Roadmapping an emerging energy technology: an ex-ante examination of dimethyl ether development in China

Yuan Zhou*, Guannan Xu, Qiang Zhi and Fang Zhang
School of Public Policy and Management, Tsinghua University, Beijing, China
Email: zhou_yuan@mail.tsinghua.edu.cn
Email: gnxu@tsinghua.edu.cn
Email: Zhi-q09@mails.tsinghua.edu.cn
Email: zhangfang09@mails.tsinghua.edu.cn
*Corresponding author

Tim Minshall
Centre for Technology Management, Institute for Manufacturing, University of Cambridge, Cambridge, UK
Email: thwm100@eng.cam.ac.uk

Jun Su
School of Public Policy and Management, Tsinghua University, Beijing, China
Email: sujun@tsinghua.edu.cn

Abstract: Technology roadmapping has been used to strategise the development of energy technologies. However, there have been limited roadmapping applications that analyse the emergence of a new energy technology that then forms a new industry and propels broad-based low-carbon economic growth. This paper, therefore, attempts to develop a roadmapping framework by integrating the lifecycle analysis tool, in order to strategise the emergence of dimethyl ether, an alternative energy based on advanced engineering technologies such as carbon capture and storage. This paper compares two scenarios of dimethyl ether vs. diesel and finds that the superiority of dimethyl ether will not arise until 2030, when the complementary engineering technologies become available. This proposed framework can also be generalised to other clean energy industries, and we anticipate our paper will spark inspiration for roadmapping and strategising the ‘right’ technologies for the growth of Chinese energy industries.

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1 Introduction

Technology roadmapping (TRM) is a management tool to support technology development strategy and long-term planning. Providing a framework to link various impact factors to technology, it has been tentatively used by government agencies and researchers to strategise the development of emerging technologies. However, there is limited practice in building and applying TRM to the clean energy industry, especially when concerned with alternative energies that may replace the existing solutions with advanced engineering technologies.

The energy industry is viewed as a highly regulated industry, where public policies are significant to its emergence and functioning; in addition, new energy technologies are becoming increasingly complex, which is closely associated with the advancement of complementary engineering technologies. Roadmapping an emerging energy industry requires answering the following questions: (i) whether or not and if so when a new energy technology can challenge the existing solution, considering both technology readiness and its low-carbon economic value; (ii) how to determine or plan the growth
trajectory of this specific industry, in a path-dependent or independent way. Thus, the roadmapping of an alternative energy technology needs to take not only the emergence trajectory of the new industry itself into consideration, but also the advanced engineering technologies that enable the low-carbon value to emerge and persist in this industry.

This paper, therefore, aims to develop a TRM framework to plan and strategise the emergence of a new energy industry that is based on engineering technologies. In order to explore the specific characteristics of an energy sector, this framework also uses lifecycle analysis to compare both technology readiness and low-carbon attributes of an new and existing energy alternatives. Dimethyl ether (DME), as an alternative fuel for transportation, has been selected to become the critical case for the examination of the current potential and the future development of strategies/stages of an emerging energy. The effects of two major supporting engineering technologies, such as carbon capture and storage (CCS) and catalytic distillation technology (CDDME), are also carefully examined in this case. In addition, TRM workshops are designed to collect and analyse data.

The remainder of this paper is structured as follows. First, this study will provide a brief literature review. Next, we describe the research methodology and the design of TRM workshops. Then, an a priori framework is then developed, followed by a case study of DME vs. diesel, through which the TRM framework will be refined. Finally, this paper concludes with a short summary.

2 Literature review: TRM, life cycle analysis, and DME in China

2.1 TRM for emerging industries: value roadmapping, policy and technology selection

Although there are many tools to study industries, Technological Roadmapping (TRM) is recognised as an effective and comprehensive tool for mapping industrial emergence when studying the complex behavior of the industrial development process (Phaal et al., 2009; Phaal et al., 2003; Phaal et al., 2010; Groenveld, 2007). The TRM approach is widely applied at both firm and sector levels to support innovation, strategy, and policy development and deployment (Robinson and Propp, 2008). It provides a structured approach for mapping the evolution and development of complex systems. For example, Uchihira (2007) proposes a new technology roadmapping methodology (middle-up-down technology roadmapping) for concurrent systems technology. The method starts from the basic functions of the technology, then looks for a for a market for these basic functions that can be applied in, further predicts the extending functional requirements of the target market, and finally conclude with the R&D direction. This method can help to solve some market uncertainty of the potential disruptive technologies. Gerdtsi (2007) puts forward the concept of 'Technology Development Envelope’ and attempts to make the emerging technology roadmap more dynamic, flexible and operability, in order to find the optimal path for the enterprise technologies’ R&D. Kajikawa et al. (2007) attempts to offer a global structure of energy research and to detect emerging technologies by using citation network analysis. The result offers an intellectual basis for constructing an energy roadmap. Robinson and Propp (2008) develop and applies the “multi-path mapping (MPM)” toolset. MPM comprises a number of tailored future oriented technology assessment tools. It is being built around the notion of the
‘deployment cycle’, which mirrors dynamics underlying technology S-curves: in early stages of technology emergence, the more flexible multi-path mapping is used; in later stages, when the technological, regulatory and business context of the (hopefully) growing start-up/SME has matured, the company can switch towards roadmapping for incremental innovation.

Adding to that, Phaal et al. (2010) have developed more than 25 “emergence maps” that examined industrial evolution processes to support the development and testing of the TRM framework as a tool for historical analysis. Their study states that the existing applications of TRM “have demonstrated the flexibility of the approach, leading to a generalised framework for strategic appraisal”. In their framework, the horizontal (time) axis of a TRM has been divided into five growth phases of emerging industries, including precursory, embryonic, growth, maturity, and renewal or decline, reflecting the entire growth cycle of an industry. In addition, this framework requires a set of themes or perspectives that characterise industrial innovation represented on the vertical axis as layers (and sub-layers). The themes (vertical axis) are usually used in the “value stream model” to define a hierarchical taxonomy, which includes three broad categories: contextual trends & drivers (e.g. market), value (capture) streams (e.g. products, services, strategic positions), value creation enablers and barriers (e.g. capabilities used to generate products and services, like research, resources, design, human resources, etc) (Phaal et al., 2010).

To date, Technology Roadmapping methods have also been used in the renewable energy sector for making energy/national strategies. The objectives involve bringing a consensus among various stakeholders, creating a common vision, providing guidelines for policymakers and decision makers, establishing goals and targets, assessing promising technology alternatives, identifying markets, gaps and barriers, formulating strategies and action items to overcome all those barriers, and improving communication and coordination for technology development in order to increase contribution of renewable resources in future (Amer and Daim, 2010). They also claim that goals and objectives of renewable energy roadmaps are different at these three levels. At national level, roadmaps focus on future energy security, energy dependence, energy policy formulation and environment protection. At industry/sector level, roadmaps are used to identify vision, common needs and evaluate barriers, constraints and risks faced by the industry from technical, political and commercial aspects. Organisational roadmap focuses on evaluation and prioritisation of R&D projects to achieve the business goals. Lee et al. (2009) presented the energy technology roadmap for Korea for next 10 years in order to provide guidelines for energy technologies development policy. European Renewable Energy Council (EREC) developed renewable energy technology roadmap for 27 EU member states and established a target of obtaining 20% final energy consumption from renewable energy resources by 2020 along with interim targets for every country. Institute for Energy and Environmental Research (IEER) and Nuclear Policy Research Institute (NPRI) jointly developed carbon-free and nuclear-free roadmap to provide guidelines to US energy policy and presented a very detailed overview, potential and viability of relevant emerging renewable energy technologies including wind energy, biomass, biofuels, hydrogen production, geothermal, wave energy, solar photovoltaic, solar thermal and energy storage. Brenden et al. (2009) prepared a wind energy roadmap for Pacific Northwest and considered government policy, environmental issues, rising fossil fuel cost, dependency on imported oil, and prospectus of future business opportunities as the most important drivers. Office of Energy Efficiency and
Renewable Energy at the US Department of Energy has developed many technology roadmaps related to various renewable energy technologies and energy efficiency technologies. National hydrogen vision and roadmap presented a framework for the coordinated long-term efforts from public and private sector required for hydrogen energy development and defined objectives and activities with consensus among government, industry, universities, national laboratories, environmental organisations, and other related parties.

However, existing Technology Roadmapping have failed to pay sufficient attention to the policy-industry dynamics when the policy dimension is particularly important in highly-regulated sectors (like new energy industries) (Zhou, 2011). Daim and Oliver (2008), as one of the few attempts to examine policy-industry dynamics, assumed that the public policy may significantly influence the emergence of some industries when interacting with other dimensional such as market/product strategy. However, they did not elaborate on the policy-industry linkages and assumed that these links are indirect and implicit. Zhou et al. (2011) developed a preliminary policy-TRM tool in order to facilitate the better understanding policy-industry interactions through the growth process of emerging industries, and gives a systematic analysis of policy (demand/environment/supply policies), markets, product and technology development through the process. However, this study needs further validation.

TRM needs supporting tools to complement the strategic decision making, i.e. to compare and select a dominant technological solutions for an emerging industry by using technology evaluation and comparison tools (Phaal et al., 2010). Scenario planning and technology valuation are the two major techniques. Scenarios can used to simulate the comparisons of technologies in future planning among uncertainties, and technology valuation will be conducted through using life cycle analyses to assess the overall performance of the alternative technologies, which will be discussed in the following section.

2.2 Life cycle analysis for new energy sectors

Life cycle analysis (LCA) method has been widely used to assess the overall performance of specific energy technologies, and a life cycle analysis of a new energy involves a study of the energy flows over its entire life (Crawford, 2009; Ou et al., 2010; Ou et al., 2010). LCA can be used as a strategic planning and policy tool, e.g. the application of the low-carbon fuel standard in California, USA (Rajagopal and Zilberman, 2008).

A life cycle of a new energy technology may include many stages or processes. For example, a LCA for wind turbines may examine the embodied energy associated with its specific life cycle, which include manufacturing process, operation, maintenance, disposal, this is then compared to the energy generated by the turbine over its life (Crawford, 2009).

Transportation fuel also has its specific life cycle for LCA analysis. For example, the life cycle of oil may include four stages such as; oil extraction, transportation, refinery, and consumption. For Gasoline and diesel, we also need to consider the set-up and diagnosis (TSD) mode (Ou et al., 2010; Rajagopal and Zilberman, 2008). This study will compare DME and diesel. In line with the existing literature, this paper defines the life cycle into three stages (see Figure 1): fuel stock stage, fuel stage and finally the vehicle stage (Blottnitz and Curran, 2007; Demirbas, 2007).
Traditionally, the energy LCA has focused on dealing with the energy output through the life cycle. This may be due to the difficulties in quantifying the life-cycle performance of energy. In reality, however, the LCA can not only be used to examine energy output through the lifecycle, but can also be used to calculate the required resources and emissions through the processes or stages, e.g. to calculate whether DME would emit less overall carbon dioxide than existing fuels for transportation, or whether DME would consume more energy, whilst also taking costs into consideration (Rajagopal and Zilberman, 2008).

There have been some studies that have considered the energy requirements and energy output associated with clean energies in order to determine the overall environmental benefit from these systems (Raugei and Frankl, 2009). The findings from these studies tend to vary considerably depending on a number of key factors, including: the method of embodied energy assessment chosen; the system boundary; and the life cycle stages considered.

Based on existing literature, this paper has defined the system boundary for the emerging energy technology, and has defined three life cycle stages, namely; fuel stock stage, fuel stage, and vehicle stage. However, in order to plan the relocation of existing transportation fuels (i.e. diesel) by using new clean energy (i.e. DME), we need to compare the new energy solution to the existing one when considering different performance indicators, e.g. environmental footprint, resource footprint, or energy cost.

The calculations of those performance indicators over the entire life cycle to compare energy solutions are very significant. In addition, those calculations will be based on certain assumptions (by experts and professionals). Those assumptions and calculations will be further explained in following sections. Based on existing literature (Crawford, 2009; Hummel, 2007; Gallagher, Holdren and Sagar, 2006; Daim and Oliver, 2008), we suggest evaluating the performance of different energy solutions by using three major indicators: environmental impact, economic value, and energy consumption.

### 2.3 DME in China: an alternative fuel for transportation

DME, given the combustion and auto ignition characteristics, is an ideal clean-burning substitute for conventional diesel or petrol. Its application helps to reduce harmful emissions and alleviate the relieve energy resource shortage (Ou et al., 2010).

In China, domestic research institutions have shown strong interests and carried out many research efforts to understand DME application technology (Shu, 2009). Several Universities, such as Shanghai Jiaotong University and Tianjin University, have conducted a series of experiments and other research on the DME production process and DME engines, supported by the National Natural Science Foundation or companies like Ford Motors. Since 2007, China has launched a number DME projects in total exceeding one million tons for operational production. For example, in August 2007, Jiu Tai Energy
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(Inner Mongolia) Co., Ltd celebrated the ground-breaking ceremony of a 1 million ton/year DME project. A few months later, Shenhua Ningxia Coal Industry Group announced their commissioning in 0.21 million-ton DME production (Zhao, 2009).

DME production capacity and output has been growing rapidly recently. In 2002, China’s DME production capacity is only 31.8 thousand tons with an output of 20 thousand tons. And by 2006, the two numbers were increased to 480 thousand tons and 320 thousand tons respectively, with annual growth rates of 97% and 96%. By 2008, there were 52 DME producers in China with existing capacity of 4.18 million tons and a further 10.64 million tons under construction. It was predicted that the production capacity would reach 15.8 million tons in 2012 (Luan, 2011). However, there are several main growth barriers to coal-based DME:

1. **High carbon emissions in the fuel stage**: Coal-based DME emits large amounts of carbon dioxide during its pre-processing from coal, although DME itself is very clean-burning. Coal contains high carbon content and a mere 5% of hydrogen content, which means carbon emission in the production process of DME synthesised from coal is about 3–9 times higher than that in the crude oil refining process. Therefore, CCS technology is considered to be the most important emissions abatement method integrated with coal chemical engineering, but CCS is still in the early stages of development in China.

2. **High production cost**: The cost of DME as an alternative oil is currently exorbitant. On average, 1.8 tons of DME can be substituted for 1 tons of diesel. For example, at the end of 2006, the price of DME was 3800 RMB/ton, thus 1.8 tons of DME would cost 6480 RMB that is 2040 RMB higher than 1 ton of diesel. Therefore, DME can be accepted by market only when the price is less than 2300 RMB/ton. Otherwise the DME production as a business would be too risky.

3. **Low energy efficiency**: The low level of utility efficiency is one of the most significant problems. In China, coal energy utilisation ratio in coal-fired power can reach 55%, while only 32–42% in coal-based methanol, 47.7% using the direct method and 28.6% in the indirect method of coal to liquid fuels. The utilisation efficiency will drop further if taking into account other energy consumptions and waste in fuel transportation and storage.

3 **Methodology**

3.1 **Research design**

The research adopts a single case study methodology, following Yin (2003) and Eisenhardt (1989) when trying to bring a new idea to the existing TRM framework. In addition, this paper selects a theoretical case (i.e. planning the development of DME in China) for detailed analysis to refine the conceptual TRM framework. A series of workshops for roadmapping and comparing DME to diesel can ensure the construct and internal validity of the data analysis for the refined framework. In addition, the TRM framework and LCA data protocol help to enhance the external validity and the reliability of this paper.
3.2 Data collection and analysis: TRM workshops

This paper develops the TRM framework through a series of workshops for data collection and analysis. This fast-start workshop approach is based on existing practices that have been published for the analysis from multiple perspectives (Farrukh and Probert, 2003; Phaal et al., 2010).

The data collection is twofold. Firstly, documentary data is significant throughout the roadmapping process. Before every workshop, documentary data and pilot interviews have been conducted to prepare for the discussions. Second, three workshops have been conducted in order to frame the vertical axis for this framework, identify the strategic landscape, and analysing the scenarios for DME (see in Table 1).

<table>
<thead>
<tr>
<th>Table 1</th>
<th>TRM workshops</th>
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<tr>
<td><strong>WS</strong></td>
<td><strong>Objectives</strong></td>
</tr>
<tr>
<td>I</td>
<td>Key dimensions (vertical axis) of this TRM framework</td>
</tr>
<tr>
<td>II</td>
<td>Landscape of this TRM framework</td>
</tr>
<tr>
<td>III</td>
<td>Scenario analysis using LCA: comparing DME to diesel</td>
</tr>
</tbody>
</table>

Experts are invited to contribute valuable comments in these workshops. The invited experts are leading professors in coal, energy and technology policy domains from key government agencies and leading universities in China, including Prof. Xie Kechang, Prof. Shao Liqin, Prof. Xue Lan, Prof. Su Jun, Prof. Li Zheng, and others.

In workshop I, a short presentation was given before the discussions, briefing the discussants on the existing literature about the dimensions for roadmapping an emerging technology. Experts’ inputs were then collated, and the key dimensions for vertical axis are presented in next section.

In workshop II, three topics have been discussed: (i) key scope, drivers, barriers, and the future vision; (ii) current status of DME in China, and gaps in the future vision; (iii) risks and key challenges or problems (obstacles). The a priori framework has been developed, with some unknowns remaining for further analysis (using LCA scenario study).

In workshop III, scenarios have been played out for comparing DME to diesel when supported by documentary data and experts’ inputs, and two scenarios have been included into the final framework, and the unknowns are explicated. This study was strengthened by the data protocol in data collection, and the scenario analysis method in data analysis.

4 A priori framework: integrating TRM and LCA

This section presents the a priori TRM framework that has been developed through workshop I and II, in order to explore whether or not and if so when alternative DME
technology can challenge diesel as the dominant transportation fuel. This framework incorporates three major elements as described in detail below when compared to diesel in different scenarios.

4.1 Key dimensions (vertical axis) of this TRM framework

In workshop I, experts have considered the key themes and dimensions for roadmapping (planning) the emergence and development of DME in China, and the themes fall into four broad categories that can be used as a checklist to design the structure of the map (see Figure 2).

**Figure 2** A priori TRM framework (see online version for colours)

<table>
<thead>
<tr>
<th>1 External factors that drive the evolution: The contextual settings within which opportunities for creating and capturing value occur, including the broad market trends and policy drivers that influence industrial emergence, such as customer needs, grant support, regulation and standards, etc.</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 Industrial technologies (competing and complementary): An alternative fuel needs to challenge an existing solution in order to be recognised by the market. Diesel, in this case, has been selected to act as the competing technology. As mentioned earlier, DME also needs some complementary engineering technologies, such as CDDME and CCS.</td>
</tr>
</tbody>
</table>
3 **DME value creation and capture**: The processes that appropriate value through establishing platform technologies and delivering competitive products, including consideration of the development strategies and key stages, the establishment of industrial standards and core firms, the applications network. These activities are influenced by both market demand (pull) and capability supply (push) dynamics.

4 **Resources**: The consideration of coal production and R&D also need significant attention so as to support the development process.

4.2 **Landscape of the TRM framework: transitions, phases, and key events**

This workshop maps the future development of DME, and together with key events that influence the process (see also Figure 2).

1 **Transitions for DME**: the transitions between science-technology/technology-application/and application-market phases are of particular interest, as they are associated with significant shifts in perspectives. The standards and application networks have been advanced through demonstrations of the technology, applications, and markets.

2 **Key events in other dimensions**: key events for market drivers and policy support have been outlined. In addition, other key milestones for the development of complementary technologies for DME have been mapped.

3 **Unknowns and key challenges to DME**: this framework aims to compare DME to diesel through the development process. However, there are unknowns left over from this workshop, which need a further analysis using LCA in the following section principally: (i) whether or not and if so when DME can challenge diesel by solving its key barriers (listed in 2.3); (ii) required policy to support the development.

4.3 **DME vs. diesel: comparing two technologies using LCA in different scenarios**

Life cycle analysis will help us to plan the growth of DME when assessing the key obstacles to DME through the entire life cycle: environmental impacts, economic value, and energy consumption. The TRM tool, in turn, will help us to plan when and why we should select DME over diesel as a transportation fuel. As per the recommendation of the experts, two scenarios have been planned for further analysis: (i) DME vs. diesel in 2020; (ii) DME vs. diesel in 2030. We hope this scenario analysis will help to address the unknowns left over in workshop II.

5 **Case study: DME vs. diesel in two scenarios**

The use of the framework for roadmapping the emergence of the new technology is illustrated below by means of a case study, focusing on the comparison between DME and diesel. There are two scenarios analysed through LCA method, in order to explore and clarify the unknowns in an a priori framework. The development strategies and key stages have been clarified in the refined framework, and the supporting policies are subsequently suggested.
5.1 Case study: objectives and basic assumption

This case study aims to plan the development strategies and key stages (unknowns in Figure 2) of DME in China. Some basic assumptions have been collated as follows:

1. **Huge market demand**: By 2030, China may need to import oil for 800,000,000 tons per year. It is an urgency to find an alternative fuel (i.e. DME) for transportation to replace diesel or petrol in China.

2. **Complementary technologies to DME**: CCS technology will develop at a fast pace. It will have market demonstrations in 2020, and will be implemented in 2030. CDDME technology is in the tech-demonstration stage now, and will be implemented in 2020.

3. **Coal production in China**: In 2030–2050, the production will be 3.8 billion tons per year.

5.2 Scenario I: DME vs. diesel in 2020

The required experts’ estimations and assumptions have been collated as follows, supported by documentary data:

1. **Energy consumption on production process**: In 2020, CDDME technology is still in its embryonic stage, and its efficiency still remained low. In the “fuel stage” of the life cycle analysis, coal-based DME needs five times the energy consumed during the production stage than that of ordinary diesel (from crude oil).

2. **Carbon emission**: In 2020, CCS technology is still in its infancy for technological demonstrations. Therefore, the carbon emission of DME production will be the two times than that of diesel.

3. **DME production cost**: DME is still in its embryonic stage, so the price in 2020 might be USD220 per barrel, compared to diesel at USD100 per barrel.

From Table 2, this paper argues that DME will not be able to challenge diesel in 2020, as its key performance indicators are significantly inferior to those of diesel.

<table>
<thead>
<tr>
<th>Table 2</th>
<th>LCA analysis: DME vs. diesel in 2020</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>DME vs. diesel</strong></td>
<td><strong>Fuel stock</strong></td>
</tr>
<tr>
<td>Energy consumption</td>
<td>0.45 : 1</td>
</tr>
<tr>
<td>Price</td>
<td>N.A</td>
</tr>
<tr>
<td>Carbon emission</td>
<td>1.76 : 1</td>
</tr>
</tbody>
</table>

5.3 Scenario II: DME vs. diesel in 2030

1. **Energy consumption in the production process**: In 2030, CDDME technology may have been significantly refined in terms of efficiency. In the “fuel stage” of the life cycle analysis, coal-based DME requires three times the energy consumed during the production stage than that of ordinary diesel (from oil).
2. Carbon emission: In 2030, CCS technology may have been in its early stage of implementation. Assuming at the 45% efficiency, the carbon emission of DME production will be the 1.08 times than diesel.

3. DME production cost: Including the carbon trading gain (benefit from CCS), DME might have the price of USD135 per barrel.

From Table 3, this paper argues that DME will start to be able to challenge diesel in 2030, as its key performance indicators are almost on par with those of diesel. The industrial strategy would need to expand the supply and penetrate the mass market.

**Table 3** LCA analysis: DME vs. diesel in 2030

<table>
<thead>
<tr>
<th>DME vs. Diesel</th>
<th>Fuel stock</th>
<th>Fuel</th>
<th>Vehicle</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy consumption</td>
<td>0.45:1</td>
<td>3:1</td>
<td>0.68:1</td>
<td>0.918:1</td>
</tr>
<tr>
<td>Price</td>
<td>N.A.</td>
<td>N.A.</td>
<td>1.35:1</td>
<td>1.35:1</td>
</tr>
<tr>
<td>Carbon emission</td>
<td>1.13:1</td>
<td>1.2:1</td>
<td>0.8:1</td>
<td>1.08:1</td>
</tr>
</tbody>
</table>

5.4 Refined framework and policy suggestions

Through analysing the two scenarios using the LCA method, the development strategies and key stages of DME technology in China have been developed, as illustrated in the refined framework (Figure 3).

**Figure 3** Refined TRM framework and final output (see online version for colours)
In 2020, policy should consist predominantly of supply policies, such as giving R&D grants, encouraging its application and demonstration, etc. In 2030, policy should be more market and environment oriented, such as industrial standards, regulations and stipulations, and application networks should be supported.

6 Conclusions

This paper has developed a TRM framework that integrates LCA method for roadmapping and strategising the emergence of a new energy sector, through an ex-ante case of comparing DME to diesel in China. Some key findings and contributions are depicted as follows:

1 Integrating LCA method to TRM for analysing future scenarios: Roadmapping an emerging energy technology or industry needs the integration of LCA method for a professional assessment of both technological advancement and low-carbon value, especially when concerned with challenging existing energy solutions with an alternative energy technology.

2 Policy factors, key engineering technologies, and competing energy technologies for vertical axis: There are a variety of factors and uncertainties associated with technological and commercial aspects that bring impacts to the emergence of a new energy sector. Therefore, it is critical to clarify the key factors or uncertainties which may determine or influence the emergence trajectory. This paper indicates the significance of three major factors for new energy emergence, including policy impacts, key low-carbon engineering technologies, and the competing energy technology such as Diesel. Specifically, two key engineering technologies, CSC and CDDME, have been considered as key factors that will shape the emergence of DME, in view of both technological readiness and low-carbon value creation.

3 Transitions and key stages in landscape: This paper highlights the significance of the transitions between the key stages of DME development (e.g. science → technology → application → market), and the implications for its growth strategies and policy design.

The framework provides a management tool for roadmapping and planning the emergence of a new type of energy source, when supporting strategy and decision making in scenario analysis. It also provides some discussion of Chinese specifics in DME development. Limitations do exist. First of all, this paper develops a framework that is used to explore a long-term future, rather than specific forecasting. This future planning is based on assumptions and experts’ discussions, so it cannot be statistically precise and accurate in that way. For the same reason, this framework will not be able to consider all the uncertainties when planning technology trajectories. Second, this TRM framework needs to be validated by more new energy cases. Third, data collection protocol can be further improved by using data mining protocols, and documentary data protocol may enhance the validity and reliability of experts’ discussions and analysis.
Acknowledgements

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