A Re-electrification Scenario Analysis at a Time of Worldwide Energy Transition

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Abstract. The world is experiencing a new round energy transition from fossil energy to clean energy. Due to the fact that the electricity is the most usual way of clean energy use, the key to build a modern energy system will be electricity-centric. This paper reviews major countries’ history of electrification and summarizes inherent laws of electrification degree rising. The main features of future energy supply turn to clean and low carbon and energy consumption turn to efficient and intelligent, it’s expected that future electrification development will leapfrog into a higher and more ubiquitous degree of re-electrification. After that, a re-electrification scenario of future energy development is designed, in which share of power generation in total primary energy consumption (TPED) and share of electricity in total final consumption (TFC) of energy exceed 66% and 40% each in 2050.

1. Introduction
With the increasing prominence of worldwide energy crisis and environmental crisis, a new round of energy transition is being conceived and developed, which will promote strategic transition of human energy utilization from fossil energy to clean energy, and construct a new energy system to cope with major challenges such as environmental pollution and greenhouse gas emissions.

Based on China's basic national resource conditions, the key of energy transition is large-scale development and utilization of wind energy and solar energy, expansion of scale and scope of electric energy, and improvement of energy use efficiency. Therefore, continuously upgrading electrification level will be a trend and the only way of China's energy transition.

In order to meet requirements of economic and social development and promote transition of national energy development strategy, this paper starts from relationship between energy transition and electrification, and focuses on the role of electrification in promoting energy low-carbon, clean, efficient and intelligent transition. Then, 10 countries including major developed countries and BRICS countries, are selected in this paper to make an international comparison of electrification process, and to analyze respective characteristics and influencing factors. Then, a clear trend on the future development of electrification, which is re-electrification, are put forward, and a re-electrification development scenario of china is studied.
2. Relationship between energy transition and electrification

The new round of energy transition needs to deal with serious challenges, like environmental pollution, greenhouse gas emission reduction and low energy efficiency. New round transition relies on large-scale development of clean energy and improvement of energy efficiency. Therefore, Electrification plays significant supporting roles in turning energy system to be clean, low-carbon, efficient and intelligent. Due to China's special national conditions, our energy transition is facing great challenges as following.

- First, we’re facing great challenge of carbon emission reduction. Reference [2] shows that China has become the world's largest carbon emitter, with carbon emissions reaching 9.1 billion tons in 2016, close to twice times to the United States, per capita emissions will be 1.3 times than the world average per capita emissions.
- Second, our environmental pollution is particularly serious, especially, eco-environmental protection has become a rigid constraint on energy development. In 2016, China's average annual particulate matter 2.5 (PM2.5) concentration was more than national standard 109%, as in [3].
- Third, our energy consumption structure is still dominated by coal, and it accounted for 62% of the total energy consumption in China in 2016, which only be the second (first is South Africa (70%)) of the world and is twice times higher than the global average (28%).
- Fourth, China's energy efficiency is relatively low. In 2016, China's energy intensity is more than the global average level 0.5 times, and more than typical developed country several times. Therefore, to promote China's energy clean and low-carbon transition, we need to improve electrification level of each energy production side and consumption side, which is carrying wind energy and solar energy transforming to electricity and promoting the overall level of energy efficiency.

In conclusion, continuously upgrading electrification level will be a trend and the only way of China's energy transition.

3. Relationship between energy transition and electrification

Because of differences of countries' basic national conditions, countries’ process of electrification development has both commonness and difference. This paper selects the United States, Britain, Japan, Germany, France and other developed countries, and China, Russia, India, Brazil, South Africa (which also known as BRICS) and other developing countries, and uses indexes of share of power generation in total primary energy consumption (TPED) and share of electricity in total final consumption (TFC) to analyze electrification level.

3.1. Historical electrification progress

Global electrification process is influenced by many factors, mainly related to energy consumption structure of power generation and industrialization degree, late-industrialization nations’ electrification degree is significantly higher than others.

Reference [4] shows that, the level of electrification on energy supply side is relatively high in developed countries, remaining at around 35%, with the highest in France (46.5% in 2014); and in emerging economies such as the BRICS, electrification level on energy supply side has increased at a faster rate, reaching around 25% to 30%, with the highest in China, reaching 39.1% in 2014. Because of the differences of resources endowment and technology state, extensive utilization of coal, hydro and nuclear power in primary energy composition has promoted the rapid improvement of electrification level. In recent years, the development speed of power generation in these major countries has slowed down due to the increasing constraints of resource and environment, also the stabilization of total energy demand.

There’s a little different with electrification level of energy consume side. Developed countries have a higher level of electrification in energy consume side, with OECD countries reaching 24% in 2014, which France (2014, 27.7%) and Japan (2014, 26.8%) were the highest, the United States (2014,
21.2%), UK (2014, 23.2%) and other natural gas utilization is lower than the significant national level. Electrification level in energy consume side is generally low in emerging economies, with the BRICS 2014 level of 18.4%, with the exception of China (2014, 23.2%) and South Africa (2014, 22.8%) exceeding 20%, while the remaining countries are lower.

From the view of different countries, industrialization has obvious effect on electrification level, and the developed countries in the later stage of industrialization are obviously higher than the developing countries. In recent years, the developed countries are constrained by the economic downturn, electrification level has a slight fluctuation. For example, the impact of American manufacturing transfer on electrification level under the background of globalization, has been hedged by booming development of services industry in information age, and the overall level maintain around 20%.

From the perspective of main cities, industrial structure has a great impact on the level of urban electrification. Hong Kong is dominated by finance and trade, with the highest level of electrification (41.8%). International cities such as Tokyo, Paris and London are in the 30% -35% range of electrification. Other cities are around 20% due to the high proportion of industrial or transport output value.

| City      | Year | Coal | Oil  | Gas  | Electricity |
|-----------|------|------|------|------|-------------|
| Hong Kong | 2014 | 17.3%| 32.4%| 6.8% | 41.8%       |
| Tokyo     | 2011 | 11.4%| 25.3%| 24.6%| 33.8%       |
| Paris     | 2011 | 0.2% | 33.0%| 32.4%| 32.8%       |
| London    | 2012 | 0.1% | 22.1%| 47.1%| 30.5%       |
| Singapore | 2014 | 1.0% | 68.7%| 7.4% | 23.0%       |
| Los Angeles | 2011 | 1.0% | 42.6%| 32.0%| 22.4%       |
| Bei Jing  | 2015 | 8.8% | 43.4%| 14.3%| 21.2%       |
| New York  | 2015 | 0.7% | 47.0%| 32.2%| 18.0%       |
| Shang Hai | 2015 | 17.7%| 53.3%| 7.7% | 17.5%       |

3.2. Future electrification progress
Furthermore, there’re still strong growth drivers of power demand because of developing countries need to accomplish their industrialization and information age being a main world development trend.

With the adjustment of energy supply to clean and low-carbon and energy use to high efficiency and intelligent, as shown in figure 3, future electrification development will be not only a continuation and enhancement of the past, but also an upgrading and quality change. In energy primary
consumption side, high proportion of clean energy development and utilization will promote a new round of electrification level quickly climbed to 40% in 2030. On final consumption side, many new types of power use are in the field of continuous expansion, which promote the deep substitution from fossil energy to clean electricity, and will trigger share of electricity in TFC to break 30% round 2040, as in [5]. And we think it’s the trend of re-electrification. This concept can be understand in the following three aspects.

Firstly, industrialization of developing countries and informatization in the worldwide push the demand of electricity “re-increase” rapidly. Since 21st century, the OECD and other developed countries have entered the post-industrial stage, and the total amount of global energy consumption has remained stable. In the future, as China, India and other developing countries to continue the process of industrialization, economic structure and industrial structure in depth adjustment, electricity as a clean and efficient power source, the demand will maintain a faster growth. At the same time, the world is at an important stage of information development, information technology to the application of electrical energy as an important carrier, the social production of new models, new patterns of electricity demand will continue to improve.

Secondly, development and utilization of clean energy resources promotes “re-adjustment” of energy structure. The large-scale exploitation and utilization of fossil energy has met the rapid growth of the demand for energy in the process of human industrialization, but the ecological environment has also suffered more serious pollution. In the future, with the gradual maturation of wind power and solar power and the gradual decrease of cost, the use of large-scale new energy generation will reduce the system supply cost and promote the level of electrification of energy supply side.

Thirdly, alternative competitiveness of electric energy will be enhanced to stimulate “re-release” of electric potential. Since entering the electrical era, popularization and application of electric motors has tapped into the electric potential of various fields. In the future, with the continuous upgrading of intelligent manufacturing and automated production in the industrial field, the potential release of electric vehicles and electrified railways in the transportation field, the expansion of the tertiary industry such as information and communication in the commercial field, the potential and scale of electric energy substitution will be increased, and the large-scale use of new energy at zero marginal cost will gradually drive the electric power consumption level up and bring about the rapid reduction of power consumption.

4. Re-electrification development scenario of China
By applying medium and long-term energy demand forecasting model based on economy, energy, environment system and power system optimization planning model, as in [6] and [7] respectively, China's long-term energy and power development are prospected.

As shown in figure 4, medium and long-term energy demand forecasting model based on energy, economy and environment (3E) system is applied to meet the constraint objectives of total volume control, pollution emission and efficiency enhancement. The trend extrapolation, energy price comparison and econometric simulation optimization algorithms are used to forecast and analyze
energy supply and demand, including primary energy, terminal energy, energy for conversion and consumption (such as power generation).

Figure 4. Energy demand forecasting model based on 3E

Based on the strategic goal of national energy development and the supply capacity of non-fossil energy power generation resources, power system optimization planning model developed independently is used to optimize the total amount, layout and cross-district power flow of various types of power supply with the objective of the lowest system supply cost, and the zoning power supply structure is recommended, as shown in figure 5.

4.1. Primary energy demand

By energetically developing clean energy, the incremental substitution and stock substitution of fossil energy are gradually realized, and the proportion of power generation energy is steadily increased.

2030 gives priority to incremental substitution. 2020-2030, energy demand growth of about 900 million tons of standard coal, of which clean energy can provide nearly 500 million tons of standard coal, the contribution rate of more than 54%; electricity demand grew about 2.8 trillion kwh, of which clean energy can provide about 1.6 trillion kwh, with a contribution rate exceeding 57%. The production side electrification level (power generation use can account for one energy supply proportion) exceeds 54%.

2050 to achieve stock substitution. 2030-2050, energy structure and power structure continued to optimize, 2050 clean energy in total energy demand and total power demand contribution rate of more than 50% and 70% respectively, production side electrification level of more than 66%.

Table 2. Total Primary Energy Consumption and its Structure of China

|       | 2030  | 2040  | 2050  |
|-------|-------|-------|-------|
| Total | 48.0  | 57.0  | 60.0  |
| Coal  | 25.3  | 25.1  | 10.75 |
| Oil   | 8.7   | 9.3   | 7.72  |
| Gas   | 4.8   | 8.6   | 10.64 |
| Non-fossil energy | 9.2   | 14.1  | 30.89 |
Table 3. Power Generation and Capacity of China

|                      | ×10¹² kWh | 2030 | 2040 | 2050 |
|----------------------|-----------|------|------|------|
| **Total generation** | 7.5       / 10.3 / 13.6 |
| Coal-fired generation| 4.6 62%  | 5.4 52% | 2.7 19% |
| Clean power generation| 2.5 34% | 4.1 40% | 9.9 72% |
| **Total capacity**   | 21.0 / 30.8 / 48.6 |
| Coal-fired capacity  | 11.0 52%  | 12.0 39% | 7.1 15% |
| Clean power capacity | 8.6 41%  | 15.0 49% | 38.9 80% |

4.2. Final energy consumption

Expanding the breadth and depth of electric energy consumption in terminal energy, improving the substitution of energy for coal and oil and gas, and promoting the substitution of electric energy in accordance with the order of "Transportation, commerce and residents" after the first industry.

From 2015 to 2030, electricity consumption will increase by 550 million tons of standard coal, oil and gas consumption will increase by 550 million tons of standard coal, and coal terminal will decrease by 360 million tons of standard coal, a decline of 27 percent. In 2030, terminal electrification levels will exceed coal as the main energy source. The industrial sector is still the main driver of China's electrification level, contributing about 40 percent of electricity growth, and residents, transportation and commerce contribute 25 percent and 17 percent of electricity respectively.

Table 4. Total Final Consumption and its Structure of China

| ×10⁸ tce | 2020 | 2030 | 2050 |
|----------|------|------|------|
| TFC      | 34.8 | 38.4 | 39.2 |
| Coal     | 34.3%| 24.5%| 15.9%|
| Oil      | 24.2%| 24.3%| 19.2%|
| Gas      | 9.6% | 13.5%| 18.3%|
| Heat     | 4.1% | 3.5% | 2.5% |
| Electricity | 25.2%| 30.4%| 40.4%|
| Other    | 2.6% | 3.8% | 3.7% |

Table 5. Total Electricity Consumption and its Structure of China

| 2020 | 2030 | 2050 |
|------|------|------|
| **Total electricity consumption**(×10¹² kWh) | 7.5 | 10.3 | 13.6 |
| Agriculture, forestry, animal husbandry and fishery | 1.6% | 1.5% | 1.3% |
| Industry | 67.8% | 59.8% | 36.0% |
| Building | 1.5% | 1.8% | 2.3% |
| Transport, storage and post | 3.1% | 6.9% | 15.0% |
| Wholesale, retail and accommodation, catering | 4.5% | 6.0% | 13.8% |
| Other | 6.5% | 6.2% | 5.7% |
| Individual consumption | 15.0% | 17.8% | 25.9% |

The final energy consumption subject status of electric energy in the 2050 continued to be consolidated. 2030-2050, electricity consumption increased by 370 million tons of standard coal, natural gas consumption than 2030 180 million tons of standard coal, oil consumption fell 220 million tons of standard coal, coal consumption and then reduce 360 million tons of standard coal, to 620 million tons of standard coal. In 2050, the terminal electrification level exceeded 40%, and the final energy consumption subject status of electric energy continued to be consolidated. With the decline of electricity consumption in the industrial sector, residents, transportation and commerce have become
the main drivers of the electrification level, contributing 52%, 42% and 39% of the growth of electricity respectively.

5. Conclusion
The process of electrification development in the world shows that the level of electrification is closely related to the factors of resource endowment condition, economic development stage, economic industrial structure and energy consumption level, and different countries choose different development paths which were suitable for their national conditions. China is rich in renewable energy resources, and has the foundation to improve electrification level of TPED. At present, there’re many small coal-fired boilers in China's industrial industry, and the proportion of oil to traffic capacity of nearly 90%, which has space to improve the electrification level of TFC. As the world's largest energy and power consumption country, China will become the leader of global future electrification process.

This new electrification development round, namely the re-electrification process, is unstoppable, which is a strategic path of achieving energy transition. In the future, China's electrification degree will show rapid growth, surpass global average level, and become an international leader. Specifically, The focus of China's re-electrification development is to energetically develop clean energy on energy production side, and gradually achieve the substitution of new incremental fossil energy to existing fossil energy, with clean energy contributing more than 50% of new incremental energy demand in 2030 and more than 50% of total energy demand in 2050. On energy final consumption side, electricity will replace first in industry sector and then in transport, commercial and residential sectors, and these three sectors will contribute more than 50% and 100% to the increase in electricity consumption in 2030 and 2050, respectively.

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References
[1] Bagheri S, Julkapli N M, Hamid S B A 2015 Functionalized activated carbon derived from biomass for photocatalysis applications perspective International Journal of Photoenergy 2015 1
[2] BP, BP Statistical Review of World Energy, Jun 2018, Available: https://www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy/co2-emissions.html.
[3] Ministry of Ecology and Environment of the People’s Republic of China, Bulletin on China’s ecological environment 2017, May 2018, Available: http://www.mee.gov.cn/hjzl/zghjzkgb/lnzghjzkgb/201805/P020180531534645032372.pdf.
[4] IEA, Available: http://www.iea.org/Sankey/.
[5] State Grid Energy Research Institute, Global energy analysis and outlook, Beijing, 2017.
[6] SHAN Baoguo, HAN Xinyang, TAN Xiandong, WANG Yongpei and ZHENG Yanan. “Research on Electricity Demand of China during the 13th Five-Year Plan and Med-Term- & Long-Term Periods,” ELECTRIC POWER, vol.48, No.1, Jan. 2015, pp. 6–14.
[7] WANG Yaohua, JIAO Bingqi, ZHANG Fuqiang, FENG Junshu and WU Shengyu. “Medium and Long-term Electric Power Development Considering Operating Character-istics of High Proportion of Renewable Energy,” Automation of Electric Power System, vol.41, No.21, Nov. 2017, pp. 9–16.