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Review

A Review on Thermal Energy Modelling for Optimal Microgrids Management

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Abstract: Microgrids have become increasingly popular in recent years due to technological improvements, growing recognition of their benefits, and diminishing costs. By clustering distributed energy resources, microgrids can effectively integrate renewable energy resources in distribution networks and satisfy end-user demands, thus playing a critical role in transforming the existing power grid to a future smart grid. There are many existing research and review works on microgrids. However, the thermal energy modelling in optimal microgrid management is seldom discussed in the current literature. To address this research gap, this paper presents a detailed review on the thermal energy modelling application on the optimal energy management for microgrids. This review firstly presents microgrid characteristics. Afterwards, the existing thermal energy modeling utilized in microgrids will be discussed, including the application of a combined cooling, heating and power (CCHP) and thermal comfort model to form virtual energy storage systems. Current trial programs of thermal energy modelling for microgrid energy management are analyzed and some challenges and future research directions are discussed at the end. This paper serves as a comprehensive review to the most up-to-date thermal energy modelling applications on microgrid energy management.

Keywords: combined cooling; heating and power; microgrids energy management; networked microgrids; renewable energy resources; thermal comfort model

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Citation: Yan, M.; Wang, D.; Lai, C.S.; Lai, L.L. A Review on Thermal Energy Modelling for Optimal Microgrids Management. *Thermo* **2021**, *1*, 63–76. https://doi.org/10.3390/thermo1010006

Academic Editors: Miguel Ángel Reyes Belmonte and Johan Jacquemin

Received: 18 February 2021
Accepted: 21 April 2021
Published: 25 April 2021

1. Introduction

With the emergence of global fossil fuel shortages and environmental issues, renewable energy sources such as wind energy and solar energy have been greatly developing [1,2]. Presently, several researchers have examined power and gas network coordination [3]. Many options are being studied for grid-scale storage. For example, power to gas (PtG) is a technology that could be useful in the short to medium term as a component of a comprehensive grid-scale storage solution in support of a power grid to accommodate intermittent renewable energy resources [4–7]. At the same time, microgrids have attracted wide attention as an integrated technology including renewable energy and other distributed power sources [8,9]. The microgrid has flexible operating characteristics and can be connected to the grid and work in islanded mode. It can simultaneously meet the electrical and thermal energy needs of local users [10] and improve the power supply reliability of the distributed power generation system. Further, microgrids can realize the integrated operation of distributed power supply and the load, thereby reducing the pollution discharge of the system, and have become an important part of the smart grid [11]. Therefore, how to effectively use energy storage components and reasonably cooperate with renewable energy power generation to ensure the efficiency of renewable energy utilization has become a research hotspot in microgrids in recent years [12,13].

At present, research in this area is mainly focused on microgrids, and is generally focused on the optimal configuration of power storage equipment, such as batteries and super capacitors [14]. An optimal joint-dispatch scheme of energy and reserve is proposed in [15] for combined cooling, heating and power (CCHP)-based microgrids. The authors of [16] propose a novel reconfigurable microgrid architecture comprising photovoltaic, wind, micro-hydro, and fuel cell based renewable energy sources. Transient and extended power backup are provided with ultra-capacitor (UC) and battery storage, respectively. The hybrid energy storage in this model uses batteries and supercapacitors but does not involve thermal energy storage. Although thermal storage technology has a long history of development, its practical application is limited to the storage and utilization of low-grade thermal energy, such as heating and hot water supply. In recent years, due to the rapid development of renewable energy and distributed energy, research on high-grade thermal storage technology and waste thermal recovery and utilization has gradually increased, and the research is mostly based on the combination of power systems and thermal systems. Reference [17] addressed the network expansion planning of an active microgrid that utilizes distributed energy resources (DERs). The microgrid uses combined cooling, heating and power (CCHP) systems with their heating and cooling network. These studies mostly focus on the overall benefits of the system after the application of high-tech thermal storage technology and the application of thermal storage, ignoring the problem of optimal configuration of thermal storage equipment capacity. As the energy demand on the user side becomes more diversified and the integrated energy system becomes more popular, and as the coupling between different forms of energy becomes closer, the optimized configuration of electric/thermal hybrid energy storage will become a new development trend. There has been some research literature on the configuration of electricity/thermal energy storage in integrated energy systems [18–21]. Reference [22] compared the optimized Solar-CCHP polygeneration system with a side-by-side photovoltaic (PV) and Solar collector with the optimized CCHP system. The comparison is made under the constraints of maximizing the overall efficiency, which integrates energy, economy, and environment. Reference [23] established a complete set of dynamic simulation models for CCHP, including a new type of CCHP and a set of double-effect absorption refrigeration system. The performance of the entire combined cooling, heating and power system is studied to reveal its impact and efficiency. High-quality research publications on thermal energy storage have been published in Applied Energy, Energy, Energies etc. These journals are with Elsevier, MDPI and other publishing groups.

This paper presents a detailed review on the thermal energy modelling application on the optimal energy management for microgrids. The contributions of this work are as follows:

- Reviewed the existing thermal energy modeling for microgrids, including the application of combined cooling, heating and power (CCHP) and thermal comfort model to form virtual energy storage systems.
- Reviewed the most recent literature related to energy storage technology, materials for Thermal Energy Storage (TES) applications, and the contribution of electrical energy storage for grid applications.
- From the TES technology perspective, the key characteristics, parameters and models of the TES system to be considered when used in microgrids and multi-energy networks, and other emerging applications are discussed.
- From the energy system perspective, the opportunities and challenges of deploying thermal energy modeling applications on the optimal energy management of microgrids are discussed.

The paper is organized as follows. Section 2 discusses the characteristics of thermal energy systems, the typical parameters considered for their evaluation, and the types of thermal energy technologies. Section 3 presents an overall review of the modeling and planning of the CCHP microgrid, and introduces that TES is a distributed type that uses refrigeration and air conditioning technologies controlled through a virtual power plant to provide load shifting. Section 4 presents an overall review of the modeling, planning and energy management of the TES microgrid. The performance of a TES microgrid from technical, economic and environmental viewpoints is closely dependent on the microgrid's design and energy management. Section 5 contains concluding remarks.

2. Thermal Energy Storage Systems and Performance Parameters

2.1. Thermal Energy Storage System Characteristics

Thermal energy storage is an important branch of energy science and technology, and it is also an effective means to solve the contradiction between energy supply and demand in time and space, and to improve energy utilization. The specific principle of thermal storage is to convert other forms of energy into thermal energy and transfer the thermal energy to a thermal storage medium in the heat accumulator. The thermal storage medium stores thermal energy under good thermal preservation conditions. When needed, the stored thermal energy is extracted and transported to the heating load through heat exchange. The advantages of TES include improved overall efficiency and better reliability [24,25]. The TES system and its maintenance costs are low, pollutant emissions are low, and operation flexibility is good. It can bring better economy, reduce investment and operating costs, and output less pollution to the environment. The disadvantage of TES is that the response of the TES system is slow. At the same time, heat (or cooling) cannot be stored for a long time, because the storage device is difficult to insulate and causes heat loss [26]. For long-term or seasonal storage, TES may be an inappropriate or at least a low-priority option. Thermal energy storage has the following characteristics:

(1) Low cost: The thermal energy storage technology converts solar energy (or absorbs other thermal energy generated in industrial production), stores and releases it again, using inexhaustible solar energy or underutilized thermal energy generated in industrial production [24].
(2) Long storage time: The storage time ranges to several months, which far exceeds the current solar energy storage time limit developed at home and abroad. As the storage is not affected by the weather, users can choose different storage periods and different storage methods according to their needs [24].
(3) Wide application: Thermal energy storage technology stores and uses solar thermal energy and other thermal energy generated in industrial production, which is a substitute for all existing underground energy sources. Wherever existing thermal energy is used, whether for power generation, heating, or modern agricultural heating, and other fields that require thermal energy, thermal energy storage technology can replace all existing fossil energy sources which can generate electricity, heat, and meet any demand for thermal energy [24].
(4) Conducive to environmental protection: In addition to the catalyst, there is no consumption of materials and none of the environmental cost attached to fossil energy, which truly realizes the win-win goal of energy use and environmental protection.

2.2. Thermal Energy Storage Technology Types

2.2.1. Technical Characteristics Comparison

Thermal energy storage is a technology that stocks thermal energy by heating or cooling a storage medium so that the stored energy can be used at a later time for heating and cooling applications and power generation. The thermal storage medium stores the thermal energy under conditions of good insulation. When the energy needs to be used, it extracts the stored heat through heat exchange and delivers it to the heating load. According to the state of thermal storage media, thermal storage can be divided into sensible thermal storage, latent thermal storage, and thermochemical energy storage [27,28]. Phase change materials (PCM) have higher energy storage density, so they have greater development potential. Due to the limitation of material cost, sensible thermal storage is still the main energy storage market. With the development and application of new thermal storage materials and the improvement of supporting equipment manufacturing processes, the cost of thermal storage technology application is decreasing year by year, and more and more commercial engineering applications are promoted. Table 1 contains a list of comparison of the three prominent types of thermal energy storage systems.

Table 1. Comparison of the three prominent types of thermal energy storage systems [28].

Technologies	Sensible Heat Storage [29]	Latent Heat Storage [30]	Thermochemical Energy Storage [31]
Energy capacity per tonne (kWh/t)	10–50	50–150	120–250
Power (MW)	0.001–10.0	0.001–1.0	0.01–1.0
Storage period	Days/months	Hours/months	Hours/days
Cost (€/kWh)	0.1–10	10–50	8–100

Compared with the other two forms of heat storage, sensible heat storage technology is the most mature one. Meanwhile, sensible heat storage has the advantages of a simple operation mode, low cost, long service life and high heat conductivity. However, its small heat storage capacity and non-constant temperature during heat release limit its future application prospects.

Compared with sensible heat storage technology, phase change heat storage has the advantage of high heat storage density per unit volume. In the range of phase transition temperatures, it has a large energy absorption and release. The temperature range between heat storage and heat release is narrow, which is conducive to the temperature stability of the charging and discharging process. However, its thermal storage medium generally has the disadvantages of supercooling, phase separation, low thermal conductivity and easy aging.

The energy storage density of thermochemical energy storage is higher than that of sensible heat storage and phase change heat storage. However, the application technology and process are prohibitively complex and there are many uncertainties, such as harsh reaction conditions, difficulty to achieve, short life of energy storage system, high corrosion of energy storage materials to equipment, a large one-time investment and low efficiency. If these problems can be well solved, it will have broad application prospects.

From the characteristics of the three forms of heat storage, each has its own advantages and disadvantages. At present, many research projects are aimed at addressing the shortcomings of the three forms of heat storage.

2.2.2. Economic Analysis of Heat Storage Technology

Generally, the cost of a heat storage system includes heat storage materials, heat storage and release equipment, and operating costs. The economic evaluation of the heat storage system mainly depends on the specific application and operating requirements, including the number and frequency of heat storage and release [32].

Sensible heat technology: Taking the molten salt heat storage system as an example, the cost includes the price of the molten salt material itself. According to the general law of unit price and total price, as the capacity of the heat storage system increases, although the cost of the overall system is high, the unit cost is significantly reduced, tending to stabilize at 31 US$ per kWh/t, compared to other energy storage technologies., Hence, the unit cost of the sensible heat storage system is relatively low [27].

Phase change heat storage technology: Phase change heat exchangers and phase change materials are key factors affecting the cost of heat storage devices. Phase change heat exchangers and phase change materials account for about 80% of the total cost of heat storage devices [33–36].

Thermochemical heat storage technology: This technology is still in the laboratory research stage and there are still many technical problems in practical applications. In addition, the one-time investment of the thermochemical heat storage system is large, and the overall efficiency of the system is low.

In general, among the three forms of heat storage technology, the cost of sensible heat storage is the lowest. This is mainly due to the lower cost of sensible heat storage materials, such as water, sand, concrete, or molten salt, which contain these heat storage media. The structure of the tank containing the heat storage medium, and the related heat storage and release equipment, are also relatively simple. However, the container of heat storage material needs effective thermal insulation, which may largely increase cost investment for the heat storage system. The system cost of phase change heat storage and thermochemical reaction heat storage are significantly higher than sensible heat storage. Due to phase changes, it is necessary to strengthen heat transfer technology and the corresponding equipment for heat storage and thermochemical reaction heat storage to make the system efficiency, energy storage capacity and other performance metrics reach certain standards. Therefore, the cost of other equipment in the system is relatively high except for materials [37–40].

2.2.3. Application Status of Heat Storage Technology

The current main application areas of sensible heat storage technology include industrial furnaces and electric heating, residential heating, solar thermal power generation and other fields. At present, the large-scale application of sensible heat technology is mainly concentrated in Concentrating Solar Power plants. In March 2009, Spain's Andasol solar thermal power generation became the world's first successful operation of commercial Concentrating Solar Power plant equipped with a molten salt heat storage system. With the maturity of molten salt heat storage technology, more and more Concentrating Solar Power plants have begun to use molten salt technology [41].

Latent heat storage technology is mainly used in clean heating, power peak shaving, waste heat utilization, and solar low-temperature light-heat utilization. In recent years, with the demands of clean heating and power system peak shaving, latent heat storage technology has been increasingly applied to the power generation side and the user side. Typical cases include: China General Nuclear Power Group's Altay City Wind Power Clean Heating Demonstration Project using Jiangsu Jinhe solid phase change heat storage material technology; Inner Mongolia Fengtai Thermal Power Plant Phase Change Heat Storage Heating Peak Shaving Project using composite binary salt phase change materials; Beijing Hua Northsoft Shuangxin Science and Technology Park Energy Storage and Heating Project of Thick Energy Phase Change Energy Storage Materials.

Thermochemical heat storage technology is currently still in the trial and research stage, and there are still many technical issues in practical applications, so there are relatively few project cases.

2.2.4. Development Trend of Heat Storage Technology

At present, only the application of sensible heat storage is relatively mature, but phase change heat storage and thermochemical heat storage have many advantages. The latter two heat storage methods will be the focus of future research. The medium and high temperature phase change heat storage materials have high heat storage density, which is beneficial to the compactness and miniaturization of equipment. However, the corrosiveness of phase change materials, compatibility with structural materials, stability, and cycle life all require further research and the commercialization path needs to be explored. Thermochemical heat storage is suitable for a wide temperature range and high heat storage density. In theory, it can be applied to the field of medium and high temperature heat storage. However, the process of thermochemical heat storage technology is complicated. So far, its technological maturity is still low. It is necessary to optimize the design and control of key technologies such as the reaction rate and heat transfer system, and to perform considerable research investment on it.

3. Modelling of Thermal Energy System in Microgrids

3.1. CCHP Systems Current Research and Development

With the energy crisis and environmental pollution becoming increasingly serious, making full use of renewable energy and realizing the cascade utilization of energy has become an important strategy to solve these problems globally. The renewable energy power generation represented by wind power generation and photovoltaic power generation has a low power generation cost and low environmental pollution. However, its output is intermittent and random, and the problem of consumption is prominent. A CCHP system provides electrical energy, thermal energy and cold energy at the same time to realize the cascade utilization of energy and reduce the emission of pollutants. Integrating renewable energy into a CCHP system can form a micro-energy network with CCHP. This is a typical application of an integrated energy system. It is an important way to improve the utilization rate of various kinds of energy and the penetration rate of renewable energy. Reasonable optimal allocation of various micro-source capacities in microgrids can realize the complementary coordination of multiple energy sources and expand the space of renewable energy consumption. A CCHP system, as an efficient and stable way of energy utilization, has wide application prospects, which can achieve energy ladder utilization and multi-energy complementary [42–45].

At present, there have been some studies on the optimal allocation of microgrid capacity with CCHPs. Reference [46] summarized the methods reported in the existing literature for energy and energy analysis, system optimization, performance improvement studies, and the development and analysis of CCHP systems. In [47], a correlation model for configuration and operation optimization based on a bi-level model construction method was established for a CCHP-coupled multi-energy system. The study finds an effective method for the design optimization of CCHP-coupled multi-energy system and gives a new idea for solving similar optimization problems. References [48,49] proposed a separated cooling, heating and power (SCHP) supply system. The optimal operation strategies and performance are compared to show the advantages of a multi-energy complementary system.

Figure 1 shows the system architecture and energy flow of the microgrids with CCHP. Among them, the renewable energy power generation system includes wind turbines (WT), photovoltaic (PV) cells, and batteries. The combined cooling, heating and power system includes a power generation unit (PGU), heat recovery system (HRS), absorption chiller (AC) and a heating exchanger (HE), boiler and electric chiller (EC). This figure represents electricity, gas, and heat input and output coupling equipment, improving the balance between supply and demand.

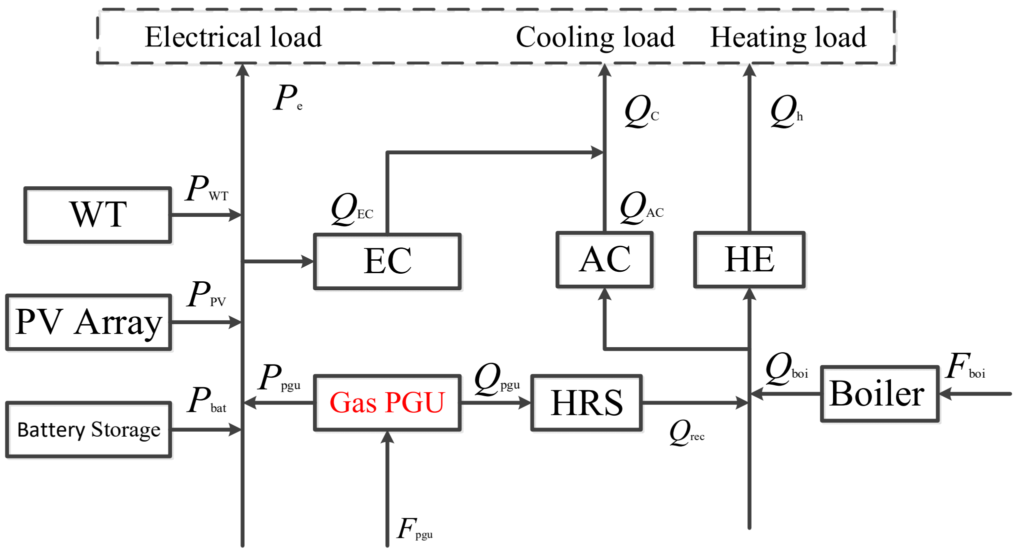

Figure 1. Structure of microgrid with CCHP.

In the system as shown in Figure 1, the WT, PV, PGU and battery are complementary and coordinated to meet the electrical load demand of the system. The waste heat generated by the PGU power generation at the same time can be recovered, complementing the boiler to meet the demand for cooling and heating loads. The proportional coefficient of electric refrigeration is optimized. Part of the cooling load will be converted into electricity load to promote the consumption of renewable energy. The source load should be balanced in real time.

The balance of electric load: the system electric load includes user electric load and electric refrigeration electric load, set the electric refrigeration proportional coefficient as y, then:

$$P_{EC,t} = \frac{yQ_{c,t}}{E_{COP,EC}} \tag{1}$$

$$P_{PV,t} + P_{WT,t} + P^{dis}_{bat,t} + P_{pgu,t} = P_{e,t} + P_{EC,t} + P^{char}_{bat,t} \tag{2}$$

The balance of heating load:

$$Q_{h,t} = (Q_{boi,t} + Q_{rec,t} - Q_{AC,t}/E_{COP,AC})\eta_{he} \tag{3}$$

where $P_{PV,t}$, $P_{WT,t,}$ and $P_{pgu,t}$ represent the output of photovoltaic, wind turbine, PGU during time t, respectively; $P_{e,t}$ and $P_{EC,t}$ represent the EC and user power consumption in t period, respectively; $P^{dis}_{bat,t}$ and $P^{char}_{bat,t}$ are the discharging power and charging power of the battery in t period, respectively; $Q_{c,t}$ and $Q_{h,t}$ represent the cooling and heating load power in t period, respectively; $Q_{Ec,t}$ and $Q_{AC,t}$ are the cooling capacity of subsidy and AC in t period, respectively; $Q_{boi,t}$ and $Q_{rec,t}$ are the heat generated by the boiler during the t period and the waste heat recovery from the PGU, respectively; $E_{COP,EC}$ and $E_{COP,AC}$ are the energy efficiency coefficients of EC and AC respectively; η_{he} is the efficiency of HE.

3.2. Virtual Energy Storage System Current Research and Development

Dispatching demand-side controllable loads with energy storage characteristics is a new way to improve the energy efficiency of microgrids. At present, researchers have started to study virtual energy storage technology. A virtual energy storage system is defined as a system of controllable loads with energy storage characteristics [50,51]. Combining virtual energy storage with conventional electrical energy storage to form a new hybrid energy storage system is a promising trend. Combining virtual energy storage with conventional electrical energy storage to form a new hybrid energy storage system is a promising trend. Applying this new hybrid energy storage system to the dispatching model of the microgrid improves the stability and reliability of the microgrid and reduces the economic cost. Due to the particularity of the controllable load, its management has strong flexibility, which will bring benefits to the microgrid system. A virtual energy storage system (VESS) can be deployed at scale with a lower cost compared with the installation of the energy storage system (ESS). ESS remains an expensive technology, although there have been declinations in the cost in recent years. VESS can use the existing network assets, i.e., the flexible demand such as the domestic fridge-freezers, wet appliances and industrial heating loads. Therefore, the research of virtual energy storage has great significance for the energy management of microgrids [52,53].

Reference [50] proposes a model to store and release energy in response to regulation signals by coordinating the Demand Response (DR) from domestic refrigerators in a city and the response from conventional Flywheel Energy Storage Systems (FESSs). Reference [54] investigated the modeling and control strategies of aggregated thermostatically controlled loads (TCLs) as the VESS for demand response. Reference [55] reported an attempt to coordinate multiple groups of centralized air conditioners for load management of the distribution network. Reference [56] analyzed the heat storage capacity of radiant floor cooling system, which is widely used in residential buildings. Residential refrigerators are modelled analogously to energy capacity and self-discharge of electro-chemical batteries using the artificial neural network based kWh modelling [57]. Reference [58] analyzed the demand flexibility realized by virtual energy storage, which couples the building level power to thermal energy conversion systems installed in residential and commercial buildings to transfer the inherent flexibility of thermal energy demand to the power sector. An optimal scheduling strategy of building-integrated photovoltaic microgrids, considering virtual energy storage, was proposed to further improve the operation economy of building integrated photovoltaic microgrids [59–61].

4. Energy Management of the TES Microgrid

4.1. TES Microgrid Energy Management Model

Both the thermal system and the power system have the basic structure of "source-network-load", and the network topology has certain similarities. The steady-state heating network also needs to meet Kirchhoff's first and second laws. The method in Figure 2 describes the heating network [62–65].

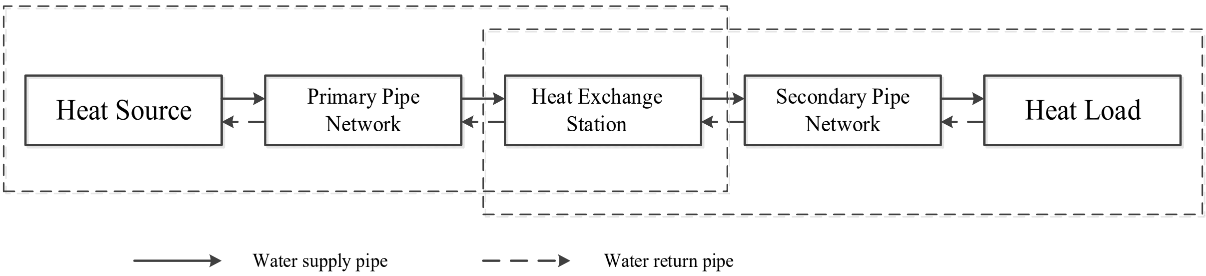

Figure 2. Basic structure of the thermal energy system.

The heat generated by the heat source of the thermal system is transmitted to the heat exchange station through the primary pipe network, and then from the heat exchange station to the secondary pipe network, and finally from the secondary pipe network to the heating load [66]. The heat medium flows back through the return pipe to form a closed loop. Usually, the secondary pipe network is short and the energy consumption is negligible. Therefore, this paper only models the primary pipe network [66,67]. The nodes where the cogeneration and electric boilers are located are regarded as heat source nodes, and the nodes where the heat exchange stations are located are regarded as load nodes. The branch characteristics of the heating network are divided into hydraulic characteristics and thermal characteristics [67]. Regarding hydraulic characteristics, ignoring fluid losses such as pipe penetration and working fluid evaporation, the basic model of hydraulic branch including node flow balance and loop pressure drop balance is established as follows:

$$\begin{aligned} \sum_{k:(ki\in Z_1)} G_{ki,t} - \sum_{j:(ij\in Z_1)} G_{ij,t} = 0 \\ \sum_{(ki,ij,\cdots,mk)\in\Psi} \left(\Delta h_{ki,t} + \Delta h_{ij,t} + \cdots + \Delta h_{mk,t}\right) = 0 \end{aligned} \tag{4}$$

$$\Delta h_{ij,t} = h_t^P + s_{ij} G_{ij,t} \left|G_{ij,t}\right| \tag{5}$$

$$S_{ij} = \frac{8 f_{ij} l_{ij}}{\rho^2 \pi^2 g D_{ij}^5} \tag{6}$$

where Z_1 is the set of branches of the heating network; $G_{ki,t}$ is the flow rate of the pipeline k_i in the period t: $\Delta h_{ki,t}$ is the pressure drop of the pipeline ki in the period t: h_t^P is the head of the pump in the period; S_{ij} is the resistance coefficient of the pipeline ij; l_{ij} is the length of the pipeline; ρ is the density of water: g is the acceleration of gravity: D_{ij} is the diameter of the pipeline and Ψ is the set of heating network loops. In the case of known heating network topology, the adjacent matrix generates any tree, and then the loop set is obtained according to the relationship between the basic incidence matrix and the loop matrix.

According to the node heat flow balance of the heating network pipeline and the pipeline temperature loss formula, a thermal branch model that considers the energy loss of the supply and return water pipelines and the temperature transmission delay is established as:

$$\begin{gathered}\sum_{j:(ij\in Z_1)}\left(c_w G_{ij,t}\right)T_{i(ij),t}-\sum_{k:(ki\in Z_1)}\left(c_w G_{ki,t}T_{i(ki),t}\right)=\phi_{i,t}\\ T_{i(ki),t}-T_t^{en}=\left(T_{k(ki),t-\tau}-T_t^{en}\right)e^{\frac{-\lambda l_{ki}}{c_w G_{ki,t}}}\end{gathered}\tag{7}$$

$$\tau=\frac{F_{ki}}{G_{ki}}\tag{8}$$

where c_w is the specific heat capacity of water; $T_{i(ij),t}$ is the temperature at the head of the pipeline during t, which is the same as the outflow temperature from node i, so this is defined as the temperature of node I; $\phi_{i,t}$ which is the injected heat power at node i during t; $T_{i(ki),t}$ is the temperature at the end of the pipeline during t; T_t^{en} is the ambient temperature during the period t; λ is the thermal conductivity of the pipeline; τ is the pipeline temperature transmission time delay, rounded to a multiple of the unit scheduling time; F_{ki} is the characteristic quantity, which is determined by the pipeline length, cross-sectional area and other parameters.

It should be noted that heat grid energy transmission has a large inertia, which mainly depends on the flow rate of the heat medium. The mass flow rate of the heat medium in the pipeline is relatively slow, and the time scale is minutes or hours. Therefore, the temperature transmission time delay τ is introduced into the thermodynamic model to describe the transmission inertia. It can be seen from Equation (8) that the size of τ is determined by the length of the pipe, the cross-sectional area, and the flow rate of the heat medium.

4.2. Optimization of TES Microgrid Energy Management

The performance of the TES microgrid depends largely on energy management. Considering the complexity of the TES microgrid, energy management is not easy. It includes the energy coupling of cold, heat, and electricity, with operating costs, energy efficiency, and emissions as multiple operating targets, as well as short-term and long-term time horizons [68]. As shown in Figure 3, many information sources must be considered, including weather forecasts, equipment characteristics, real-time energy prices, and operational targets to produce the best operational plan under actual operating conditions. In addition, since the microgrid becomes an important part of the integrated energy system, the energy management of the TES microgrid forms an integral part of the energy system management of the entire community [69].

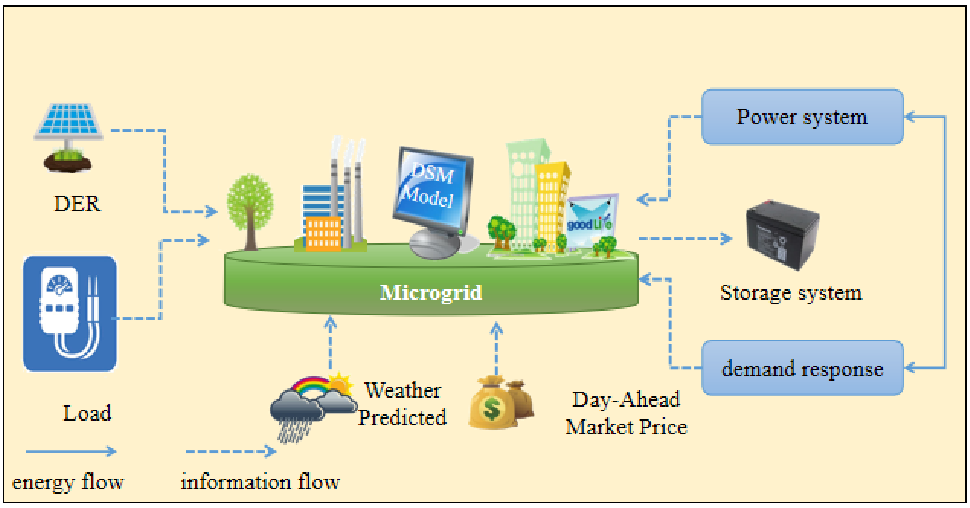

Figure 3. TES microgrid energy management system [70].

Renewable energy generation has no fuel cost and the dispatch strategy of microgrids is generally to give priority to the use of renewable energy generation. The forecasting system predicts the output value of renewable energy and load, and arranges the output of dispatchable units and energy storage systems on this basis [68]. The constraints of schedulable units include the upper and lower limits of power generation, unit climbing constraints, and minimum start-stop time constraints. As for the modeling of energy storage systems, the commonly used models include the power library model and the kinetic battery model (KIBAM) model. The constraints generally include power capacity constraints, upper and lower charge and discharge limits. For the system, it includes the power balance contract, the thermal energy balance constraint, the system standby constraint, the line power flow limit, and the bus voltage limit. For equipment with special control requirements, some additional constraints can be added, such as the battery charge and discharge times. For distributed power sources with inverter interfaces, their active power/frequency droop characteristics are often used as constraints [71–75].

Multi-objective optimization problems are often solved by converting the weight of the objective function into a single-objective optimization problem, and using single-objective optimization methods. In addition, it can also be solved by multi-objective optimization methods, such as non-dominated multi-objective genetic algorithm [76]. Without considering the forecast error of renewable energy, the microgrid energy management model is a unit commitment problem. At present, most microgrid energy management models consider the constraints of system power flow. The solution methods used mainly include mixed integer linear programming methods, dynamic programming methods, genetic algorithms, particle swarm optimization algorithms, ant colony algorithms and other intelligent algorithms, as well as algorithms such as expert systems based on rule judgment. Among them, the mixed integer linear programming method converts the optimization problem into a mixed integer programming problem by converting the nonlinear function in the optimization model into a linear function. Using mature professional software to solve usually has higher solving accuracy and faster solving speed. For a model that considers the power flow, it is generally the subroutine of the distribution network power flow calculation such as the optimal power flow or the forward and backward method in the calculation process. Due to the dramatic increase of nonlinear constraints, intelligent algorithms such as genetic algorithm and particle swarm algorithm are usually used for optimization. The randomness and intermittent nature of the output of renewable distributed power sources such as photovoltaics and wind power in the microgrid pose challenges to the short-term dispatch of the microgrid. The random distribution characteristics of photovoltaic and wind power are often described by their probability density distribution functions [76]. In general, photovoltaic output can be considered to obey Beta distribution, and wind power output can be obtained by the wind speed following the Weibull distribution through the output-wind speed conversion function of the wind turbine [77]. The load generally obeys Gaussian distribution [78]. At present, the short-term scheduling methods that consider the distribution of renewable energy output forecast errors mainly include the random planning method based on chance constraints, the scene reduction method based on sampling technology, and the point estimation method. Among them, the scene reduction method uses the scene reduction technology to transform large number of scenarios to perform scheduling analysis for countable typical static scenarios; point estimation law analyzes by calculating probability statistics of random function values composed of multiple random variables [79,80].

5. Conclusions

The impact of global energy consumption has promoted the development of efficient, reliable and sustainable energy technologies, where TES has played a major role in closing the gap between energy supply and energy demand. Thermal energy storage has been widely used in multiple scenarios such as power, industry, cold chain, district cooling and heating, and buildings. Various thermal energy technology routes such as water heat storage, solid heat storage, and phase change heat storage have been developing rapidly. This paper presents a comprehensive review of the thermal energy modelling application on microgrids energy managements. The thermal energy storage technology uses the original abandonment of wind and electricity to produce heat, effectively reducing carbon emissions caused by coal-fired heating and improving air quality. The TES system can use the available electrical energy during off-peak periods for charging, so it can be regarded as a green solution to cope with the high consumption of fossil energy.

Future work will focus on the integration of the proposed energy management and the thermal storage system in the microgrid and its consequent experimental validation. Moreover, other aspects could be investigated, such as energy management of the thermal storage system in different types of tariffs for microgrid market environment.

Author Contributions: Conceptualization, writing—original draft, data curation, M.Y. and D.W.; conceptualization, writing—review & editing, supervision, C.S.L.; writing—review & editing, supervision, funding acquisition, L.L.L. All authors have read and agreed to the published version of the manuscript.

Funding: This work is sponsored by the Department of Finance and Education of Guangdong Province 2016 (202) Key Discipline Construction Program, China; the Education Department of Guangdong Province: New and Integrated Energy System Theory and Technology Research Group [Project Number 2016KCXTD022]; Brunel University London BRIEF Funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors claim that there are no conflict of interest involved in publishing this article.

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