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A Review on the current accommodation status of renewable energy in China and its methods of improvement in the power and thermal systems

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ABSTRACT

Improving the large-scale renewable energy accommodation plays an important role in accelerating energy transformation and optimizing energy consumption structure, which has outstanding economic significance and environmental benefits. China's vast territory and the renewable resources are rich in the northwest, southwest, northeast, north China. This paper reviews the current accommodation status of renewable energy in China and its methods of improvement in power and thermal systems related in recent research. In latest years, the renewable energy curtailment problems have become more and more serious due to that the existing power systems are not able to absorb the renewable energy with intermittence and randomness. Hence, several methods are proposed to improve the flexibility of power systems, which is needed for the renewable energy up to the power grid. Some of researchers proposed methods in the field of power systems, such as electric storage, power-to-X, virtual power plants, power demand side management, etc. Some of others developed methods in the field of thermal systems, which is closely related to the power systems, such as by-pass auxiliary heating, active heat storage, passive storage, ice thermal storage, etc. Different approaches are compared comprehensively and it is found that only seeking methods within power systems is not enough. Thermal systems contain great flexibility which can be utilized in the power systems. Key issues of research lies in developing combined heat and power dispatch with fully consideration of the operation constraints and performance evaluation index for the power and thermal systems.

Keywords: renewable energy accommodation, power system, thermal system, electric storage, thermal storage

1. INTRODUCTION

As an important part of the future energy system, renewable energy has the characteristics of clean, green, pollution-free and carbon-free. Large-scale renewable energy accommodation plays an important role in accelerating energy structure optimization and the sustainable development, which has outstanding economic significance and environmental benefits [1]. China has a vast territory with abundant renewable resources, which is shown in Fig.1. Northwest China has a long sunshine time, which concentrates a large amount of photovoltaic resources. Southwest China is rich in water and electricity resources because of abundant rainfall. Gansu, Xinjiang and other provinces as well as northeast China have strong wind power in winter, which is the gathering area of wind power [2]. In recent years, China has made great efforts to develop the renewable energy and achieved remarkable results, with installed capacity of hydropower, photoelectric and wind power ranking the first in the world, and installed capacity of renewable energy growing rapidly. However, due to the intermittence, volatility and randomness of the renewable energy, the curtailment of photovoltaic power, wind power and hydropower has become increasingly serious in the whole country [3]. According to statistics from the China National Energy Administration, the amount of water, wind and photovoltaic to be abandoned in 2019 reaches 30 billion kW·h, 16.9 billion kW·h and 4.6 billion kW·h, respectively.

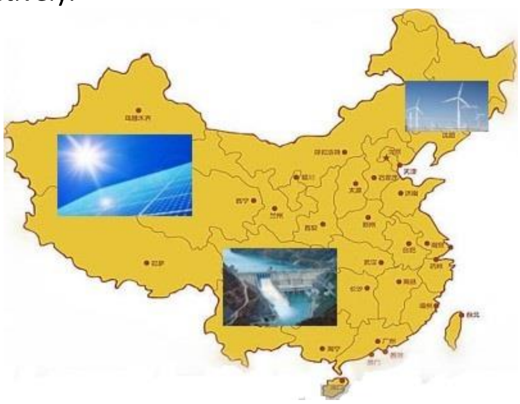

Fig.1 Geographical distribution situation of renewable energy sources in China

There are three reasons [4-5] that mainly cause the serious curtailment of renewable energy. First, due to the insufficient construction of power grid, the transmission capacity of spare renewable energy from the renewable-energy-rich areas, in north China, to the high electricity demand areas, in southeast China, is restricted. Second, the inter-regional electricity trade mechanism lacks so that the abundant renewable energy meet challenges to deliver electricity to the nearby provinces. Third, the existing power system lacks flexibility for the renewable up to the power grid. Taking the northeast China as an example, the operation mode of "heat-led" of CHP(combined heat and power) units brings difficulty in breaking the strong coupling relationship between heat and power, causing serious wind curtailment phenomenon. The effective solutions to the above problems include [6-7] : accelerating the establishment of a strong power grid framework, promoting local flexible loads, improving the flexibility of the power system, building a flexible power market, and improving the cross-regional trading mechanism and policies of renewable energy. The construction of power grid network frame involves the theoretical research of specific power transmission equipment. The other three approaches all involve the comprehensive modeling and optimization analysis of electricity, heating, cooling and other multi-energy systems.

CHP unit involve thermodynamic analysis, heating and cooling building load in the total power load proportion is increasing, and therefore, the thermal system and the power system have a natural correlation. The improvement of the flexibility of power system is directly restricted by the operation mode of thermal system. On the contrary, thermodynamic technology can also be developed and popularized depending on the policy support of power system. In addition, since the electricity energy is easy to transport and difficult to store, but the thermal energy is easy to store and difficult to transport, thus the thermal energy storage has gradually become one of the effective ways to supplement electric energy storage. This paper reviews the research progress of promoting renewable energy consumption in power and thermal systems in recent years. Beyond the framework of the power system, the great potential of the thermal system in improving the flexibility of the power system and solving the problem of renewable energy consumption is explored.

2. RENEWABLE ENERGY IMPROVEMENT METHODS BASED POWER SYSTEMS

In the field of power system, the technologies widely studied and applied at present include power storage technology, virtual power plant, power demand side management, etc. Power to X technology is another promising method to improve renewable energy utilization, but it is not discussed in this paper because this involves in other types of energy systems and other subjects.

2.1 Electric energy storage technologies

Electric energy storage refers to a series of technologies and measures that use chemical or physical methods to store the energy in the form of electricity and release it when needed. Its purpose is to break the real-time matching of energy supply and demand, improve the regulating ability of power system, and provide sufficient space for renewable energy accommodation on the power grid. Electric energy storage includes four categories, the first is the mechanical energy storage, such as the pumping energy storage and flywheel energy storage, compressed air energy storage. The second category is the electromagnetic energy storage, such as the super capacitor energy storage and the superconducting energy storage. The third kind is the electrochemical energy storage, namely, the lead-acid batteries, the lithium-ion batteries, the sodium sulfur batteries, the all vanadium flow batteries. The fourth category is the pure chemical energy storage, such as the hydrogen storage which refers to the use of hydrogen or synthetic natural gas as a secondary energy carrier. P2G (Power to gas) is one of the most popular related hydrogen storage technology. The principle is that the surplus renewable energy is connected to the power grid to electrolyze water to produce hydrogen, which is then stored as backup fuel [8].

The application of pumped storage in China has been very mature. However, due to the natural conditions of water resources, it is difficult to be applied in northwest, northeast and North China. Flywheel energy storage technology was approved by NASA in the 1990s, and has made great progress in research and been widely used in aerospace field. The research progress of flywheel energy storage in China lags far behind that of developed countries, so the country should increase the investment of capital and technology to make this technology go to market as soon as possible. In terms of electrochemical energy storage, according to statistics, the application proportion of the lithium battery, the lead-acid battery and the fluid battery energy storage in China's battery market in 2013 was 60%, 20% and 14% respectively [9].

2.2 Virtual power plants

With the increasingly serious problems of the energy crisis and the environmental pollution, the distributed generator has been adopted by more and more countries due to its characteristics of reliability, economy, flexibility and environmental protection. However, distributed power supply has the problems of small capacity, discontinuity and randomness, so it is not feasible to directly participate in the power market. In 1997, Dr. Shimon Awerbuch put forward the concept of virtual power plant, that is, to integrate geographically dispersed distributed new energy, energy storage system, controllable load, electric vehicle and so on through advanced communication technologies. It aims at coordinating and optimizing multi-type energy forms from the perspectives of economy, energy conservation and low carbon emissions [10], breaking the boundary between the generation side and the load side [11], and becomes a power supply coordination management system for a special power plant to participate in the power market and power grid operation [12].

At present, the research and implementation of virtual power plants are mainly concentrated in Europe and North America. Because virtual power plants show great adaptability to the situation of power supply and demand [13], this scheme has great application potential for China, which is faced with the contradiction of "power shortage and low energy efficiency". A number of Chinese universities, enterprises and other research institutions have approved projects to carry out in-depth research on relevant technologies[14].

2.3 Power demand side management

DSM (power demand side management) was proposed in the 1970s in western developed countries. It means that the power industry (on the supply side) adopts policy guidance, economic means and technical measures to encourage users (on the demand side) to adopt various effective energy-saving technologies to change the way of the power demand. Its purpose is to reduce the investment in new power plants and the pollution of the atmospheric environment by primary energy by reducing energy consumption and electricity load while maintaining the energy service level, and achieve obvious economic and social benefits [15]. China has carried out extensive and in-depth theoretical research and engineering applications since 2000. The main technical solutions include electricity price means guidance and user side distributed cold storage units. Denmark, Germany and other regions promote distributed energy consumption through the electricity market mechanism of real-time electricity price, such as guiding users to consume renewable energy through low price in the wind power release period, or realizing the off-peak operation of air conditioning through the distributed cooling storage on the user side in summer, so as to improve the flexibility of the power system [16].

3. RENEWABLE ENERGY IMPROVEMENT METHODS BASED THERMAL SYSTEMS

The thermal system and the power system are connecting each other naturally, which is shown in Fig.2. On the supply side, these two systems are coupled by a heat and power cogeneration unit. The flexibility of the power system is restricted in the heat and power cogeneration unit due to the electrical output changing along with the thermal output but not the electrical demand under the "heat-led" operating mode of CHP units. On the demand side and energy storage side, the thermal system has a great ability to improve flexibility and promoting renewable energy proportion in the power system. The thermal inertia of the thermal system can provide flexibility for the power system. And the thermal energy storage has a low cost and technology mature advantages, which is one of the hot research directions of electric energy storage.

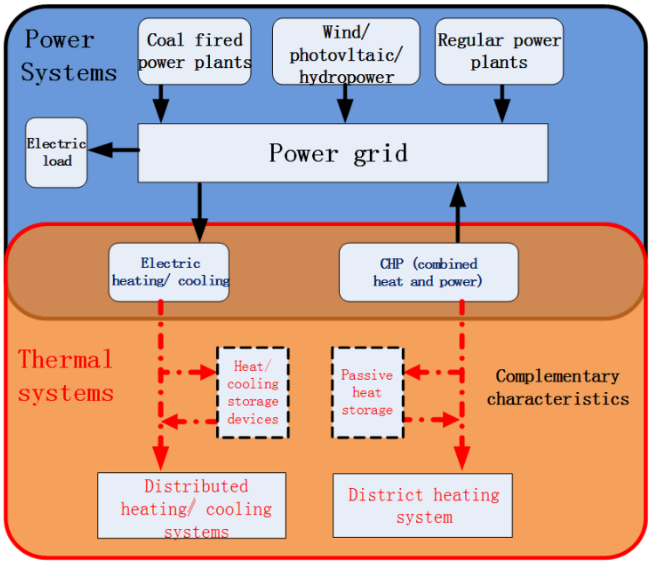

Fig.2 Natural connection between the power and the thermal systems

Therefore, scholars have generally recognized that it is difficult to improve the flexibility only in the power system, and further studies should be carried out from the coupling perspective of the power system and other energy systems, such as the coupling of the power system and the thermal system, to find a variety of technical solutions to improve the flexibility of the power system. A comprehensive review of several technologies based on thermal systems to enhance flexibility and promote renewable energy consumption shows in the following.

3.1 *By-passing auxiliary heating*

The thermodynamic efficiency of CHP unit is higher than the straight condensing units due to the CHP unit outputting heating and electricity simultaneously. Hence, the straight condensing units were transformed into CHP units, several decades ago in northern China. And this leads to the wind power curtailment because the power output of CHP units is too high under the "heat-led" operation mode in the night when the heating demand reaches high and the wind power is abundant. In order to reduce the thermal output for CHP units, the by-pass compensation heating method was proposed to improve the flexibility of power systems. The mechanism of the by-pass compensation heating scheme refers to by-passing a part of the high-temperature and high-pressure steam through a temperature- and pressure-reducing device in parallel with the steam turbine and transferring heat to the heat users directly, hence decreasing the heating and electricity output of CHP units[17]. Andersen et.al.[18] studied the effects of the by-pass compensation heating method, and results show that it can improve the feasibility and economical of the power system in a short time operating. However, in a long time operating, the by-pass compensation heating scheme leads the low operating efficiency, poor system stability, and other problems of the CHP unit due to the operating conditions deviation from the design conditions seriously. Hence, the by-pass compensation heating scheme is not suitable for the long-term running in northern China.

3.2 *Distributed electricity-heating conversion equipment*

The electricity-heating conversion equipment includes electric boiler, heat pump and so on. The use of electric boilers and heat pumps is to improve the flexibility of the power system by reducing the power output of the heating unit. The use of electricity-heating conversion equipment has a double peak-regulating effect. Firstly, the electric boiler provides part of the thermal load instead of the CHP(combined heat and power plant) units, so the thermal output of the thermal power plant can be reduced. Second, the use of electric energy for heating can promote the accommodation of the wind power [19]. Researchers [20-23] also proposed a solution to reduce the thermal load during wind power high generation period by installing electric boilers, heat pumps and other electro-thermal conversion methods.

The distributed electricity-heating device means to install the electric boiler in each user and realize the peak regulation through intelligent control of the electric boiler on the user's side[20]. At present, in Denmark and German, the thermal load is supplied through combined heating systems which include a number of small CHP units and the distributed electricity-heating conversion equipment, so as to achieve the purpose of power peak regulation[21, 23]. However, China adopts central heating systems and centralized power dispatching mode, which is difficult to carry out accurate control of the distributed electric heating equipment at the users' side[22]. In addition, it is hard to realize the real-time synchronous coordination between wind power and distributed electricity-heating equipment, which has little effect on the large-scale renewable energy accommodation[24].

3.3 *Centralized wind-power-supplied heating*

The basic principle of centralized wind power heating is to use electric boilers to convert part of the electric energy into heat energy for heating during the off-peak period of nighttime load and when there is excess wind power. Thus, thermal output of the CHP units can be reduced at some extent. Literature[25] proposed the theoretical model of the wind-power-supplied district heating system. The operation mode of this system is to equip the electric heat pump and the electric boiler in the CHP units as auxiliary heating sources, and these electricity-heating conversion devices are all driven directly by the wind power plants. Operating limits of the electricity-heating devices depend on the wind power forecast data. Then the operation of the power plants, i.e. the wind power and thermal power plants, and the electric boilers are all determined by the power grid dispatch module. Finally, the combined heat and power dispatch model is established by setting the optimization objectives as the minimum wind curtailment, to realize the enhancement of the wind power accommodation [19].

Su K. et al. [26] established an optimal dispatching model of power system considering the application of the wind power central heating device. In this model, a hybrid optimization algorithm based on immune genetic Lagrangian relaxation is constructed on the basis of system stability and wind power uncertainty constraints. The good convergence and stability of the algorithm are verified by example simulation, and it is also confirmed that the wind power central heating scheme has an positive effect on the wind power accommodation. State Grid Energy Research Institute [2] drew the conclusion that wind-power-supplied district heating technology can improve the consumption capacity of wind power to a certain extent. However, it is found that due to the uncertainty of wind power and the relatively stable electric load of electric heating boiler, it is difficult to realize real-time matching. Therefore, the fundamental solution of wind power in the off-peak period cannot only rely on wind power heating scheme.

3.4 *Thermal energy storage of district heating systems*

Abduljalil A. [27] pointed out that the purpose of energy storage is to solve the time wrap between energy demand and energy supply. The use of energy storage in the district heating system can break the real - time matching of heat source output and user's heat load. According to the different forms of energy storage, thermal energy storage can be divided into active energy storage and passive energy storage. The energy storage caused by the thermal inertia of an object is called passive energy storage, which has similar effects to active energy storage. According to the interval of energy storage temperature, it can be divided into heat storage and cold storage.

3.3.1 Active heat storage in CHP units

Heat storage has the similar function with the power energy storage which can provide flexibility for the power systems, so as to improve the renewable energy accommodation. By applying the heat storage in district heating systems, the thermal output and the power output of CHP units can be decoupled greatly. The principle is as follows: the heat is stored during the day when the users’ thermal load is low and the wind power is low, while the stored heat is released in the night when the thermal load is relatively high and the wind power is extremely higher than the day. Thus, the heat supply of CHP units can be reduced in the night to spare more space for the wind power on the grid. In order to control the heat storage device together with CHP units, it is necessary to integrate the heat storage operation into the power grid dispatch model.

Chen Lei et al. [28] analyzed the performance of improving the flexibility of power system by using large capacity heat storage. In addition, two methods were proposed, in which the heat storage devices are respectively installed on the heat source side and the load side. The principle is shown in Fig.3, where the red dash line boxes refer to the install position of heat storage equipment. In this paper, the combined heat and power optimization scheduling model under two patterns were established. The optimization objective is the minimum wind curtailment, and the decision variables are the hourly electrical output of each unit, the hourly thermal output of the heating unit and the heat storage and release capacity. The operating constraints of the thermal system include operation limits of the heat storage device, the rate of heat storage and release, and the thermal load constraints of users, etc. By comparing the wind power output data before and after heat storage, the results showed that the application of heat storage in the heat source (referring to CHP units) side can reduce wind abandon and increase wind power accommodation.

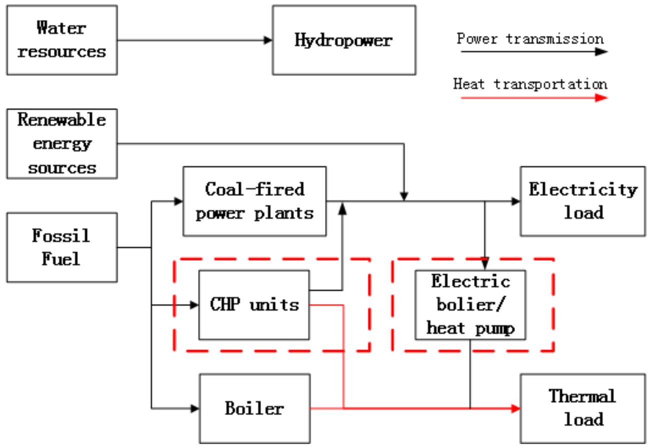

Fig.3 Schematic of two heat storage methods with different install positions in the district heating systems

The existing researches have basically completed the preliminary construction of the district heating system model and the combined heat and power dispatch model. However, the influence of heat storage and release temperature and the heat storage mode on the implementation effect is not fully considered, and the coupling operation mechanism between district heating system, the heat storage equipment and the power system is not fully considered. As the heat storage device will directly change the optimal operation regulation mode of district heating system and power system, further analysis is needed in the next step.

3.3.2 Passive heat storage in district heating systems

Typical district heating system consists of the heat source, the networks, the heat exchangers and the heat users. The district heating networks connect the heat source and the end users, and the heat transfer between the heat source and the heat exchanger. The district heating network has thermal inertia, that is, the high temperature water at the heat source needs to go through a certain "transmission time delay" before it reaches the heat user. In other words, the heat flowing into the heat user at any given moment is equal to the heat output of the heat sources before the "transfer time delay". It is equivalent to a thermal fluid storing heat during its flow and releasing it after "transfer time delay". Such passive heat storage due to thermal inertia is similar to active heat storage [27]. In practical engineering, it sometimes takes several hours for heat to be transferred from the heat source to the heat user, so the passive energy storage cycle is the same as the transmission time delay. The time delay generally lasts for several hours. The longer the time delay is, the greater the passive heat storage capacity will be.

Since the network is an existing facility for a district heating system, the use of passive heat storage to enhance the flexibility of the power system does not require any additional initial investment. It can be realized only by reforming the operation regulation module of central heating system. At present, the modeling of district heating network and the combined heat and power optimization dispatch are the difficulties in implementing the method. In terms of modeling, the Nordic countries used computers to conduct numerical method to solve the heat transportation modelling of the district heating networks earlier, and a set of mature theories and methods have been developed. However, the iterative process of the traditional numerical solution involves multiple intermediate node temperatures, which makes it difficult to be compatible with the power system scheduling algorithm. In order to integrate the dynamic characteristics of the district heating network into the optimal operation of the power system, the scholars simplified its application appropriately. B. Awad studies the central heating network as a point, only considering the heat balance constraints, but ignoring the time delay characteristics of the network and heat transfer loss. Ling Hao [29] and Jingwei Yang [30] respectively put forward two models with both good compatibility and high precision, which have certain reference significance. In the aspect of the combined heat and power dispatch, the optimization scheduling with the power system as the main body pays less attention to the performance evaluation of the thermal system, which leads to the calculation deviation. Therefore, in order to give full play to the role of the district heating networks in improving the flexibility of power system, it is necessary to further construct a joint heat and power dispatch system which fully considers the thermal systems constraints and the performance evaluation index from the perspective of thermodynamic analysis.

3.5 Ice storage technology applied in the district cooling system

The application of ice thermal storage technology into the district cooling system can achieve the purpose of cutting peak load and improving renewable energy utilization. Under the guidance of the off-peak electricity price mechanism, the operation cost of cooling can also be significantly reduced [27]. In the summer of surplus renewable energy areas, the ice storage technology is applied to the regional cooling system, and the real-time off-peak electricity price mechanism can guide users to convert electric energy into cooling capacity and store it in solid ice during the off-peak period. The purpose is to shift a large number of cooling loads from the on-peak period to the off-peak period, so as to reduce peak filling and promote the consumption of renewable energy during the off-peak period. Especially in southwest China, where cooling demand is high and hydropower resources are abundant, there is a great market potential. Xu[31] proposed a scheme to promote the household independent distributed photovoltaic utilization by applying the ice storage driven. AlHadban. Yehya[32] took the ice storage air conditioning of an office building in Kuwait as an example, established the demand side management model , and optimized the hourly cooling storage and releasing curves to guarantee for the stability operation of the power systems. Fakeha Sehar[33] analyzed the demand-side response strategy under the combination of photovoltaic and ice storage, so as to achieve peak filling and valley cutting and maintain the stable operation of the power system. X. Luo[34] studied the method of transforming large ice storage device into controllable intelligent load to improve the oscillation caused by renewable energy to the stable operation of power grid. At present, there are few researches in this field at home and abroad. The disadvantage of such schemes is that no communication channels have been established between ice storage devices and renewable energy operation, such as photovoltaic and wind power. And the renewable energy can only be moderately consumed from the demand side such as small buildings, which makes it difficult to realize the overall optimization from the supply side.

4. CONCLUSIONS

Among the above methods for promoting renewable energy consumption in power systems and thermal systems, the power system level methods include the electric energy storage, the demand-side management mechanism and the virtual power plant technology, etc. The common goal is to explore the flexibility of the power side, the demand side and the dispatch and control side. Among them, the power storage technology relies on the power technology to improve the flexibility of the system, while the demand-side management and virtual power plant technology all need to carry out comprehensive coordinated scheduling according to the electricity, heat, traffic and other energy demands. Therefore, the power supply and load allocation method only from the power level cannot meet the current requirement of the power grid trend of high renewable energy penetration.

Measures at thermal system level include by-pass compensation heating, distributed electricity-heating conversion equipment (electric boiler or heat pump), the wind-power-supplied district heating, the active/ passive energy storage and the ice thermal storage in the district energy systems. Among them, the continuous running of by-pass compensation heating system leads to the decrease of system efficiency and poor stability, so it can only participate in short-term wind power peak regulation, not for long-term operation. Distributed electricity-heating conversion device is hard to realize the response regulation with wind power. Under the background of centralized power generation, heating and centralized dispatching in China, it is difficult to participate in the large-scale wind power consumption. The method of wind-power-supplied heating method is to integrate the electric heating conversion equipment into the large power grid dispatching system to realize the real-time linkage with wind power. However, the fluctuation and randomness of wind power increase the difficulty of heat load prediction and control in the specific implementation.

In sum, to solve the problem of renewable energy, the necessary way is to break the spatiotemporal restrictions of energy supply and demand through thermal energy storage, and fundamentally overcome the uncertainty caused by wind power volatility and randomness. Heat storage and cooling devices are not isolated in the regional thermal power system, but are incorporated into the combined heat and power dispatch system to realize real-time linkage with wind power/hydro power in the power grid. The future research should focus on the following three points: First, the establishment of regional thermal system components and the system as a whole thermodynamic and hydraulic models; Secondly, for the three scenarios of active heat storage, active cold storage and passive energy storage, a combined heat and power dispatch model corresponding to them is proposed and established to analyze the direct effects of energy storage promoting renewable energy consumption in terms of energy and environment. Third, it is essential to puts forward the comprehensive technique and economic evaluation index to analyze the economic performance of each method, and accordingly puts forward the electricity price mechanism and trading strategy supporting each scheme.

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