Establishment and analysis of micro-net model considering the enhancement of photovoltaic power utilization for air-source heat pump

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Abstract. Since the stability of the power grid and the quality of electricity supply can be affected, the intermittent and unpredictable features make the renewable energy generation cannot be absorbed by the power grid easily and completely. "Abandoning the wind and solar power" phenomenon also becomes more serious in recent years. As an efficient thermoelectric conversion device, the heat pump system can couple thermal energy and electricity to eliminate excess electricity of the system theoretically. However, the influence of the heat pump technology on the microgrid system which needs to be analysed case by case lacks a unified evaluation method. Therefore, based on the Energy PLAN, an energy microgrid model of an ecological region in Qingdao is established to study the impact on the renewable energy integration and the enhancement of renewable energy utilization through applying the air-source heat pump system. The simulation results showed that the maximum photovoltaic penetration rate in the region is 19.23% initially. After applying the air-source heat pump, the photovoltaic capacity corresponding to the critical point of 100% renewable energy utilization is in direct proportion to the heat pump capacity. Additionally, the maximum photovoltaic penetrations can reach 25%. In this paper, we also propose relevant suggestions for the designing and building of the micro-net energy system.

1. Introduction

With the development of the living standard, human beings show more demand for energy. Energy becomes more indispensable in industry, agriculture, service and daily life. However, the traditional energy structure is dominated by fossil fuels, which will not only lead to environmental pollution and energy crisis, but will threaten the development even the survival of human beings in the long term. Under these circumstances, renewable energy becomes the alternative choice of fossil fuel for its cleanliness and sustainability. Renewable energy source consists of wind power, solar power etc., their common point is inexhaustible. Therefore, the utilization of renewable energy is rising throughout the world. According to the “Global Renewable Energy Status Report 2018”, the total installed capacity of renewable energy in the world reached 178 GW in the year 2017, the increasing rate is 9% compared to the situation in the year 2016 [1]. However, renewable energy has some characteristics which make it difficult to be predicted and controlled, such as intermittency and volatility. As a result, the timely production of renewable energy cannot always match the fluctuating load perfectly. Moreover, with the continuous development of renewable energy power, the assignment of eliminating it has become increasingly prominent. For example, in areas like northern China where a large scale of wind power
is developed, the “abandoning the wind and solar power” phenomenon is serious. In order to alleviate the energy system stability problem caused by the integration of large-scale renewable energy, multi-energy systems and energy conversion technologies have become hot research objects.

A multi-energy system is an “energy network system” which contains multiple energy and material flows, multiple functions and transport modes [2]. The complementary supply of renewable energy and fossil energy is an effective way to alleviate the volatility of renewable energy and the lack of fossil fuel resources. The multi-energy system does not simply combine different energy sources together, but rather achieve their organic integration, mutual transformation and coordinated supply. Yang et al [3] believed that only the multi-energy system which combined thermal, electric power and gas could entirely explore the potential of the energy system and thus absorb more renewable energy. Zheng et al [4] established a model of multi-energy system and optimized its operation aiming at the minimal cost. The simulation results showed that the multi-energy system is more flexible and environmental protective. Therefore, in order to achieve a high-level integration of various types of energy sources, the application of energy conversion equipment and technology is indispensable. Among the technologies, the heat pump plays a key role in coupling the thermal system and power system. Additionally, Research shows that the electric compression heat pump can save about 40% of primary energy compared to coal-fired boilers, and can reduce CO$_2$ emission by 68%, SO$_2$ emission by 93%, and NO$_x$ emission by 73% [5]. Therefore, the heat pump system becomes an optimal choice for its high efficiency and energy-saving.

The working principle of the heat pump system is to utilize high-grade energy such as electric power, which can raise the low-grade thermal energy in the low-temperature heat source to relatively high-grade. Based on the heat source, the heat pump system can be divided into the geothermal heat pump, the air-source heat pump and the water-source heat pump etc. From the demand side, the heat pump system mainly plays a role to supply heat, while the heat pump system is considered to couple the thermal energy and electric power and convert the excess electricity into thermal energy to meet the heat demand of the time from the supply side. Relative researches have been carried out about the effect of applying the heat pump into the renewable energy system. Lund et al [6] established a 100% renewable energy system in Danish, 2060 based on the Energy PLAN model and compared multiple energy scenarios. The simulation conclusion showed that the independent heat pump technology is the best alternative technology for district heating. Liu et al [7] used scenario analysis method to study the energy system in Chongming District of China. The comparison results showed that the heat pump technology can reduce the regional excess electricity the most effectively among various energy conversion technologies. Wang et al [8] compared four energy conversion technologies applied in Chongming, 2040, including the heat pump system. The conclusions were based on the excess electricity, primary energy consumption and imported electricity etc. Guo et al [9] introduced heat pump device into the cogeneration microgrid, which was mainly used to eliminate excess wind power. An optimal economic operation strategy of a microgrid with the heat pump was also proposed. The results showed that the heat pump system could effectively reduce the wind abandonment of microgrid and improve the economy of microgrid. It can be seen from the above literatures that heat pump system can convert surplus electricity into heat to meet the demand, thus effectively improving the penetrator of renewable energy in micro-grid system. However, the specific impact of heat pump on renewable energy utilization in micro-grid system needs to be analyzed in combination with case studies, under the condition of no unified mode or method existing up to now. To evaluate the integration level of renewable energy and the impact brought by the heat pump system, an evaluating indicator should be brought about. Pou I Ø [10] reviewed previous literature around Energy PLAN and indicating the most five usually used parameters are primary energy supply, CO$_2$ emission, costs, excess electricity and duration of various units. Brian Tarroja et al [11] developed some new metrics to evaluate the impact of renewable energy on the energy balance of demand and supply. By studying these metrics, the maximum renewable penetration can be obtained under different energy scenarios. Considering the outputs of Energy PLAN, a suitable indicator is given to support more suggestions from another perspective.
In this paper, the Energy PLAN model is used to establish a multi-energy micro-grid model of heat and electricity. The effective utilization of renewable energy is used as an indicator to evaluate the ability to absorb renewable energy of the system. An ecological region in Qingdao City, Shandong Province is taken as an example to study the impact of individual air-source heat pump on improving the renewable energy utilization rate.

2. Methodology
The research method used in this paper is simulation and analyzing. A simulation model of the energy system and an evaluation model are built and used during the research. In order to establish a model based on the actual energy system, the mathematical model and operation principle of each device are necessary. Since the based simulation data are directly output from the Energy PLAN without organizing, the determination of evaluation indicator is ought to be significant and the data limitation should be well considered.

2.1. Model of the main devices
The main devices of the micro-energy system are photovoltaic system, the lithium bromide absorption chiller, the geothermal heat pump, the gas-fired internal combustion engine, and the gas-fired boiler. One of the basic operation strategies is the timely energy balance. Thus, the calculation method of timely power should be determined in this term. The mathematical models based on the operation strategy are shown as following.

The electricity generation of the photovoltaic system is mainly affected by the solar radiation intensity and the installed capacity. When the rated capacity of the device is given, the stronger the solar radiation intensity is, the more power is generated. The mathematical expression of photovoltaic power and annual electricity generation is shown as equations (1) and (2).

\[ e_{pv}(t) = C_{pv} \times d_{pv}(t) \]  
\[ E_{pv} = \sum_{t=1}^{8760} e_{pv}(t) \times t \]  

Where \( e_{pv}(t) \) represents the timely electricity generation of the photovoltaic system, its unit is MW; \( C_{pv} \) represents the rated installed capacity of the photovoltaic system, its unit is MW; \( d_{pv}(t) \) represents the timely distribution of the annual electricity production. The specific data can be obtained in the built-in database in Energy PLAN or defined by users. \( E_{pv} \) represents the annual electricity generation of the photovoltaic system, the unit of which is MWh; \( t \) represents the simulation time step, which is 1 hour in the Energy PLAN model.

The heat required by the lithium bromide absorption chiller is supported by the regional heat network. The mathematical model can be expressed as equation (3).

\[ q_{district}(t) = d_{c}(t) \times \frac{Q_{c}}{t \times \text{COP}_{AC}} \]  

Where \( q_{district}(t) \) is the timely heat needed during the chilling process, its unit is MW. \( d_{c}(t) \) represents the timely distribution of cold demand. \( Q_{c} \) represents the annual cold demand, its unit is MWh; \( \text{COP}_{AC} \) is the performance coefficient of the absorption chiller. The heat demand of the refrigeration process is included in the total heat demand during calculation.

The inputs of the geothermal heat pump are the amount of annual heat supply \( Q_{hp-hp} \) and its timely
heat supply distribution \(d_{g-hp}(t)\) which can be obtained in the built-in database of Energy PLAN. The timely thermal energy supplied by the geothermal heat pump can be calculated by multiplying the two inputs, its unit is MW. The mathematical expression is shown as formula (4).

\[
q_{g-hp}(t) = Q_{g-hp} \times d_{g-hp}(t)
\]  

(4)

The gas-fired internal combustion engine which operates based on the “Following the thermal load” (FTL) strategy in this system, also undertakes the assignment to meet part of the electrical demand. Therefore, the electrical power supply is determined by the simultaneous heat demand. The timely power output of heat and electricity is shown as equations (5)–(7).

\[
q_{CHP}(t) = \begin{cases} 
D_{heat}(t) & C_{CHP} > D_{heat}(t) - q_{g-hp}(t) \\
C_{CHP} & C_{CHP} \leq D_{heat}(t) - q_{g-hp}(t) 
\end{cases}
\]

(5)

\[
f_{CHP}(t) = \frac{q_{CHP}(t)}{\rho_{CHP}}
\]

(6)

\[
e_{CHP}(t) = f_{CHP}(t) \times \mu_{CHP}
\]

(7)

Where \(q_{CHP}(t)\) represents the timely thermal power output of the gas-fired internal combustion engine, its unit is MW. \(D_{heat}(t)\) represents the timely heat demand of the district, in MW. \(C_{CHP}\) represents the rated capacity of the internal combustion engine, in MW. \(\rho_{CHP}\) indicates the efficiency of heat producing process; \(f_{CHP}(t)\) indicates the timely fuel consumption during the operation process, in MW. \(e_{CHP}(t)\) indicates the timely power generation from the gas engine, in MW; \(\mu_{CHP}\) indicates its power generation efficiency. If the hourly electricity demand is still not satisfied by the photovoltaic system and internal combustion engine, the electricity from the power grid should be purchased.

The remaining heat demand is satisfied by the gas-fired boiler and the regional heat network. The mathematical model of the gas-fired boiler is shown in equation (8).

\[
q_{boiler}(t) = \begin{cases} 
D_{heat}(t) - q_{CHP}(t) - q_{g-hp}(t) & C_{boiler} > D_{heat}(t) - q_{CHP}(t) - q_{g-hp}(t) \\
C_{boiler} & C_{boiler} \leq D_{heat}(t) - q_{CHP}(t) - q_{g-hp}(t) 
\end{cases}
\]

(8)

Where \(q_{boiler}(t)\) represents the timely thermal energy output of the gas-fired boiler, in MW; \(C_{boiler}\) represents its rated power, in MW. If the heat demand is not fully met by the boiler, the internal combustion engine and the geothermal heat pump, the residual heat is provided by the regional heat network.

The mathematical models of each device are established as mentioned above. These equations have been built in the Energy PLAN model while each calculation strategy is not introduced adequately unless a specific case is focused. The output parameters from Energy PLAN are annual value without timely analysis, which makes it hard in evaluating the energy system with the limited data. Therefore, to estimate the renewable energy penetration, an evaluation model is established.

2.2. The simulation tool and evaluation indicator

The Energy PLAN simulation platform was developed and maintained by the Sustainable Energy Planning Research Group of the Aalborg University in Denmark. The platform is mainly used to plan and study the regional energy supply systems. The model helps many researchers, organizers and government planners study the economics, environmental friendliness and supply-demand matching degree of regional energy systems. The model includes multiple energy devices and sections including electricity, heat and transport. The simulation time step of Energy PLAN model is an hour. When the
rated capacity of each controllable device, the rated capacity and distribution of uncontrollable system, the total demands and their timely distribution are given, the required parameters such as the hourly actual power of each device and the excess electricity can be obtained according to formulas (1) to (8). The energy system model established through Energy PLAN follows the constraints of energy balance, the priority use of renewable energy, and so on. Additionally, the operation of each equipment is subject to certain operational strategies: for example, the gas-fired internal combustion engines follow the “Following the thermal load” strategy. Domestic and foreign scholars have used this model to conduct a lot of researches on multi-energy systems. Lund et al [12] used this model to study the impact of integrating large-scale of wind power in Danish energy systems and analyzed the feasibility of implementing relevant strategies. Yue et al [13] used this model to estimate the optimal integration degree of renewable energy on Wangan Island.

In order to measure the degree of the renewable energy integration in the regional energy system, researchers have proposed relevant indicators. The excess electricity, primary energy supply and the installed capacities ratio of renewable energy under energy balance condition and economic balance condition etc. have been widely used. However, these indicators are hard to reflect the impact of renewable energy volatility on the system and the matching extent of supply and demand simultaneously. In this paper, output parameters of Energy PLAN model are organized to determine the renewable energy utilization efficiency as an indicator. The indicator is used to measure the level of renewable energy integration and the supply-demand matching level in an energy system. The mathematical expression of this indicator is shown as equation (9).

\[
UERE(\%) = \frac{\sum RE_2(t) - \sum PP_{else}(t) - \sum import(t)}{\sum RE(t)}
\]  

In the equation, \( RE_2(t) \) represents the amount of electricity generated by the renewable energy, which is absorbed by the energy system, its unit is TWh. \( \sum RE(t) \) represents the total amount of renewable energy generation, in TWh. \( \sum D(t) \) represents the annual electricity demand, in TWh. \( \sum PP_{else}(t) \) indicates the annual amount of electricity generated by the other power generation equipment except renewable energy, in TWh. \( \sum import(t) \) represents the part of annual electricity purchased to meet the demand, in TWh. If the calculation result of the molecular term is negative, it is counted as zero to avoid the round-off error. After the introduction of the heat pump system, part of the excess electricity can be utilized. The calculation formula of the renewable energy utilization rate can be expressed as the formula (10). In the equation, \( \sum HP(t) \) represents the annual amount of electricity consumed by the heat pump, in TWh.

\[
UERE(\%) = \frac{\sum RE_2(t) - \sum D(t) + \sum HP(t) - \sum PP_{else}(t) - \sum import(t)}{\sum RE(t)}
\]  

To study the regional energy system, the description model is established through Energy PLAN model firstly. The operating output of each device in the system is calculated by equations (1) to (8). The specific calculation process in Energy PLAN is shown in figure 1. The output parameters of Energy PLAN model are arranged to determine the utilization efficiency of renewable energy according to formulas (9) to (10). Through the calculations above, the influence on the renewable energy integration level of applying the heat pump system can be evaluated.
3. Results and discussion

3.1. Introduction of the energy system

In this paper, an ecological park located in Qingdao City, Shandong Province is taken as an example to research. The energy providing area of this park is 757.77 million square meters. The main energy load types are cold, heat, electricity, natural gas and steam. Based on the data supported in the designing documentation of the system, the heat load is 242.2 GWh/year, the cold load is 189.595 GWh/year and the electrical load is 520.96 GWh/year. In order to meet the various energy demands of the system, the main energy supply equipment are the 55MW gas-fired internal combustion engine, the 10MW lithium bromide absorption chiller, the 276MW gas-fired boiler, the 8MW photovoltaic system and the 10MW geothermal heat pump, etc. These devices constitute a multi-energy system.

The electricity load is mainly satisfied by the gas-fired internal combustion engine, the photovoltaic system and power grid. The heat load is mainly met by the gas-fired internal combustion engine, the
gas-fired boiler and the geothermal heat pump. The cold load is supplied by the lithium bromide absorption chiller. The specific system schematic diagram is shown in figure 2. And the hourly electricity demand in a certain day of the simulation year is shown as figure 3. The electricity load is fluctuating, so the energy supply side should be flexible enough to meet the demand.

![Figure 3](image)

**Figure 3:** The hourly electricity demand in a certain day in the case.

### 3.2. The Impact of photovoltaic power integration

In order to improve the environmental protective of the region, it is necessary to increase the penetration rate of renewable energy. Increasing the PV capacity will reduce the purchased amount of electricity in the case of “Demand Over Supply”. However, it may result in excess electricity in the case of “Supply Over Demand” without energy storage system, which leads to energy waste. Additionally, unlimited increase of installed capacity will also lead to a significant increase in the initial cost of the energy system. Therefore, the balance degree of energy supply and demand is the key factor which can affect the maximum installed PV capacity of the energy system, and the degree can be shown from the import and excess electricity. The change in annual purchased electricity and excess electricity in the region with the increase of photovoltaic capacity are shown in figure 4.

![Figure 4](image)

**Figure 4:** The purchased and the excess electricity changed with the PV installed capacity in the region.

The two curves in Figure 4 have different trends with the increasing installed capacity of PV. The
annual purchased electricity indicates the self-sufficiency of this energy system. The annual excess electricity indicates the saturation degree of the energy supply in the system. The former indicator decreases with the increasing PV capacity, proving that the increase of photovoltaic penetration reduces the necessity of the electricity import. The fuel consumption would not be affected since the CHP system follows the FTL principle. The annual electricity consumption curve dropped steeply when the PV installed capacity is less than 60MW. But it tends to be flat after reaching the 27.3% of the initial value. This phenomenon is caused by the property of daily solar energy distribution: The photovoltaic power generation is limited by the intensity of solar radiation, which approximately follows the normal distribution in a day time. Therefore, the electricity demand in the evening and the morning time cannot be satisfied by PV completely without energy storage system. In a word, increasing the PV installed capacity can only obviously improve the supply-demand balance at noon. The reduction of purchased electricity in the range of 0MW~60MW is more obvious in figure 4, indicating that an appropriate increase of PV installed capacity can improve the imbalance phenomenon in the energy system better. Excess electricity in the system increases gradually from 0 after the PV installed capacity exceeds 60MW, representing the acceptance of photovoltaic power production at the critical point becomes saturated, which is named “the saturation point” in the following discussion.

According to the current policy, the power generated by the distributed energy system does not connect to the grid, so the excess electricity cannot be utilized. Therefore, the determination of the saturation point is based on the annual summary of the timely excess electricity, for which the critical value is 0. Once the energy supply and the demand structure are determined, the renewable energy saturation point considering the annual timely benefit can be obtained.

The microgrid preferentially uses photovoltaic power to meet the electrical load, and the power generation of the gas-fired internal combustion engine is determined by the thermal load at the same time. Therefore, the excess electricity may come from the extra photovoltaic or CHP power generation due to the unreasonable allocation of the photovoltaic installed capacity. With the increase of photovoltaic capacity, the accepted photovoltaic power and total PV generation also rise up. The former cannot linearly increase limited by the energy structure, while the latter increases by a certain slope. By comparing the two parameters, the renewable energy utilization efficiency of the region under different PV penetration rates can be obtained, thereby helping in analyzing the benefits brought by the reasonable photovoltaic installation. The curve of utilization efficiency of PV changed with its installed capacity is shown in figure 5.

![Figure 5](image_url)

**Figure 5.** The utilization efficiency of PV changed with PV installed capacity.

Figure 5 shows that with the increase of PV installed capacity, the utilization efficiency rate of PV does not show a linear increase or decrease, but maintains the 100% in the range of 0~60MW, and
drops quickly after 60MW. When the installed capacity of photovoltaic is less than 60MW, the output power summary of hourly photovoltaic and gas combustion engines is less than the hourly electrical load. It can be seen from figure 4 that there is no excess electricity in this range as well. Therefore, the renewable energy is fully utilized, and the utilization efficiency of PV is 100%. When the installed capacity exceeds 60MW, indicating that part of the electricity supplied is wasted. The positive effect of increasing PV would reach its maximum at 60MW. Continually expanding the scale of PV systems would result in unnecessary waste of cost and electricity.

The research above proves that the penetration rate corresponding to the maximum photovoltaic installed capacity is 19.23%, which represents the maximum acceptance of PV in the region. It can be seen that the main reason for the saturation is that there exists excess electricity which is not utilized. In order to improve the ability of the energy system to accept more photovoltaic power, it is necessary to apply thermoelectric conversion technology. The introduction of the technology would not change the original energy supply-demand structure a lot. Excess electricity is used for producing thermal energy to meet the heat load. The technology cannot only reduce the waste of electricity, but also change the structure of heat demand, reducing the electricity generation form CHP and making more room for the consumption of photovoltaic power. Morten B. Blarke[14] indicated that if the well-designed heat pump system is more cost-effective than the electric boiler. Karsten Hedegaard et al.[15] researched the energy scenario in Danish, 2020 and got the conclusion that the individual heat pumps and heat storage system could enhance the integration of wind power by using EnerPlan. The fuel saving costs and the excess electricity are taken as indicators to determine the optimal capacity. Poul Alberg Østergaard[16] investigated how the different heat pump system affect the wind power penetration by comparing the fuel-fired boiler production and excess electricity. The simulation results showed that the heat pump system could improve the operating characteristics of the energy system but it differed with the type, the absorption heat pumps or the compression heat pumps. As above mentioned, the independent air source heat pump system can efficiently realize the thermoelectric conversion process, and becomes an important way to improve the renewable energy utilization rate and reduces energy waste. However, the specific impact on photovoltaic penetration of the heat pumps system lacks analysis by definite case. In this paper, the ecological region in Qingdao is taken as an example to research the concrete impact of air-source heat pump.

The capacity of the air-source heat pump is determined by the annual heat supply as an input parameter in the Energy PLAN model. The power consumed during operation can be considered to be derived from the excess electricity. Actually, the power generation of CHP is determined by the day scheduling. When the heat load exists, the gas-fired internal combustion follows the FTL principle while the individual air-source heat pump consumes electricity, which may come from the PV, the CHP or the purchased electricity. Even though it is hard to tell which one support the operation of heat pump, it is taken from the microgrid. Figure 5 shows the effect of the increasing heat supply from air-source heat pump system on decreasing the excess electricity in the region as the PV installed capacity increases.

In the figure 6, the abscissa indicates the installed photovoltaic capacity, the ordinate indicates the excess electricity of the energy system. Each curve represents the different annual heat supply of the air-source heat pump. From figure 6, it can be seen that with the gradual increase of the annual heat supply of heat pump, the critical point of photovoltaic power gradually shifts forward on the abscissa. It indicates that the containable capacity of PV becomes larger gradually in this region since the air-source heat pump consumes part of the excess electricity. If the electricity consumption comes from the internal combustion engine, more space is provided for the photovoltaic generation; if it comes from the PV, the utilization of the power is directly utilized. When the heat load is fully met by the individual air-source heat pump system, the excess electricity in the system can be reduced up to 0.04TWh per year comparing to the system without the heat pump system. Additionally, the maximum installed capacity of PV in this energy structure can reach 80MW. Researches proved that the application of the absorption heat pump system worked well where the natural gas supply to CHP plants[17]. Poul A Ø[18] indicated that the heat pump system is a logical option in Denmark energy
system with CHP plants and district heating grids, as the ecological region in Qingdao. As he mentioned: “The heat pumps can reduce the heat tied production on CHP plants”. The qualitative conclusions are in accordance with these previous literatures and the results support more specific data and reference index. The result indicates that the application of an individual air-source heat pump system can efficiently increase the integration ability for photovoltaic power.

![Figure 6](image_url)

**Figure 6.** The excess electricity changes with the increasing PV installed capacity under different heat supply from air-source heat pump condition.

![Figure 7](image_url)

**Figure 7.** The utilization efficiency changed with installed capacity of PV under different annual heat supply of air-source heat pump condition.

The curves in figure 7 indicate the change in PV utilization with photovoltaic production under the condition of different annual heat supply of air-source heat pumps. The utilization efficiency of renewable energy is greatly improved compared to the non-addition of heat pump systems. With the increase of annual heat supply of air-source heat pump, the part of curves below 100% shows the upward trend overall. When the whole heat load is met by independent air-source heat pump, the PV
penetration rate corresponding to the maximum installed capacity in the system to photovoltaics increased from 19.23% to 25%. When the installed capacity of photovoltaic increased to 100MW, the utilization efficiency of PV increased by 25% compared to the non-introduction condition of air source heat pump. The results show that the air-source heat pump system cooperating with the photovoltaic system will effectively enhance the renewable energy utilization rate in the energy structure. Therefore, the phenomenon of "solar abandoning" is reduced, more photovoltaic power can be utilized.

4. Conclusions
In this paper, the regional heat, cold and electricity multi-energy network model is established by using Energy PLAN model, the output data is organized to calculate the evaluation indicator, the utilization efficiency of renewable energy. The energy system of an ecological park in Qingdao, Shandong province is modeled and evaluated by the methodology above, and the integration ability of the energy system for renewable energy is analyzed. Finally, the air-source heat pump system is applied to study the influence of the energy conversion system on the actual energy structure. According to the case analysis, model establishment and results discussion, the following conclusions are obtained:

- When the air-source heat pump system is not applied, the maximum photovoltaic penetration of this region is 19.23%, and the corresponding installed capacity is 60MW. When the penetration exceeds the saturated point, the excess power appears.
- After the application of the air-source heat pump system, the maximum PV penetration of the system can be increased to 25%, corresponding to the installed capacity of 80MW.
- Since the photovoltaic power generation is subject to a certain distribution, even if the cost of increasing the photovoltaic installed capacity is not considered, there is still a large amount of photovoltaic power not used. Additionally, the installation of PV is limited by the regional area. Therefore, the electricity load needs to be met by other power supply ways. Therefore, we should consider the complementary supply of renewable energy to improve the current imbalance of supply and demand in the energy system, and further improve its cleanliness and economy.

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