Journal of Physics: Conference Series

PAPER • OPEN ACCESS

# Natural Gas Power Generation Trends from a Technological Paradigm Perspective

To cite this article: Na Luo *et al* 2020 *J. Phys.: Conf. Ser.* **1549** 042144

# Natural Gas Power Generation Trends from a Technological Paradigm Perspective

**Na Luo[1, *], Meihui Li[2, a], Xueying Yu[3, b]**

[1]Chongqing Business Vocational College, Chongqing, China
[2]Business School, Chengdu University, Chengdu, China
[3]The State Key Laboratory of Power Transmission Equipment and System Security, Chongqing University, Chongqing, China

[*]Corresponding author e-mail: 624761781@qq.com, [a]limeihui0430@163.com, [b]scuyuxueying@foxmail.com

**Abstract**. Natural gas power generation is a clean, environmentally friendly use of fossil fuel. However, natural gas development has strong competition from renewable energy and at the same time, the environmental impact of methane leakages during natural gas exploitation and transportation has raised concerns as to its overall safety. Through the research of literature, this paper finds that NGPG has experienced three stages: natural gas direct combustion, combined cycle generation, and distributed generation, that is, natural gas power generation technology paradigm. At the same time, hybrid power generation is due for a paradigm shift which will ensure that natural gas development is more competitive in the future; however, for this to happen, adequate policy support is required.

## 1. Introduction

With continuing population growth, economic development, and technological progress, global electricity consumption continues to increase [1]. The main driver of energy source changes has been the increasing global concerns about the effects of environmental pollution on quality of life [2]. Power plants have been one of the major contributors to greenhouse gas emissions (GHG) and have caused local air quality deterioration and other global environmental impacts [3]. As natural gas burns more cleanly than other hydrocarbon fuels, for an equivalent amount of heat, burning natural gas for power generation produces about 45% less $CO_2$ and far lower amounts of $SO_X$ and $NO_X$ than burning coal [4], so it is expected to be a power production fuel in many countries for decades to come. Along with advances in hydraulic fracturing, shale gas has become a recent resource development possibility; however, deriving natural gas from shale fracking has caused significant controversy because of the risks of water table and soil pollution [5]. In addition, the GHG methane released during the NG exploitation and transportation process can cause more severe climate change damage than $CO_2$ [6].

The goal of this study was to reveal the current and future natural gas power generation technological developments by combining theory and technology. To date, a majority of research has focused on building models to improve system power generation efficiencies or have used life cycle assessments to compare natural gas and other fossil fuel power generation [7]. However, few studies have focused on the natural gas power generation technical paradigm (NGPGTP), and most have had little integrity or universality in the field of natural gas power generation [8]. Further, as NGPG requires significant energy, to make it more competitive, economical and environmentally friendly [9], the development of new NGPG technology and possible future trends such as using complementary energy sources need to be fully explored.

## 2. NGPG technological paradigm

Through literature mining and analysis, it was concluded that NGPG development met the laws of the technological paradigm as a technical trajectory was determined. Each of the three technological paradigm stages was characterized by different technological trajectories, as shown in Fig. 1. NGPGTP is a new research concept that describes the natural gas generation development path.

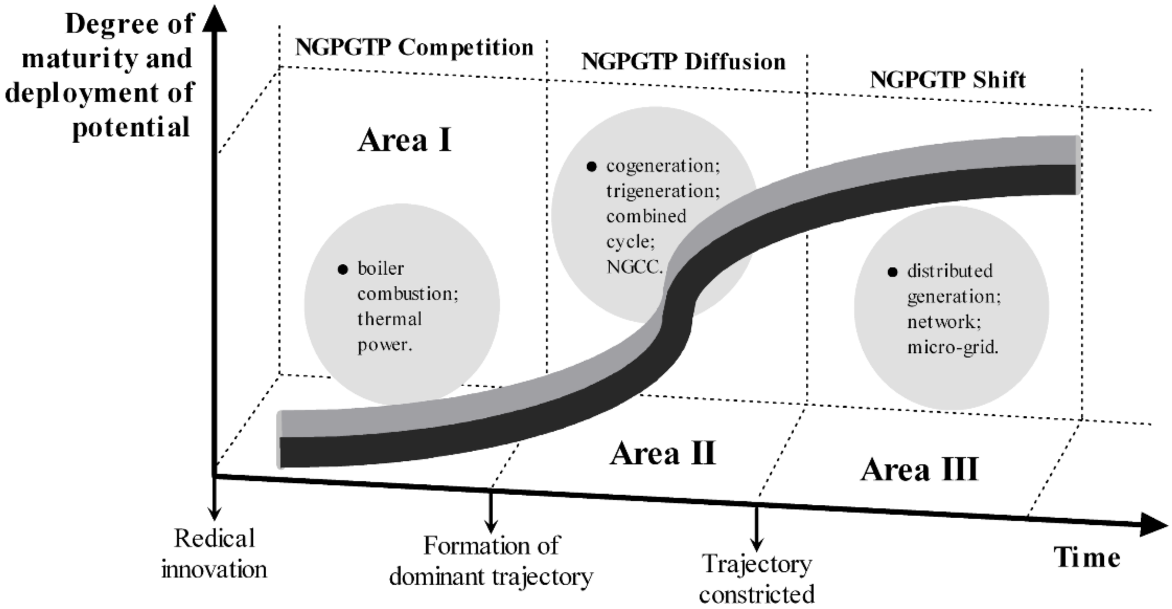



**Figure 1.** NGPG evolution based on the technological paradigm.

### *2.1. Competition phase*

During the technological paradigm evolution, economic, institutional and social forces all affect technological development, with selection and location being the main features of the competition phase. From Area I, the competition phase, natural gas burned directly in conventional boilers was the main power generation technology in this phase.

This phase was competition-oriented and involved several natural gas utilization technologies. Since the mid-20th century, the power generation industry has developed significantly. As gas turbine techniques developed and were gradually installed, natural gas was being burned in thermal power plants [10]. The two main techniques were both single cycle power generation; direct natural gas combustion was either divided in a gas turbine to drive the generators that produce electricity or burnt in a conventional boiler to produce high temperature high pressure steam to drive a steam turbine which then drives a generator [11], Fig.2 shows a typical power generation process by using gas turbine. However, because the gas turbine and steam turbine had small capacities due to the technological limits and were somewhat inefficient, these methods were used as emergency standby power sources and peak-regulating units. In this stage, as these two methods were either energy inefficient or had low thermal efficiency, NG was not widely used; therefore, there was a need to improve technology before multi-level energy generation could be considered.

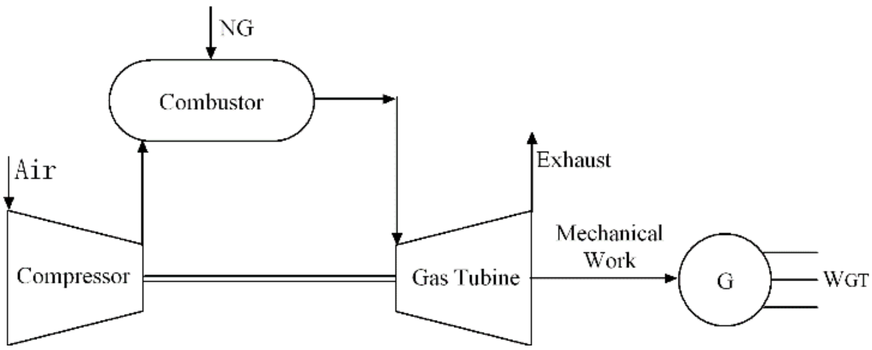


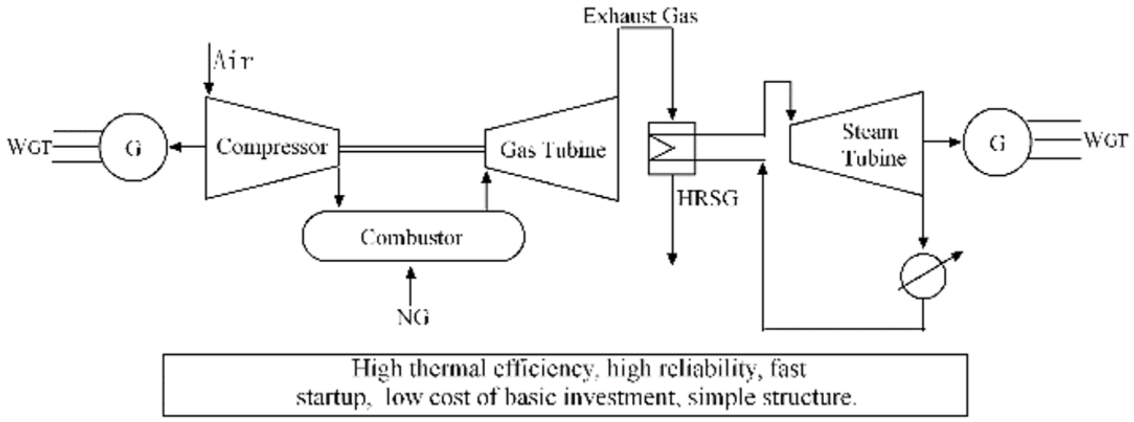

**Figure 2.** A simple gas turbine generator.

*2.2. Diffusion phase*

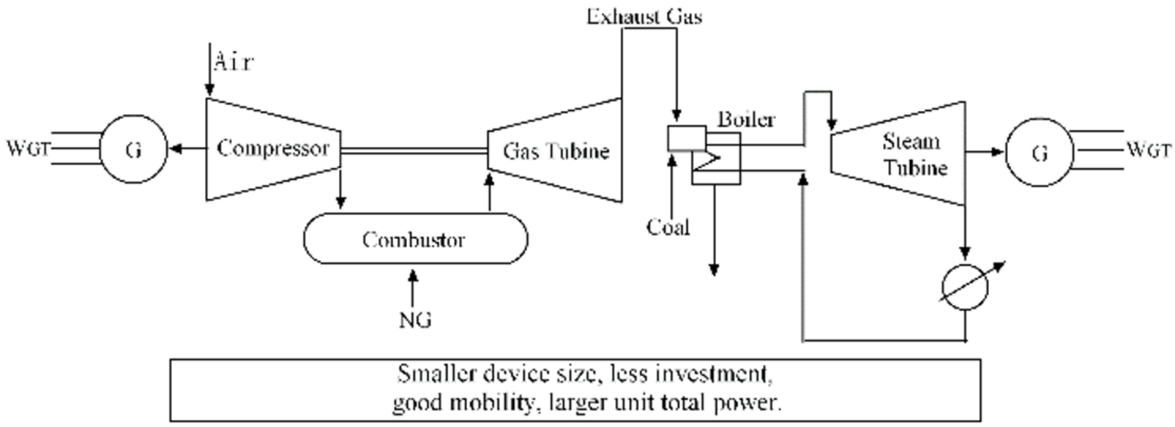
Driven by the interactions between the energy demand in the market and industrial competition, a dominant trajectory (or trajectories) inevitably emerged, indicating the gradual movement into the diffusion phase. In the paradigm evolution, it is believed that the most important feature of these common technical innovations evolves during the diffusion phase, which can be divided into three main categories [12]: multi-generational technologies which mutually coexist and compete; a dominant technology which stands out from the other technologies; and the emergence of an innovative diffusion. In the 1990's, the fast growth experienced in the natural gas power industry was because the gas-steam combined cycle unit was much more competitive than other methods. Further, the increasing recognition of worldwide environmental problems prompted natural gas technological innovation in the diffusion stage. As shown in Fig. 1, the diffusion phase includes combined cycle, natural gas combined cycle (NGCC), cogeneration and trigeneration.

Natural gas power generation technology in the diffusion phase, known as advanced power generation systems, combined cycle generators with gas turbine generators to improve power plant generating capacity and efficiency [13]. However, from an energy use perspective, the use of natural gas either for heating and/or power generation was still inefficient; for heating, the energy utilization rate was too low, and if only natural gas was used to generate electricity, the cost of the combined cycle plant was a key limiting factor for its development. Cogeneration or Combined Cooling and Power (CHP) uses the heat from an engine or power station to concurrently generate electricity and useful heat. Trigeneration or Combined Cooling Heating and Power (CCHP), which has become the second generation energy technology in the world, uses natural gas as the primary energy source to generate secondary energy in the form of electricity, heat or cold [14].

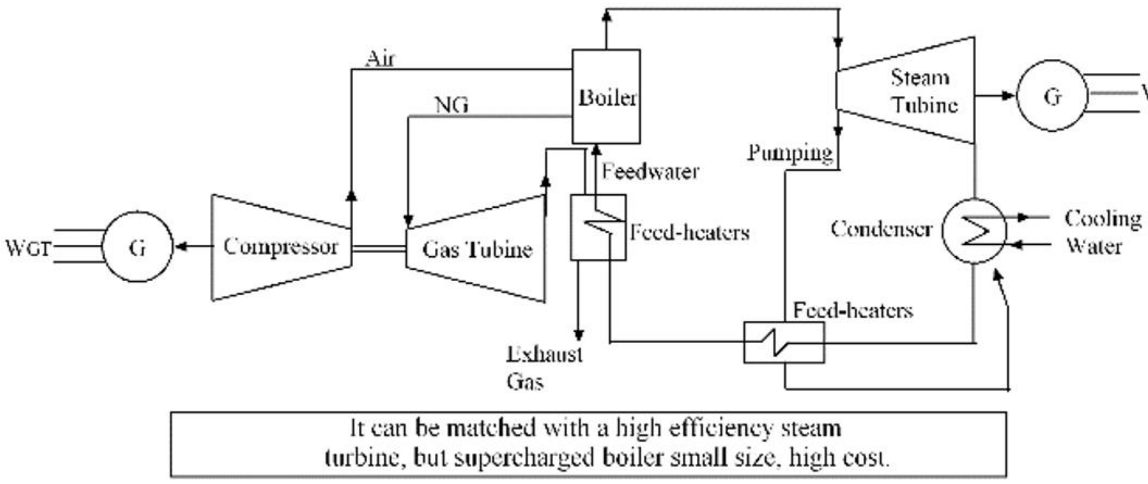
In Fig. 3, the installed capacity and generation efficiency of several different kinds of power generation technology are compared, from which it can be seen that the CCHP can achieve an 80% utilization rate, making it more efficient than traditional power production [15]. The CCHP system using natural gas as fuel shown in Fig. 3 is made up of a gas turbine, a heat recovery steam generator (HRSG) and an absorption chiller. In this system, the gas turbine uses natural gas to first generate electricity, after which the waste heat in the flue gas is recovered and converted into steam in the HRSG. In the winter, the heat exchanger is used to heat hot water and in summer, the absorption chiller is used for cooling purposes. Based on the principle of energy cascade utilization, the CCHP technology can achieve high grade heat energy for power generation, and low grade heat for heating or absorption so as to realize a multilevel utilization of the natural gas chemical energy. The core part of this system is the HRSG, which has been the most common combined cycle technology, and has been widely used in natural gas power plants, has high efficiency, high reliability, fast startup and low basic investment costs [16]. Therefore, the CCHP could be a possible approach to solving electricity shortage and pollution emissions problems. The technology of CCHP, however, is now relatively mature, so focus needs to turn to technologies that can reduce investment and operational costs in distributed network systems, prevent power transmission and distribution losses and guarantee electricity supply security.



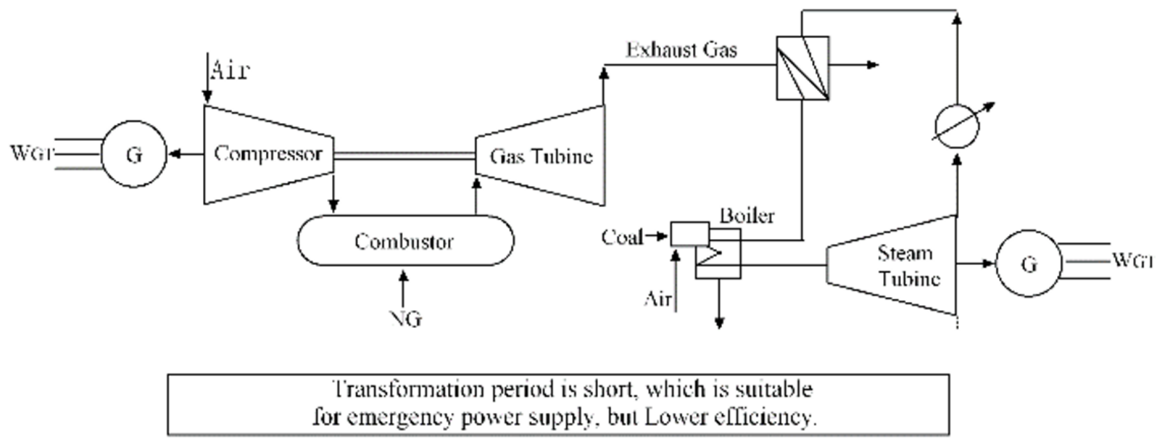

**a: Heat recovery steam generator (HRSG) combined cycle**




**b: Exhaust gas repair combined cycle**




**c: Pressurized combustion boiler combined cycle**




**d: Heating boiler feed water combined cycle**

**Figure 3.** A typical CCHP system with HRSG.

*2.3. Shift phase*

Area III in Fig.1 indicate the shift phase before the emergence of a new paradigm, with the keywords focused mainly on distributed generation and networks, together with micro-grid. Distributed Energy Systems (DES) are comprehensive energy utilization systems distributed on the user side and include distributed generation, energy storage devices and systems connected with the public power grid. Micro-grid coordinate the control of the distributed generation, energy storage devices and loads to form a single controllable unit that is directly connected to the user [17]. Distributed generation (DG) generally refers to relatively small power generation/energy storage devices (Below 50MW) located in the vicinity of the load with capacities of between tens of kW and tens of MW [18]. The energy used includes natural gas, solar, biomass, wind and other clean energy or renewable energy. To improve energy use efficiency and reduce costs, it is often used with CHP or CCHP.

DG has been attracting increased worldwide attention because its wide application to peak clipping. Distributed generation that combines cooling heating and power systems (DG-CCHP) are new concept power plant systems which have been developed as a backup to centralized energy systems to reduce the effects of blackouts such as the blackout caused by the 1999 Taiwan earthquake and the 2003 blackouts in Northeastern United States, Southeastern Canada and Italy, all of which raised concerns about electricity supply security and the economics and efficiency of large power grid systems [19]. DG can provide independent generation in out-of-the-way areas and can also be built in rural areas, pastoral areas, mountainous areas, developing cities or business districts to address the needs of the local users. Compared with traditional centralized power supply modes, DG-CCHP has the advantages of high energy efficiency, clean environmental protection, good safety, peak shaving and valley filling, and good economic benefits and can improve total energy about 70%-90% [20].

## 3. Discussion

Driven by Kuhn's innovative scientific revolution, the ‘paradigm’ concept was developed to represent a thinking model for any scientific discipline. It is an integrated cognitive model that provides ideas and rules to examine problems and develop possible solutions. The ‘Paradigm shift’, also known as ‘Paradigm change’, it is the fifth and final step in the Kuhn Cycle (see Fig. 4). Once a new paradigm is determined by influential supporters, the paradigm shift begins and there is a paradigm shift from the old to the new and then again to maturity. Finally, the old paradigm is replaced and the new paradigm becomes the new normal science, and when it comes to an end, a new paradigm becomes the new normal science, after which the Kuhn Cycle is completed. Therefore, paradigm shift is not only a gradual process, but also represents a revolutionary change from one way of thinking to another.

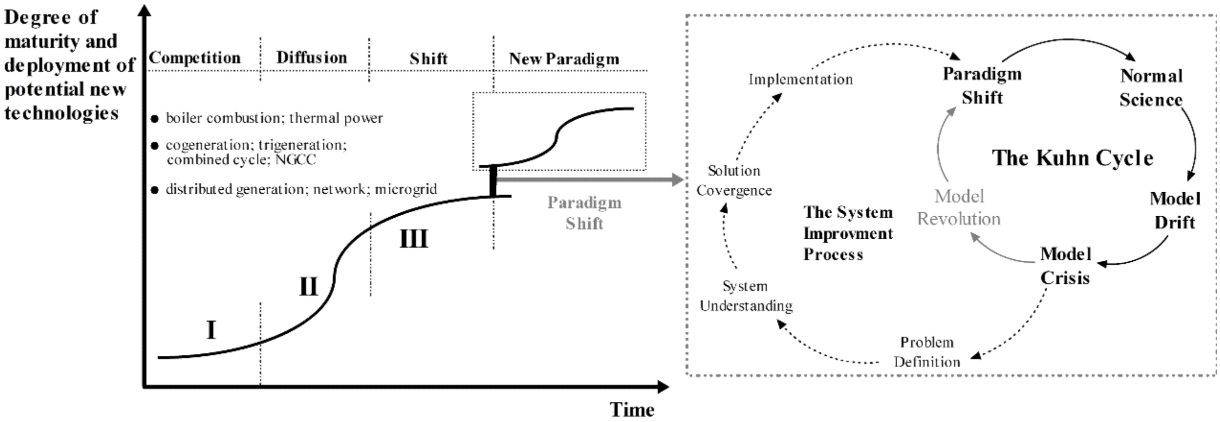



**Figure 4.** The Kuhn Cycle.

*3.1. Paradigm shift*

At present, as the world demand for energy is growing, the need for a viable energy transformation is becoming more urgent; however, it takes a long time to adjust energy structures and change the energy use mode to achieve sustainable energy development. During this adaptation period, the use of natural gas resources is essential as it is more attractive to many developed countries. However, the development of natural gas extraction from shale fracking and because of the release of greenhouse gases during the transport and exploitation of natural gas [5], researchers are wondering whether this method can help curb climate change or whether it contributes to climate change [21]. At the same time, as natural gas suffers from price volatility, to be competitive, a reasonable solution needs to be found. The paradigm theory and research analyses highlighted several new keywords in recent years: hybrid, system and integrated; therefore, the future natural gas generation research trend is mainly focused on hybrid power generation.

The share of natural gas and renewable energy in energy generation is growing and both have been identified as key elements in the transition to a more secure, clean energy future. From a traditional point of view, there is competition between natural gas and renewable energy in the electricity market; however, some studies have pointed out that there are potential development trends [22]. Long-term strategies should focus on a mix of gas and renewable energies. Strategically, NG-RE integration can be developed on multiple levels, from tightly coupled hybrid technologies to more loosely coupled integrated systems and market design. The widespread use of techniques such as horizontal drilling and hydraulic fracturing, or ‘fracking’, has led to a rise in gas production. In addition, natural gas generation is clean and efficient and requires spend less time to start-up or stop the power plant than thermal power plants; therefore, compared to intermittent renewable energies (wind and solar energy), natural gas is a better energy producer. Today, the integration of natural gas and renewable energy is no longer a concept, and many successful hybrid power plants have been established such as the hybrid solar and natural gas power generation systems at the Mexico Baja California Norte power plant, the Indian Mathania power plant, the Algerian HassiR’Mel power plant, the Irani Yazd power plant and the Jordan Quwairah power plant [23].

Relative to NG-only and RE-only systems, hybrid NG-RE generation systems have economic and non- economic benefits as this type of system can hedge market risk and policy uncertainty by diversifying the electricity mix, and can significantly reduce the risk of the total investment in the power sector, while reducing carbon emissions, hedging fuel risks and improving reliability. An example of a natural gas and biomass co fired power generation plant that embodies hybrid power generation advantages is shown in Fig. 5. The biomass is gasified in a Circulation Fluidized-Bed Reactor, with the heat required being generated by biomass combustion, after which the biogas and natural gas are mixed and combusted in the gas turbine, the electrical energy from which is then supplied to the user [24]. The waste flue gas heat can be used for heating or cooling in the gasification system and the cooling unit and the biogas and natural gas mixture can be used as a fuel for the users. This hybrid biomass-natural gas distributed generation system has the following benefits:

(1) The mixture of biomass gas and natural gas ensures energy supply security.

(2) As biomass gas and natural gas are complementary, the whole system runs efficiently and steadily.

(3) Not only is a distributed energy system provided, the excess biomass gas can be mixed with natural gas as a fuel for life.

(4) Gas turbine power generation not only meets user needs, but also provides a gasification system and cold-hot units and as the power supply is not online, investment and operational management costs are reduced.

*3.2. Policy support*

Although industry cooperation between natural gas and renewable energy has been rare, there are many opportunities to develop such partnerships to enable integrated research and information exchange. In the face of climate change and infrastructure aging, ensuring the reliability, resilience and flexibility of the hybrid NG-RE generation system is becoming increasingly important. Due to the history, geography and political environment has determined the final form of the natural gas market, consequently, the soft path dependence has become a major feature of the natural gas market. For example, the natural gas market regulation and supporting policies are determined by the political tendencies and events, they are deeply affected by economy towards the market and reduce carbon emissions and other macro policies and trends. Therefore, in order to achieve and maintain the properties of this system, policy support is needed. Policy makers can action the results of collaborative analysis and dialogue to design complementary energy policies.

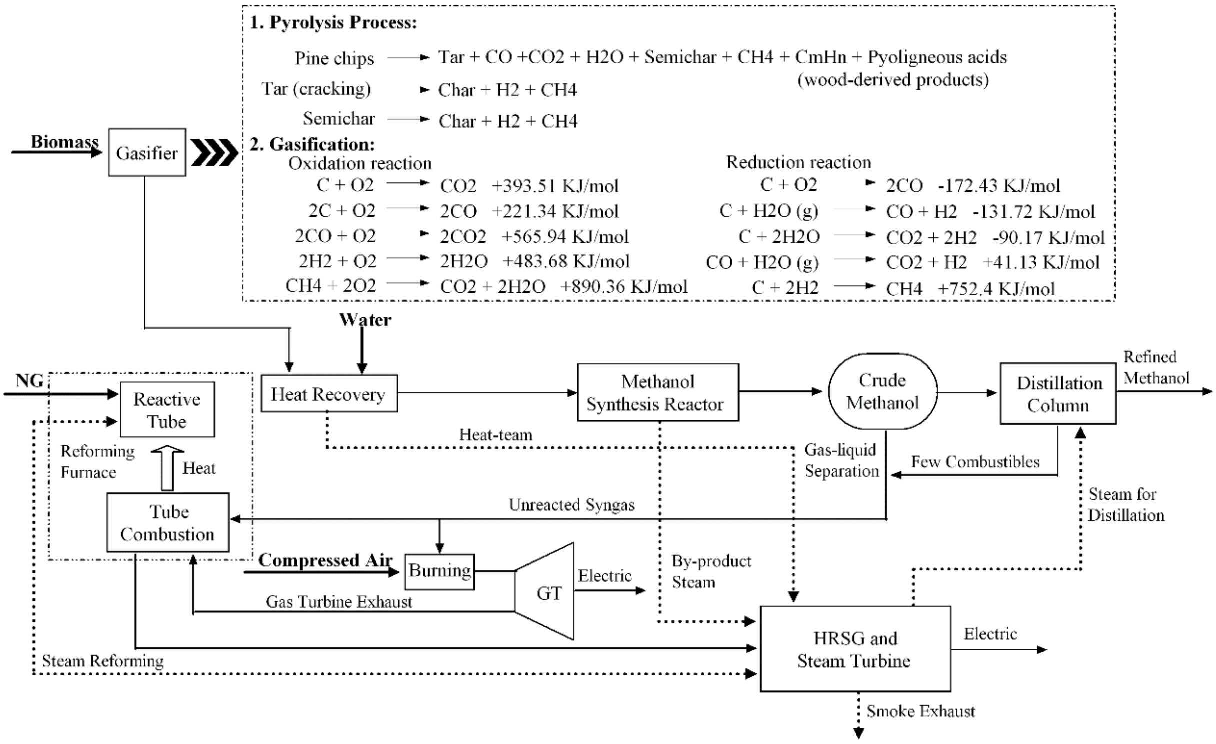



**Figure 5.** NG-Biomass hybrid power systems.

As natural gas is a clean-burning fuel, there has been a slow transition from coal to natural gas power generation. Unfortunately, natural gas does not have a price advantage compared with coal; therefore, positive policies and monitoring systems are necessary to improve the competitiveness of natural gas. For example, the European Union's environmental policy puts a price on the high emissions costs of coal enterprises, thereby enhancing the competitiveness of natural gas. To encourage the use of natural gas, it is necessary to make appropriate changes to environmental protection policies. Theoretically, the simplest way to establish a carbon price is through a carbon tax or carbon-cap and trade, as shown in Fig. 6. As pointed out in the 2015 Paris Climate Talks, a carbon tax can effectively address climate change concerns and reduce GHG emissions. Further, governments can provide economic incentives for producers and consumers to reduce GHG emissions and move to emissions free power generation.

### *3.3. Policy support*

Although industry cooperation between natural gas and renewable energy has been rare, there are many opportunities to develop such partnerships to enable integrated research and information exchange. In the face of climate change and infrastructure aging, ensuring the reliability, resilience and flexibility of the hybrid NG-RE generation system is becoming increasingly important. Due to the history, geography and political environment has determined the final form of the natural gas market, consequently, the soft path dependence has become a major feature of the natural gas market. For example, the natural gas market regulation and supporting policies are determined by the political tendencies and events, they are deeply affected by economy towards the market and reduce carbon emissions and other macro policies and trends. Therefore, in order to achieve and maintain the properties of this system, policy support is needed. Policy makers can action the results of collaborative analysis and dialogue to design complementary energy policies.

As natural gas is a clean-burning fuel, there has been a slow transition from coal to natural gas power generation. Unfortunately, natural gas does not have a price advantage compared with coal; therefore, positive policies and monitoring systems are necessary to improve the competitiveness of natural gas. For example, the European Union's environmental policy puts a price on the high emissions costs of coal enterprises, thereby enhancing the competitiveness of natural gas. To encourage the use of natural gas, it is necessary to make appropriate changes to environmental protection policies. Theoretically, the simplest way to establish a carbon price is through a carbon tax or carbon-cap and trade, as shown in Fig. 6. As pointed out in the 2015 Paris Climate Talks, a carbon tax can effectively address climate change concerns and reduce GHG emissions. Further, governments can provide economic incentives for producers and consumers to reduce GHG emissions and move to emissions free power generation.

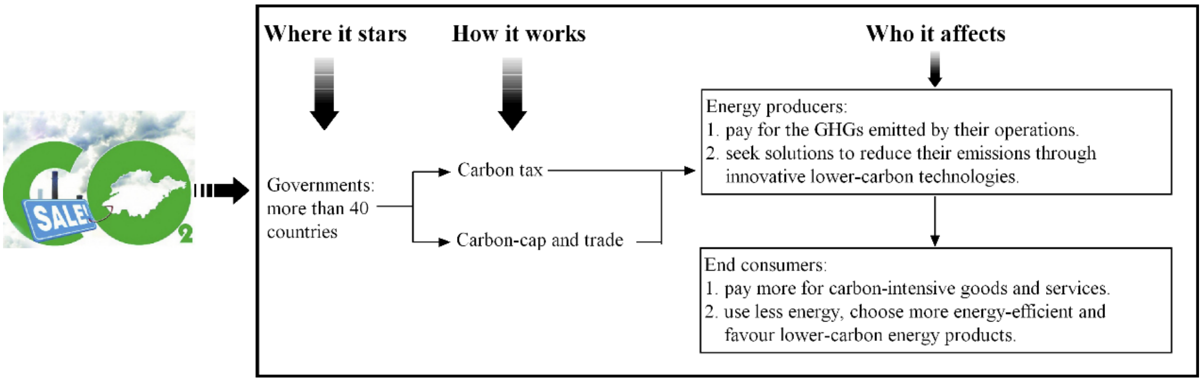



**Figure 6.** Carbon pricing mechanism.

Apart from the environmental protection policy concerns, future energy security also needs to be considered. As renewable energy development can ensure energy security, direct tax and financial incentives to help eliminate the barriers to renewable energy production could attract long-term investors. Investment subsidies, which have been already used in many countries to encourage renewable energy grid connection infrastructure investment, could also be used to promote overall renewable energy development, support enterprise research and development, conduct marketing and public welfare activities and promote public support for the renewable energy market.

It has been found that the promulgation of supporting policies to promote environmental or technological progress in the natural gas market can have significant positive effects; however, the mutuality of such supporting policies has been found to be somewhat unpredictable. For example, in the European Union natural gas market, while environmental policies have increased coal enterprise costs and increased the competitiveness of natural gas relative to other fossil fuels, these policies could also lead to a coal and renewable energy 'energy predicament', which many not be conducive to natural gas market development. Therefore, favorable policies specifically focused on the development of natural gas and renewable energy power generation are needed.

## 4. Conclusion

To elucidate current and future natural gas generation technological developments, this paper introduced the natural gas power generation technology paradigm through an innovative approach towards paradigm theory. Through an analysis of the paradigm, the key technology in the third stage, which combined cooling, heating and power with distributed generation (DG-CCHP), was found to be the dominant natural gas power generation technology. A paradigm shift was found with the emergence of a competitive electricity power market between natural gas and renewable energy and hybrid NG-RE systems were proposed as a key power generation technological development trend. From this research, possible technological directions for future natural gas generation and resilient, reliable, flexible, and affordable electric grids were illuminated. It was concluded that NG-RE integrated generation based on the expansion and diversification of energy use to promote energy supply would provide reliable and environmentally friendly energy in the future.

With rising concerns about environmental pollution and energy shortages, natural gas is at present an important basic energy resource that is crucial to economic growth for rapidly urbanizing and industrializing economies. Therefore, further studies on NG-RE integrated generation should be closely related to the global goals of sustainable development; it is therefore our hope that the conclusion of this paper can provide policy makers and scholars with new research ideas.

## References

[1] N. Lior, P. Chair, Brief summary of the ecos'05 panel on "future power generation", Energy 32 (4) (2007) 254–260.
[2] P. J. Landrigan, R. Fuller, R. Horton, Environmental pollution, health, and development: a lancet-global alliance on health and pollution-icahn school of medicine at mount sinai commission., Lancet 386 (10002) (2015) 1429–31.
[3] E. Mastrangelo, D. Burtraw, Regulating greenhouse gases from coal power plants under the clean air act, 2013.
[4] J. A. D. Gouw, D. D. Parrish, G. J. Frost, M. Trainer, Reduced emissions of co2 , nox, and so2 from u.s. power plants owing to switch from coal to natural gas with combined cycle technology, Earths Future 2 (2) (2014) 75–82.
[5] E. Kintisch, Hunting a climate fugitive, Science 344 (6191) (2014) 1472–1473.
[6] R. W. Howarth, R. Santoro, A. Ingraffea, Methane and the greenhouse-gas footprint of natural gas from shale formations, Climatic Change 106 (4) (2011) 679–690.
[7] J. Xu, N. Luo, M. Li, H. Xie, A novel paradigm-oriented approach towards ng-re hybrid power generation, Energy Conversion and Management 145 (2017) 220–232.
[8] P. Akbar Akhgari, H. Kamalan, Economical–environmental evaluation of natural gas and renewable energy systems, International Journal of Energy Research 37 (12) (2013) 1550–1561.
[9] S. S¸evik, An analysis of the current and future use of natural gas-fired power plants in meeting electricity energy needs: The case of turkey, Renewable & Sustainable Energy Reviews 52 (2015) 572–586.
[10] J. Islas, The gas turbine: a new technological paradigm in electricity generation, Technological Forecasting and Social Change 60 (2) (1999) 129–148.

[11] B. Ali, A. Kumar, Development of life cycle water footprints for gas-fired power generation technologies, Energy Conversion & Management 110 (2016) 386–396.
[12] Z. Griliches, Hybrid corn: An exploration in the economics of technological change, Econometrica, Journal of the Econometric Society (1957) 501–522.
[13] A. M. K. Vandani, F. Joda, R. B. Boozarjomehry, Exergic, economic and environmental impacts of natural gas and diesel in operation of combined cycle power plants, Energy Conversion & Management 109 (2016) 103–112.
[14] M. B. Tookanlou, M. M. Ardehali, M. E. Nazari, Combined cooling, heating, and power system optimal pricing for electricity and natural gas using particle swarm optimization based on bi-level programming approach: Case study of canadian energy sector, Journal of Natural Gas Science & Engineering 23 (2015) 417–430.
[15] G. Mohan, Development of natural gas fired combined cycle plant for tri-generation of power, cooling and clean water using waste heat recovery: Techno-economic analysis, Energies 7 (10) (2014) 6358–6381.
[16] J. Huang, C. Jiang, X. Rong, A review on distributed energy resources and microgrid, Renewable & Sustainable Energy Reviews 12 (9) (2008) 2472–2483.
[17] F. W. Bliek, A. V. D. Noort, B. Roossien, R. Kamphuis, J. D. Wit, J. V. D. Velde, M. Eijgelaar, The role of natural gas in smart grids, Journal of Natural Gas Science & Engineering 3 (5) (2011) 608–616.
[18] J. Wang, Y. Yang, J. Sui, H. Jin, Multi-objective energy planning for regional natural gas distributed energy: A case study, Journal of Natural Gas Science & Engineering 28 (2016) 418–433.
[19] Y. Li, Y. Xia, Des/cchp: The best utilization mode of natural gas for china's low carbon economy, Energy Policy 53 (2013) 477–483.
[20] J. Rodr´ıguez-Molina, J. F. Mart´ınez, P. Castillejo, A study on applicability of distributed energy generation, storage and consumption within small scale facilities, Energies 9 (9) (2016) 745.
[21] S. Kamalinia, L. Wu, M. Shahidehpour, Stochastic midterm coordination of hydro and natural gas flexibilities for wind energy integration, IEEE Transactions on Sustainable Energy 5 (4) (2014) 1070–1079.
[22] A. Lee, O. Zinaman, J. Logan, Opportunities for synergy between natural gas and renewable energy in the electric power and transportation sectors, National Renewable Energy Laboratory.
[23] G. Zhu, T. Neises, C. Turchi, R. Bedilion, Thermodynamic evaluation of solar integration into a natural gas combined cycle power plant, Renewable Energy 74 (2015) 815–824.
[24] M. Li, N. Luo, Y. Lu, Biomass energy technological paradigm (betp): Trends in this sector, Sustainability 9 (4) (2017) 567.