Study of Coal-to-Electricity Project influences on electric distribution systems in North Hebei Province in China

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Abstract. Coal-to-Electricity Projects are being carried on in North China in order to reduce air pollution. These projects have brought many challenges to present electric distribution networks. Therefore, this paper focuses on how the practical electric distribution systems act facing a large quantity of electric heating integration and how to improve the behaviours. Field researches are conducted covering all cities in North Hebei Province. The current problems in planning, operation and investment of the power distribution networks supporting Coal-to-Electricity Projects are founded, and the reasons are analysed. The suggestions on the above three aspects are put forward accordingly. Case study on the distribution system in Xianghe County is conducted, and the effectiveness of the proposed approaches are verified. This study may give reference on Coal-to-Electricity related electric distribution work for other places and for the future, and also guide practical planning, operation and investment of power distribution systems on special issues.

1. Introduction
With fast development of industry and economy, environment deteriorates quickly at the same time. Air pollution becomes a big problem in China. In December 5th, 2017, Clean Winter Heating Plan in North China (2017-2021) [1] was printed and distributed by ten ministries and commissions in China such as National Development and Reform Commission (NDRC) and National Energy Administration. In this plan, it was proposed to carry out clean heating work in 14 provinces/autonomous regions/municipalities including Beijing, Tianjin, Hebei, Shanxi, Inner Mongolia, Liaoning, Jilin, Heilongjiang, Shandong, Shaanxi, Gansu, Ningxia, Xinjiang, Qinghai, and parts of Henan Province. The aims of 50% clean heating rate in northern regions by 2019 and 70% clean heating rate in northern regions by 2021 were also put forward in this plan.

Coal-to-Electricity Projects, which take an important part in clean heating work, have been conducted in North Hebei Province (i.e., Jibei area, which includes 5 cities: Tangshan, Langfang, Zhangjiakou, Chengde and Qinhuangdao) since 2016. According to the overall goals proposed by Hebei government and provincial work programme, the aim of Coal-to-Electricity Projects in North Hebei is put forward based on local requirements. That is, during 2017-2021, completing Coal-to-Electricity Projects covering 2105 villages/streets/communities, 674 thousand households, and 2733 enterprises/institutions; the total electric heating area is 83.75 million square meters, among which
distributed electric heating takes up 67.4 million square meters and the centralized one covers 16.35 million square meters.

Some work has been done on Coal-to-Electricity related distribution systems. An attribute-theoretic method for distribution network capability evaluation with electric heating loads is proposed and a robust optimization with multi-objectives covering power losses, voltage quality and load balance is modeled and solved in [2]. A comprehensive index system to judge the adaption level for Coal-to-Electricity Project development modes is set up, covering electric power grid, society and users [3]. Harmonics evaluation of distribution systems interconnected with Coal-to-Electricity Projects of different electric heating device types is conducted in [4]. A forecasting method which combines back propagation (BP) neutral network algorithm and ensemble empirical mode decomposition (EEMD) is applied on short-term load forecasting for a 10kV transformer with electric heating devices, which indicates a better result than using BP only [5]. A statistic method, TOPSIS (i.e., technique for order preference by similarity to ideal solution), is introduced to conduct a benefit evaluation for Coal-to-Electricity Projects in [6], which considers economic benefits, social benefits and operation status of the distribution systems. A method to model electric heating load characters is put forward, in which user behaviours, environment factors, response differences and load classifications are considered [7]. Adjusting ability of electric heating loads is estimated, clustering control strategy is simulated, and economic benefits of electric heating clusters’ participating demand side response are analysed [8]. An attempt on using electric heating load to improve integration capacity of renewable energy generation (REG) is done in [9]; while electric vehicles and electric heating systems in distribution networks are studied together in [10-11]. The previous work expands theoretical studies on distribution systems integrated with quantities of electric heating devices, especially on electric heating load characters and cluster applications. But how do the practical distribution networks behave after many Coal-to-Electric Projects are completed? Is there any problem in practical work? And what can we learn from it?

This paper focuses on answering these questions by conducting field researches through every city in North Hebei Province and analysing from the aspects of planning, operation and investment. Case study on practical distribution system in Xianghe County is conducted, and three approaches to promote distribution device using ratios and optimize operation status are proposed. The effects of taking the three approaches are evaluated and compared, and hence the most recommended approach is selected for Xianghe. The work may not only guide future tasks on Coal-to-Electricity and/or other special projects, but also enhance the levels of practical planning, operation and investment for distribution systems.

2. Existing problems analyses

Problems on current Coal-to-Electricity related distribution system work are put forward and analysed through planning, operation and investment.

2.1. Planning

The problems and reasons are stated through the outside and inside of electric power companies.

2.1.1. Complicated and continuously changeable outside conditions and requirements. Coal-to-Electricity Projects are led by the government in fact, especially the transformation scope and construction timing are determined by the government. Electric power companies have limited voices and restricted decision-making participations in the projects. Moreover, affected by various factors such as national and other multiple levels of government policies, regional topography and climate characteristics, implementation status of Coal-to-Gas Projects, and diverse household statistics, the reconstruction ranges of Coal-to-Electricity Projects are hard to be determined and easy to change. And it brings many difficulties in electric power pre-construction work related with Coal-to-Electricity Projects, such as the original planning has to be adjusted time after time, resulting in overall progress lags.
2.1.2. Lack of experience and weak foundation in key planning indices measurement. Electric power companies have little experience in planning and construction of Coal-to-Electricity related power grid work. In the process of exploration, multiple factors are difficult to be considered comprehensively in early stages, and remedies are usually applied afterward. Some districts, such as in Langfang and Zhangjiakou, have carried out the project early in North Hebei Province, and there is a certain amount of operational data accumulation. However, other cities in North Hebei cannot apply it directly for planning. This is because the existing power grids status, topographical and climatic characteristics, and electric heating equipment mainly used, are various for different cities and towns, which results in diverse thoughts guiding planning and construction for power grid items. Therefore, practical operation experience in other areas is only for reference. The measuring methods for important indices, such as load simultaneity rate, increasing 10kV transformer capacity per household in need, reactive compensation, need to be improved constantly according to practical conditions, to reduce forecasting deviation compared with operation data.

2.2. Operation

2.2.1. Distribution device underloading. For the area in which dispersed electric heating devices are used, the values of peak load and electric energy quantity in heating season are much less than forecasted ones, and the loads of 10kV transformers are light. Take practical operation data in 2017-2018 heating season for instance. The peak load and electricity quantity in the heating season in Langfang only reached about 1/3 of the predicted values, and the average of the maximum load rates for 10kV transformers serving Coal-to-Electricity inhabitants in Xianghe (i.e., a county in Langfang, Hebei Province, in which Coal-to-Electricity Project was accomplished in October, 2017) was just 26% in the heating season. Therefore, economic operation efficiency of the distribution system is greatly reduced. The main reasons are: a) one family with multiple residences usually concentrates in one place for winter especially around the Spring Festival; b) only one electric heating device is in use at home, although several heating devices are installed; c) the policy is modified in the late heating season, which allows using coal, and therefore the utilization ratios of electric heating are reduced.

![Figure 1. Practical load curves of two 10kV transformers in Coal-to-Electricity villages with decentralized heating devices in Xianghe in a typical heating day.](image-url)
2.2.2. Changes of transformer load curves. The use of electric heating equipment has also changed the load curve characteristics of 10kV distribution transformers in Coal-to-Electricity areas. For instance, typical winter load curves of two 400kVA transformers in two Coal-to-Electricity villages with decentralized heating devices in Xianghe County, are shown in Figure 1. The two load curves both indicate a basin-shape character. It can be seen from either transformer load curve in Figure 1 that, during the daytime, the transformer load is small, while the load increased obviously at night. The peak period appears at 21:00-3:00. However, the overall load rate of the transformer is low. Figure 1 indicates that the peak load rates in this typical day of Caizhuang Village West Coal-to-Electricity Transformer 1# (10kV, 400kVA) and Xiaxinzhuang Coal-to-Electricity Transformer 2# (10kV, 400kVA) are 20.50% and 13.75% respectively. Generally speaking, the characteristic of transformer load curve with many heating devices, is completely different from that of traditional daily load curve. It brings new challenges to operation and regulation, which requires new ideas.

2.3. Investment

2.3.1. Business state deterioration of electric power companies. Large amount of investment on a great number of Coal-to-electricity related electric grid construction projects is conducted by electric power companies. Therefore, the companies’ asset-liability ratios increase, and in turn would affect their loans and investment capabilities in the future. Moreover, in the coal-to-electricity area with a large quantity of heating devices, many 110kV substations and 10kV distribution transformers are constructed. And during non-heating season, almost all heating devices are not in operation, and the load rate of electric distribution equipment closely related with these heating devices is relatively low. Therefore, the two important indices to judge electric distribution system investing outcome, the increased load of the unit investment and the increased electric energy supplied of the unit investment [12], are both in low levels, which represents poor investment effect and profit. In addition, even during the heating season, practical utilization ratios of decentralized heating devices are far less than prediction, so the practical load levels of the transformers interconnected with large quantities of decentralized heating devices are also much lighter than their designed ones, i.e., the economical operation levels. In other words, even during the heating season, many transformers closely related with decentralized heating devices are working in non-economical operation levels (especially an obvious quantity is light-loaded), which promotes the proportion of iron consumption (i.e., fixed consumption) in transformation consumption, reduces transformer operational efficiencies, increases power loss rates, and decreases operating incomes of electric power companies.

2.3.2. Hardness in finding profitable modes. Through initial calculations, it is difficult for an electric power company to find and conduct an obviously profitable business mode, due to electricity price especially for Coal-to-Electricity customers, lack of experience and time, obvious deviation of predicted usage ratios of both heating devices and electric distribution equipment from the practical ones, excessive investment and non-economical operation status. Only under strict conditions (e.g., in the area with centralized heating devices, restricted investment scale, considerable unit heating electricity price and enough charge rate of heating fees) and ignoring the investment on Coal-to-Electricity related distribution grids, the electric power company might find one profitable mode. Take Zhangjiakou for example. Under the four-party transaction mechanism (i.e. "government + electric power company + power generation enterprise + user" cooperation mechanism), if the electric power company invests on and operates a centralized heating project, with charge rate of heating fees more than 90% ,enough unit heating electricity price (which is decided and announced by the government), and limited total investing money, the electric power company is profitable, without consideration of its investment on Coal-to-Electricity related distribution grids. Preliminary calculations show that, under present using ratios of decartelized heating devices, present and foreseen business modes of the electric power company are not economical.
3. Suggestions

The suggestions are also put forward through three aspects accordingly for the electric power companies.

3.1. Planning

3.1.1. To be professional and to voice more in government’s decision-making process. Site and line selection of Coal-to-Electricity related substations needs to be optimized by monographic study and/or subject planning. Communication with the government should be improved. Professional and reasonable advice on Coal-to-Electricity reconstruction requirements, scope and time are required to be provided by electric power companies, based on the advantages of well-known on regional electric power grids characters and early awareness on economy developing trends. Attempts should be made to get the government’s support on long-term subsidies. Preparatory procedures of electric power grid projects supporting Coal-to-Electricity work need to be speeded up. The government’s important information is required to be followed up in time, such as relevant policies, decided Coal-to-Electricity villages and households, and subsidy standards for consumers’ purchasing electric heating equipment and thermal modification of houses. A regular supervising, assessing and notification system needs to be established, in which commendation and rewards to districts with fast progress and good results are given, while accountability for slow progress and poor work is strengthened.

3.1.2. To formulate planning and construction principles of Coal-to-Electricity related electric distribution projects comprehensively and systematically. Present conditions and developing plans of local electric power grids, regional terrain and climatic characteristics, recommended heating modes and equipment characteristics, need to be taken into account when the principles are set up. Taking the aspect of local power grid current status as an example, in places with relatively developed power grids, the projects could concentrate on distribution transformer capacity increasing and line connection promotion, to enhance structures and improve reliabilities of the distribution systems; while in districts with relatively immature and behindhand electric systems and/or with fast increasing loads, the projects are suggested to mainly focus on new substation laying and related line construction, supplemented with some distribution transformer capacity increasing and line connection promotion projects, to increase the development level of local electric grids and meet the requirements of load increasing.

3.2. Operation

3.2.1. To improve distribution equipment utilization levels through operation approaches such as switching. In high voltage level of distribution power grids, load status of Coal-to-Electricity related substations and the surrounding ones should be compared and analysed. If there is one or more nearby 110kV substation with heavy load, load switching might be conducted through 35kV and 10kV line connections to average load levels of these adjacent substations (e.g., a light-loaded Coal-to-Electricity related substation and a nearby substation with heavy loads before switching) and balance electric equipment utilization ratios to some extent. In medium voltage level of distribution systems, line connection of low voltage level and load switching could be applied, to shut down some stations for a certain period of time in order to increase total load rate of distribution transformers in use; and/or methods might be found to connect rural water irrigation related loads with Coal-to-Electricity transformers to promote load levels of these distribution devices in non-heating season; and/or transformer interchange could be applied, such as to swap places of a Coal-to-Electricity related, light-loaded and big transformer and a heavy-loaded and small transformers integrated with other loads.

3.2.2. To take transformer load rate approving methods like on-load capacity regulating distribution transformers through trail applications. The use of capacity regulating transformers can effectively
avoid possible household-transformer correspondence problems in various information systems in use; but in North Hebei, we are short of application experience on them and available type chosen in standard materials is limited. If pilot applications indicate effectiveness and feasibility for relatively widespread usage, it is recommended to expand the optional types of on-load capacity regulating distribution transformers in North Hebei standard materials. In addition, seasonally shutting down of some Coal-to-Electricity closely related distribution devices and utilization of mother-and-child transformers (i.e., two transformers with different capacities which are placed together, the bigger capacity transformer is used for a certain time period, and the one with smaller capacity is in operation for another period) would both cause troubles in present household-transformer correspondence requirements and current same period line loss calculations, though they are effective methods to promote total using ratio of distribution equipment in use. And therefore, advice on calculation methods improvement of line loss calculations and excluding case consideration in household-transformer correspondence assessment need to be given, in order to use these transformer load rate approving approaches to promote operation economy.

3.2.3. To guide user electricity consumption behaviours to optimize the load curves. For areas where decentralized heating devices are planned to be applied, the directly-heated type is suggested in places with relatively mature electric grid structures, high reliabilities on power supply and/or high residents' living standards; while the heat accumulating type (i.e., thermal storage electric heating equipment) is recommended in districts with relatively weak electric power systems, low energy supply reliabilities and/or low economic developing levels. Especially for decentralized thermal storage electric heating devices, it is recommended that manufacturers could set the gear of low-power and long-time thermal storage at the factory, or increase thermal storage capacity to increase heat storage time under the same power value. Consumers are also suggested to avoid the time interval of peak load. Moreover, new approaches such as demand side response [13-14] and virtual power plant (VPP) [15-16] could be applied, to achieve a load curve with better adjustability.

3.3. Investment

3.3.1. To expand centralized electric heating projects appropriately. Practical utilization ratios of both heating devices and electric distribution equipment in centralized electric heating areas are higher than those in decentralized electric heating areas in present North Hebei. According to previous calculation, some centralized heating projects are profitable. Therefore, the electric power company could invest on centralized heating projects after beforehand profit assessment, based on the latest policy. Moreover, negotiation and cooperation among electric power company, government, power generation enterprise and heating users need to be built up or maintained to improve electricity pricing mechanism and business modes continuously, which may encourage benign development of centralized electric heating.

3.3.2. To explore profitable business modes for decentralized electric heating projects. Though present economic estimation results on decentralized electric heating projects are not profitable, it is still necessary to find new business mode and effective operation pattern to get enough earnings when applying decentralized heating devices, since they take up an obvious proportion in scales of electric heating in North Hebei. For instance, let the electric heating projects which meet the electricity market access conditions actively participate in electricity market transactions to improve economic efficiency. In addition, it is recommended that the government moderately increase the electricity price difference between the peak and the valley, and subsidize on new investment and/or income reduction which is because of special electricity prices on Coal-to-Electricity Projects for electric power companies.

3.3.3. To enhance propaganda of electric heating to the public. Planned, organized, comprehensive and systematic popularization of electric heating related issues should be conducted to the public
especially the users. Diverse and creative forms for publicity should be adopted. Popularization of science and knowledge on advantages of and matters need attention in electric heating equipment application should also be carried out. Though these approaches and attempts, people may accept this new heating style easily, and both using ratios and electricity consumption of electric heating devices may be improved.

4. Case study
There are altogether 1759 10kV transformers in Xianghe County in 2019. Among them, 424 transformers are supporting Coal-to-Electricity Projects, which are closely related with electric heating devices. Maximum load rate and average load rate (i.e., the average among the time period) value distribution of the 10kV transformers supporting Coal-to-Electricity Projects and all 10kV transformers in Xianghe in a typical heating month (February, 2019) and a typical non-heating month (August, 2019) are shown in Table 1 and Table 2.

Table 1. Load rate distribution of 424 10kV transformers supporting Coal-to-Electricity Projects in Xianghe in a typical heating month and a typical non-heating month in 2019.

| Period   | Index (monthly) | Average among transformers (%) | Transformer number |
|----------|-----------------|--------------------------------|--------------------|
|          |                 | 0~20% | 20%~40% | 40%~60% | 60%~80% | >80% |
| February, 2019 | Maximum load rate | 29.51  | 172     | 149     | 68      | 22   | 13  |
|          | Average load rate | 15.60  | 325     | 85      | 13      | 1    | 0   |
| August, 2019  | Maximum load rate | 26.05  | 218     | 103     | 65      | 20   | 18  |
|          | Average load rate | 15.07  | 316     | 67      | 39      | 2    | 0   |

Table 2. Load rate distribution of all 10kV transformers in Xianghe in a typical heating month and a typical non-heating month in 2019.

| Period   | Index (monthly) | Average among transformers (%) | Transformer number |
|----------|-----------------|--------------------------------|--------------------|
|          |                 | 0~20% | 20%~40% | 40%~60% | 60%~80% | >80% |
| February, 2019 | Maximum load rate | 41.01  | 358     | 466     | 592     | 196  | 147 |
|          | Average load rate | 26.48  | 684     | 494     | 513     | 58   | 10  |
| August, 2019  | Maximum load rate | 39.22  | 449     | 434     | 522     | 197  | 157 |
|          | Average load rate | 25.16  | 729     | 502     | 470     | 52   | 6   |

It can be seen from the tables that, no matter in February or August, the average value of the maximum load rates of the 424 10kV transformers supporting Coal-to-Electricity Projects, is distinctly less than that of all 10kV transformers in Xianghe; and the comparison result on the average value (among the transformers) of the average load rates (among the time period, i.e. the month) between the 424 10kV transformers and all 10kV transformers is similar. They reveal an averagely lower utilization level of distribution devices related to electric heating compared with that of normal ones, which to some extent indices over-construction of Coal-to-Electricity related distribution systems. Take the proportion of 10kV transformers with its monthly maximum load rate lower than 20% for instance. It covers 40.57% of the 424 transformers in February and 51.42% in August; while it takes up 20.35% of all Xianghe’s 10kV transformers in February and 25.53% in August. In other words, low utilization level of Xianghe’s 10kV transformers which support Coal-to-Electricity Projects is obvious in the heating season, and gets worse in the non-heating season. Therefore, three approaches are put forward to optimize the operation of 10kV transformers and the effects are estimated.

Approach 1: transformer interchange in pairs. Each pair contains: a normal 10kV transformer which is heavy-loaded and with a smaller capacity, and a Coal-to-Electricity related 10kV transformer with its annual maximum load rate lower than 20% and a bigger capacity. What is more, several principles are followed for transformer pair selection. First, the two transformers in each pair are in the
same type, including insulation cooling mode (e.g., dry type, oil-immersed) and placing form (e.g., pole-mounted, box type, in room). Second, the interchange relieves heavy loading status and does not increases new light-loaded transformers. Third, transformers with their operation lives less than 15 years are taken into consideration. Hence, 26 pairs of 10kV transformer are chosen.

Approach 2: on-load capacity regulating distribution transformers application. The approach is to replace Coal-to-Electricity related 10kV transformer with obvious utilization differences in heating season and non-heating season by on-load capacity regulating distribution transformers with appropriate capacity settings. Therefore, 32 transformers closely related with electric heating are chosen to be changed, whose maximum load rate in heating season is 20% higher than that in non-heating season.

Approach 3: electric heating utilization encouragement. Through propaganda, popularization and user behaviour guidance methods to promote electric heating device using level by 10%.

Annual index evaluation among transformers supporting Coal-to-Electricity Projects in Xianghe before and after taking the above three approaches are conducted by simulations, and the results are shown in Table 3. It can be seen that, the indices describe transformer using level and economically operation percentage increases obviously after either approach is taken. Therefore, it reveals that every approach of the three is effective in optimizing electric heating relevant transformer status. The results also show that among the three approaches, Approach 1 takes the lead in improving average (among transformers) of annul average load rates and transformer proportion excluding the light-loaded, heavy-loaded and overloaded, while Approach 3 contributes most in enhancing average (among transformers) of annul maximum load rates. This is because Approach 1 is effective in both heating season and non-heating season, while Approach 2 focuses on improvement in non-heating season, and Approach 3 mainly aims at enhancing electric utilization in heating season. Furthermore, Approach 1 can also optimize operation status of transformers interconnected with other normal loads in the chosen pairs. Generally speaking, Approach 1, i.e. transformer interchange in pairs, is recommended to Xianghe among the proposed three. In this way, present 10kV transformer capacity resource in Xianghe is well-distributed.

Table 3. Annual index evaluation among transformers supporting Coal-to-Electricity Projects before and after the approaches are taken in Xianghe.

| Index (annual)                                                   | Original Value (%) | Approach 1 (%) | Approach 2 (%) | Approach 3 (%) |
|-----------------------------------------------------------------|--------------------|----------------|----------------|----------------|
| Average (among transformers) of annul maximum load rates        | 29.62              | 32.60          | 33.29          | 38.21          |
| Average (among transformers) of annul average load rates        | 15.37              | 18.35          | 17.81          | 17.09          |
| Transformer proportion excluding the light-loaded, heavy-loaded and overloaded | 23.35              | 30.90          | 28.77          | 30.19          |

5. Conclusions
Conducting Coal-to-Electricity Projects is an effective way to reduce air pollution. At the same time, many influences and challenges are brought by Coal-to-Electricity Projects to electric distribution networks. Based on field researches among North Hebei Province in China, problems on current Coal-to-Electricity related power distribution systems are put forward and analysed through planning, operation and investment. The problems include: complicated and continuously changeable outside conditions and requirements, lack of experience and weak foundation in key planning indices measurement, distribution device underloading, changes of transformer load curves, business sate deterioration of electric power companies, and hardness in finding profitable modes. The suggestions
are also put forward through three aspects accordingly, which cover: to be professional and to voice more in government’s decision-making process, to formulate planning and construction principles of Coal-to-Electricity related electric distribution projects comprehensively and systematically, to improve distribution equipment utilization levels through operation approaches such as switching, to take transformer load rate approving methods like on-load capacity regulating distribution transformers through trial application, to guide user electricity consumption behaviours to optimize the load curves, to expand centralized electric heating projects appropriately, to explore profitable business modes for decentralized electric heating projects, and to enhance propaganda of electric heating to the public. Case study on 10kV transformers in Xianghe County is conducted, and three approaches are put forward accordingly to optimize distribution system operation related with Coal-to-Electricity Projects. The results verify the effectiveness of proposed methods, and recommend transformer interchange in pairs most to Xianghe. This study may not only help practical planning, operation and investment of distribution system enhancement on special issues, but also encourage related techniques development for future smart electric power grids.

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