture the system load and renewable energy generation, thus enabling a more accurate system costs analysis. The hourly modelling approach has been widely adopted by researchers in the study of energy system, based on the survey analysis conducted by Chang et al. [89]. On the other hand, spatial modelling of the energy system can provide details over the representation of the energy system at the urban, regional or global level, providing a detailed survey with aggregated technical details [89]. Dominkovic et al. [67] modelled the integrated urban energy system, including Singapore's power, gas, cooling, gas, mobility, and water desalination sectors. Integrating district cooling and renewable energy mix was found to be feasible with lower social-economic costs and greenhouse gas emissions. This indicates that modelling tool development is essential to link the system design with the user-needs and policy-making processes, thereby facilitating the decision-support in a real-world perspective.

3. Novel materials for energy storage and conversion

One of the main challenges of integrating renewable energy and sustainable energy sources into the existing energy supply chain is the effectiveness of compensating the temporal differences in peak energy production and demand [91]. The intermittency of renewable energy sources, such as the fluctuating energy from the sun, for which non-operational times at night often meets with peak demand, results in the mismatch between production and consumption. An effective energy storage system could be developed to account for the mismatch between supply and demand, i.e. storing the excess energy during the day and then discharging them when needed. Some promising technologies in thermal energy harvesting are thermoelectric, thermomagnetic, thermoelastic, pyroelectric approaches [92] and an efficient heat storage system to use the heat during low-production times. Similarly, waste heat from industrial processes is considered a valuable source of energy that can be recovered and exploited via the integration of a thermal energy storage (TES) system in the energy network. A TES system requires a specific design that allows the charging and discharging of heat at desired timing, while the heat storage material requires certain thermal properties and criteria. Muller et al. [91] investigated the potential of transition metal salts with ammonia as a thermochemical energy storage material for a medium temperature range of 25 °C and 350 °C. The combined $CuSO_4$ and NH_3 exhibit the characteristics with the highest energy storage density of 6.38 GJm^{-3}. Full reversibility of the storage reaction and no material degradation over cycling was observed, but the long-term stability of the materials has yet to be ascertained. Kocak et al. [93] assessed the potential of demolition waste from urban regeneration as thermal energy storage material. The demolition waste was found to have a good thermal storage performance of 750 °C, making it a sustainable, eco-friendly storage material to recover waste heat.

Zhang et al. [94] designed a shell-and-tube thermal energy storage unit with phase change material that can enhance the heat transfer process in the energy storage unit by over 40%. Based on the topology optimisation method, the optimal volume ratio of the fins was reported to be 20%. The conversion of agricultural waste into energy storage material is another promising route. Cocoa pod rusks, banana ranches and rice husks are rich in lignocellulosic and can be utilized to produce porous carbonaceous material with good thermal storage properties. Biochar prepared from banana ranches possesses the best properties as an electrical material for energy storage. The supercapacitor cells assembled using banana ranchis with $NaSO_4$ electrolyte interface represent greater energy storage than the acidic ones [95]. The use of low-cost agro-waste to produce useful value-added products also conforms to the circular economy concept, maximising the value of by-products to ensure
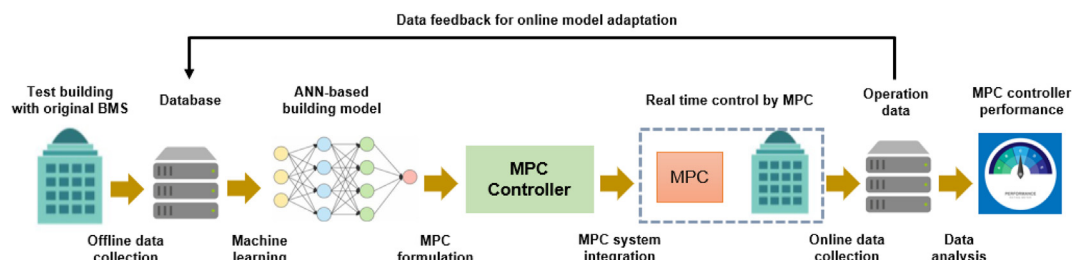

Fig. 4. An overview of the approach for developing the model predictive control (MPC) system with an adaptive machine learning-based building model - Yang et al. [84].

environmental sustainability.

Thermochemical materials (TCMs), which functions based on chemical reaction and chemisorption, have shown high potential for storing energy with high energy storage density, moderate storage temperature and long-term storage capabilities. Examples of TCM include metal oxide/metal carbonates, metals/metal hydrides, ammoniates and salt hydrates. The design and operating conditions of the thermochemical energy storage system are critical to obtaining optimum performance [96]. Considerable advancement has been achieved with research on phase change materials (PCMs) as heat thermal energy storage in advanced energy-efficient systems. However, due to the intrinsic rigidity and brittleness of conventional phase change materials, the application to complex confined surfaces has been restricted. Recent research has focused on flexible phase change material that can withstand certain deformation and make compact contact with integrated devices [97]. Such emerging material is envisioned to offer huge potential in wearable applications and electronic thermal management. Several types of flexible PCM structure has been designed and explored, such as (1) confinement of PCM into flexible porous scaffolds, (2) encapsulation of PCM into elastic shells, and (3) molecularly engineer the PCM structure to make it inherently flexible. The potential application of the flexible PCM includes thermal therapy of the human body, such as the wearable thermal management device, as shown in Fig. 5 [98]. Zhou et al. [99] extensively reviewed the progress in wearable energy storage device technology within the context of flexible and stretchable electronics. 2D materials with a high surface-to-volume ratio, high capacitance and energy density are among the properties required for developing a flexible energy storage device. Examples of such materials are graphene, MXenes, transition metal dichalcogenides and oxides.

In recent years, the search for higher efficiency energy storage material has led to novel materials such as metal-organic frameworks (MOFs). The MOFs are porous crystalline hybrid materials fashioned by linkage of the metal centres (clusters) and organic linkers (organic ligands), which have attracted the research community due to their unique properties, including tunable porosities, high surface area with modifiable morphologies. The MOFs are recognized as promising energy storage and conversion materials with vast applications in solar cells, fuel cells, lithium-ion batteries, supercapacitors, hydrogen production and storage. Chuhadiya et al. [100] provided an extensive review on the MOF design, composition and application in energy storage and conversion devices. The utilization of MOF thin films in the perovskite solar cells and dye-sensitized solar cells are shown in Fig. 6. The MOF layer can be used for electron transfer, light absorption, or photoanode purpose. The MOFs can be used as a surface modifier or additive for the passivation of defects in perovskite solar cells to increase the performance of the device [100]. Salarizadeh and Askari [101] developed a ternary hybrid nanostructure consisting of MOS_2-ReS_2/rGO

as pseudocapacitor electrode materials. The MOS_2-ReS_2/rGO showed good stability of 92% after 5,000 cyclic voltammetry cycles with a specific capacitance of 949 F/g, which can be used as an electrode in the energy storage field. Another new class of phase change material known as MXene has attracted much interest as an energy storage material [102]. MXene means that it derives from max phase ceramic materials and "ene" means that it has a graphene-like microscopic sheet structure [103]. Jamil et al. [102] reviewed the fabrication process of the MXene process and the characteristics of 2D materials. Some of the applications of MXene in thermal applications include lithium-ion batteries, supercapacitors, and electrocatalysis for carbon-free production of fuel. MXenes are excellent energy storage/delivery due to their lamellar structures and exceptional electrical conductivity [104]. Ali et al. [105] reported that a significant enhancement in the electrochemical performance could be attained with Fe_2O_3/MXene nanoparticles as anode materials for lithium-ion batteries. The MXene/transition metal oxide composites can be extended to other applications such as energy storage, electrocatalysis, and electrochemical sensors. The titanium carbide (Ti_3C_2) MXene was shown to be an efficient noble-metal-free co-catalyst with commercial titania (P25) for photocatalytic CO_2 reduction [106], paving the way for the possibility of producing solar hydrocarbon fuels via photocatalytic reduction of carbon dioxide with only solar light as the input energy source. Fig. 7a shows the CO_2 reduction mechanism of Ti_3C_2−OH/TiO_2 under irradiation. Ran et al. [107] showed that Ti_3C_2 nanoparticles as an MXene material could be integrated with cadmium sulfide to induce a super high visible-light photocatalytic hydrogen production activity, enabling the construction of high performance, low-cost photocatalyst/photoelectrode for the generation of hydrogen from solar energy. Fig. 7b illustrates the mechanism for photocatalytic H_2 production in the CdS/Ti_3C_2 system under visible-light illumination.

Combustion is an energy conversion process that will play an important role in many industries, including power generation, manufacturing, and transportation. Developing a highly efficient combustion system is critical to ensure the chemical energy stored in fuel is fully utilized while minimising the emissions of harmful pollutants and greenhouse gases. Hidegh et al. [108] and Józsa et al. [109] have developed a novel mixture temperature-controlled combustion concept that enables to operate biofuels with low emissions at certain operating conditions and fuel injection strategy. Such a system can be used for industrial processes or as part of the distributed energy system for district heating that would meet the ever-increasing stringent emissions regulations. Chong et al. [110] proposed a dual-fuel swirl combustion method that enables the concurrent burning of natural gas and biofuel. The use of an airblast type atomizer allows the injection of viscous liquid fuel, thus allowing the adoption of lower grade biofuel. The combustion process can be optimised to achieve low pollutant emissions. Bio-liquids derived from a waste stream such as lignocellulosic biomass,
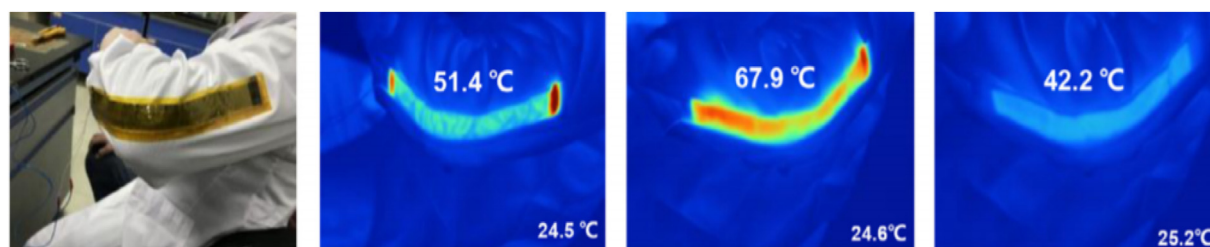

Fig. 5. The photos of flexible thermal control device under bending condition, IR images of bending thermal control device representing the shape stability during heating and cooling process − Kou et al. [98].
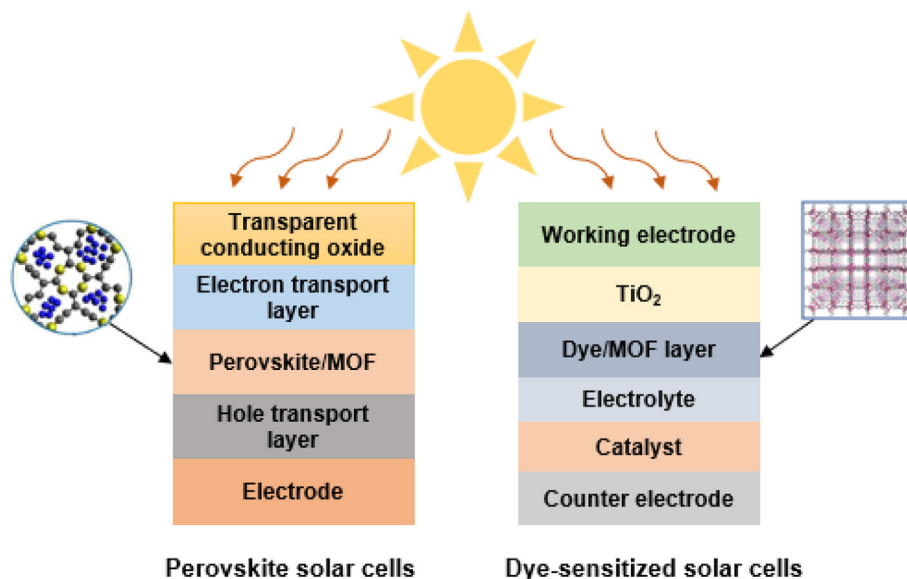
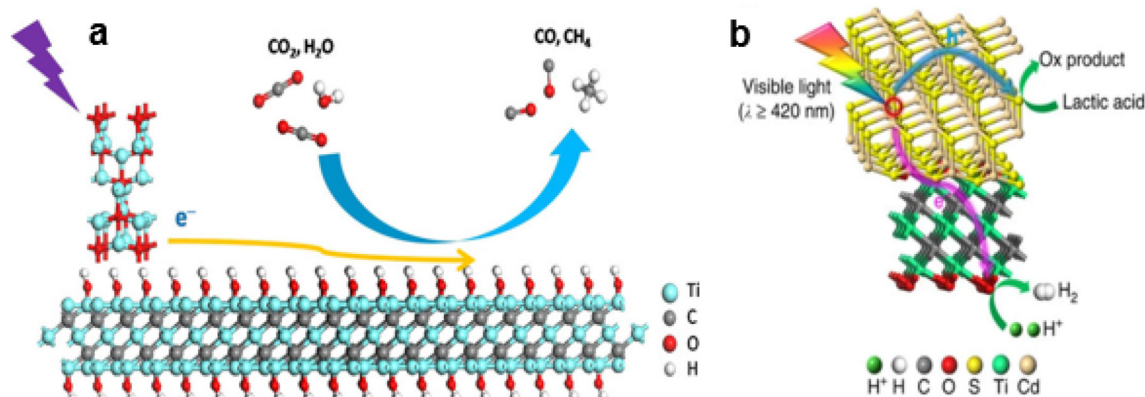**Fig. 6.** The role of MOF thin films in perovskite and dye-sensitized solar cells- Chuhadiya et al. [100].

Fig. 7. Proposed photocatalytic CO_2 reduction mechanism of Ti_3C_2-OH/TiO_2 under irradiation-Ye et al. [106], (b) Proposed mechanism for photocatalytic H_2 production in the CdS/ Ti_3C_2 system under visible-light illumination- Ran et al. [107].

crude glycerol, sludge, waste lipids, waste liquor can be upgraded or used directly in fuel-flexible combustion systems such as micro gas turbine for power generation, albeit some adaptation to the combustion system is needed to accommodate the higher viscosity, impurities and low calorific value for the inferior fuel [111]. Such low carbon fuels derived from biomasses or industrial wastes are important and can contribute to achieving the carbon neutrality target. The European Union Renewable Energy Directive (RED) has imposed the objective of 10% renewable energy consumption in transport (RES-T) in 2020, highlighting the importance of biofuel. The use of waste-based feedstock such as waste cooking oil or biowaste is highly encouraged as they contribute to the RES-T share via double-counting rules [112].

Ammonia and hydrogen fuels that contain no carbon are expected to be important alternative fuels in the future as part of the global decarbonization campaign [113]. It has been projected that green ammonia synthesized from a hybrid PV-wind power plant is priced at 370–450 €/t by 2030 [114], which would be market competitive against the fossil-based ammonia, making it feasible for wide adoption in the power generation sector. Recent advancement in ammonia-fuelled engine shows that ammonia

burning is feasible by mixing with hydrogen for power generation, but the potentially high NO emissions need to be addressed [115]. Due to the convenience in storage, ammonia is suitably be used as marine fuel for low and medium-speed engine operations [116]. However, the low energy intensity for ammonia and hydrogen makes the fuels unsuitable for aviation turbine engine operation due to the aircraft's limited fuel tank space and weight distribution consideration. Sustainable aviation fuel production from biomass for use in the aviation industry has gained much momentum in the aviation sector [117], as evident by the global carbon emissions offset scheme adopted by the International Civil Aviation Organisation. At present, seven biojet fuels have been approved under ASTM D7566 to blend with conventional jet fuel in the jet engine [118]. The production of biojet fuel via the hydrogenated esters and fatty esters pathway is the most technologically matured and commercially viable. Using non-food resources such as microalgae to produce biojet fuel has attracted much attention given the potential high yield. Hydroprocessing of microalgae oil with zeolite catalyst produced a high yield of 76% [119]. The utilization of biomass such as agricultural waste and animal manure to produce bioenergy is gaining momentum. China is expected to produce over

20×10^9 (m^3) of biogas derived from anerobic digestion process by 2030 [120], partially reducing the reliance on natural gas. Some of the challenges associated with the efficiency of the production of biogas such as fluctuation of organic loading rate, varied temperature and acidification should be resolved. Guo et al. [121] examined the role of conductive material on facilitating direct interspecies electron transfer during the process of methanogenesis via a thermodynamic cycle analysis. The conditions that favor the methanogenesis reaction were identified, leading to a better understanding of the aenerobic digestion process.

Waste validation for bioenergy production and bioproducts has become a hot topic [122]. The vast amount of waste produced from agriculture and manufacturing industries can be converted into useful products, maximising the waste materials' values and lowering the carbon footprint. The recent pandemic of COVID-19 has generated a significant amount of medical waste, particularly face masks, which present a new threat to the environment [123]. Pyrolysis could be applied for medical waste treatment, valuable products such as biochar and bio-oil can be produced while minimising the environmental impact [124]. Mong et al. [125] evaluated the potential of waste activated sludge from the food manufacturing industry as feedstock for thermal processing via the kinetic study and thermodynamics analysis. The volatiles produced from the pyrolysis process can be condensed into phenols, alkanes, aromatics compounds. The non-condensable portion forms the biogas, indicating the potential of the product to be fuels. Model-free methods such as the Flynn-Wall-Ozawa or Kissinger methods [126] can be deployed to describe the kinetics and complexity of the devolatilization process. Advanced thermochemical conversion methods such as microwave-induced pyrolysis can be deployed to pyrolyze lignocellulosic biomass, animal manure [127], scrap tyres [128] and other types of biowaste [129] to obtain value-added products. To investigate the relations between biofuel combustion and particulate emissions, Sitek et al. [130] reported that volatile matter is the dominant source of fine particle formation. The absence of oxygen during pyrolysis results in two times higher particle mass than standard atmosphere conditions. A thorough investigation of the formation of emissions from biofuel combustion is important to ensure the impact on the environment is minimised, apart from ensuring their sustainability.

4. Smart renewable energy systems

The concept of new energy systems has been proposed as the new paradigm of energy systems that integrates multiple energy sectors, emphasising the inclusion of a high portion of renewable energy sources. Extending beyond the concept of "smart grid" which mainly refers to the single electricity sector, *Smart Energy System* has been redefined to take a broader but more holistic approach that refers to cross-sectoral inclusion, including electricity, heating cooling, industry, buildings and transportation, allowing for the identification of more achievable and affordable solutions to the transformation into future renewable and sustainable energy solutions [131]. In addition, the growth of Industry 4.0 technologies such as the Internet of Things (IoT) has provided the ideal push factor for the revolution of energy systems [132]. It has been projected that the IoT worldwide energy market is expected to be worth USD 26.5×10^9 by 2023 [132]. Developing a smart energy system with low or near-zero carbon emissions through intelligent control and management is possible. The word "smart" focuses on the control and management performance and the intelligence level of an energy system. The "energy" emphasizes the evolution of conventional fossil-based energy to renewable energy, while the word "system" refers to the integration and optimisation of the various energy subsystems to function as a unit

as a whole [133]. The term "system" has also been defined by some researchers to refer to the inclusion of all sectors/or all energy carriers, such as those combining the heat, cooling, power, gas and transport markets, via a cross-sectoral integration approach [134]. From the system viewpoint, the smart energy system has also been used to express the interaction from "homes to network to cities", which include all cross sectors and wider scale, covering the residential to power generation systems [134]. Among all the smart systems, the issue of storage is particularly highlighted, indicating the importance of the energy to be effectively stored and distributed through a regulating storage system [131]. In view of the global transition of energy supply and demand, faster development in renewable energy, energy storage and energy efficient technologies is expected. This provides the catalysts to accelerate the development of smart meters as increasing level of electrification and a larger level of digitalization is expected. Further, development of smart grids, energy infrastructure and energy storage systems which involved cross-sector integration and high level of renewable energies are expected to gain momentum to meet the global decarbonization goals [88].

A typical smart system consists of four main subsystems: energy generation systems, energy end-users, energy distribution and storage systems, and smart energy management systems [133], as illustrated in Fig. 8. The alignment of the energy generation, storage, and consumption aspects is the key to ensuring the system's optimised performance. It remains as part of the main challenges to be addressed. There have been extensive studies conducted on the design and management of a smart energy system. Different design and operation optimisations have been proposed to achieve the synergies and subsystems while maintaining individual systems' high performance [135]. Different objectives, models and algorithms for design optimisation of a smart energy system are compared. Xu et al. [133] provided an extensive review on the four common energy models used, including the HOMER, EnergyPLAN, Energy Hub and TRANSYS. These optimisation algorithms have been widely applied, including deterministic, stochastic, fuzzy, and other potential algorithms. Advanced analysis of smart energy systems via cross-sectoral interaction is enabled, such as the capability shown by EnergyPLAN, that bridges the conversion of renewable electricity into other energy carriers such as heat, hydrogen, green gases and electrofuels, as well as different sectors such as building, industry and transport [136]. The main challenge for smart energy system design is to synergistically complement the advantages of the subsystems involved to enable an energy-efficient, robust, grid-friendly system to achieve the energy balance between supply and demand in the network considered.

The intermittency of renewable energy resources, e.g. solar and wind energies, has posed a challenge to the energy system as the fluctuating power demands from power may not be well matched. Different renewable energy planning strategies and tools have been developed to ensure the combination of various subsystems can achieve a high level of interaction and efficiency. Mah [137] proposed a multi-period P-graph optimisation framework to optimise photovoltaic (PV)-based microgrid with battery-hydrogen energy storage, which optimises the microgrid based on the hourly and seasonal mismatch of energy supply and demand. The author noted that coupling the PV-battery system to the grid is economically viable while reducing a substantial carbon footprint. Some models have been developed that consider the environmental conditions while solving the stochasticity of renewable energies. The near-zero carbon emissions multi-energy system (ZC-MES) optimisation model proposed by Alabi et al. [138] coupled the Monte Carlo scenario generation, fast forward scenario reduction approach, chance-constrained programming, duality theory, and big-M linearization approach. The comprehensive model enables optimal
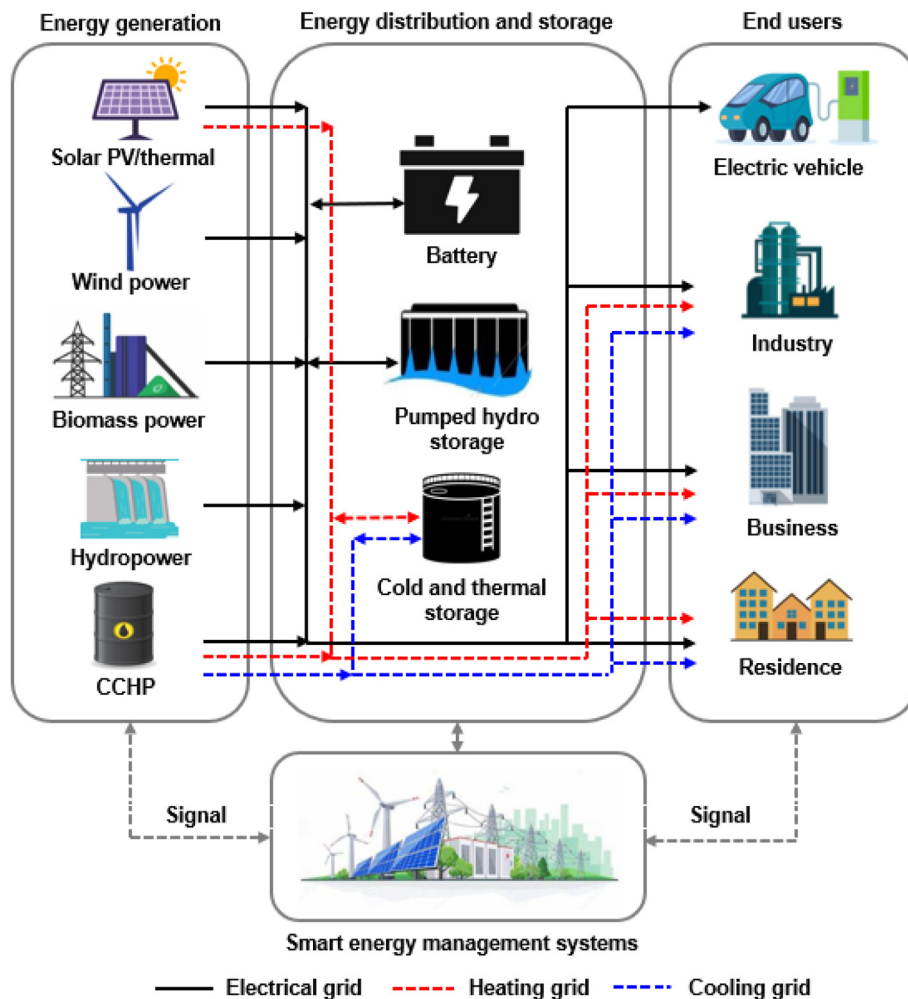
Fig. 8. Composition of a typical smart energy system − Xu et al. [133].

planning, emphasising energy waste minimisation and transmission loss reduction and optimal design to contribute to a carbon-free environment. The author applied the model to assess the multi-energy system that comprises distributed energy infrastructure, including generation, transmission, storage, and distribution) while ensuring the interaction between different energy type conversion processes to achieve zero-emission during the operation phase. Another important aspect of energy design and planning is the risks involved. Zeinalnezhad et al. [139] presented the hybrid ISM-CPN model based on Coloured Petri Nets and Interpretive Structural Modelling approach to assessing the risks associated with the development of wind farms, particularly the relationship between risk factors in the form of quantitative indicators. A risk analysis model is a useful approach to identifying the main risks to enable informed decisions.

Effective utilization of local biomass for energy generation is another way to diversify the energy profile and reduce GHG emissions. The application and integration of various renewable energy sources into the energy system of the smart city present an opportunity to optimise the benefits of the bio-economy, such as transforming waste into energy, leading to the reduction of waste and carbon emissions [135]. Mah et al. [140] showed that co-firing biomass could reduce bioenergy cost up to threefold via spatio-temporal optimisation model as the supply chain cost is reduced. Modelling the energy usage in the Zagreb city via EnergyPLAN

shows that up to 49% of the annual total electricity production can be obtained from intermittent renewable sources. This option is more favourable than the traditional non-integrated system that utilises 50% more biomass, as the former is techno-economically feasible [141]. A study has shown that an integrated solar energy system comprised of concentrated solar power, PV thermal, integrated with an organic Rankine system and an absorption refrigeration system can meet the demand of electricity, cooling and heating for a small city of 5,000 homes with an efficiency of 53.4% [142]. For nations enriched with renewable sources such as solar and wind, energy storage becomes necessary to overcome intermittency.

Effective energy storage must be developed to enable a higher penetration rate of renewable energy. Ajanavic et al. [143] reviewed the types of electricity storage options available. Fig. 9 shows the storage time of various storage technologies for the storage capacity [144]. Short-term electricity storage options are pumped hydro storage and batteries. Excess electricity not intended for immediate use can be in thermal storage, district heating network, or converted to hydrogen or methane as chemical storage. The conversion of electricity into mobile clean fuel such as hydrogen can benefit the transportation sector if used as a transport fuel, reducing fossil fuel reliance. Lund et al. [145] opined that electricity storage is 100 times more expensive than thermal storage and even more expensive than storage for gas and liquid. Hence, a cross-
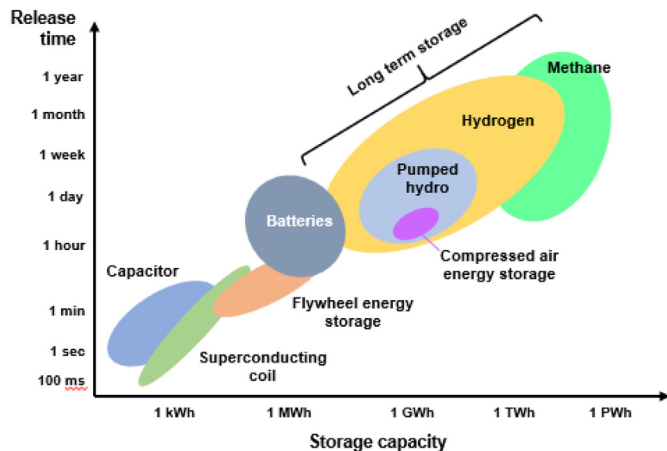
Fig. 9. Typical storage time of various storage technologies as a function of installed storage capacity - Scientific J [144].

sector approach that integrates energy conversion and storage technologies has been proposed as a more viable option. For example, heat pumps used in rural or district heating can connect the electricity sector to the thermal sector, while electric vehicles and electrofuels can connect the electricity sector to storage in the transport sector. In designing the smart energy system, Wang et al. [146] developed a four-step analysis framework to evaluate the impact of the energy storage system with multiple energy carriers and provide a basis for quantifying the uncertainties for utilizing renewable energy in process industries. The framework consists of developing a deterministic optimisation model, characterizing the uncertain parameters in the system, performing global sensitivity analysis and conducting Monte Carlo simulations to quantify the uncertainty analysis. In the study, the energy storage system has been identified as the most critical uncertain parameter. At the time of writing, many researchers have focused on integrating various energy storage systems with renewable energy sources. Mah et al. [147] optimised the design and operation of standalone microgrid with hybrid battery-hydrogen storage, using an energy management strategy developed via particle swarm optimisation algorithm. Energy storage becomes an essential part of the energy system to function as an intermediate station for energy regulation to ensure optimised usage.

At least two renewable energy components, e.g. solar, wind, geothermal, fuel cell etc., can be integrated into energy systems at various scales (household or industry) at various scales. However, various challenges such as system performance optimisation, management issue, connection problem, operating cost, installations and economics need to be overcome to enable large scale deployment of renewable energies. From the operation perspective, a smart energy system needs to be reliable and energy-efficient. Smart grid application systems need to be monitored and metered effectively. Voltage source inverters capable of pulse-width modulation are generally utilized to connect renewable energy sources and the grid. The planning for an optimal number of power conversion stages requires constant monitoring and sensing of data [148]. The interlinking of energy sub-sectors, including electricity, heat and gas, requires an efficient management system based on real-time principles. Intelligent algorithms are vital to ensure system stability and reliability at multiple energy levels at varied operating conditions [135]. Both software and hardware need to be developed to manage, optimise, coordinate and distribute various energy sectors in alignment with the demand and usage profiles. The internet data centre is an integral part of the

smart energy system as it can significantly affect the operation of the power grid. It also serves as the intermediate unit to process the requests from end-users to regulate the temporal-spatial power demand distributions. The study optimised the data centre to meet different objectives in a smart grid with a battery energy storage system, including the system's total cost, load profile, and energy storage, to improve the overall quality of service [149]. A smart energy system needs to couple with a highly effective data centre to manage the information flow between the power production and consumption terminals.

In the thermal sector, the development of 4th generation district heating (4GDH) is envisioned to meet the demand for more energy-efficient buildings and integrate district heating and renewable energy sources into a smart energy system [87]. The 4GDH system is defined as a smart thermal grid that integrates the supply of heat to low-energy buildings with low grid losses, utilizing low-temperature heat sources that is integrated into the operation of smart energy systems, by considering the planning, cost and incentive structures to ensure the sustainability of the systems [150]. Unlike the previous generations of district heating in which buildings had high heat demands, high district heating temperature requirements, and the supply of heat supply was based on fossil fuels, the 4GDH is essentially based on non-fossil fuel heat sources and delivery of heat to buildings with low heat demand. The optimum interaction of renewable energy sources, distribution and consumption in addition to the two-way district heating is among the key features of 4GDH, as illustrated in Fig. 10. Quantification of the cost and benefits of such system has been performed in a Danish district heating model [87]. The study shows the costs involved are the upgrade of heating systems and the operation of district heating grids, while the benefits include the lower grid losses, better utilization of low-temperature heat sources and improved efficiency in the heat pumps, CHP units and boilers [87]. Lund et al. [151] further proposed an integrated smart energy system approach that considers different sub sectors with the least cost solution. The existing gas and district heating grids in Denmark with significantly higher capacity than the electricity distribution grid can be utilized to pave the way to achieve 100% renewable energy goal. Overall, the benefits exceed the cost, but the actual implementation of the revolutionary smart energy system may require a new set of legal framework, ownership and economic incentives [87].

The residential sector contributes a significant portion of GHG emissions. The consumption terminals within the smart energy system can effectively utilize smart technologies and strategies to control energy in the residential sector. Smart homes are the new trend in the residential sector [152]. The smart home has been defined as "homes where different services are integrated through the use of a common communication system" [153]. Many studies have developed smart home energy management systems and energy conversation systems within the residential sector. Integrating smart applications and load monitoring systems can save 12−20% energy [154]. The installation of solar photovoltaic-thermal (PVT) panels with a heat storage tank in a building could potentially meet the annual hot water demand. The excess heat can be sold to compensate for the building energy's cost [155]. Celik et al. [156] reviewed the optimal combination of HEMS components, such as renewable energy, energy storage systems (ESS), and smart meters, using various analysis methodologies (e.g., heuristic algorithm, game theory, and fuzzy programming). An energy management system that can adapt to accommodate different user objectives, different building structures (including passive design), information about the unit's location and orientation, and different heating or cooling systems, varied demand response was proposed by Salerno et al. [157] to achieve the optimum operating conditions
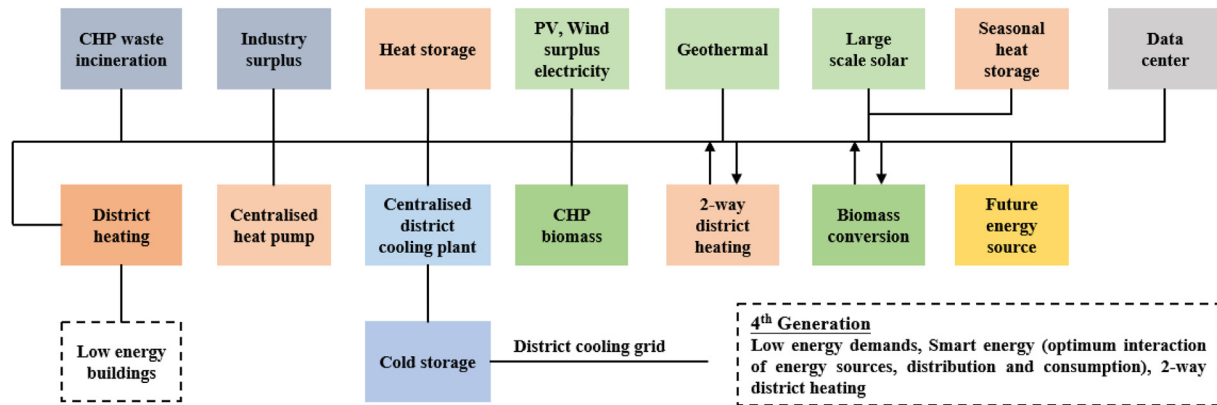
Fig. 10. The concept of 4th generation district heating— Lund et al. [87].

and minimise energy consumption. The performance of the individual part unit was enhanced and provided grid flexibility to the grid. Zheng et al. [158] developed a smart home energy management model for smart home energy management with grid-connected residential PV-battery systems under uncertain loads and PV generations, based on the functional layers covering monitoring, analyzing and forecasting, scheduling, and scheduling coordinating. Smart Energy Island is also at high research attention with great potential, of which the European Union has identified as one of the priorities towards low carbon emission and sustainable energy systems. Groppi et al. [159] suggested that battery energy systems and pumped hydro energy storage are the most used technologies on islands to overcome the unpredictability of integrating Variable Renewable Energy Sources into the electricity grid. de São José et al. [160] highlighted that one of the current challenges in the smart energy community is to analyse the synergistic improvement in multi-purpose energy communities, including adaption for land communities.

5. Assessments of energy sustainability

Energy utilization is an integral aspect of the economic and social development of a country. However, the huge demand for energy in tandem with economic growth has led to the mass consumption of fossil fuel and caused serious environmental pollution. The transformation from a fossil-based economy to a green circular economy has been highlighted [161]. The United Nations has introduced sustainable development goals (SDGs) that emphasise humanity-centric policies, so that social and natural resource sustainability could be more equitably built [162]. Elavarasan et al. [163] examined the impacts in the energy sector and its influence on sustainability. It was shown that SDG 7 (Affordable and clean energy) serves as the foundation that will lead to spill-over effects on the broader scale of sustainable developments, as shown in the mapping of SDG 7 against other sustainable development goals in Fig. 11. In the post-pandemic era, it is expected that sustainable energy demand will increase. The leaps and bounds to enable the economy's recovery and aligning clean energy development with the environmental and social-economy aspects are pivotal to ensure long-term sustainability.

Various sustainability indicator frameworks and models have been proposed based on a regional approach. Wang et al. [164] examined China's water-energy-carbon (WEC) nexus from China's regional and sectoral perspective via the introduction of WEC efficiency derived from the Multiregional Input-Output approach.

The regional embodied WEC efficiency has been identified, in which Xinjiang, Hebei and NingXia provinces in China dominate the provincial coefficients of water consumption, energy consumption and CO_2 emissions. The study enables the understanding of the regional WEC efficiency performance and locations which requires the most attention for CO_2 emissions reduction. Wang et al. [165] evaluated the energy economic security of China via an evaluation index system that accounts for the energy industry development, energy supply capacity, energy utilization level and environmental energy impact. Such index shows that the energy development supply, utilization and capacity for clean energy are interdependent and should be checked and balanced to achieve an overall energy economic security. China has introduced various environmental regulation policies to stimulate the green development of the renewable energy industry. Brodny and Tutak [166] assessed sustainable energy development in the Central and Eastern European countries by using 21 indicators covering energy, environmental, economic and social security for the years 2008 and 2018. It was found that Latvia and Croatia were ranked best in terms of sustainability. From an econometric modelling study, the deployment of renewable energy was found to have profound positive effects on the West African population [167]. Yürek et al. [168] calculated the sustainability index for deploying renewable energy technologies in Turkey by considering key factors such as uninterrupted supply, economic supply and environmentally friendly supply. It was reported that hydro + solar and wind + solar hybrid alternatives have the highest sustainability index value. Biodiesel production sustainability has been assessed from the energy-water-food nexus for various countries [169]. The limiting factors for biodiesel production were identified, with water being one of the primary factors. The study showed that government intervention in subsidy is important to make biodiesel profitable in certain countries. The studies are useful for authorities to formulate effective measures for sustainable energy development.

The transition of energy from fossil fuel to the bio-based economy can improve the quality of people's livelihood, national energy and food security [161]. A thorough understanding of the distribution and availability of biomass types is important to ensure a sustainable supply chain. Fan et al. [170] assessed the biomass resource utilization scenarios in the Tomsk region in Russia. By using local biomass such as manure, residual and forest wood as feedstock in the integrated biomass system design, a significant greenhouse gas footprint can be reduced without compromising the energy demand. Cho and Strevoz [171] assessed the environmental impact of 197 thermal power stations in Australia. The

Fig. 11. Relationship of SDG 7 (Affordable and clean energy) with other SDGs - Elavarasan et al. [163].

impacts were ranked according to the source of fuels, in which brown coal and sewage gas result in the environmental impact for fossil and renewable sources. It was projected that the CO_2 emissions in Australia could be reduced by 30% when renewables constitute 50% of the total electricity mix. Woon et al. [172] proposed a food waste management framework that produces electricity via anaerobic digestion. Effective utilization of food waste can reduce 0.4% of total carbon emissions and contribute 1.1% of total electricity consumption in Malaysia, reducing reliance on landfills. The sustainability of anaerobic digestion of various feedstock was assessed from the energy point of view [173]. Livestock residues attain the highest long-term sustainability score compared to other biomass resources and municipal solid wastes. The feedstock source needs to be thoroughly assessed for bioenergy to ensure sustainability.

Understanding the spatiotemporal evolution and the influencing factors of energy intensity can assist in formulating a carbon reduction policy. Shi et al. [174] examined the relative variation of energy intensity among provinces in China by using the Geographic Information System (GIS). The energy intensity of each province in China was spatially correlated, the western area with highly energy-intensive. In contrast, the eastern coastal area with low energy-intensive has been identified. Phuang et al. [175] assessed the environmental impact of palm cultivation and biodiesel production in Malaysia using a life cycle assessment methodology. It was identified that air particulate matters, greenhouse gases and heavy metals are among the key impacts to the environment. The environmental impacts can be reduced by up to 12.2%, integrating anaerobic digestion within the mill, implying technology innovation can lead to more sustainable agricultural practices. In the carbon-intensive iron and steel industry, the cost of carbon capture can be reduced by increasing the CO_2 concentration in the flue gas. Higher CO_2 concentration is favourable for absorption-based processes and membrane-based processes, leading to dramatic cost

reduction for the latter [176]. Apart from energy planning, technology is important to reduce the carbon emissions footprint for different sectors. Continuous monitoring via sustainability indexes or metrics customized to each sector is important to provide a check and balance.

6. Conclusion and way forward

This review highlights the innovations and opportunities for renewable energy and sustainability, including low GHG emission technology, efficient energy modelling, intelligent energy systems, biomass conversion technology, and environmental protection assessment tools. Modelling energy components, thermodynamic cycles, and energy systems is important to design a more efficient and optimised system. Energy system modelling is commonly performed via the optimisation approach and simulation approach. The former sets the objective function to identify the optimal solution, while the latter focuses on the optimum system response and design. The development of efficient energy conversion and storage devices requires new types of highly efficient energy materials. This has driven the research in phase change materials and functional materials catering for energy system application. The development of clean energy conversion technologies is another hot research area. Considerable attention has been focused on clean combustion technologies using low emission fuels such as biofuels, ammonia or hydrogen. The use of biomass to produce low emission fuels and renewable energy sources such as solar or wind for producing hydrogen or ammonia is important given the decarbonization need for the transportation and power generation industries.

It is envisaged that the future energy system will gradually depend less on fossil fuels, while the portion of renewable energy sources will increase in the energy system. The integration of IoT allows the management of the smart energy system that bridges

the power generation and consumers, thus enabling efficient regulation of loads and energy supply. A cross-sectoral approach that integrates energy conversion, distribution and storage technologies is expected to be important in future energy system design to enable greater inclusion of renewable energy utilization and effective energy consumption. As such, robust energy system modelling technique that is able to capture the spatial-temporal and technology resolutions is envisioned to be critical to capture the elements of cross-sectoral interactions. The development of 4th generation district heating was shown to integrate a high portion of renewable energy and utilize low grade heat to meet the demand of building's energy with the least cost solution. While the development of the renewable energy sector is greatly desired, the sustainability and the impact of the energy system on resources and society needs to be thoroughly assessed, in line with the Sustainable Development Goals (SDGs) of the United Nations. The sustainability index can assess the regional and local impact of energy systems on food and water resources. This review also highlights the potential pitfall of a narrow perspective in assessing and optimising different energy alternatives or development, which could overturn the status as a sustainable solution, including carbon neutrality. A standardised understanding supported by fair assessment methodologies and a wide range of environmental footprints is essential to ensure the sustainable development in the energy system is not setback by decisions adopted through a single lens.

This review is a compilation of energy-related papers selected from the ICLCA'20 and SPIL'20 Conferences. The transitioning of the energy system from fossil-dependent to sustainable green energy largely stem from the need to regulate the emissions of greenhouse gases to combat global climate change. The black swan of the COVID-19 pandemic occurring in 2019 has greatly impacted the energy system. The electricity demand has dropped due to the implementation of lock-down, and the environment was given a short period for recovery. This provides room for another important 6th innovation wave. However, that demands more energy for novel emerging e-activities (e-mobility, e-shopping, e-learning, e-meetings, e-medical etc.), and the transformation towards a more sustainable energy system becomes a key issue for further development. Turning crisis into opportunity is a great challenge that is critical to ensure sustainability in the post-COVID-19 recovery. The development of reduced environmental footprints energy resources and energy systems should capitalise on the momentum gained in the transition from a fossil-based economy into renewable and low GHG energy-based sources.

Credit author statement

Cheng Tung Chong: Review and data analysis, Visualization, Writing − original draft. Yee Van Fan: Review and data analysis, Visualization, Writing − original draft. Chew Tin Lee: Revise, Supervise, Comments, Editing. Jiří Jaromír Klemeš: Revise, Supervise, Comments, Editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

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