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Blockchain-based Carbon Emission Accounting Method for Multi-Energy Systems

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***Abstract*—To achieve carbon neutrality and effectively record carbon emissions, it is imperative to establish a user-friendly and tamper-proof carbon emission accounting method. Considering that most of the existing studies focus on single loads, this study designs a multi-energy flow framework encompassing electricity, heating, gas, and cooling loads, and presents the corresponding user-side carbon emission models. In order to ensure the safety and traceability of carbon emission data, this paper proposes a user-side carbon emission accounting method empowered by blockchain smart contracts. By conducting several experiments in a simulation environment, this research analyzes the seasonal variation of user-side carbon emissions in Hengqin, China and verifies the feasibility of blockchain technology for carbon emission accounting.**

***Index Terms*—blockchain, carbon emission accounting, multi-energy system, smart contract**

I. Introduction

With the increasing global concern about climate change, carbon emission reduction and sustainable development have become important issues worldwide [1]. China has pledged to peak carbon emissions by 2030 and achieve carbon neutrality by 2060 [2]. In order to effectively curb the increase in carbon emissions and continuously implement carbon neutrality, an accurate and credible carbon emission accounting method is needed. This will help us build a finer-grained, more secure and credible carbon emission database to promote carbon neutrality and the reduction of carbon emissions [3].

Accurate carbon emission accounting has been a hot research topic for several decades [4]. International Public Cleaning Council has developed a method for estimating national carbon emissions, known as the "emission factor method" [5].This method relies on evaluating the consumption of carbon-containing fossil fuels and the inherent carbon content of these fuels. In addition, commonly used methods like Input-Output (IO) analysis follows a "top-down" approach, aiming to measure CO_2 emissions at various scales, including the national, regional, or sectoral level, by examining the dependencies between inputs and outputs of economic sectors as reflected in IO tables [6]. Such methods can only be applied on macro level, although relatively straightforward to implement. There be time-consuming and susceptible to inaccuracies due to data quality and statistical errors.

In recent years, there has been a noticeable shift toward user-side carbon emission accounting, as well as a focus on enhancing temporal accuracy and data granularity. Real-time/near-real-time accounting methods offer a different perspective, catering to user-side emissions. Techniques such as those used by Buchwitz *et al.* [7] utilize ground monitoring data and remote sensing satellite data to evaluate carbon emissions. However, the complexity and immaturity of this technology can make it challenging to implement in real-world scenarios. In contrast, Life Cycle Assessment (LCA) is another approach that offers a more detailed understanding of emissions throughout a product's life cycle and related processes [8]. Nevertheless, these methods place high demands on data acquisition.

On the other hand, most research only consider loads such as electricity-gas [9] and electricity-gas-heating [10]. In addition, the existing carbon emission accounting methods focus on the carbon emissions generated by primary energy consumption [11], but in the actual carbon emission accounting, it is necessary to determine the user-side carbon emissions by various types of energy loads [12]. There are few studies on the carbon emission accounting of multi-energy systems (MES) that simultaneously consider the four loads of

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electricity, heating, gas, and cooling.

With continuous technological development, new methods and tools are introduced into user-side carbon emission accounting to improve the accuracy of the measurements [13]. For example, considering carbon emissions from thermal power plants to optimize joint peaking strategies [14], and modeling carbon emissions to optimal dispatch of flexible resources in a regional energy system [15]. These methods promote the accurate accounting of carbon emissions, while they ignore the trusted and credible recording of these data.

Blockchain technology is decentralized, tamper-proof, and traceable, allowing carbon emission data to be recorded and stored in a secure and credible manner [16]. Therefore, blockchain technology has been introduced in many studies. Examples include the utilization of blockchain technology in carbon emission monitoring [17], the establishment of a blockchain-based IoT framework to address recurring carbon emission accounting and monitoring challenges [18], and the blockchain-based tokens that store user-sensitive information separately from carbon emission data [19]. These studies demonstrate the advantages of blockchain technology in recording data. Blockchain technology can be deployed to record carbon emission data of MES in a safe and credible way.

To summarize, most of the existing research results are theoretical studies or mechanism design. Few studies validate the methodology of user-side carbon emission accounting through experiments [20], [21]. The aim of this paper is to explore innovative approaches and frameworks for user-side carbon emission accounting, especially the application in multi-energy systems based on energy flows and blockchain technology. The main work and contributions are as follows:

1) We design a multi-energy-flow-based framework for MES with electricity, heating, natural gas and cooling loads to comprehensively analyze user-side energy consumption. By considering conversions and interactions between different energy sources, the user-side carbon emissions are properly assessed.
2) This paper uses blockchain technology as a credible accounting tool to ensure the accuracy and transparency of user-side carbon emission recording. By utilizing blockchain technology, we establish a credible carbon emission accounting system that enables user-side carbon emission data to be effectively verified.

The remainder of this paper is organized as follows. Section II introduces the user-side carbon emission accounting framework. Section III presents the design of a blockchain-based carbon emission accounting system. Section IV demonstrates a case study of user-side carbon emission in Hengqin, China. Section V concludes the paper.

II. User-side Carbon Emission Accounting Framework

The development of MES brings new challenges and impetus to the construction of carbon neutrality. Due to the large number of users in the region, the different living habits of each user, and the different shares of carbon emissions of different loads, it is necessary to characterize and mathematically model the carbon emissions of each user-side load, in order to complete the optimal operation of the entire user-side carbon emission accounting system.

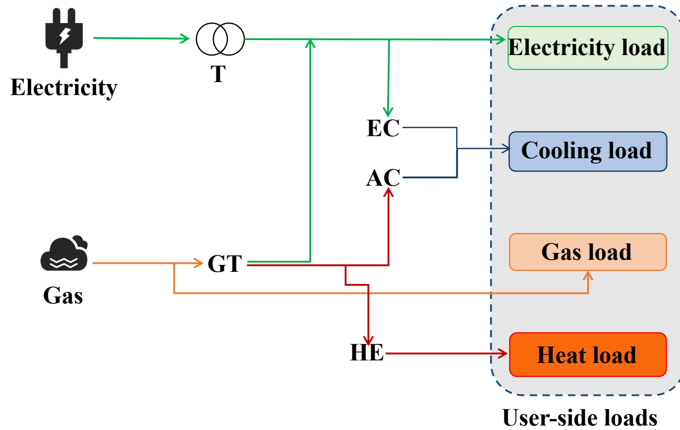

Fig. 1: The structure of the proposed MES.

A. Structure of the proposed multi-energy system

The regional MES is generally dominated by electricity and natural gas, and the system contains various types of energy conversion equipment to meet the demand for electricity, heating, gas and cooling loads on the user side, and the structure of the proposed system is shown in Fig. 1.

The MES can be divided into energy input module, energy conversion module and energy output module, as follows:

1) The energy input module includes the gas pipeline and power grid. The electricity is input into the system through transformers (T).
2) In the energy conversion module, gas turbine (GT) converts gas into electricity and heat; electric chiller (EC) and absorption chiller (AC) realize the conversion from electricity and heat to cooling energy, and the heat exchanger (HE) realizes the heating supply.
3) The energy output module focuses on user-side energy consumption, including electricity, heating, gas, and cooling loads, to enable user-side carbon accounting.

B. Carbon emission accounting model of multi-type loads on user side

1) Emission Models: This study only considers the energy consumption of electricity, heating, gas and cooling on the user side, with the goal of obtaining the carbon emission accounting on the user side. The models are as follows.

$$F = \sum_{t=1}^{n} C_t^e + C_t^h + C_t^g + C_t^c \tag{1}$$

$$\boldsymbol{E}=\begin{bmatrix} E_1^e & E_2^e & \cdots & E_t^e \\ E_1^h & E_2^h & \cdots & E_t^h \\ E_1^g & E_2^g & \cdots & E_t^g \\ E_1^c & E_2^c & \cdots & E_t^c \end{bmatrix} \tag{2}$$

$$\boldsymbol{E_t}=\begin{bmatrix} E_t^e, & E_t^h, & E_t^g, & E_t^c \end{bmatrix}^{\mathrm{T}} \tag{3}$$

$$\boldsymbol{EF}=\begin{bmatrix} EF_1^e & EF_2^e & \cdots & EF_t^e \\ EF_1^h & EF_2^h & \cdots & EF_t^h \\ EF_1^g & EF_2^g & \cdots & EF_t^g \\ EF_1^c & EF_2^c & \cdots & EF_t^c \end{bmatrix} \tag{4}$$

$$\boldsymbol{EF_t}=\begin{bmatrix} EF_t^e, & EF_t^h, & EF_t^g, & EF_t^c \end{bmatrix}^{\mathrm{T}} \tag{5}$$

$$E_{total}=\sum_{t=1}^{n}\boldsymbol{E_t}^{\mathrm{T}}\cdot\boldsymbol{e} \tag{6}$$

$$\boldsymbol{C}=\boldsymbol{E}\odot\boldsymbol{EF} \tag{7}$$

$$C_{time}=\sum_{i=1}^{4}\boldsymbol{C}_i=\sum_{t=1}^{n}\boldsymbol{E_t}^{\mathrm{T}}\cdot\boldsymbol{EF_t} \tag{8}$$

$$C_{load}=\sum_{j=1}^{n}\boldsymbol{C}^j \tag{9}$$

where C_t^e,C_t^h,C_t^g,C_t^c are carbon emissions from electricity, heating, gas and cooling loads, respectively; $\boldsymbol{E}$ is energy consumption for different load types; $\boldsymbol{EF}$ is the carbon emission factor of these loads. These matrices are of n×4 dimensions, representing n time periods and 4 load types. And $\boldsymbol{E_t}$ represents energy consumption at time t; $\boldsymbol{EF_t}$ indicates the carbon emission factor at time t; E_{total} is the total energy consumption; $\boldsymbol{e}$ is an n-dimensional column vector with an element of 1. Meanwhile, $\boldsymbol{C}$ denotes carbon emissions; $\odot$ is Hadamard product; C_{time} is the total carbon emissions at different time periods; C_{load} is the total carbon emissions of different load types; i represents the number of rows and j represents the number of columns in the summing process.

2) Physical Models:

a) Load-Related Models:

$$E_e=P_e t \tag{10}$$
$$E_h=Q_h\rho_h c_h\Delta t \tag{11}$$
$$E_g=V_g\rho_g H_g \tag{12}$$
$$E_c=Q_c\rho_c c_c\Delta t \tag{13}$$

where P_e is the electric power; t is the time; Q_h is heating quantity; ρ_h is the density of the heat medium; c_h is the heat capacity; ΔT is the temperature difference; V_g is the volume of natural gas; ρ_g is the density of the natural gas; H_g is the heat value of the natural gas; Q_c is the cooling quantity; ρ_c is the density of the cooling medium; c_c is the heat capacity of the cooling medium.

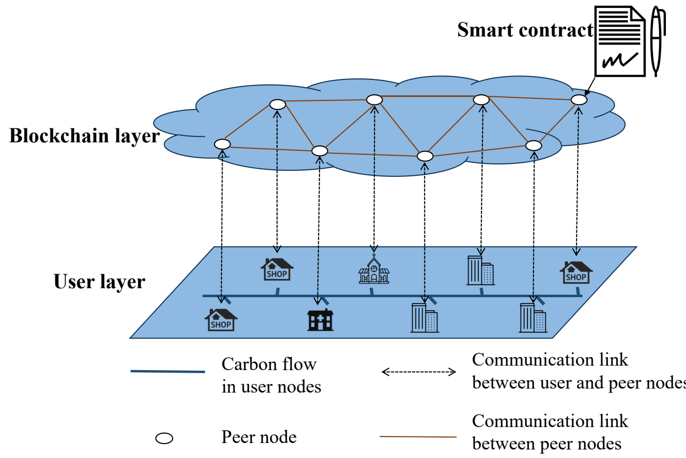

Fig. 2: The structure of the blockchain-based system.

b) Equipment Models:

$$Q_h=P_{GT}\cdot\mu_{GT}\cdot\eta_{HE} \tag{14}$$
$$Q_c=P_{EC}\cdot CO_{EC}+P_{AC}\cdot\mu_{AC} \tag{15}$$

where P_{GT}, P_{EC}, and P_{AC} are the power consumption of GT, EC, and AC, respectively; μ_{GT} is the heat production efficiency of Gt; η_{HE} is the heat exchange efficiency of HE; CO_{EC} is the energy conversion coefficient of EC; μ_{AC} is the heat-to-cool conversion efficiency coefficient of AC.

III. Design of Blockchain-Based Accounting System for User-Side Carbon Emission

This section aims to demonstrate the application of blockchain technology in the user-side carbon emission accounting model, ensuring precise recording and effective management of carbon emission data.

A. Blockchain-based system framework

This paper presents a novel blockchain-based system framework, as depicted in Fig. 2, which endeavors to establish a decentralized, secure, and trustworthy carbon emission accounting system, thereby providing users, including commercial buildings and public facilities, with credible carbon emission data.

Firstly, the user layer is the core component of the system framework, including various user entities like commercial buildings, public facilities, and others. Each user entity is connected to the blockchain network through an independent peer node in the blockchain layer.

Secondly, the blockchain layer is a decentralized network built on blockchain technology, responsible for ensuring credible carbon emission accounting on the user side. It consists of multiple Peer Nodes where smart contracts are deployed. These smart contracts are essential components that validate user's carbon emission data and record it on the blockchain. Due to the decentralized nature of the blockchain network, all users share the same trusted data source, avoiding the possibility of data forgery and tampering.

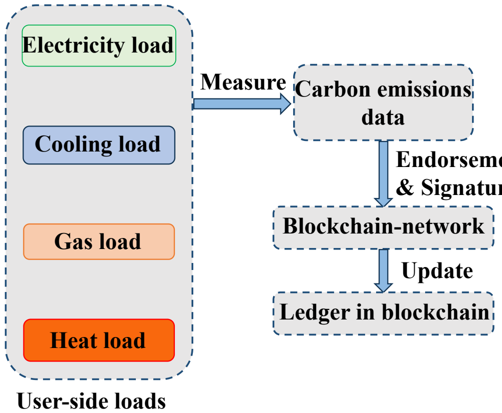

Fig. 3: The flow of blockchain-based user-side carbon emission accounting.

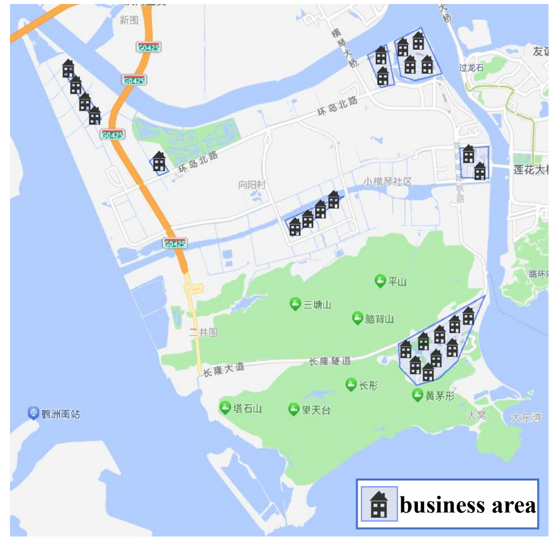

Fig. 4: Hengqin New District Business Area.

B. Blockchain-based system implementation

As shown in Fig. 3, the user side, including commercial buildings and public facilities, collects real-time energy consumption data and calculates carbon emissions using sensors and smart meters. The data cover various energy loads, including electricity, heat, gas, and cooling. These carbon emission data are then securely transmitted to the blockchain network in the blockchain layer.

Meanwhile, as the smart contract is an automatically executed program, the carbon emission data on the user's side undergoes multi-party verification and consensus through smart contracts, ensuring its credibility and consistency. Subsequently, this data is recorded on the blockchain's distributed ledger in a tamper-proof manner.

IV. Case Study

A. Experiment Setting

1) This research focuses on studying commercial buildings located in Hengqin New District, China, as shown in Fig. 4. The regional structure comprises a power station, steam heat network, cooling station, and pipeline network. It utilizes natural gas from the South China Sea and operates without external heat purchase.
2) In this study, a proposed blockchain framework is deployed using the open-source platform Hyperledger Fabric v2.3 [22]. The smart contract named "mdcc" is implemented in GO language. The study conducts a multi-node simulation to emulate user-side carbon emission accounting in the region, as shown in Fig. 5a. In addition, a web-based tool is utilized to visualize the activities of the proposed blockchain framework. The visualization is depicted in Fig. 5b, the six nodes represent the six main commercial areas.

B. Results analysis

In this study, we select two typical days in one of the commercial buildings, one in summer and the other in winter. Each day is divided into 24 time periods with a 1-hour interval, constituting an operational cycle. The energy use of each load is presented in Table 1, and the corresponding carbon emissions are illustrated in Fig. 6.

On the typical day of summer, Fig. 6a illustrates that CO_2 emission from electricity load peaks primarily between 09:00 and 21:00. CO_2 emission associated with cooling load reaches the highest levels mainly from 11:00 to 20:00, with the peak occurring at 15:00. CO_2 emission from natural gas peaks at 06:00 and 15:00. However, it should be noted that CO_2 emission from heating load is minimal.

In Fig. 6b, we observe a rise in carbon emission from electricity load during winter when compared to summer. The emission predominantly peaks between 08:00 and 23:00. Notably, carbon emission from heating load increases significantly during winter, while emission from cooling load is minimal. Furthermore, carbon emission resulting from natural gas exhibits distinct peaks at 06:00, 16:00, 20:00, and 23:00.

V. Conclusion

In this paper, carbon emission accounting is introduced into the MES containing four loads of electricity, heat, gas and cooling on the user side, and a blockchain-based carbon emission accounting smart contract is created. According to the experiment and analysis results,it is evident that electricity consumption stands as the primary source of user-side carbon emissions in commercial buildings. The peak carbon emissions primarily occur between 09:00 and 21:00, exhibiting distinct peak and valley patterns. Additionally, it is notable that the carbon emission contribution from cooling load rises in summer, while heating load has a bigger impact on carbon emissions in winter.To reduce user-side carbon emissions, it is necessary to improve the energy efficiency of heating and cooling loads and increase the share of clean energy.

In general, introducing blockchain technology and carbon emission accounting methods in MES, user-side carbon emission data can be recorded. It can contribute to the implementa-

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2023-07-23 17:38:17.858 CST 0001 INFO [chaincodeCmd] chaincodeInvokeOrQuery -> C
haincode invoke successful. result: status:200
(base) keke@kedeMacBook-Pro test-network % peer chaincode query -C mychannel -n
mdcc -c '{"Args":["QueryMeterData", "Carbon-e"]}'

{"meterId":"Carbon-e","electricPower":10,"electricTime":"2023-07-23T17:00:00Z"}
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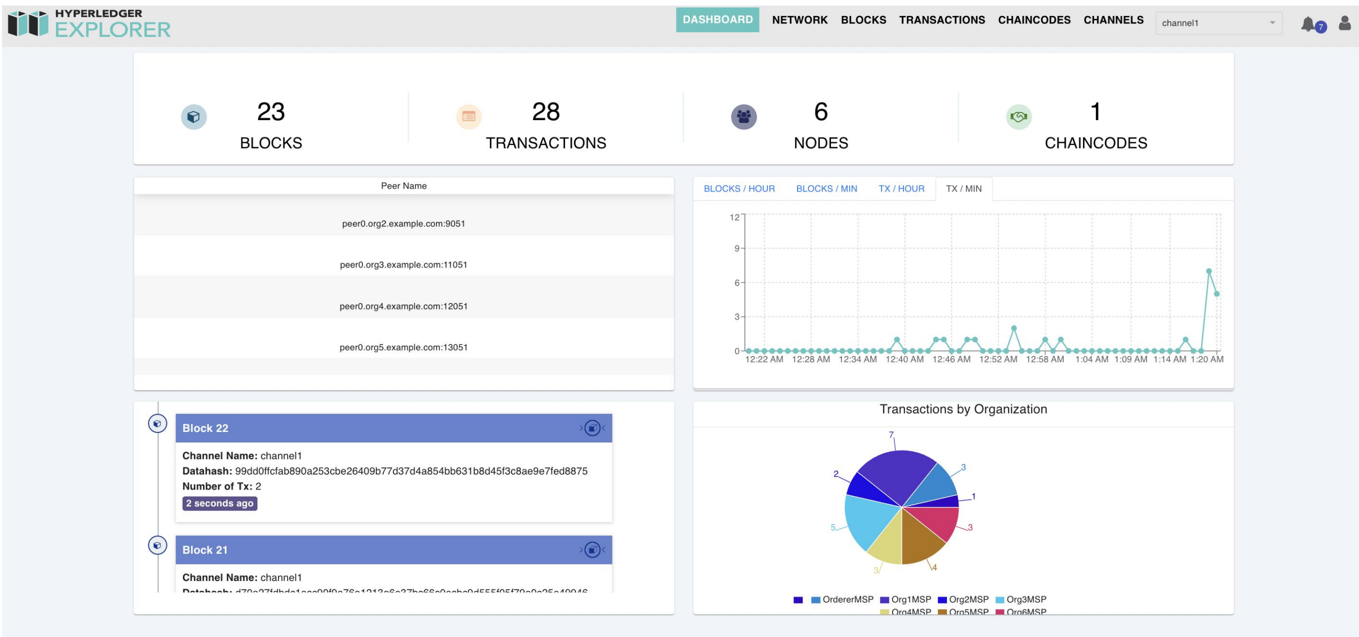
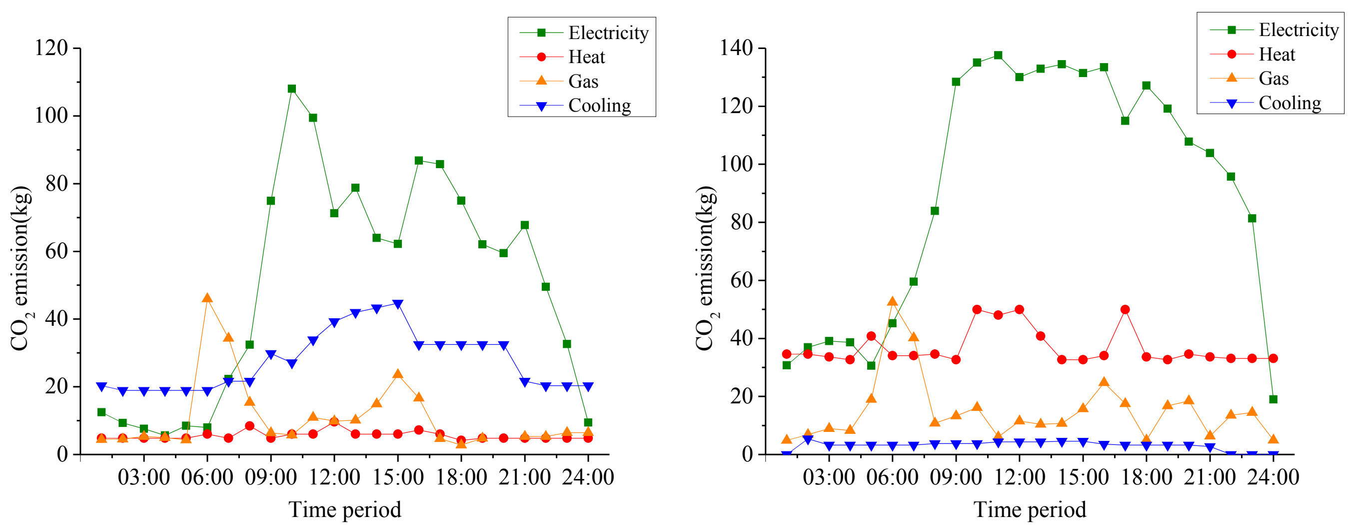
(a) Terminal-based interface for user-side carbon emission accounting.



(b) Web-based visualization of blockchain framework information.

Fig. 5: Terminal-based interface for user-side carbon emission accounting and web-based visualization of blockchain framework information.



(a) Typical day of summer.

(b) Typical day of winter.

Fig. 6: User-side carbon emission on a typical day.

tion of carbon emission reduction policies. In future research, we will explore the integration of renewable energy sources like photovoltaic and wind power to enhance the efficiency of our multi-energy system. Simultaneously, we will assess the carbon emissions throughout the building's operational cycle and enhance user-side carbon emission accounting method with the goal of minimizing carbon emissions.

APPENDIX

TABLE I: Energy Consumption for Each Load

Time period	Summer				Winter			
	Electricity (KW)	Heat (m^3)	Gas (m^3)	Cooling (KW)	Electricity (KW)	Heat (m^3)	Gas (m^3)	Cooling (KW)
00:00 -01:00	21.88	41.04	2.18	77.01	53.90	73.87	2.43	6.16
01:00 -02:00	16.29	41.04	2.26	71.88	64.81	73.87	3.39	10.27
02:00 -03:00	13.32	41.04	2.64	71.88	68.48	71.82	4.44	12.32
03:00 -04:00	9.93	41.04	2.48	71.88	67.69	69.77	4.11	12.32
04:00 -05:00	14.92	41.04	2.13	71.88	53.63	87.21	9.39	12.32
05:00 -06:00	14.01	51.30	22.76	71.88	79.28	72.85	25.96	12.32
06:00 -07:00	39.07	41.04	16.99	82.15	104.39	72.85	19.88	12.32
07:00 -08:00	56.82	71.82	7.62	82.15	147.22	73.87	5.34	14.38
08:00 -09:00	131.35	41.04	3.17	112.95	225.12	69.77	6.60	14.38
09:00 -10:00	189.48	51.30	2.86	102.68	236.78	106.70	8.02	14.38
10:00 -11:00	174.31	51.30	5.42	128.36	241.21	102.60	3.02	16.43
11:00 -12:00	124.89	82.08	4.89	148.89	227.96	106.70	5.70	16.43
12:00 -13:00	138.15	51.30	5.03	159.16	233.07	87.21	5.15	16.43
13:00 -14:00	112.20	51.30	7.41	164.29	235.80	69.77	5.29	17.46
14:00 -15:00	109.05	51.30	11.65	169.43	230.42	69.77	7.80	17.46
15:00 -16:00	152.18	61.56	8.24	123.22	233.98	72.85	12.26	13.35
16:00 -17:00	150.30	51.30	2.33	123.22	201.56	106.70	8.67	12.32
17:00 -18:00	131.50	35.91	1.39	123.22	222.94	71.82	2.45	12.32
18:00 -19:00	108.78	41.04	2.39	123.22	208.96	69.77	8.29	12.32
19:00 -20:00	104.30	41.04	3.05	123.22	188.95	73.87	9.15	12.32
20:00 -21:00	118.76	41.04	2.64	82.15	182.15	71.82	3.15	10.27
21:00 -22:00	86.79	41.04	2.64	77.01	167.88	70.79	6.70	6.16
22:00 -23:00	57.15	41.04	3.20	77.01	142.62	70.79	7.18	9.24
23:00 -24:00	16.49	41.04	3.20	77.01	33.31	70.79	2.45	9.55

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