

CHALMERS



Barriers and solutions to the successful diffusion of dual-fuel trucks in Europe

An innovation systems approach

*Master of Science Thesis in the Master Degree Program Industrial Ecology for a
Sustainable Society*

In collaboration with Volvo Truck Corporation

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ABSTRACT

The transport sector is one of the major contributors to anthropogenic GHG emissions. In particular, road freight transport contributes to approximately 7% of global energy-related emissions (Mattila and Antikainen, 2010). To reduce this impact, low-carbon technologies are being developed. In this thesis we focus on the dual-fuel truck. This new product has the potential to contribute to GHG emissions reduction in the freight transport sector. Even though this product is technically available and economically feasible it is facing difficulties to diffuse in the European market.

The purpose of this thesis is to identify the main barriers, and suggest solutions, to the successful introduction and diffusion of dual-fuel trucks on the European market. In order to address this question we use the Technological Innovation Systems (TIS) framework.

Our analysis reveals that the TIS is facing five mechanisms blocking the development of the system. These main barriers include the lack of European standards and regulations for the dual-fuel trucks and the LNG filling stations; the lack of customers' experience and familiarity with a dual-fuel truck; the current small market size of LNG for vehicles which is not attractive for oil/gas companies; the "chicken and egg" dilemma regarding the launching of trucks and the construction of filling stations; and, the concerns about the fossil origin of LNG which might affect customer's acceptance of the dual-fuel truck.

Using the results of our analysis we develop strategy recommendations for Volvo Truck. These solutions could help weaken/remove the five blocking mechanisms and speed up the diffusion of the dual-fuel truck in the European market. First, in order to accelerate the creation of standards and regulations Volvo Truck could join existing groups working at the EU level. Second, in order to alleviate the lack of experience and familiarity with the dual-fuel truck Volvo should prioritize demonstration programs and adopt a clear communication strategy. Third, in order to stimulate the LNG demand from the transport sector Volvo Truck should support the use of this fuel in other transport modes. Fourth, in order to solve the "chicken and egg" dilemma Volvo could establish formal and informal networks with key actors at the national level. Finally, Volvo should adopt a PR and marketing strategy considering the country-specific environmental concerns about the fossil origin of LNG.

Keywords: innovation systems, business strategy, low-carbon technology, dual-fuel truck, methane-diesel truck, LNG, bio-methane.

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Table of contents

1. Introduction	1
2. Technological Innovation Systems (TIS)	3
2.1. Structure and <i>Functions</i> of a TIS	4
2.2. Phases of development and <i>blocking mechanisms</i>	6
2.3. A firm in the TIS.....	6
3. Method	8
3.1. Data collection	8
3.2. Step-by-step method	10
4. Structural components of the dual-fuel truck TIS and its exogenous factors. 12	
4.1. The technology: vehicle-fuel system	12
4.2. <i>Actors, networks and institutions.</i>	21
4.3. Exogenous factors of the dual-fuel truck TIS	29
5. Functional Analysis	36
5.1. Knowledge development and entrepreneurial experimentation	36
5.2. Influence on the direction of search.....	38
5.3. Market formation	40
5.4. Materialization and resource mobilization.....	42
5.5. Legitimation.....	45
5.6. Positive externalities	46
5.7. Summary of <i>functional pattern</i>	47
6. Blocking Mechanisms	49
6.1. <i>Blocking mechanism I: Lack of standards and regulations</i>	49
6.2. <i>Blocking mechanism II: Lack of experience of and familiarity with the dual-fuel truck</i>	50
6.3. <i>Blocking mechanism III: Small market size of LNG as a vehicle fuel</i>	51
6.4. <i>Blocking mechanism IV: The “chicken and egg” dilemma</i>	51
6.5. <i>Blocking mechanism V: Concerns about fossil origin of LNG</i>	52
7. Discussion	54
7.1. Interpretation of our strategy recommendations	54
7.2. Other strategic issues	55
7.3. Suitability of the TIS framework for our case study.....	58
8. Conclusion	60

9. References	62
A. Annex	74
A.1. Bio-methane <i>trajectories to market</i>	74
A.2. Fuel price and tax in selected countries	80
A.3. Second generation bio-methane projects in Europe.....	81
A.4. First generation liquid bio-methane projects in Europe.....	82
A.5. Filling stations dispensing LNG in Europe.....	83
A.6. The emergence of the TIS in Sweden, UK, the Netherlands and Spain.	84
A.7. <i>Blocking and inducement mechanisms</i> in the dual-fuel truck.....	97
A.8. Contact list	98

List of Figures

Figure 1. Vehicle-fuel-system.....	12
Figure 2. Dual-fuel truck trajectories to market.	15
Figure 3. GHG balance of LNG and pipeline supply chain.	18
Figure 4. LNG trajectories to market.	20
Figure 5. Map of actors' configuration of the European dual-fuel truck TIS.....	23
Figure 6. Current state of diffusion of the dual-fuel truck TIS.	25
Figure 7. Lower and upper share of various cost items in total LNG chain.....	33
Figure 8. Second generation bio-methane production process.	77
Figure 9. LBM trajectories to market.	79
Figure 10. Inducement and blocking mechanism in the dual-fuel truck TIS.	97

List of Tables

Table 1. TIS functions.....	5
Table 2. Elements of the TIS.....	21
Table 3. Composition of biogas, landfill gas and natural gas.....	75
Table 4. Diesel price and taxes in selected European countries.	80
Table 5. Natural gas prices and tax estimation for selected EU countries.	80
Table 6. Natural gas price vs. diesel price in selected European countries.....	80
Table 7. Second generation bio-methane projects in Europe.	81
Table 8. LBM plants in Europe.	82
Table 9. Identified LNG / L-CNG filling stations currently serving LNG in Europe....	83
Table 10. LBM filling stations in Europe.....	83
Table 11. Fuel tax for natural gas as a road fuel in UK.	91

List of abbreviations

AEA	AEA Group, Energy and climate change consultancy
Aven	Valencia's Energy Agency
Bio-SNG	Bio-synthetic natural gas
BRG	Business Region Göteborg
BtL	Biomass to liquid
CAP	Clean Air Power
CBF	Circulating fluidized bed
CBM	Compressed bio-methane
CEN	European Committee for Standardization
CHP	Combined heat and power
CNE	National Commission for the Energy, Spain
CNG	Compressed natural gas
CTU	Conzepte Technik Umwelt
DBFZ	German Biomass Research Centre
Dft	Department of Transport, UK.
ECN	Energy Centre of Netherlands
EdF	Electricité de France
EEG	European Expert Group on Future Fuels
EEV	Environmentally Enhanced Vehicles
EIA	Energy Information Administration, US
EPC	EPC Group
EST	Energy Saving Trust, UK
EU	European Union
FICFB	Fast internal circulating fluidized bed
GHG	Greenhouse gas
GIE	Gas Infrastructure Europe
GPP®Plus	Gastreatment Power Package, GtS's biogas upgrading patent
GtS	Gastreatment Service bv
HC	Hydrocarbons
HD	Heavy duty
HD-system	Westport's Heavy duty System, Westport's dual-fuel technology for heavy duty vehicles.
HDV	Heavy duty vehicles
HPDI	High pressure direct injection, Westport's dual-fuel technology.
HVC	HVC Groep
IDAE	Spanish Institute for Energy Saving and Diversification
IPCC	Intergovernmental Panel on Climate Change

IS	Innovation System
ISO	International Organization for Standardization
I&M	Ministry of Infrastructure and Environment, the Netherlands
JES	Journal of Energy Security
LBM	Liquid bio-methane
LNG	Liquid natural gas
L-CNG	Liquid to compressed natural gas
MITC	Spanish Ministry of Industry, Tourism and Commerce
NG	Natural gas
NGV	Natural Gas Vehicle Global News
NGVA	Natural Gas Vehicles Association Europe
NGVJ	Natural Gas Vehicle Journal
NSCA	National Society for Clean Air and Environmental Protection, UK
NSR	Nordvastra Skanes Renhallningbolag
OEM	Original Engine Manufacturer
OIGI®	Oil Ignition Gas Injection, Hardstaff's dual-fuel patent
OPEC	Organization of the Petroleum Exporter Countries
PR	Public relations
PSA	Pressure swing adsorption
PSI	Paul Scherrel Institut
RDW	Department of Road Transport, the Netherlands
RFA	Renewable Fuels Agency, UK
ROC	Renewable Obligation Certificates
RTFC	Renewable Transport Fuel Certificate
RTFO	Renewable Transport Fuel Obligation
R&D	Research and development
SBI	Swedish Biogas International
SEA	Swedish Energy Agency
SGtS	Scandinavian Gastreatment Service
TIS	Technological Innovation System
TNO	Organization of Applied Scientific Research, the Netherlands
TUV	Vienna University of Technology
UL	Uppland Lokaltrafik
VAT	Value added tax
ZSW	Zentrum für Sonnenenergie und Wasserstoff

1. Introduction

The freight transport sector is a socio-technical system necessary for economic development since it provides access to goods in markets and production sites. However, transportation is one of the major contributors to anthropogenic greenhouse gases (GHG) emissions with a share of 23% of world energy-related GHG emissions; three quarters of them comes from road transportation (Kahn Ribeiro et al, 2007). In particular, freight transport on road contributes to approximately 7% of global energy-related emissions (Mattila and Antikainen, 2010). The Intergovernmental Panel on Climate Change (IPCC) advises that, to avoid the worst impact of climate change, global CO₂ emissions must be cut by at least 50% by 2050. To achieve this target, reduced emission from the transport sector will have to play a significant role (EU, 2011b).

A number of alternative fuels and innovative powertrain technologies are being developed in order to meet the climate challenge in the transport sector. In this thesis, we focus on a particular product that Volvo Truck Corporation is currently developing: the dual-fuel truck.¹ This new technology will allow heavy duty trucks to run on a mixture of 25% diesel and 75% liquid methane. Given that methane generates lower CO₂ tailpipe emissions than diesel, this technology has the potential to contribute to GHG emissions reduction in the freight transport sector.

This low-carbon solution is technically available and economically feasible; however, it is facing difficulties to diffuse. In line with this, Volvo Truck Corporation wants to understand the mechanisms blocking the introduction and diffusion of the dual-fuel trucks on the European market. Understanding these challenges is a key factor for developing effective and appropriate business strategies.

The purpose of this thesis is to identify the barriers and solutions to the successful introduction and diffusion of the dual-fuel trucks on the European market. The aim of this thesis is to provide Volvo Truck with strategy recommendations to tackle the identified barriers. The purpose is broken down into three research questions:

RQ1: What is the current state of diffusion of the dual-fuel truck and its complementary technologies in Europe?

¹ Volvo Truck Corporation named this truck the MethaneDiesel truck.

RQ2: What are the main barriers hindering the adoption of the dual-fuel truck in the European market?

RQ3: How can Volvo address these barriers and thereby speed up the adoption of dual-fuel trucks in Europe?

The Technological Innovation Systems (TIS) framework has been used in this thesis. This tool has mainly been used to analyze industrial transformation and economic growth of a number of technology fields in different countries (Bergek et al., 2008a; Jacobsson, 2008; Simoa O. Negro, 2007; Roald A.A. Suurs et al 2010), deriving mainly policy implications. However, in this report we will use this framework to derive strategy recommendations for Volvo Truck regarding its new product. This thesis contributes therefore to the TIS literature by illustrating how the framework can be used as a tool for business strategy.

The remaining part of the thesis is structured as follows. Section 2 presents the analytical framework. The research method is explained in Section 3. Section 4 gives a description of the dual-fuel truck TIS in terms of *technology*, *actors*, *networks*, *institutions*, and its exogenous factors. Section 5 presents a function-by-function assessment and a summary of the *functional pattern* of the TIS. In Section 6, we present our results which are the key *blocking mechanism* hindering the development of the TIS and our strategy recommendations for Volvo Truck to remove/weaken such mechanisms. In Section 7, we discuss our results. Finally, in Section 8 we summarize our main conclusions.

2. Technological Innovation Systems (TIS)

This section describes the approach used to address the research questions. The theoretical framework used throughout the thesis guided our research and helped us give coherence to our empirical study.

A system can be defined as a set of interrelated components working toward a common objective or overall function (Carlsson et al., 2002). An innovation, in simple words, is an invention implemented and taken to market (Chesbrough, 2003). Edquist (1997) defines systems with respect to innovation activities as “complexes of elements or components, which mutually condition and constrain one another, so that the whole complex works together, with some reasonably clearly defined overall function”.

Innovation system (IS) is an analytical tool to understand how a set of components interact to generate, diffuse, and use new technologies² or products that have an economic value. An innovation system (IS) can be national, regional, sectoral or technological (Carlsson et al., 2002). In this thesis our main focus is a specific technology; therefore, we will use the concept of technological innovation system (TIS). We follow the definition of a TIS given by Markard and Truffer (2008b):

“A technological innovation system is a set of *networks* of *actors* and *institutions* that jointly interact in a specific technological field and contribute to the generation, diffusion and utilization of variants of a new technology and/or new product”.

The TIS approach has been used by researchers and policy analysts interested in the processes underlying innovation (Bergek et al., 2008a). It has mainly helped derive policy implications. The literature presents little information about its application for developing firm strategies.³ Therefore, in order to develop Volvo’s strategies we follow the same scheme of analysis used to derive policy recommendations, however, taking into consideration the firm scope of action.

² Technology here refers to the physical artefacts as well as technical know-how (Carlsson et al. 2002).

³ Bergek (2000) explores the use of the TIS framework together with the business strategy theory to identify factors that influence firm’s responses to technological opportunities. This is, however, not straight forward related to our purpose.

In the following sections we describe, first, the structure and *functions* of a TIS. Second, we present the theory behind phases of development and *blocking mechanisms*. Finally, we discuss the role of a single firm in the evolution of a TIS.

2.1. Structure and *Functions* of a TIS

The TIS framework is used to study the emergence and development of a new technology or product. It is a tool used to better illustrate and understand system dynamics and performance (Bergek et al., 2008a). This dynamics can be described using the two interrelated sides of a TIS: the structure and the *functions*.

The structural components of a TIS are *actors*, *networks*, *institutions* and the *technology*. First, *actors* may be firms of the whole value chain and organizations such as universities, research institutes, industry associations, professional organizations, venture capitalists and governmental bodies. Second, *networks* are channels to transfer tacit and explicit knowledge. Learning *networks* develop when individual *actors* join to increase their access to information and knowledge (e.g. user-supplier *networks*, university-industry *networks* and competitors *networks*) (Bergek and Jacobsson, 2004). Political *networks* emerge when *actors* join to influence the institutional framework (i.e. standardization *networks*, lobbying *networks*, advocacy coalitions and public-private partnerships) (Bergek and Jacobsson, 2004). Learning and political *networks* can be formal or informal.⁴ The third component of the TIS is *institutions* which specify the norms and rules regulating the interaction between *actors* (e.g. culture, norms, laws, regulations and routines) (Bergek and Jacobsson, 2004). These three components of the system contribute to the development and diffusion of the new technology. Finally, the *technology* is a structural element made up of artifacts (e.g. tools, plants, and machinery), coded knowledge (e.g. patents, drawing) and knowledge embodied in people (Bergek et al., 2008c).

The structural approach traces the evolution and interdependence of the components of a TIS. Traditional methods of analysis that focus only on the structure of a TIS have proven to be insufficient (Hekkert et al. 2007). According to Jacobsson and Bergek (2004), there is no reason to expect a particular system structure to be directly related to

⁴ Informal *networks* are more difficult to map.

its performance.⁵ Hence, for analytical purposes the innovation literature has supplemented the structural focus with a process focus.

Using a process focus means systematically mapping the activities taking place in an innovation system that result in technological change. These processes are called *functions* and are emergent properties of the interplay between structural components and the exogenous factors. The innovation systems literature recognized eight *functions* within TISs shown in Table 1.⁶

Table 1. TIS *functions*.

<i>Functions</i>	<i>Concerns...</i>
<i>Knowledge development and diffusion</i>	the creation of new knowledge; the actual knowledge base and how it changes over time.
<i>Influence on the direction of search</i>	the set of mechanisms that influence firms and other organizations to enter the TIS and deploy their resources. The strength of these mechanisms can be mapped by analyzing the visions, expectations and beliefs in growth potential.
<i>Entrepreneurial experimentation</i>	the number of new entrants, the different types of applications, the breadth of technologies used and the character of the complementary technologies. This should help understand how the uncertainty is reduced by entrepreneurs exploring new technologies and applications.
<i>Market formation</i>	both the actual market development (i.e. market phase) and the drivers for market formation (i.e. institutional stimuli).
<i>Legitimation</i>	the value base in industry and society and the institutional alignment of the new technology. This could be done by verifying how legitimacy influences demand, legislation and firms' behavior.
<i>Resource mobilization</i>	how the TIS manages to mobilize competence/human capital, entrepreneurship, management and finance, financial capital and complementary assets (e.g. complementary products, services, network infrastructure, etc).
<i>Materialization</i>	the development and investment in artifacts such as products, production plants and physical infrastructure.
<i>Development of positive externalities</i>	external economies that solve uncertainties, increases in political power, improved legitimacy, guidance of new entrants and knowledge flow. This function strengthens the other <i>functions</i> and can be an indicator of the overall dynamics of the system.

Source: Based on Bergek et al. (2008a) and Bergek et al. (2008c).

⁵ In other words, there is no clear “recipe” that dictates the exact configuration and attributes of the structural components in a well performing innovation system.

⁶ This section aims at familiarizing the reader with common terms used throughout our thesis; therefore, we will not examine in detail these functions. For further information about the eight functions see Bergek et al., 2008a : 414-419.

The *functions* are interdependent of each other, and are influenced by the structural components as well as by exogenous factors. For instance, strong political *networks* can achieve the alignment of *institutions* needed to increase legitimacy of the technology. This may in turn, strengthen the function of direction of search. Furthermore, some examples of exogenous factors affecting the functions are EU-Directives and economic crises.⁷

2.2. Phases of development and *blocking mechanisms*

The TIS literature focuses on two main phases in the evolution of a product or an industry—the *formative phase* and the *growth phase*.⁸ In the former phase, the TIS is in the process of formation and is characterized by many competing designs, small markets, high uncertainty, many firms entering the system and a very long time span (Bergek and Jacobsson, 2004). Furthermore, one can expect some *functions* in the *formative phase* to be weak (e.g. legitimacy, market formation and positive externalities).

After this *formative phase*, the TIS may “change gears” and enter into a period of market expansion. This *growth phase* is characterized by virtuous circles that lead to a self sustained growth of the system. According to Jacobsson and Bergek (2004), the condition under which the TIS “change gear” is difficult to predict, and there is a high risk that a new technological system develops very slowly or in a stunted way. In such a case, the system may experiment weaknesses that can lead to “system failure”, i.e. a system that fails to develop (Bergek et al., 2008a). The functional approach is a way to systematically analyze these weaknesses and identify mechanisms blocking the system development.

2.3.A firm in the TIS

A single firm has little chance of succeeding in the introduction and diffusion of an innovative technology without the support of other *actors* and its context. A firm is not working alone but it is embedded in an innovation system that aids and constrains the development and diffusion of its new technology. Therefore, the innovation and

⁷ Exogenous factors are those related to the “landscape” in the multilevel framework.

⁸ The TIS framework takes the concept of “phases” from the life cycle framework.

diffusion process is actually both an individual and a collective act (Jacobsson and Bergek, 2004). As Van de Ven (2005) says:

“Collective action is necessary to build and sustain an industrial infrastructure that makes it possible for individual firms to succeed and prosper. The structure of these *networks* where innovation takes place is collective achievements involving numerous *actors* from public and private sectors who pursue their different partisan interests and roles in constructing the infrastructure.”

The TIS approach is a meso-level perspective strongly rooted at a micro-level⁹, i.e. the *actors* are assigned a key role in innovation systems analysis. This approach acknowledges that a single actor can change (parts of the) structures around him, thus forcing technical change in new directions (Hekkert et al. 2007). That is to say, a single actor can deliberately influence the development of a TIS by fulfilling several important *functions* during its evolution.

More specifically, the innovation literature emphasizes the importance of firms in the evolution of a TIS. For a technological opportunity to be realized, some key firms need to respond to it by participating in the development and diffusion process. Moreover, in the case that the new technology is competing with established technologies and TISs, these firms need to actively take part in shaping the innovation process (Bergek, 2002).

Thanks to the role assigned to individual *actors* (firms), the TIS approach can be regarded as a potential way to connect the micro-level theory of firms' behavior with system dynamics (Coenen and Díaz López, 2009). Bergek et al. (2008b) suggest that the functional approach is useful to identify means of speeding up the diffusion of a technology that has been defined as desirable by a relevant actor. In other words, this approach can be used to identify mechanisms blocking the development of a TIS that a firm could address in order to speed up the diffusion of a certain technology. However, one must not forget that it is the system's dynamics that finally determines the direction and the outcome of the system.

⁹ Meso-level perspective looks at the innovation system or the context that surrounds the firm and the micro-level perspective looks, for example, at an individual actor.

3. Method

This section describes the method followed throughout the thesis. Since our research questions are basically constituted of “what” and “how” questions we chose a case study, which according to Yin (2003) is appropriate to examine this type of questions. A case study is an empirical inquiry used to investigate a contemporary phenomenon within its real-life context, especially when the boundaries between phenomenon and its real-life context are not clearly evident (Yin, 2003).

This section begins with the description of our data collection and continues with a step-by-step approach to analyze innovation systems. We use it to identify strategic issues and develop business strategy recommendations.

3.1.Data collection

The case study is based on data from different sources:

- Literature review of documents and archival records such as written reports, formal studies, news papers clipping, articles, slides, maps and charts. These documents were obtained from Volvo Truck and other firms, Energy Agencies, European Union, universities, interest organizations, consultants and research institutes.
- Interviews with guided conversations.
- Direct observations, such as conferences and field visits.

Literature review

As a starting point we used the literature review to familiarize us with the dual-fuel engine and its complementary technologies. Then, we used the available information from the aforementioned sources to identifying previous and ongoing projects related to the technology in focus and its complementary technologies. Specifically, we reviewed projects in Europe related to the fuel¹⁰ (including bio-methane production and LNG/LBG filling stations) and the engine (dual-fuel engine development and

¹⁰ With the fuel we refer to liquefied methane from fossil and renewable sources, i.e. liquefied natural gas and liquefied bio-methane. In the case of liquid bio-methane we explored both first and second generation bio-fuel.

commercialization). We limited our scope by studying in depth only those projects related to the use of these technologies for road transportation.¹¹

The literature review about projects helped us identify some structural components of the TIS and gave us some inputs for the functional analysis.

Interviews

We performed a set of interviews consisting of telephonic and face-to-face conversations to collect data from 15 key *actors* in the European dual-fuel truck TIS. We documented our interviews by recording them and by writing a report which includes a summary of the interview and conclusions.¹²

The purpose of the interviews was to obtain information about the structure and the *functions* of the TIS. After the literature review, the key *actors* in our TIS were classified into four categories:

- 1) LNG/LBM related firms
- 2) dual-fuel trucks related firms
- 3) public bodies
- 4) other organizations (e.g. research institutes, universities, standard organizations).

From the first category, we chose to interview firms through the whole value chain (e.g. LNG or LBG producers, distributors, filling station owners, etc). From the second category, we selected key *actors* in the development of the new dual-fuel trucks (e.g. dual-fuel engine developers, users, etc). Further, for the rest of the categories we chose to interviewed *actors* that could provide us with a European perspective.

The questions for these interviews were designed in order to identify further key *actors* and structural components in the TIS, and to understand the actor's activities in relation to the eight function of our TIS.

¹¹ Other projects not related to road transportation (e.g. ship transportation) were also examined to identify key actors and drivers in other complementary and competing TISs. However, we did not study these projects in depth.

¹² Annex A.8 contains a complete list of interviews and contacts made during the thesis work. The first 15 contacts correspond to our interviewees. Another 12 persons have been contacted, either by phone or face-to-face, in order to obtain information about the dual-fuel truck TIS.

All these interviews were semi-structured in order not to miss important topics. The questions were open-ended and the interview was flexible and exploratory; more like a guided conversation.¹³ In addition, the questions were different for each interviewee, i.e. they were based on the nature of the actor.

3.2. Step-by-step method

The step-by-step approach used in this thesis was developed by Bergek et al. (2008a) who suggest a number of steps to follow in order to systematically analyze a TIS and identify relevant issues that hinder or enhance the diffusion of a new technology. This step-by-step scheme of analysis is presented below:

Step 1. This step consists on defining the TIS in focus. In this thesis, we made three key choices, first, to focus on a new product: the dual-fuel truck running on liquid methane gas¹⁴. Second, we limit our study and analyze the use of the dual-fuel trucks for long-haul and regional freight transportation. Third, we chose Europe¹⁵ as the spatial domain of analysis.

Step 2. In this step we identify the structural components of the TIS (*actors, networks, institutions and technology*). In addition we identify the exogenous factors influencing the development of the system.

Step 3: In this step we describe the *functional pattern* of the TIS in focus, i.e. describe how each function is currently fulfilled in the system. However, this description does not tell us whether the TIS is well functioning or not.

Step 4: In this step we assess how well the *functions* in our TIS are being performed.¹⁶ To achieve this we compare the current TIS *functional pattern* to an “ideal” standard of system dynamics: “desirable pattern”.¹⁷

¹³ In practice we adapted each interview to the situation and the interviewee’s talkativeness.

¹⁴ Volvo Truck requested us to study the introduction of their new dual-fuel truck running on LNG and LBG: Volvo FM 13 litres with LNG/LBG tank system.

¹⁵ Even if the TIS is global in character we chose to focus in Europe because of the question raised by Volvo Truck Corporation: how to achieve a successful introduction of this new product in the European Market. However, our analysis considers global components without explicitly assigning a section to this topic.

¹⁶ For a new product/technology to diffuse, all the aforementioned functions need to be fulfilled to some degree (Bergek, 2002). Nevertheless, if a particular function is weak (not fully fulfilled) does not always constitute a problem. In the same way, a strong function is not always an important asset (Bergek et al., 2008a). Therefore, there is a need to assess the functionality of our TIS using a “desirable pattern”.

¹⁷ It is important to mention that this step is normative, i.e. we base the assessment on our own perception of how the system should be functioning.

Bergek et al., (2008a) suggest using the development phases of a TIS to describe a “desirable pattern” and use it as a base for the functionality assessment. Therefore, we analyze the *functional pattern* of our TIS with respect to the requirements of each phase.

First, we identify if the TIS is currently going through a *formative phase*. For this purpose, we use the indicators presented by Bergek et al., (2008a: 419) and evaluate if the *functional pattern* obtained in Step 3 presents some of the *formative phase* characteristics. Second, in the case that our TIS is going through a *formative phase*, we will define a “desirable pattern” based on the *growth phase* requirements. Third, we raise the question whether our current TIS *functional pattern* matches the need of the “desirable pattern”. Finally, we assess how our TIS should develop to achieve the “desirable pattern”, i.e. how our system can reach a higher functionality (a transition to a *growth phase*).¹⁸

Step 5: In this step we identify weaknesses in the *functional pattern*. By analyzing these weaknesses we should be able to find out what is holding back a transition to the *growth phase*. As a result, this step will yield a list of *blocking mechanisms* related to the dual-fuel truck TIS.

According to Bergek et al., (2008b), after completing a functional analysis, relevant issues for firm strategy are readily definable.

Step 6: In this step we will evaluate the list of *blocking mechanisms* presented and determine how these could be addressed by Volvo Truck. In other words, we will develop strategy recommendations for Volvo Truck taking into consideration its current role in the TIS and some of the firm specific characteristics.

¹⁸ This step represents an analytical procedure only. It is not presented as one specific section on the report.

4. Structural components of the dual-fuel truck TIS and its exogenous factors.

This chapter contains a description of the structural components of our TIS and the exogenous factors influencing the development of our system. We aim to give an understanding of the current state of the dual-fuel truck in the European market and to identify the lack of structural components hindering the development of the system. The chapter starts with a description of the two main artifacts (i.e. dual-fuel truck and liquid methane as a vehicle fuel). It continues with the key *actors*, *networks* and *institutions* driving the development and diffusion of this product and its complementary technologies. Finally, we describe the main exogenous factors that are also influencing the development of the system.

4.1. The technology: vehicle-fuel system

A characteristic of the transportation system is that it requires a number of technologies to co-develop. In particular it requires the simultaneous use of two interlinked and compatible artifacts (i.e. vehicles and fuels) which constitute the vehicle-fuel system. This section aims at familiarizing the reader with these two artifacts.

Figure 1 portrays the vehicle-fuel system for the technology in focus comprising the dual-fuel truck and its fuel, liquid methane. Each blue box in the figure shows one “link” in the whole value chain of the artifacts, such as raw material supply for fuel production. The figure represents a simplification of the fuel and vehicle value chain.

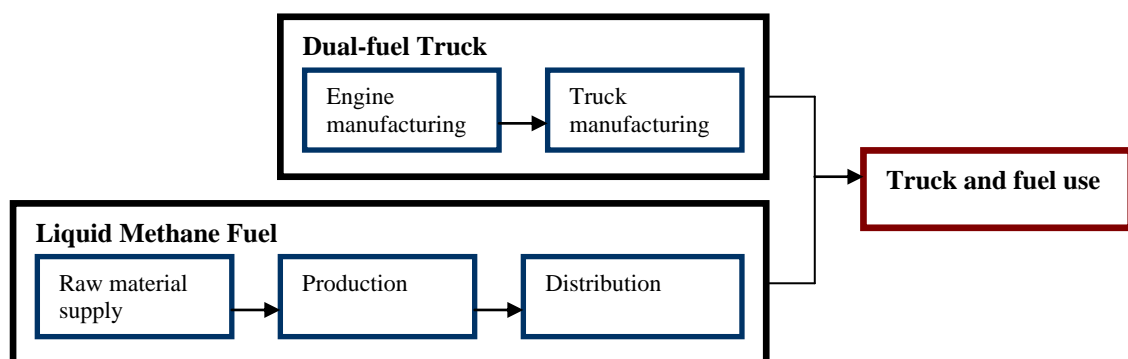


Figure 1. Vehicle-fuel-system.

It is important to notice that the vehicle-fuel-system is part of a wider road transport system which also includes, for example, the road and traffic systems. However, we will not regard these related systems in our study since we consider them less relevant.¹⁹

The dominant artifacts for road freight transportation are heavy duty vehicles (HDVs) fuelled by diesel.²⁰ According to AEA (2011), HDVs are estimated to account for around 26% of all CO₂ emissions for road transport in the EU. More specifically, HDVs consume ~3200 PJ of (predominantly diesel) fuel and generate direct emissions of ~240 Mt CO₂. Of this, over 85% is due to trucks, and the rest to buses and coaches. Further, AEA (2011) analysis highlights the importance of long-haul and regional distribution activities in total energy consumption and emissions. These account for around 37% and 14% of all the HDV fuel consumption respectively. Therefore, in order to solve the abovementioned environmental problem, innovative solutions for long-haul and regional freight transportation are needed.

There are three main options to reduce GHG emissions in heavy duty vehicles: alternative powertrains, energy efficiency measures in conventional powertrains (i.e. Otto and diesel engines) and alternative fuels.

Regarding alternative powertrains, there are two technically available solutions: dual-fuel engines and electric engines (AEA, 2011). Electric powertrains are currently not an economically feasible option for HDVs, leaving the dual-fuel engine as the only current commercial alternative powertrain (Interview Boisen, 2011).

Regarding conventional engines, there have been incremental improvements to the Otto and diesel engine performance of HDVs (e.g. fuel efficiency and emission) (Lejeune, 2011). Conventional engines have also been adapted to run on alternative fuels; nevertheless, their use for regional and long distance transportations in Europe is very limited mainly due to the lack of refueling infrastructure (AEA, 2011). The most common alternative fuels for HDVs is methane, which has been mainly used in compressed form in Otto engines.²¹ However, the use of compressed gas limits the operational range to around 200 km making it unsuitable for long distance

¹⁹ We consider the road and traffic systems less relevant since we will not study a reconfiguration of the whole transport system. We make the assumption that these related systems remain without significant change.

²⁰ HDV are vehicles with gross weight of at least 12,000 kilograms.

²¹ Some of these alternative fuels include: natural gas, bio-methane, biodiesel, methanol, ethanol, DME, synthetic diesel and hydrogen.

transportation. Therefore, liquid methane has become an interesting option since it has higher energy content than compressed gas (Interview Mårtensson, 2011; Interview Boisen, 2011). Its energy content is 2.3 times higher than compressed methane and it is comparable to diesel.²²

The combination of the dual-fuel engine and liquid methane has the potential to increase the truck operational range to 800 km (Volvo Truck Material, 2011a). This is due to the higher fuel efficiency of the dual-fuel engine (compared to the Otto engine) and the high energy content of liquid methane (Interview Pilskog, 2011).²³ Additionally, dual-fuel trucks running on liquid bio-methane have approximately 70% lower CO₂ (tailpipe) emission compared to conventional diesel trucks (Volvo Truck Material, 2011a).

The dual-fuel truck

The dual-fuel technology is based on the diesel technology; however, it enables a diesel engine to run on methane gas using diesel as a spark plug (Interview Franzén, 2011). These engines work with a small amount of diesel injected into the cylinders and ignited by compression, which in turns ignites the methane gas/air mixture. Although diesel and methane burn simultaneously in the engine, the vehicle has two independent fuel systems; in other words, it has both a diesel tank and a methane tank (Interview Franzén, 2011). Furthermore, some of these trucks have the ability to run on 100% diesel which reduces the risk for users to run out of methane fuel.²⁴ The typical level of diesel substitution is 50% to 90% gas (AEA, 2011).²⁵ These substitution rates vary depending on the level of system integration and the engine operating point, i.e. vehicle duty cycles.²⁶ CO₂ reduction benefits are very dependent on the level of gas substitution and tend to be higher with long haul than with urban cycles (AEA, 2011).²⁷

The dual-fuel truck can follow different *trajectories to market*. Understanding these *trajectories* is particularly important for this technology since the dual-fuel truck has not

²² This estimation was done using LNG energy content as 21 MJ/liter, CNG energy content as 9 MJ/liter and the diesel energy content as 34 MJ/liters.

²³ The combination of diesel engine, turbocharger, and intercooler offers high efficiency performance: approx. 45% for highly demanding transportation such as HDV. In contrast, the Otto engine offers approx 30% efficiency which means 50% higher fuel consumption than diesel trucks (Interview Pilskog, 2011).

²⁴ Note that these trucks cannot run on methane alone, the diesel is needed to ignite the gas.

²⁵ An average of 70% is representative for fleet operation (NSCA, 2006).

²⁶ That is to say, engine efficiency depends on the use of the truck. Continuous, long distance duty cycles with heavy loads increase the benefits of this new technology (Interview Landin, 2011).

²⁷ The substitution rate increases as the vehicle is used for long distance.

reached the market in a conventional way. So far, most of the dual-fuel trucks have not been sold directly by OEMs.

Figure 2 summarizes the possible *trajectories* to design, produce, certify and finally sell a dual-fuel truck in the European market. These *trajectories* are presented in the following paragraphs.

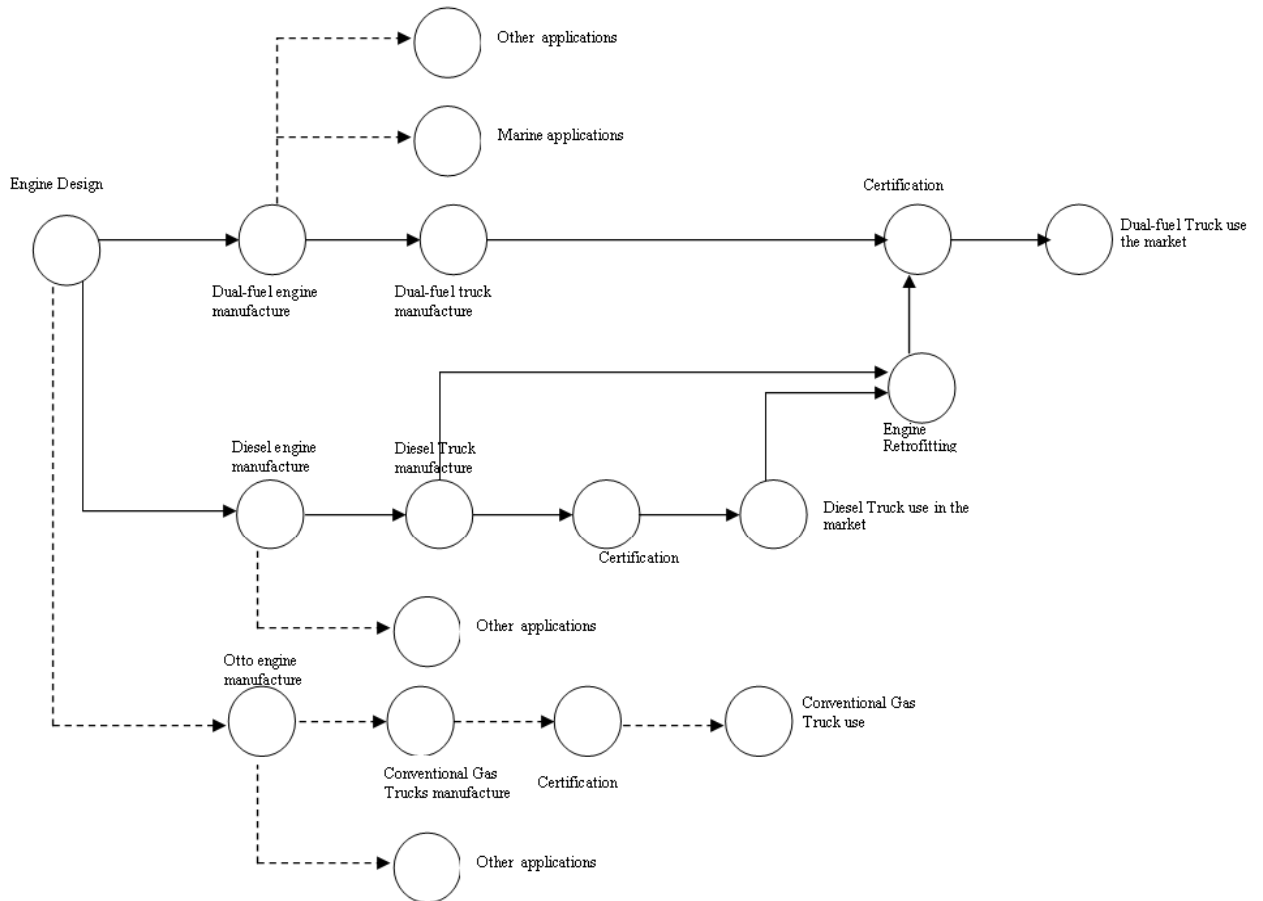


Figure 2. Dual-fuel truck trajectories to market.

Three entities are involved in the different activities: OEMs, system suppliers and certification bodies. The OEMs could be responsible for engine design, vehicle manufacture (including body manufacture and engine manufacture) and engine retrofitting. System suppliers could be in charge of engine design, engine manufacture and engine retrofitting. Certification bodies are organization that award vehicle certifications²⁸, however; it is the OEMs and the system suppliers who are responsible for obtaining this certification.

²⁸ A certification body is accredited by an authorising body to award and withdraw certifications.

The two main internal combustion engines manufactured for HD trucks are the diesel engines²⁹ and the Otto engines³⁰ which are designed and manufactured by OEMs. Both engines are manufactured and assembled in a truck. Then, the truck is certified and introduced in the market.

In the case of the dual-fuel trucks, the *trajectories to market* are not so straightforward. These trucks can follow three different *trajectories*. The first trajectory is pretty linear and similar to the diesel and conventional gas engine trajectories described above involving a full integration of the dual-fuel technology in the truck since the design stage.³¹ In this trajectory a dual-fuel engine is designed and manufactured by a system supplier and/or an OEM. Then this engine is assembled in a dual-fuel truck by the OEMs and finally the truck is certified and introduced to market under the OEM's brand.³² Although expected, this is not the path that dual-fuel trucks are currently following.

In the second and third *trajectories*, a conventional diesel engine is retrofitted to become a dual-fuel engine. Retrofitting refers to adding the new dual-fuel technology to the conventional diesel engine. These retrofitting systems are currently developed as "bolt on" technologies that can be added or removed when necessary (Seisler, 2010b). In the second trajectory, a diesel engine is designed, manufactured and assembled in a conventional diesel truck by an OEM. However, this truck does not reach the market until it is retrofitted by a system supplier. Finally, this truck is certified and sold as a dual-fuel truck by an OEM. The third and last trajectory consists on an aftermarket retrofitting, which is the main source of dual-fuel trucks in Europe today. In this case an OEM sells a conventional diesel truck which is used as a diesel truck until it is taken back to a retrofitting facility to be converted. This aftermarket retrofitting is currently done by system suppliers.

²⁹ In a diesel engine the fuel is injected into the cylinders in which it mixes with air and is ignited by the heat generated when the pistons compress the fuel/air mixture, and this engine is often known as a compression-ignition engine (EDD,2000)

³⁰ The characteristic feature of the Otto engine is that an electric spark from a spark plug ignites a mixture of fuel and air, and this is thus known widely as a spark-ignition engine. (EDD,2000)

³¹ In this case the system is integrated into the engine therefore not removable. One of such technologies is the Wesport system HDPI (high pressure direct injection). In this system approximately 95% replacement of diesel with natural gas/LNG is achieved. Further in this system, the "diesel-only" operation is not an option because the diesel injectors are too small (Interview Boisen, 2011).

³² Nowadays, dual-fuel systems are being developed specifically for and in conjunction with major OEMs and are sold to customers as a factory-built vehicle (Seisler, 2010b).

Even though the technology is available and has environmental benefit regarding CO₂ emissions, the dual-fuel trucks have not been widely diffused on the European market. There is still great uncertainty on the future large scale application of dual-fuel engines (e.g. in ships, truck, tractors, electricity generation). Although there are currently some dual-fuel trucks on the European market, there are no clear statistics on the world-wide population of dual-fuel vehicles.³³

Liquid methane as vehicle fuel

This section provides an overview of liquid methane *trajectories to market*, from the raw material supply to the final use in refueling stations. Liquid methane can originate from fossil resources (i.e. liquid natural gas or LNG) or renewable sources (i.e. liquid bio-methane or LBM). Currently, the dual-fuel truck uses LNG as a fuel; therefore, our main focus is LNG. Further information about LBM can be found in Annex A.1.

Liquid natural gas (LNG) could come from many different countries and follow different trajectories to reach the LNG filling stations (See Figure 4). First, natural gas is extracted by oil/gas companies in countries with gas reserves.³⁴ This gas is processed at the extraction site. The processed gas can follow two different paths: liquefaction and transportation by ship, or pipeline distribution.

The larger part of NG imported to Europe follows the second path, i.e. approximately 98% of the imports to Europe are via pipeline (EU, 2008a). Industry and heat and power production plants can use this gas directly from the pipeline. Furthermore, CNG filling stations use pipeline gas compressed to 200 bars as a transport fuel (Interview Berggren, 2011). Alternatively, pipeline gas could be used in LNG filling stations if previously liquefied in a small scale liquefaction plant (Interview Marhaug, 2011). Although technically possible, this latter trajectory is not followed in Europe.

The remaining 2% of European NG imports comes in LNG deliveries by ship or truck (EU, 2008a).³⁵ As shown in Figure 4, once the LNG ship arrives to a European

³³ However, according to some “company claims” there are around 3000 dual-fuelled road vehicles in the market. The inventory is difficult because internationally there is confusion between bi-fuel gaseous vehicles and dual-fuel diesel systems (Seisler, 2010).

³⁴ For instance Russia, Norway and Algeria.

³⁵ In 2007, the countries exporting LNG to the European Union were: Qatar, Algeria, Nigeria, Trinidad & Tobago, Egypt, Oman, Libya and Norway (Kavalov et al, 2009). LNG is imported by trucks only in the case of Norwegian origin and Northern Europe destination, such as Norway to Sweden deliveries.

receiving terminal it is discharged and stored in cryogenic tanks in liquid form.³⁶ At this point, LNG could be regasified and injected into the natural gas grid (Kavalov et al, 2009).³⁷ However, when LNG is used directly as a vehicle fuel, it is transported in liquid form from the receiving terminal to the filling station (Interview Murugó, 2011).³⁸ In that case, LNG is distributed by trucks and discharged into a cryogenic tank at the filling station. As shown in Figure 4, LNG could also be delivered to peak-shaving storage facilities³⁹ or to remote areas without access to the natural gas grid (Kavalov et al, 2009).

The LNG supply chain tends to be more energy and GHG intensive than the supply chain for pipeline gas because of the extra processing steps (Kavalov et al, 2009). See figure below.

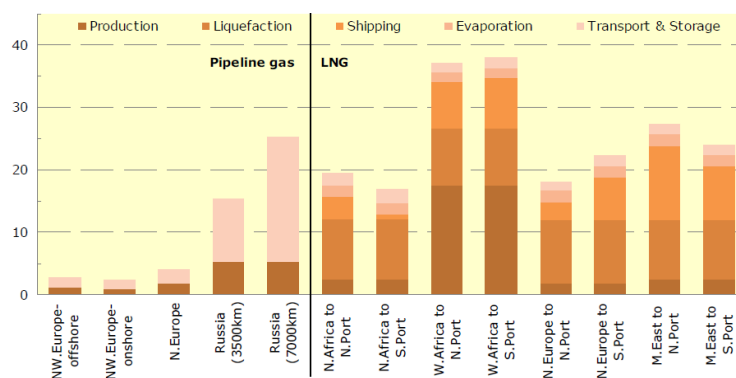


Figure 3. GHG balance of LNG and pipeline supply chain, gCO₂-eq emitted to deliver 1MJ of gas. Source: B. Kavalov et al, 2009.

LNG could be environmentally preferable (to pipeline gas) if it is supplied to remote areas or used in liquid form by the end-users. An additional advantage of LNG compared to pipeline gas is its higher purity, methane and overall energy content (Kavalov et al, 2009).

Coming back to Figure 4, when natural gas is used as vehicle fuel it is important to know that there are different types of filling station. Three main filling station

³⁶ There are 19 import terminals around the European coast. Further, the EU plans to enlarge this LNG infrastructure with four new import terminals under construction and 32 more are under consideration (GIE, 2010).

³⁷ Regasification of LNG at the import terminals to distribute NG through pipelines constitutes the most common practice in Europe.

³⁸ It is worth noting that once NG is liquefied its composition cannot be modified without regasifying and treating it in gas form. Therefore, LNG dispensed in filling stations has the same composition as it had at the receiving terminal without any treatment in between.

³⁹ An LNG peak-shaving facility is used to store surplus natural gas needed to meet the requirements of peak consumption later in the year.

configurations have been identified: CNG stations supplied by pipeline gas, LNG stations supplied by LNG storage tank and L-CNG (liquefied to compress natural gas) stations supplied by LNG storage tanks. The latter can exclusively supply CNG or can incorporate both LNG and CNG dispensers.⁴⁰ Traditionally, L-CNG stations supply CNG to remote areas without access to the gas grid (Vanzetti, 2011). In Europe, we identified 19 filling stations supplying LNG which are listed in Annex A.5.

Even though the dual-fuel trucks are currently using LNG as a fuel it can also run on liquid bio-methane (LBM). Today, only first generation bio-methane is commercially available while second generation remains at demonstration state.

First generation bio-methane is produced by anaerobic digestion of organic matter in landfills or bio-digesters. Some biogas producers are incorporating upgrading and liquefaction facilities at their production site in order to produce liquid bio-methane. A driver for biogas producers to liquefy their production is that LBM can be transported efficiently by truck when gas pipelines are not available thus, having the possibility to expand their market (Interview Leaf, 2011) We identified one LBM production plant in UK and six projects in Sweden that aim at incorporating upgrading and liquefaction into the biogas production to supply LBM filling stations.⁴¹ Liquefaction and upgrading are currently the most expensive steps in the LBM production and also the most active areas of research (Pettersson and Wellinger, 2009).⁴²

Second generation bio-methane refers to methane gas produced by thermal gasification of biomass (e.g. forestry residuals). Four relevant bio-methane projects have been identified in Europe⁴³. Those projects are taking place in Austria, Germany, the Netherlands and Sweden. They develop gasification technology and test upgrading processes to produce bio-methane. According to our research none of them have integrated the liquefaction unit yet (See Annex A3).

In summary, currently the few liquid methane dual-fuel trucks are running on liquid natural gas. LNG is widely accessible in Europe; this accessibility can be measured in terms of LNG import terminals since the EU does not have indigenous production of LNG. However, the refueling infrastructure to use LNG for vehicles is very limited. In

⁴⁰ Some sources name this type of refuelling stations L-CNG +LNG.

⁴¹ A list of LBM production plants in Europe can be found in Annex A.4.

⁴² For further information about bio-methane see Annex A.1.

⁴³ There are other gasification projects that aim at developing liquid bio-fuels such as DME.

regards to LBM, the availability of this fuel for trucks depends on future integration of upgrading and small scale liquefaction technology in biogas production plants. Further, second generation liquid bio-methane is not currently a commercial option (Interview Boisen, 2011). Finally, a future application of liquid methane is uncertain since it could be used for other sectors such as chemical industry or power generation.

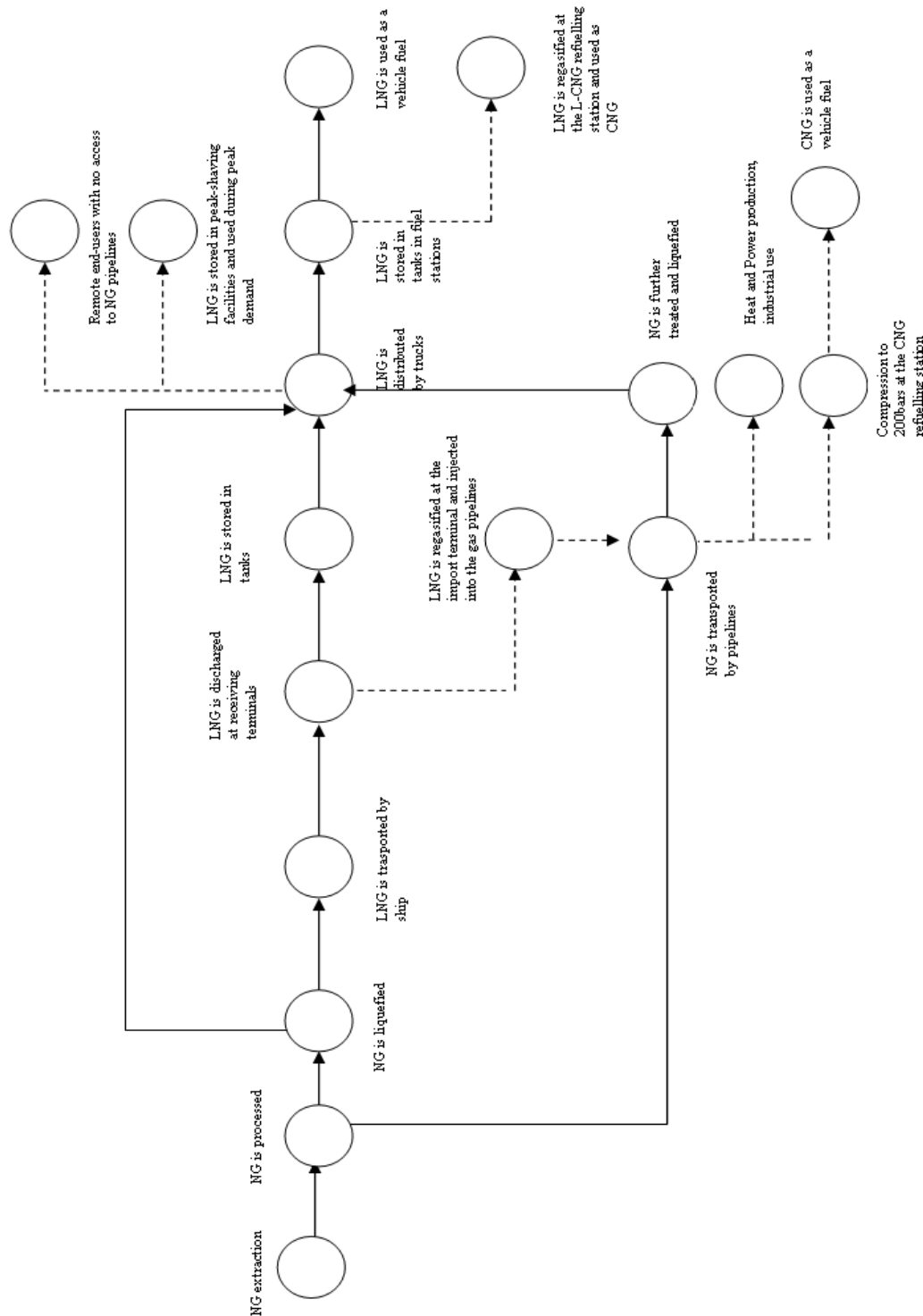


Figure 4. LNG trajectories to market.

4.2. *Actors, networks and institutions.*

So far the technology has been described in terms of its two main artifacts. The rest of the TIS elements (i.e. *actors*, *networks* and *institutions*) are summarized in Table 2 and are described in this section. First, we address *actors* and *networks* which are stocks and structures building up each one of the “links” (blue boxes) in the truck and fuel value chains (Figure 1). There are also *actors* not directly located in a “link” of the value chain but still part of the TIS, such as public bodies and universities. Second, we address the *institutions* or the “rules of the game” regulating the interaction between *actors*.

Table 2. Elements of the TIS (stock and structures).

<p><i>Actors</i></p> <p>Dual-fuel trucks related firms: Westport, Clean Air Power, Hardstaff, Volvo, MAN, DAF, Mercedes-Benz.</p> <p>Users: Renova, Götene Kyltransporter, DHL, HAM, Transportes Monfort, Gasnor, Wiseman dairies, Sainsbury’s, etc.</p> <p>LNG/LBG related firms: FordonsGas, AGA (Linde Group), Cryostar, HAM, Chive Fuel, Statoil, Nordic LNG, Rolande LNG, NexGen, Terracastus, Gasrec, waste and water treatment companies, SGtS, E.ON, Göteborg Energi, etc.</p> <p>Public Bodies: Swedish Energy Agency, European Union, Generalitat de Valencia., IDAE, Energy Saving Trust, Dutch Ministry of Economic Affairs, etc.</p> <p>Other organizations: Vienna University of Technology, Paul Scherrel Institut, Loughborough University Chalmers, NGVA, ISO, CEN, Business Region Göteborg, etc.</p>
<p><i>Networks (formal and informal)</i></p> <p>Lobbying groups, university-industry <i>networks</i> (gasification projects), truck demonstration programs, filling station projects.</p>
<p><i>Institutions (rules)</i></p> <p>Legislation, regulations and standards, perception, beliefs and expectations.</p>

Actors and networks.

To provide a better understanding of the TIS structure, the *actors* and *networks* are shown in Figure 5 which represents a “snap-shot” of the current state of the TIS. This diagram portrays *actors* involved in the innovation process and the interactions between the TIS in focus, established sectors, other TISs and external factors. The central circle represents the boundaries of the TIS in focus which is surrounded by a number of competing and complementary TISs that influence the development of our system (Sandén and Hillman, 2011).

Outside the TIS boundaries, we identified that the conventional gas truck TIS and the LNG ship⁴⁴ TIS are relevant systems competing and complementing our dual-fuel truck TIS. In other words, the LNG ships and conventional gas truck can substitute a dual-fuel truck for freight transportation. However, they can also help develop the LNG infrastructure. For instance, part of the LNG infrastructure in Norway has been driven by ships, which are subjected to stringent emission regulation (Interview Marhaug, 2011).⁴⁵ This is raising ship owners’ interest in LNG as a maritime fuel since it is cleaner than the common fuel for ships, i.e. heavy fuel oil.

Additionally, other countries such as the United State are also developing the dual-fuel technology and its infrastructure. The US dual-fuel truck TIS is influencing the European homologous in several ways. First, due to its later state of development, the US’s TIS might increase expectations about the dual-fuel technology among European *actors* (Interview Murugó, 2011). Second, US is transferring technology to Europe. For instance, some *actors*, such as Westport, are present in both TISs which are transferring knowledge to the European TIS and some European firms are testing their technology in the US in collaboration with other American firms (Beyer and Brown, 2009).

Inside the TIS boundaries, we identify a number of truck and fuel related *actors*. Regarding truck related *actors* we find two types of firms: OEMs such as Volvo, MAN, and Mercedes, and system suppliers such as Westport, Clean Air Power and Hardstaff. In addition, MAN supplies dual-fuel engines for marine applications and Wärtsilä for ships, CHP and electricity production.

⁴⁴ The LNG ship TIS has as central technology ships running on LNG. This must not be confused with LNG cargo vessels.

⁴⁵ In particular, due to sulfur and NO_x limits in the so-called SECA areas in the North Sea and Baltic Sea (Interview Marhaug, 2011).

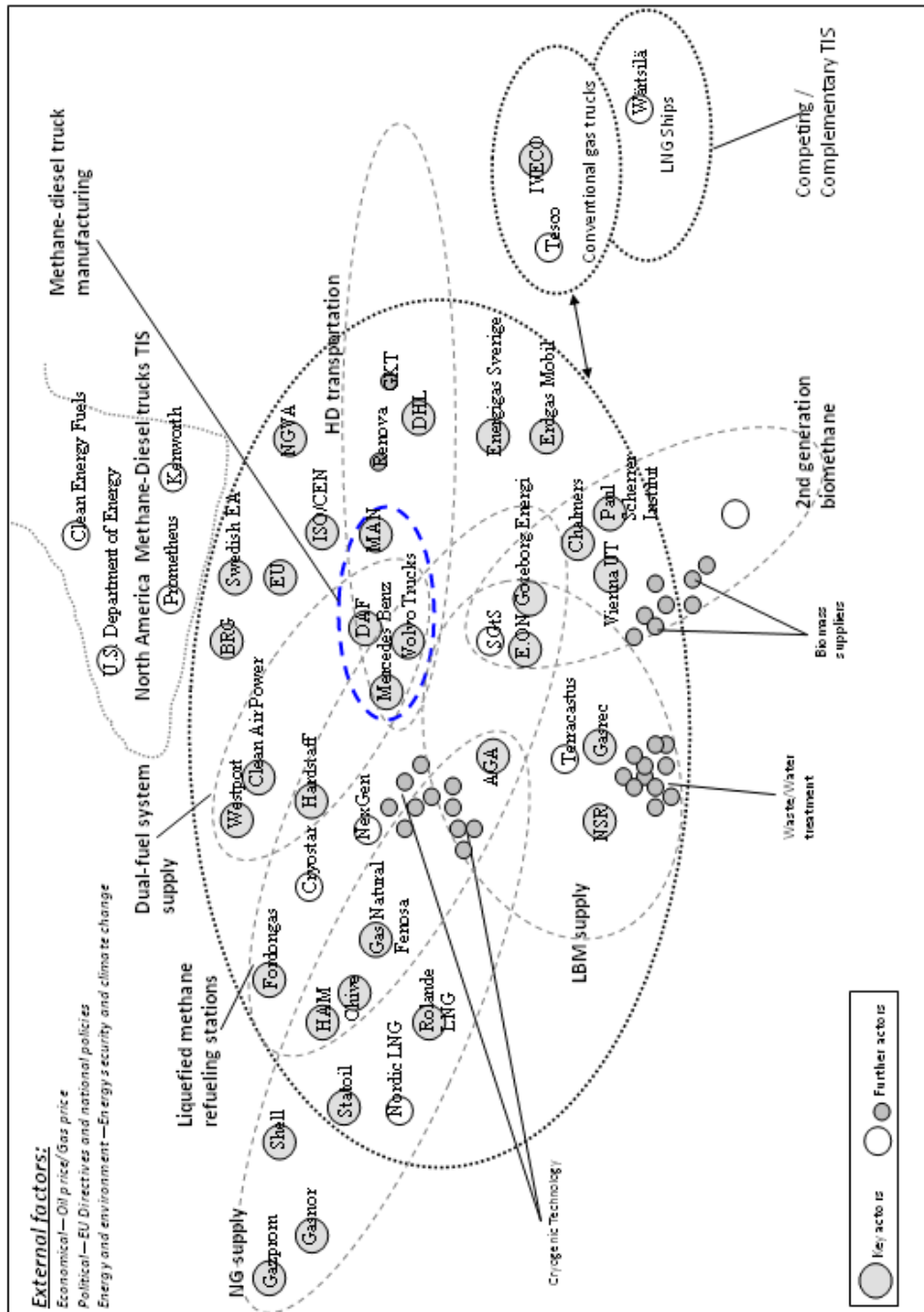


Figure 5. Map of actors' configuration of the European dual-fuel truck TIS.^{44, 45}

⁴⁶ Markard et al. (2009) present a similar picture for the biogas TIS in Switzerland.

⁴⁷ The figure should be read in terms of actors; thus, an actor in an overlapping area is performing activities related to the different niches/established sectors overlapping. For instance, if the second generation bio-methane oval overlaps with liquid methane filling stations oval, it means that the actors in the overlapping area are working on both activities. This should not be interpreted as if second generation bio-methane is being supplied to a filling station.

The main automotive LNG dual-fuel engine developers in Europe are system suppliers such as Clean Air Power and Hardstaff (Bäckström and Jonsson, 2008). They are establishing relationships with OEMs that can be categorized as learning *networks*: system suppliers are transferring the dual-fuel technology to OEMs (Interview Landin, 2011). These relationships are as follows: Westport works with Volvo; Clean Air Power works in collaboration with Paccar⁴⁸ and Volvo; and Hardstaff collaborates with Volvo and Mercedes-Benz (NGV, 2009; CAP, 2006; Mercedes-Benz, 2011).

Currently, there only three OEMs offering the dual-fuel trucks under their brand: Volvo, Mercedes-Benz and MAN.⁴⁹ The major part of dual-fuel trucks in the European market are retrofitted diesel trucks (Bäckström and Jonsson, 2008). Some customers of LNG dual-fuel trucks (including aftermarket conversion customers) are DHL, HAM, Wiseman dairies and Sainsbury's.

Regarding fuel related *actors*, we identified that firms constructing LNG refueling infrastructure are crucial for the evolution of the TIS. These *actors* often coordinate with truck related firms for the construction of filling stations. There are three types of *actors* involved in these projects:

- National/regional gas distributors such as FordonsGas in Sweden, Chive Fuels in UK, HAM in Spain and Rolande LNG in the Netherlands, which buy LNG from receiving terminals.
- National and/or regional public bodies such as Swedish Energy Agency, IDAE in Spain and the Dutch Ministry of Economic Affairs co-financing the infrastructure.
- Equipment and components suppliers. In regards to equipment suppliers, companies such as Cryostar and AGA provide the cryogenic technology that is characteristic of such filling stations (Interview Andersson, 2011). In regards to components suppliers, there is a lack of specialized *actors* (e.g. nozzles suppliers). Therefore, the filling station components must be specifically designed and become rather expensive (Interview Berggren, 2011). Additionally, the filling stations need further refinement in order to become

⁴⁸ Clean Air Power works with a division of Paccar Ltd. called Foden Trucks.

⁴⁹ Mercedes-Benz's and MAN's dual-fuel truck are local solution for the UK and Holland respectively.

more “user friendly”. This can be done by learning from customer’s feedbacks (Interview Berggren, 2011).

Other fuel related *actors* are biogas producers such as Gasrec in UK which are incorporating upgrading and liquefaction facilities at their production site. There are still few biogas producers selling liquid bio-methane in Europe. Regarding second generation bio-methane, the related *actors* involved are mainly universities and research centers that establish relationships with industry to develop gasification projects.

Networks in our system are mainly informal which were identified through discussions with industry experts: active communication between interested parties is frequent. In regards to formal *networks*, collaboration between *actors* from the fuel (LNG or LBM) industry and vehicle industry exist in the form of joint projects. The strong *networks* between fuel and truck related *actors* results in the materialization of the LNG/LBG refilling infrastructure which in many cases was coordinated with the launch/test field of LNG trucks. These *networks* were identified in four countries where the dual-fuel truck TIS is emerging: Sweden, UK, Spain and the Netherlands.

Figure 6 summarizes the current LNG/LBM infrastructure and trucks running on liquid methane available in Europe. For further information about specific *actors* and *networks* in Sweden, UK, Spain and the Netherlands see Annex A.6.

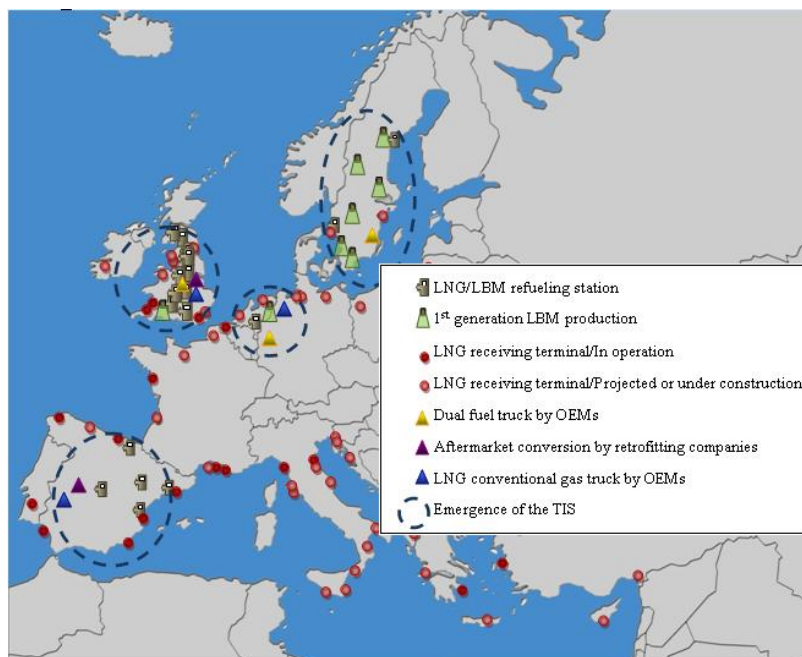


Figure 6. Current state of diffusion of the dual-fuel truck TIS in Europe.

From the analysis of *actors* and *networks* in the TIS we can conclude that there is lack of both truck and fuel related *actors*, while there are strong and wide *networks* across the TIS.

In terms of *actors*, there is a lack of OEMs offering dual-fuel trucks as well as specialized engine components suppliers. Regarding filling stations, there is lack of specialized components suppliers. Furthermore, we can notice that only national/regional gas distributors are participating in the TIS, thus the construction of filling infrastructure is slow. We can conclude that there is a need for international oil/gas companies supplying LNG as a vehicle fuel that can speed up and enlarge the refuelling infrastructure.

In terms of *networks*, relationships between OEMs and systems suppliers are strong and constitute a channel to transfer the dual-fuel technology. Additionally, *networks* between truck and fuel related *actors* are strong and a key element for ensuring the availability of both trucks and fuel.

Institutions

In the following paragraphs we present the identified *institutions* in the dual-fuel truck TIS. First, we describe the perception and beliefs on the growth potential of the technology and the EU legislation on public procurement. Second, we highlight a key feature of our TIS: the absence of technology specific regulations and standards.

An important *institution* in the dual-fuel truck TIS is the relation between environmental performance of the truck and the customers' image. In this line, the dual-fuel truck provides a better environmental performance due to its high fuel efficiency and the use of an alternative fuel. The image a dual-fuel truck can confer on customers could be closely related to the social perception of the fuel. While LNG might be questioned due to its fossil origin, LBM is widely recognized as "environmental friendly" (Interview Boisen, 2011).

The beliefs on growth potential of the dual-fuel truck TIS have been captured through our interviews. Most of the interviewed *actors* consider the dual-fuel truck running on LNG a real alternative to diesel trucks for long haul freight transportation because of its fuel autonomy. In this line, LNG is also perceived accessible compared to other alternative fuels (Interview Hammarberg, 2011). There are also expectations on growth

potential of LNG as a maritime fuel, especially in Northern Europe (Interview Wetemans, 2011; Interview Marhaug, 2011).

The expectations on growth potential of bio-methane as a vehicle fuel have been influenced by the EU's Biogasmax program and the European expert group on future transport fuels. The former program focused on demonstrating the feasibility of producing bio-methane from wastes resources and its use as a transport fuel (Biogasmax, 2010). This program has helped strengthen the expectations of biogas as a vehicle fuel, mainly as compressed gas. The latter EU expert group recommends that bio-methane should be feed into the natural gas grid and vehicles should be supplied from the common grid (EEG, 2011). This recommendation might weaken the belief in the growth potential of liquefied bio-methane as a vehicle fuel.⁵⁰

Concerning legislation, the EU Directive on the Promotion of Clean and Energy Efficient Road Transport Vehicles is setting the criteria for vehicle procurement (EU, 2009c). With this Directive the EU obliges to take into account the operational lifetime energy and environmental impact⁵¹ in public tender purchase of road transport vehicles. Therefore, it stimulates the uptake of clean and efficient road transport vehicles.

The institutional set-up of the dual-fuel truck TIS is characterized by a lack of regulations and standards. There is currently a lack of regulations for the dual-fuel truck certification, lack of standards for LNG/LBM filling stations and lack of fuel quality specifications.

Regarding the engine, an ordinary diesel and Otto engine must be certified following the legislation on type approval for motor vehicles (EU, 2007b). This legislation does not contemplate the dual-fuel engine; consequently, its safety and environmental performance standards, measurement procedures and tests are not defined. The Directive 2007/46/EC, for certification of new vehicles, states that certification of new technologies incompatible with the current regulation can follow an alternative (or exemption) procedure. Thus, following the exemption procedure, the engine certification must be done in a country-by-country basis. This procedure tends to be complex constituting an administrative burden (Interview Franzén, 2011).

⁵⁰ This recommendation could guide biogas producers to inject their gas into the natural gas grid instead of liquefying it. This could challenge the availability of LBM as a vehicle fuel.

⁵¹ At least energy consumption, emissions of CO₂, NO_x, NMHC and particulate matter should be considered when assessing the environmental impact.

The dual-fuel technology was totally prohibited before the amendment of the UNECE Regulation No. 115 in 2005.⁵² Current, dual-fuel safety requirements can be certified through the UNECE safety regulations for natural gas and LPG vehicles (Seisler, 2010b). Furthermore, an ISO standard (i.e. ISO/NP 12614) for fuel systems components is under proposal stage. However, in terms of emissions there is still large uncertainty concerning emission levels and test procedures. The industry is working to create regulations for the dual-fuel engine at the EU level, in particular Euro V and VI standards (EU, 2009d).⁵³

Regarding LNG filling stations, there is currently no standard that homogenize the LNG filling station design around Europe (Interview Berggren, 2011). Thus, filling stations have been built and optimized for a certain truck design and might not be compatible for other LNG trucks (Interview Hendrickx, 2011). The main parameters that determine the compatibility of the filling station with the truck are: nozzles geometry and LNG pressure/temperature at the hosepipe (Interview Berggren, 2011). Currently, there is ongoing work to create an ISO standard (i.e. ISO/NP 16924) for the design, the construction and the operation of stations for fuelling CNG/LNG to vehicles; including equipment, safety devices and maintenance. Additionally, an ISO standard (i.e. ISO/WD 12617) that defines the connectors for refuelling LNG vehicles is currently under preparation.

Regarding fuel quality, LNG from different sources varies in composition. Engine manufacturers require certain stability in the fuel composition in order to optimize the engine to the fuel dispensed at the filling station. A variation in the methane number and energy content of the fuel can lead to technical problems in the engine such as knocking (Interview Franzén, 2011). Currently, there are no European quality specifications for neither LNG nor LBM (Interview Mariani, 2011). In the case of LNG, there is an ISO standard under proposal that will homogenize the fuel composition in the upstream area (i.e. treatment at the extraction site), the ISO/DIS13686. In the case of bio-methane, it is

⁵² In order to legalize the new engine the following statement was added to the UNECE Regulation No. 115:

“17.10.2. Vehicles with more than one fuel system shall have a fuel selection system to ensure that no more than one fuel at the same time is supplied to the engine for more than 5 seconds. *Dual-fuel vehicles, using diesel as the primary fuel for igniting the air/gas mixture, are allowed in cases where these engines and vehicles meet mandatory emission standards.*” (UNECE, 2008a)

⁵³ It is worth noting that Euro standards only regulate emissions that affect air quality, not CO₂ or other GHGs (although CO₂ emissions have been measured since Euro V). Legislation has been developed to address CO₂ emissions from cars and vans, but not yet for heavier commercial vehicles (AEA, 2011).

a priority for the EU to harmonize standards for bio-methane injection into the natural gas grid. In December 2010, the Biogasmax program suggested a European bio-methane standard to CEN (Huguen and Le Saux, 2010). National quality specifications for bio-methane used in vehicle are available only in some countries such as Germany and Sweden (Persson et al., 2006).

In conclusion, there are institutional incentives for the adoption of any low-carbon technology including the dual-fuel truck. In regards to perceptions, generally, the dual-fuel truck is perceived as an “environmental friendly truck”. However, this perception might differ when the dual fuel truck runs on a fossil fuel. In regards to beliefs and expectations, all the interviewees believe that the TIS has a great growth potential. In regards to European standards and regulations, the industry is in an early stage of alignment of regulations and standards of the engine, the LNG filling stations and the LNG/LBG fuel quality.

4.3.Exogenous factors of the dual-fuel truck TIS

The TIS is also affected by exogenous factors that are external to the TIS. In this section we describe four exogenous factors that are relevant to our system: the EU’s targets, the European energy security policy, the oil price, the natural gas price, and the fuel taxes. These factors are considered exogenous since they influence our system but they cannot (in the short term) be influenced in return by the dual-fuel truck TIS.

EU targets

The EU regulatory framework derives from the decisions made by the European Commission which leads to EU Directives. These directives are transposed to the national level by each Member State. Thus, EU targets set in these directives are expected to guide national legislation. The EU has set targets in two main legislative areas that directly influence the transport sector. These are the European 2020 strategies and legislation on the promotion of bio-fuels.

The European 2020 strategy published in March 2010 (EU, 2010) aims at promoting a low-carbon, resource efficient and competitive economy. The targets for 2020 consist of:

- reducing GHG emissions by at least 20% (based on 1990 emission levels),

- increasing the share of renewables in EU's energy mix to 20%, and
- 20% increase in energy efficiency.

In the long term the CO₂ emissions objectives are even more ambitious aiming at an overall reduction of 80-95% by 2050 (EU, 2009b; EU, 2011b). The EU estimates that transport sector should reduce 60% GHG emissions in order to reach 80% total reduction by 2050 (EU, 2011b). The European Transportation Policy will be developed in the form of legislative proposals during the next decade in order to ensure the 60% GHG emissions reduction from transport by 2050 (EU, 2011c).⁵⁴ These targets affect positively our TIS providing incentives for *actors* to choose to enter the system. However, most of the scenarios included in the Impact Assessment accompanying the white paper on transport policy consider modal shift from road to rail and maritime transport as one of the solutions to achieve this emission reduction (EU, 2011c). This modal shift in freight transportation could imply a reduction of the size of the truck market.

Regarding the use of alternative fuels, the European Union adopted the Directive 2003/30/EC on the promotion of the use of bio-fuels or other renewable fuels for the transport sector.⁵⁵ A target of 5.75% share of renewable energy in the transport sector has been set for 2010 (EU, 2003a). In 2009, this target was increased to 10%⁵⁶ by 2020 and sustainability criteria for bio-fuels were defined (EU, 2009a).

In general terms, there is a widespread agreement in the EU that all alternative fuels will be needed to meet the expected fuel demand and that different transport modes will require different alternative fuels. Methane (fossil or renewable) is regarded as a complementary fuel in the transport sector and LNG is regarded as a fuel for long distance road transportation (EU, 2011a).

In conclusion, the EU targets affect the visions, expectations and beliefs in the growth potential of any low-carbon technology. Specifically, these targets work as an incentive

⁵⁴ An important document that outlines the debate around the future of the transport sector in terms of fuels is the report on Future Transport Fuels issued the 25th January this year. This report was elaborated by a group of experts on future transport fuels established by the Commission in order to advice it on strategies to substitute fossil oil as a transport fuel in the long term. It will also constitute an input to the future fuel strategy that will be launched in the end of 2011 under the so called *Clean Transport System (CTS)* initiative.

⁵⁵ The current transport sector relies almost exclusively on oil which is a largely imported fossil fuel since 98% of the fuel consumed by the transport sector is derived from conventional mineral oil (EU, 2007).

⁵⁶ This target is equal for every Member State.

for firms to enter the dual-fuel truck TIS. Furthermore, these targets influence expectations among managers and, by implication, their strategy.

Energy security

The EU's dependence on gas imports from a reduced number of countries is currently driving the diversification and expansion of natural gas infrastructure. LNG availability will increase which in turn will favor the dual-fuel technology.

The EU is a net importer of natural gas which has steadily increased its imports since the 1970s (B. Kavalov et al, 2009). In 2006, imports comprised 61% of EU gas gross inland consumption. These imports come 42% from Russia, 24% from Norway, 18% from Algeria, and 16% from other countries. The latter was mostly in the form of LNG (EU, 2008a). This apparent diversification of supply at the EU level does not correspond with the reality of every single Member State. Some of the EU countries rely entirely on a single supplier to fulfill its gas demand. This increases EU's vulnerability to political incidents in supplier or transit countries, accidents or natural disasters (EU, 2008a).

To tackle this problem the EU launched the Energy Security and Solidarity Action Plan (EU, 2008a). Under this framework, the Commission proposes several points to address including gas infrastructure projects. These projects concern enlargement of both gas pipelines and LNG infrastructure.⁵⁷

Therefore, the energy security policy is helping to mobilize capital and build the required infrastructure to access LNG in Europe. This policy might increase the belief in the growth potential of LNG as a vehicle fuel. However, it only sets in motion the construction of LNG import terminals not the complete deployment of the vehicle refueling infrastructure.

Oil and gas prices

The price gap between natural gas and diesel makes gas an attractive fuel for road transportation. In Spain, for example, the compressed natural gas price (for vehicles) was almost 60% cheaper than the diesel price in 2010.⁵⁸ Specifically, dual-fuel engines

⁵⁷ One of these projects affects directly the LNG infrastructure. The EU aims at providing sufficient LNG capacity consisting of liquefaction facilities in the producing countries and LNG terminals and ship-based regasification in the EU. This is especially relevant to countries that depend on one single gas supplier (EU, 2008a).

⁵⁸ Diesel price: 1,15 €/litre and CNG price: 0,67 €/per litre diesel equivalent (NGVA, 2011a).

running on NG are increasing in interest due to this price gap (AEA, 2011). It is not certain that this gap will remain since prices are not static and depend on several complex factors. Some of the key factors driving the diesel, oil and NG prices are described below.

In the case of diesel the final price for the customer depends on three factors:

- International crude oil price and international diesel price.
- Distribution and commercialization margin.
- Taxes

International crude oil price and international diesel price are set by the market. The distribution and commercialization margin varies depending on geographic location, local promotions, marketing of the company, etc. The taxes correspond to those set by the government of each country (MITC, 2011).

The crude oil prices are volatile. Since 2000, with few exceptions, crude oil prices have increased. The long-term oil price is driven by several factors; some of these include: geophysical considerations (e.g. depletion of resources), economic issues (e.g. uncertainty about demand) and geopolitical issues⁵⁹ (van Ruijve and van Vuuren, 2009).

Most analysts expect that the oil prices will keep increasing, some others argue that prices may also remain relatively low as oil reserves are still considerable (van Ruijven & van Vuuren, 2009). Crude oil prices are likely to remain high in the short and medium term because of the tightness of supply and demand, low spare capacity, and worries over disruptions combined with OPEC's determination to maintain prices over \$50/bb (ICF, 2007).⁶⁰ Further, increase in the price is being exacerbated by the global mismatch between the spreading demand for clean light end products, particularly gasoline and diesel, and the ability of refineries to process the available global crude oils (Interview Boisen, 2011; ICF, 2007).

The natural gas industry is regional thus different from the global oil industry. The key drivers of the end-user price of natural gas are:

⁵⁹ Geopolitical factors behind these price fluctuations include the destabilization of the Middle East situation.

⁶⁰ Even by reducing production, if necessary.

- the raw fuel costs which account for about 60% of final costs. This price is mainly driven by current demand and both current and future supply. Some factor affecting demand include: seasonal fluctuation⁶¹ and weather, demographics, economic growth, fuel competition, storage, and exports. Some factors influencing supply of natural gas include: pipeline capacity, drilling and storage, natural phenomena, technical issues and imports (NaturalGas.org, 2011).
- the transmission and distribution costs which account for the remaining 40% of the NG end-use price (NaturalGas.org, 2011).

In regards to LNG, the current cost breakdown of the average LNG chain shows that liquefaction accounts for the bulk of the costs (See Figure 7).⁶² Furthermore, shipping is the cost that varies the most, therefore shipping together with liquefaction are likely to define the relative competitiveness of suppliers versus receivers worldwide (Kavalov et al., 2009).

In regards to the market price of LNG⁶³, this is dependent on the worldwide available liquefaction capacity, which is currently increasing, driving the LNG price downwards. However, the demand for LNG is also increasing which makes the LNG prices increase (Hansson, 2008).

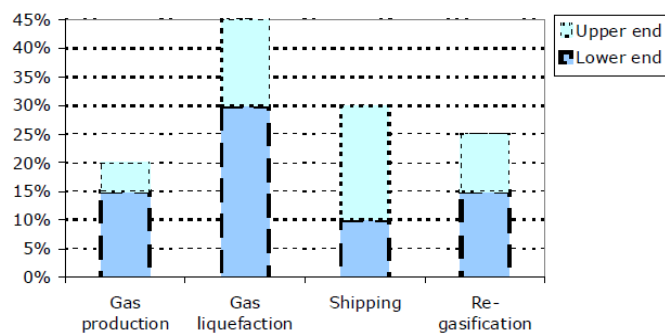


Figure 7. Lower and upper share of various cost items in total LNG chain (%) Source: Kavalov et al., 2009

The relationship between natural gas prices and oil prices is complex. Oil and natural gas prices have been coupled since the 1970s (Suurs et al., 2010; van Ruijven & van

⁶¹ Natural Gas price are typically seasonal, peaking in the winter and hitting low on the summer when heating is not needed (NaturalGas.org, 2011).

⁶² While liquefaction is extremely costly, regasification capacity, on the other hand, is relatively cheap and easy to establish (B. Kavalov et al, 2009).

⁶³ The LNG prices are also linked with the building costs of the liquefaction facilities, which are in turn very much influenced by the price of steel at the time of construction (Hansson,2008)

Vuuren, 2009).⁶⁴ Currently in Europe, the price of gas under long-term supply contracts is indexed to oil.⁶⁵ This correlation can be explained using two facts:

- Oil and NG are substitutes for many end users⁶⁶.
- NG and oil are often found in the same geological formations. The technological oil recovery is accompanied by some gas recovery (associated gas⁶⁷). In this regard, the OPEC influences the gas market by directly contributing to gas supply.⁶⁸ Furthermore, the OPEC (still) has some control over oil prices and exercises some control over gas prices too (Kavalov et al., 2009).

In addition, some production cost of oil and gas are correlated i.e. some tools are used for both develop oil and gas resource (Strauss, 2008).⁶⁹

Similarly to the oil prices, some authors project gas price to increase. However, others state that an increase in gas resources could lead to a drop in gas price (EU, 2003c). It is important to know that in the EU, reliance on natural gas supply from Russia is currently the largest source of volatility. Furthermore, uncertainty regarding later stages of the EU carbon trading system is also likely to have an impact on gas demand and pricing (ICF, 2007).

There is currently an attractive price setting of natural gas compared to diesel, where NG is around 60% the price of diesel⁷⁰ (see Annex A.2). According to our interviews, this represents a main driver for market formation of the dual-fuel trucks TIS. This influences the direction of search of firms and induces them to experiment with the dual-fuel technology. However, future fuel prices are surrounded by huge uncertainties. One can make an educated guess that oil price will increase and that the NG will

⁶⁴ Mark Wiltsher, a spokesman for the British energy regulatory agency Ofgem, said that there are some “historic” reasons for this link. He stated: "when it was found economic to use gas, it was pegged to the oil price. They didn't know how else to price it..."(Strauss, 2008).

⁶⁵ Since the long-term trend in oil prices has been upward, the link between oil and NG has delivered rising profit margins, a particularly attractive feature when combined with long-term supply contracts (Strauss, 2008).

⁶⁶ There are substitutes for industrial and transport consumers, not for residential consumers.

⁶⁷ Gas is often found where oil exists but it was actually flared off as worthless until after World War II. Today a large portion of associated gas is flared. In 2006, the oil producing countries burned approximately 70 Bm³ of gas equal to 80% of global LNG production (Kavalov et al., 2009).

⁶⁸ In 2007, the OPEC supplied more than 80% of LNG imports to Europe (Kavalov et al., 2009).

⁶⁹ When the oil price increases, the cost of the tools needed to develop more oil resources tends to go up and those same tools are used to drill and develop natural gas (Strauss, 2008).

⁷⁰ Except for Sweden, NG price is around 70% the price of diesel (See Annex A2).

continue to be coupled to oil prices, however the future is unknown. Therefore, firms can handle this situation by carefully examining some of the aforementioned factors in order to make strategic decisions about which technological opportunities to pursue. For instance a decoupling of NG price from the oil price could completely change the external drivers and the incentives for *actors* to enter the dual-fuel TIS.

Fuel taxes

Fuel taxes complicate the final price structure of fuels, influencing the market interest for gas, diesel and bio-fuels. According to the EU Directive 2003/96/EC the minimum levels of taxation applicable to motor fuels in 2010 are:

- diesel taxation should be at least 8,85 €/GJ
- natural gas taxation should be at least 2,6 €/GJ⁷¹
- pure/blended bio-fuels taxation: Member States are free to reduce excise duty rate

In regards to natural gas, the fuel tax imposed in Europe is very country dependant. The final price of NG varies (mainly) according to the fuel tax levied in each country. In some countries like the Netherlands, Germany, UK and Sweden the taxes represent more than 30% of total price of NG. In line with this, one can conclude that in these countries there is less incentives for final consumers to use NG as substitute for oil.

In regards to bio-fuels, the tax regime constitutes an uncertainty. In general terms, the EU promotes the use of alternative fuels in the transportation sector by lower taxes compared to diesel (EU, 2003b). However, since each Member State decides the actual tax level, there is still uncertainty regarding the future tax that each country will levy on the different fuels.

⁷¹ The diesel tax presented in the Directive 2003/96/EC has been converted to €/GJ using the following values: High Heating Value (HHV) 44,80 MJ/kg and density 0,832 kg/l.

5. Functional Analysis

This chapter presents a function-by-function assessment of the dual-fuel truck TIS in the *formative phase*. Our aim is ascertaining to what extent the eight *functions* are currently fulfilled in the dual-fuel truck TIS. The final outcome is a summary of the *functional pattern* of the TIS.

5.1. Knowledge development and entrepreneurial experimentation

Knowledge development and diffusion is closely related to entrepreneurial experimentation in the dual-fuel truck TIS. In some cases it is hard to separate these *functions* since part of the knowledge is created and spread by experimenting with the dual-fuel technology. Therefore these *functions* are described together in this section.

The dual-fuel technology is the result of a combination of existing knowledge in diesel engine and gas systems. According to Clark, K.B. (1985), this type of innovation can be considered an architectural innovation since it relies on existing technologies linked in a novel way. In general terms it relies on the existing scientific knowledge on combustion engines which is currently well developed (Interview Landin, 2011).

The first experiments with these engines took place in ships and heat and power production more than 20 years ago. Later, scientific evolution from mechanical to computer controlled fuel injection improved engine performance and allowed for other applications (Interview Boisen, 2011). This dual-fuel technology has developed since the 80's mainly using CNG as a fuel.⁷² In the past five years some companies have started experimenting with the dual-fuel trucks running on LNG in Europe (Interview Boisen, 2011). Nowadays, there are more than 34 different companies engaged in some form of development of dual-fuel engines in its different applications (Seisler, 2010).

Technical, business and market knowledge for dual-fuel trucks is embedded in system suppliers such as Hardstaff and Clean Air Power. They have converted existing diesel engines under customer demand; they know the technology and have established *networks* with customers and suppliers for a decade (Interview Landin, 2011). Their experience with the dual-fuel engine is now being transferred to OEMs through

⁷² At the beginning they used mechanical “fumigated” approach. Today, the systems are computer controlled and achieve efficiencies close to diesel engines but with superior emissions performance (Seisler, 2010).

cooperation projects to develop dual-fuel trucks (NGV, 2009; CAP, 2006; Mercedes-Benz, 2011). At the same time, OEMs are transferring to the system: their business experience, powerful *networks*, solid knowledge on diesel technology, and experience on the heavy duty truck market. Further, OEMs have the experience and resources to enlarge production volumes.

With regards to the fuel technology, we can find large differences in the knowledge base of LNG and LBM. LNG scientific and technical knowledge is well developed and embedded in the oil/gas industry and the industrial equipment suppliers (Interview Andersson, 2011). However, there is a lack of experience in the use of natural gas as a vehicle fuel in liquid state. National/regional gas distributors are experimenting with this new LNG application and therefore establishing *networks* and building the knowledge base for the business of LNG as vehicle fuel.⁷³ In addition, these national/regional gas distributors together with gas equipment suppliers are building the first filling stations (Interview Berggren, 2011; Interview Hendrickx, 2011).

In the case of LBM, in particular first generation bio-methane, the scientific and production knowledge is also available and relies on biogas producers and gas industry (Interview Leaf, 2011; Interview Andersson, 2011). Bio-methane has traditionally been consumed in gas form; liquefaction has rarely been used for this gas. Scientific and technical knowledge on liquefaction relies on gas equipment suppliers from the gas industry and gas treatment companies. Thus, some of them have diversified their activities to biogas upgrading and liquefaction technology development.⁷⁴

The LNG filling stations are currently at the heart of knowledge development and diffusion in the TIS in terms of integration of the different artifacts (i.e. truck, fuel and refueling infrastructure). In general, the filling station results from cooperation between different *actors* in the truck and the fuel supply chain.⁷⁵ Further, it constitutes a platform

⁷³ A characteristic of the market development for LNG as a vehicle fuel is that international gas companies, although having the knowledge and resources, are currently following the market development without taking action.

⁷⁴ A difference between biogas liquefaction and NG liquefaction is the size of the liquefaction plants. Biogas liquefaction plants are smaller than conventional natural gas liquefaction plants (Interview Wetemans, 2011; Interview Marhaug, 2011). Thus, biogas producers are the first ones experimenting with small scale liquefaction units in order to sell their product in liquid form.

⁷⁵ The filling station is considered part of the fuel supply chain.

for understanding each other's business and their limitations.⁷⁶ The business to business relations are therefore crucial in the formative phase of the TIS.

5.2. Influence on the direction of search

By setting emission targets for the transportation sector, the EU is guiding engine manufacturers towards investing in more efficient vehicles and alternative power-trains (EU, 2009c; EU, 2003a). However, the EU does not give direct support to the dual-fuel technology. It is at the national level where technology specific support can be found.⁷⁷

Regarding the truck, customers are also guiding OEMs' direction towards dual-fuel trucks. According to our study some companies that have tried to retrofit their diesel trucks with systems suppliers have experienced some difficulties (Interview Marhaug, 2011).⁷⁸ Therefore, their current demand is for dual-fuel trucks directly from OEMs. Customers prefer establishing business relation with the OEMs rather than with retrofitting companies since they perceive OEMs to be more reliable (e.g. warranty issues) (Interview Marhaug, 2011; Interview Monfort, 2011).

Further, environmental concerns are increasing among customer (Interview Hammarberg, 2011).⁷⁹ Some logistic services companies experience customers' demand for reducing environmental impact in their operations. Thus, truck owners articulate their interest for "environmental friendly" trucks to OEMs (Interview Eriksson, 2011). However, their purchase decision does not depend exclusively on the environmental performance of the vehicle. Other important parameters are truck cost and features (e.g. horse power, efficiency and acceleration) as well as fuel price and fuel availability (Interview Hammarberg, 2011). The latter parameters might make truck owners hesitate to buy a dual-fuel truck.

Regarding the fuel, the EU is clearly guiding direction of search towards alternative fuels (EU, 2003a; EU, 2007a; EU, 2009a; EU, 2011a). A strong signal to the transportation sector is the bio-fuel target, which specifies that 10% of transport fuel should come from

⁷⁶ For instance, nozzles at the filling stations and receptacle on the vehicle tank should be compatible which currently is not ensured due to lack of standards. Moreover, the filling station should deliver LNG with the right temperature and pressure.

⁷⁷ For instance, in the case of Sweden we found direct governmental support through the BiMe programme.

⁷⁸ Aftermarket retrofitting requires information about the original engine that is in the hands of the corresponding OEM. This information is hard to obtain and may prevent customers from converting their engines.

⁷⁹ In many cases environmental concerns are related to business reputation and branding issues.

renewable sources by 2020. This target is stimulating bio-methane production since it is one of the current commercial bio-fuels (Biogasmax, 2010).

Additionally, the EU and its energy security policy are also making natural gas an attractive substitute to oil in Europe. Thanks to the infrastructure expansion planned by the EU, natural gas availability is expected to increase (EU, 2008). This fact coupled with the price difference between oil and gas might constitute a great stimulus for any sector to consider natural gas as an alternative energy source to oil. In particular, the already high diesel price is expected to keep increasing leading truck owners to look for alternative and cheaper fuels (Interview Murugó, 2011).

In the case of LNG, a characteristic of the market development for LNG as a vehicle fuel is that international oil/gas companies, although having the knowledge and resources, are currently following the market development without taking action (Interview Wetemans, 2011). These oil/gas companies might find unattractive to sell LNG to the transport sector because of the current small market size of LNG for vehicles. This could explain that the largest part of LNG is consumed in industry and heat and power production, which are much larger segments. In addition, these sectors are more flexible regarding gas quality becoming even more attractive for natural gas suppliers.

All interviewees agreed that LNG has a great potential as a fuel for heavy duty transportation due to its high energy content. A number of truck owners consider that LNG is currently the only real alternative to diesel for HDVs. Further, these expectations are increasing the attractiveness of dual-fuel trucks since it is able to burn methane more efficiently than the Otto engine (Interview Pilskog, 2011).

In some countries such as UK and Sweden there is also a belief on growth potential of LBM as a transport fuel (Interview Berggren, 2011; Interview Leaf, 2011). However, in other countries such as the Netherlands customers might not be willing to pay the high price of LBM (Interview Kättström, 2011). Hence, influence on direction of search in regards to LBM differs from country to country.⁸⁰

⁸⁰ This might not blocking the production of LBM in Netherlands, but could affect the availability of LBM in this country. The Dutch production of LBM could be exported to Northern Europe where willingness to pay is perceived higher by some Dutch producers (Interview Kättström, 2011).

5.3. Market formation

Our TIS market is in a “nursing” phase. The volume of trucks in the global market, according to “company claims” is 3000 dual-fuel vehicles (Seisler, 2010). The volume of dual-fuel trucks in the market has increased in the last decade thanks to system suppliers/retrofitting companies which have converted vehicles on a customer-by-customer basis (Seisler, 2010). They have provided a learning space for dual-fuel trucks. The current market is just a fraction of the potential market that could be achieved if dual-fuel trucks were sold directly by OEMs. OEMs are now entering the system (See Annex A6). The successful commercialization of this technology by the OEMs will likely influence the transition to a “bridging market”.

In order to assess the market formation of our TIS we evaluated the purchasing process, identified the uncertainties faced by customers, reviewed the articulation of demand and the institutional stimuli. These three aspects are presented below.

A couple of years ago, the purchasing process of a dual-fuel truck was quite complicated. Now with OEMs starting to sell dual-fuel trucks directly to customers the purchasing process is simplified. Traditionally, customers would have to approach a retrofitting company and ask for the conversion of their operating fleet (Interview Boisen, 2011). Then, depending on the trucks brand, the retrofitting company would need to access specific data related to the engine (Interview Landin, 2011). These data was sometimes confidential, so the truck customer would need to make a great effort (money and time) to obtain these data from OEMs (Interview Marhaug, 2011). Nowadays, OEMs like MAN and Volvo are offering dual-fuel trucks directly to customers. Even if the OEMs are working together with retrofitting companies such as Hardstaff and Clean Air Power the customer buys a dual-fuel truck under the OEM’s brand and with the OEMs warrantee (Interview Eriksson, 2011).

Currently, one uncertainty that buyers face relates to fuel availability. The lack of LNG/LBM filling stations poses a threat to trucks running on these fuels for long distances. However, customers perceive that using dual-fuel technology (that can run with 100% diesel) reduces this risk (Interview Hammarberg, 2011).⁸¹

⁸¹ Westport’s HDPI system cannot run with 100% diesel (Interview Boisen, 2011).

A second uncertainty for customers is the lack of clear information about environmental impact of the dual-fuel truck running on LNG. There are currently few studies (e.g. LCA analysis) that calculate the environmental impact associated to this truck. Using an LCA perspective the environmental impact of a truck depends on both the supply chain of the fuel and the tailpipe emissions. Since the supply chain of LNG as a vehicle fuel is not established yet, the calculation of current environmental impact of the product is difficult to make. Thus, there is large uncertainty regarding the current and future environmental impact. This uncertainty increases because of the wide range of supply chain configuration possibilities.

A third uncertainty that customers face is economic benefits they could get by buying a dual-fuel truck. The dual-fuel truck is currently more expensive than an ordinary diesel truck (Interview Hammarberg, 2011).⁸² Thus, the main economic savings for customers are related to the fuel.⁸³ However, there is high uncertainty regarding the future price of natural gas. An increase on NG price (e.g. due higher fuel taxes) would threaten the economic benefits for customers. Furthermore, these uncertainties about economic benefits are intensified by the fact that price of the secondary (used) market for these trucks is still unknown (Interview Wetemans, 2011).

A fourth uncertainty for customers regards the functionality of the truck. As mentioned above, these trucks have not been widely demonstrated around EU. Therefore, potential customers face uncertainty regarding practical technical aspects such as maintenance, spare parts availability and breakdown frequency of this new truck.

The articulation of demand from customers is poor. Customers demand “environmental friendly trucks”; in other words, they want trucks with low CO₂ emission, NO_x, particles, etc. However, the environmental benefits of this truck are very dependant on the operation of the truck, i.e. environmental benefits increase with heavy load and long distance operations. On the other hand, these characteristics are clearly articulated by system suppliers (Interview Landin, 2011).⁸⁴

⁸² The price of a dual-fuel truck is 1,6M SEK while the price of an ordinary diesel truck is 1,2M SEK (Interview Hammarberg, 2011).

⁸³ Economic savings comes from higher fuel efficiency and lower price of natural gas (compared to diesel).

⁸⁴ For instance, when customers demanding “environmental friendly trucks” approach Hardstaff, this company clearly states the best uses for this truck (Interview Landin, 2011). However, some customers disregard this explanation and buy dual-fuel trucks that are not suitable for their operations.

Institutional stimuli for market formation come from national/regional governments subsidizing dual-fuel trucks purchase and LNG/LBM filling stations construction. In some countries like Sweden and UK, the national governments give financial support to customer buying clean technologies for road transportation (Interview Pilskog, 2011; Interview Landin, 2011).⁸⁵ In the Spanish, Swedish and Dutch cases governments also co-finance the construction of LNG/LBM filling stations. This support is given to national/regional LNG distributors and is not enough to build a national infrastructure.⁸⁶

Market formation is very dependent on fuel price and fuel availability therefore stimulus like fuel tax exceptions at national levels is crucial. LNG tax exemptions vary largely from country to country. For instance, in Sweden the fuel tax for NG is 12€/MWh while in the Netherlands is 3€/MWh (Jönsson, 2010). In the case of bio-methane, generally all the EU countries agree on low taxation. For example, in Sweden biogas is exempted from CO₂-tax and energy tax, and in the Netherlands this fuel has no taxes (See Annex A.2 for further information on fuel prices in the different European countries).

It is important to differentiate stimuli that help market formation of vehicles running on compressed bio-methane from stimuli that aid market formation of vehicles running on liquefied bio-methane. Although both types of vehicles can run on bio-methane, the availability of liquefied bio-methane depends extensively in the incentives the biogas producers have to liquefy this gas.⁸⁷ Some identified drivers for producers to liquefy biogas include lack of NG grid access and/or existence of an LBM market.⁸⁸ The lack of NG grid access could be due to the lack of the physical NG grid or because the government prohibits the injection into the natural gas grid (Interview Leaf, 2011).

In regards to institutional change needed for market formation, standards and regulations are required in order to facilitate the entrance of new firms and reduce technical uncertainty.

5.4. Materialization and resource mobilization

In regards to the dual-fuel technology, the interviewed *actors* perceive that human resources are accessible. Competence on dual-fuel technology is mainly found in the

⁸⁵ See Swedish and UK cases in Annex A.6.

⁸⁶ The financial support comes from the government through different public or semi-public organizations and agencies.

⁸⁷ Instead of injecting it into the natural gas grid or burning it directly in industry.

⁸⁸ The LBM market is, for instance, trucks running on LBM.

system suppliers while OEMs have expertise in diesel technology. Furthermore, OEMs have the financial resources to scale up the production of the dual-fuel truck.

In regards to LNG as a vehicle fuel, it is important to recall that part of the NG production is in the hands of the same oil companies that produce petrol and diesel (Kavalov et al, 2009). So far, the incentives for oil/gas companies to develop NG as a vehicle fuel option have been rather weak. In other words, diesel generates so high profit margins that introducing vehicle fuel products that compete with diesel (such as natural gas) is undesirable (Interview Boisen, 2011). This is an important issue at the heart of resource mobilization and materialization of LNG filling station.

In regards to the bio-methane fuel, materialization of upgrading and small scale liquefaction plants for LBM (first generation) is poor at the EU level: in Sweden there are six LBM plants built and one in UK.⁸⁹ This indicates that, generally, the access of LBM as a vehicle fuel in the EU is limited. Furthermore, there are four demonstration plants for second generation bio-methane in Europe.⁹⁰ However, these plants do not have a liquefaction unit yet. Therefore, there is no availability of second generation LBM in EU.

In regards to the filling stations, the *actors* in our TIS perceive it as difficult the access to LNG/LBM as a vehicle fuel. The poor materialization of LNG/LBM filling stations is accompanied by the “chicken and egg” dilemma, where LNG suppliers do not want to risk and built these stations unless there are enough LNG/LBM trucks on the market. Parallel, the truck manufacturers do not want to sell trucks until a sufficient LNG/LBM infrastructure is available (Interview Wetemans, 2011).

Despite the “chicken and egg” dilemma, there are a few LNG/LBM filling stations available in the EU. This materialization of filling stations has been achieved differently in each EU country analyzed:

- In Sweden there are strong informal and formal *networks* between truck manufacturers and LNG related firms. This allowed the coordination for the opening of the first LNG filling station and the launching of the first LNG dual-fuel trucks. Further, a strong advocacy coalition between these *actors* was

⁸⁹ See Annex A.4 for further information about the identified first generation LBM production plants in Europe.

⁹⁰ See Annex A.3 for further information about the identified demonstration plants of second generation bio-methane in Europe.

formed. These *actors* are now working in a formal *network* (i.e. BiMe Trucks) which is co-financed by national and regional public bodies to materialize the construction of three more filling stations (Interview Berggren, 2011).

- In UK, truck customers (e.g. big supermarkets) built private LBM/LNG filling station, while at the same time they decide to retrofit their own diesel truck or buy LNG/LBM trucks. Retrofitting of vehicles was co-finance by the national government through an impartial organization (Interview Landin, 2011). This country has already available public LNG filling stations. According to our study, the UK is the European country that has materialized the largest LNG filling infrastructure, thus the “chicken and egg” dilemma is currently not relevant.
- In Spain, national/regional gas distributors built public LNG filling stations for their own use, while at the same time they decide to retrofit their own diesel trucks or buy OEMs’ LNG trucks (Interview Murugó, 2011).⁹¹ These companies receive subsidies from national and regional public bodies for filling station construction (Interview Monfort, 2011).
- In the Netherlands, there is currently a single national gas distributor putting in place the entire supply chain of LNG/LBG fuel (Interview Hendrickx, 2011). It also works together with OEMs in demonstration programs of LNG/LBM trucks. This company constructs LNG filling stations co-financed by the national government.

In all the abovementioned cases part of the financial resources comes from national or regional public bodies. Furthermore, in these four countries there is a small number of key *actors* mobilizing resources and catalyzing the materialization of artifacts. For further information about the four countries studied in depth see Annex A.6.

Furthermore, external factors such as energy security and LNG demand from ships help mobilize resources. First, enlargement of the LNG import infrastructure is being driven, to a large extent, by energy security issues at an EU level (EU, 2008a). This is stimulating the mobilization of financial resources for the construction of import terminals. Second, increasing demand of LNG attracts more investment in LNG terminals (Interview Boisen, 2011). Establishing LNG infrastructure is a big investment.

⁹¹ Furthermore, HAM let borrow its dual-fuel trucks to firms that are interested in dual-fuel technology such as INDITEX.

Therefore, LNG suppliers need large consumers like the industry or/and ships to establish that infrastructure (Interview Weteman, 2011). When the LNG import terminal is constructed, it is easier to build smaller terminals along the road which could supply LNG trucks (Interview Marhaug, 2011).

5.5. Legitimation

The legitimacy of our TIS can be described in its two different levels: social acceptance of the technology and compliance with relevant *institutions*.

Social acceptance of the dual-fuel truck and its proponents is based on environmental and safety issues.⁹² The entrance of OEMs in the dual-fuel market might transfer their good environmental and safety reputation to the dual-fuel truck, which in turn could increase the legitimacy of the system.

Currently, the dual-fuel truck running on LNG is not widely used nor known in society (i.e. there is no public awareness of the technology). Therefore, legitimacy of this truck might be mainly based on the social acceptance of its fuel. Natural gas is accepted world-wide as a vehicle fuel in compressed form, therefore society is familiarized with the fuel. Thus, CNG has, to some extent, helped legitimize LNG as a vehicle fuel.

In general terms, at the European level, the methane fuel is socially accepted regardless its origin (Interview Boisen, 2011). Nevertheless, NG acceptance is a country specific issue mainly connected to the environmental perception of this fossil gas. For instance, according to our interviews, in Spain natural gas might be widely accepted due to its lower tailpipe emissions. In Sweden, some *actors* perceive that NG is socially accepted because it can constitute a bridge⁹³ to LBM while some others reject it due to its fossil origin (Kärmarck, 2011; Mathiasson, 2011).

In terms of compliance with relevant *institutions*, we found that the dual-fuel truck is not completely in line with the current legislation. Lack of legislation for the dual-fuel engine has already been identified by the automotive industry which is currently working on it (Interview Klintbom, 2011). There are currently different advocates working for the engine regulation and standards, fuel quality specifications and standardization of LNG filling stations at the EU and international level (ISO

⁹² Environment and safety could constitute two minimum prerequisites for a new technology to be accepted in society, however they might not be sufficient conditions to ensure market uptake.

⁹³ In Sweden, LNG is considered a provisional fuel until LBM is available, or as a backup for LBM.

standards). According to Boisen (2011), the standards for the engine will be done in around one year and the standards for filling stations in around three or four years. In regards to the gas quality issue, there is currently an ISO group working on the standards for the untreated gas in the upstream area. There are different perspectives on the dimension of this issue. For instance, the vehicle manufacturers believe that fuel standards are needed in order to optimize the performance of the engine (Interview Pilskog, 2011). On the other hand, gas producers believe the requirements should be as wide as technically possible to allow consumers to use gas from various supply sources (Interview Evers, 2011).

5.6. Positive externalities

Although this function is rather weak, we can find some sources of positive externalities that are emerging in the system: information flows, knowledge “spill-overs”, and entrance of new firms.

Firstly, large formal and informal *networks* constitute a channel for information to flow; this information is flowing internationally. Vehicle manufacturers and retrofitting companies, because of their international nature, are spreading the dual-fuel technology across national boundaries. This flow of technological knowledge is spread at the firm level; however, there is slight public awareness of this technology. This might be intensified by a general confusion between the dual-fuel, bi-fuel and flexi-fuel technologies which are not even clear in statistics records (Seisler, 2010).

Second, systems suppliers are the main source of knowledge “spill-overs” since they have the dual-fuel technology and they are transferring it to OEMs. Another important source of “spill-overs” is the advocacy coalitions. They are an important source of knowledge and, at the same time, constitute a platform for discussion and information diffusion (Interview Boisen, 2011).

Finally, the entrance of new LNG and engine related firms is strengthening the rest of the *functions*. The participation of more *actors* in the system is increasing political power of advocacy coalitions. In particular, the entrance of OEMs develops positive externalities by solving market uncertainties and influencing direction of search of other OEMs and LNG suppliers.

Finally, specialized intermediate goods and service providers are an additional source of positive externalities that is not yet available. For instance, filling stations are currently not built by specialized firms but by gas equipment suppliers that are pulling the knowledge from their past business experience. When specialized suppliers emerge, the barriers to entry for yet more firms could be lowered.

5.7. Summary of *functional pattern*

In this *formative phase* the *functional pattern* can be summarized as follows:

- *Knowledge development and diffusion*: Engine and fuel related technologies already exist. Knowledge development is strong and concentrated in refining and manufacturing the technology.
- *Entrepreneurial experimentation*: more than 34 different companies engaged in some form of development of dual-fuel engines in its different applications.
- *Influence on the direction of search*: EU targets (i.e. emissions and bio-fuels), fuel price, and energy security are guiding engine manufacturers and customers towards methane gas as a vehicle fuel. However these are also drivers for the use of methane in other sectors. The belief in LNG/LBM growth potential for HDV and the high efficiency of the diesel engine (compared to Otto) increases attractiveness of the dual-fuel truck.
- *Market formation*: aftermarket retrofitting by system suppliers constitutes the “nursing market” for the dual-fuel trucks running on LNG. The market is fragmented and very dependant on LNG filling infrastructure development. Besides, high uncertainties make customers hesitate to buy a dual-fuel truck thereby, slowing down market formation.
- *Resource mobilization*: OEMs and system suppliers are mobilizing resources in regards to the engine. There is slow mobilization of resources for the fuel infrastructure, which is co-financed by national or regional public bodies.
- *Materialization*: slow materialization of artifacts (e.g. trucks and filling stations) due to lack of standards and regulations coupled with uncertainty about materialization of complementary technologies (i.e. “chicken and egg” dilemma).
- *Legitimation*: legitimation of the dual-fuel engine is partly underdeveloped. The social acceptance of the fuel is country specific.

- *Development of positive externalities*: lack of positive externalities due to the early stage of the TIS. However, some sources of positive externalities such as advocacy coalitions and powerful *networks* are emerging.

6. *Blocking Mechanisms*

The functional analysis in Section 4 helped us identify *blocking* and *inducement mechanisms* influencing the development of the dual-fuel truck TIS. To be coherent with the purpose of this thesis, we limited this section to the key *blocking mechanisms* that Volvo Truck could address through strategies to enhance the diffusion of the dual-fuel truck in Europe. A summary of the *inducement* and *blocking mechanisms* can be found in Annex A.7

6.1. *Blocking mechanism I: Lack of standards and regulations*

So far, the system suppliers have been introducing the dual-fuel technology to the market. These companies have not been powerful enough to align emissions and safety regulations for dual-fuel trucks at the EU level. Therefore, legitimation of the dual-fuel technology has been rather weak. This in turn deviates direction of search from dual-fuel technology making more attractive the established diesel and Otto engines. As a result there are very few OEMs participating in the dual-fuel truck TIS. This slows down the materialization of a dual-fuel trucks and its introduction to the market.

Furthermore, the use of LNG as a road transport fuel is immature and the *actors* involved in the construction of LNG filling stations are few, small and dispersed. This has impeded the homogenization of the refueling infrastructure and threatened the compatibility between truck, fuel and refueling infrastructure. This in turn has slowed down materialization of both, dual-fuel trucks and refueling infrastructure. This weak materialization affects market formation inhibiting the enlargement of the TIS. Thus, new LNG related *actors* hesitate to enter the system.

In conclusion, the lack of standards and regulations constitutes a key barrier to market expansion of dual-fuel trucks and deployment of a European refueling infrastructure.

Strategy I

Volvo Truck need to get involved not only in the standardization of the engine and fuel system but also in the standardization of LNG filling stations. The later standardization is important for truck manufacturers because: first, the receptacles in the fuel tank have to be compatible with the nozzles at the filling; second, the LNG must be delivered with the right temperature pressure to the truck. Thus, Volvo should try to define nozzle

geometry as well as fuel pressure and temperature at the hosepipe in the filling stations since it affects the fuel tank design. Moreover, Volvo can collaborate with the NGVA which is a powerful advocacy coalition with experience on solving these issues.

6.2. *Blocking mechanism II: Lack of experience of and familiarity with the dual-fuel truck*

While the Otto and diesel truck TIS have had decades to secure their position as familiar and socially accepted; the dual-fuel truck TIS needs to overcome its “liability of newness”. Dual-fuel truck demonstration programs have been few and dispersed around Europe, with a small number of customers experiencing this new technology. There is also a lack of assessments about the expected environmental performance of the technology. Therefore, in the eyes of the customers the dual-fuel truck might have weak *legitimacy* which in turn hinders *market formation* and impedes further entry of new customers into the system. Additionally, the uncertainty regarding future natural gas prices could make customers hesitate to adopt the dual-fuel truck and weakens even more *market formation*. Consequently, the lack of experience of and familiarity with the dual fuel truck constitutes a barrier for a wider adoption of the dual-fuel truck in the European market.

Strategy II

Volvo Truck should prioritize demonstration programs around Europe to increase legitimacy of the dual-fuel truck in the eyes of the customers.

In addition, Volvo Truck needs to clearly communicate the environmental benefits of this new technology which depend on several factors. First, Volvo should emphasize that the environmental benefits depend on the duty cycle of the truck. Second, it is recommendable that Volvo understands not only the current, but also the future possible environmental impact of the dual-fuel truck which depends on how the future LNG supply chain develops. Therefore, further studies of the environmental impact of the different LNG supply paths and their relation to the overall environmental performance of the dual-fuel truck could help legitimize this technology.

Further, for marketing purposes Volvo should differentiate the dual-fuel truck from other technologies. The general public confusion about this new technology (confusion with bi-fuel and flexi-fuel vehicles) highlights the importance of this strategy.

6.3. Blocking mechanism III: Small market size of LNG as a vehicle fuel

The mobilization of resources to establish LNG as a road vehicle fuel is slow and limited to national/regional gas distributors, which do not have enough resources to deploy a European LNG network. International oil/gas companies do not actively participate in the development of LNG as a vehicle fuel. LNG for vehicles is currently a small market compared to other fuels such as CNG or diesel. This small market size might not be attractive for international oil/gas companies. This could guide their direction of search to provide other fuels (not LNG) to the transport sector. This in turn, decreases entrepreneurial experimentation and slows down the enlargement of the TIS by limiting market formation to a regional level.

Therefore, the small market size of LNG indirectly hinders the creation of positive externalities at a European level and poses a barrier to entry for yet more firms.

Strategy III

The success of the dual-fuel truck in Europe will depend (to a large extent) on the adoption of LNG as a large scale transport fuel. A strong *inducement mechanism* in the TIS is the belief in LNG/LBM growth potential as a transport fuel⁹⁴. Aggregation of LNG demand between different transport modes (e.g. ships and busses) could increase incentives for oil/gas producers to enter the LNG vehicle fuel market. We suggest that Volvo Truck coordinates strategies with other Volvo business branches (e.g. Volvo Buses) for the launching of LNG vehicles. Furthermore, Volvo Truck could publicly support the use of LNG for maritime transport; thereby strengthening influence on the direction of search. Volvo Truck should also promote the construction of L-CNG filling stations. These stations allow CNG vehicles to refill from natural gas stored in liquefied form; hence, further aggregating LNG demand could be achieved.

6.4. Blocking mechanism IV: The “chicken and egg” dilemma

LNG/LBM refueling stations and LNG/LBM trucks availability is mutually dependent. Currently, there is poor materialization of refueling stations as well as trucks. One of the main barriers for resource mobilization and materialization of these artifacts is the so called “chicken and egg” dilemma. The risk associated to this makes new firms hesitate

⁹⁴ LNG is regarded as potential transport fuel for ships, buses and trucks.

to enter the TIS. This in turn hinders the formation of positive externalities and the growth of the system. This dilemma can be solved through the creation of *networks* where fuel and vehicle related *actors* collaborate to enhance resource mobilization of financial capital and coordinate for the materialization of filling stations and trucks.

Strategy IV

There is small number of key *actors* that are currently slowly mobilizing resources for the construction of LNG filling stations. Following the experience of Volvo Truck collaboration with Fordonsgas in Sweden, we recommend to establish informal or formal *networks* with the following *actors* in other EU countries: Rolande LNG, HAM Group and Gasrec. These *networks* are intended to reduce uncertainties about fuel and vehicle availability and increase mutual trust.

6.5. Blocking mechanism V: Concerns about fossil origin of LNG

One important driver for customers to buy a dual-fuel truck is the environmental image the truck confers on them. The social acceptance of the truck might be closely related to the social perception of the fuel, which currently is LNG. This fuel could be controversial since it is considered an alternative to diesel but it is still a fossil fuel. Thus, environmental concerns regarding the fossil origin of LNG could affect the social acceptance of the dual-fuel truck, and thereby its legitimacy. At the same time legitimacy of the technology is also affected by exogenous factors such as the climate debate, which might create a critical opinion about the different alternative fuels among the *actors* in the TIS. Weak legitimacy could constitute a barrier for market formation, especially in countries where environmental concerns are strong. This in turn could guides direction of search towards other technologies and fuels; thereby, engine and LNG related firms hesitate to enter the TIS. Therefore, concerns about the fossil origin of LNG could constitute a barrier for the adoption of the dual-fuel truck in the European market.

Strategy V

First, the marketing of these trucks should consider the environmental perception of NG which varies between countries. In countries where environmental concerns are strong Volvo Truck should establish formal *networks* with LBM related firms that would transfer environmental legitimacy to the technology. This would encourage new firms to

enter the system. Second, in order to dissociate the perception of the dual-fuel truck from the opinion about LNG, the marketing of the truck should emphasize other advantages not related to cleaner combustion of natural gas compared to diesel. The dual-fuel truck has higher fuel efficiency than the Otto engine, and energy efficiency is one of the priorities to meet the climate challenge in Europe. Additionally, the dual-fuel truck could constitute a stimulus for bio-methane production. Biogas producers may find a niche market in the transport sector since their product has higher price as a vehicle fuel than in other applications.

7. Discussion

This section is divided into three parts. First we discuss how Volvo should interpret our five strategy recommendations. Second, we highlight other issues raised in the analysis that could affect Volvo's strategy choice. Finally, we argue about the usefulness and limitations of the TIS framework to derive business strategy.

7.1. Interpretation of our strategy recommendations

The five strategies recommendations should be interpreted as possible actions that may help remove/weaken *blocking mechanisms*. In order to integrate such recommendations in Volvo's strategy plan they should be assessed and further developed. This requires extensive research about Volvo's motives to venture into the dual-fuel technology. A firm decides which technological opportunity to pursue depending on how they relate to their existing competences, its available resources, its perception of uncertainty and risk associated with the opportunity, its culture, value and norms and the firm's politics and power structure (Bergek 2002). A further study could involve an assessment of Volvo's internal determinants or reasons to enter the dual-fuel truck TIS.

It is also important to notice that these recommendations are suitable for the current state of our system (i.e. *formative phase*). When the system moves to a *growth phase* its dynamics and *functional pattern* will change. This would point out to new *blocking mechanisms* that would require different actions. Hence, when the system evolves the conclusions extracted by a similar analysis might differ from ours.

Further, these strategies are the result of a qualitative evaluation of limited amount of information. We have performed 15 interviews that we assume provided us with an overview of reality in Europe regarding the use of the dual-fuel truck and liquid methane for vehicle use. Because of time restrictions we could not perform more interviews, therefore we selected carefully our interviewees to cover the key *actors* along the value chain of the truck and the fuel as we explained in Section 3. In addition, in order to increase the reliability of our data, the information obtained in the interviews was contrasted with other sources of information.

7.2. Other strategic issues

Our strategy recommendations focus on removing/weakening the five key *blocking mechanisms* currently hindering the system development. Besides these key *blocking mechanisms*, the analysis also helped us identify other issues that affect firm strategies.

The first issue regards the current price gap between natural gas and diesel. This gap is larger in some EU countries (e.g. Italy or the Netherlands) than in others (e.g. Sweden). In the former countries, the lower price of NG could make market introduction of dual-fuel trucks easier. Thus, Volvo could focus on selling the dual-fuel truck under the “cost efficient” flag in the former countries and under the “environmental friendly” flag in the latter.

The second issue regards the EU targets. The EU estimates that the transport sector should reduce 60% GHG emissions in order to reach 80% total reduction by 2050 (EU, 2011b). In most of the scenarios presented by the EU, modal shift (from road transportation to train or ship) is required to achieve this target.⁹⁵ Modal shift could cause a reduction of the market for trucks. However, the exact impact that modal shift could have on the dual-fuel truck segment needs further research.

A third issue with implication for Volvo relates to its key customers. Although it is vital for Volvo to work with customers to build the TIS, Volvo must be aware that key customers could provide wrong guidance (Christensen, 1997). On the one hand, the fact that customers demand dual-fuel trucks to OEMs does not imply that dual-fuel will be the right choice for OEMs in the long term. On the other hand, these lead users might become an early source of feedbacks and could constitute a source of secondary innovations. Additionally, if satisfied, lead users might become advocates of the technology.⁹⁶ Therefore, Volvo should establish strong links and good relation with them and, at the same time, be critical about their demand.

A fourth issue that affects strategy choice regards the lack of LBM production. A dual-fuel truck will provide (evidently) more environmental benefits running on bio-methane than on LNG. However, the lack of LBM production plants is an important structural weakness that cannot be overlooked. Volvo cannot fully rely on the availability of LBM

⁹⁵ These scenarios are presented in the impact assessment section of the Roadmap to a Single European Transport Area.

⁹⁶ See the case of HAM Group in Spain. They were the first users of the dual-fuel technology and they now promote the use of these trucks.

to develop its dual-fuel market. The limited fuel availability poses a risk of slowing down the dual-fuel truck market development. Therefore, if an immediate growth expansion of the dual-fuel truck market is desired there is a need to use LNG as a fuel.

A fifth issue relates to a successful transition to bio-methane in the transport sector. As mentioned above, the current dual-fuel truck would definitely help building the infrastructure for LBM and might create a niche market for LBM producers. However, it is arguable whether or not the dual-fuel truck would help the transition to bio-methane. Shifting to biogas is not ensured by the availability of dual-fuel trucks. Ultimately, filling station owners and truck users can choose to buy LNG or LBM. For instance, it is reasonable to believe that fuel price will drive user's decisions. In that case, lower LBM availability might result in a higher price compared to LNG, raising attractiveness of the fossil fuel for final buyers. Thus, the transition from LNG to LBM for HDV is not straightforward nor should it be taken for granted. In general, there is a risk for a lock-in in fossil fuels associated to any technology that intends to use LNG as a bridge towards LBM. This risk might be intensified by vested interest from oil/gas companies that would see their core business threatened.

A sixth issue regards the responsibility to maintain strong *networks* in the TIS. For instance, Volvo has strong *networks* in Sweden with fuel suppliers. These *networks* are and should continue to be characterized by a mutual understanding. Therefore, we recommend that Volvo understands the LNG and LBM fuel business including its supply chain and its related standards described below.

Volvo should differentiate between CNG and LNG availability. Our analysis of the fuel trajectory to market highlights this issue (See Section 12). The existence of CNG does not directly imply the availability of LNG. Currently, LNG filling stations are directly supplied by LNG imports whereas CNG filling stations are usually supplied by pipeline gas.⁹⁷ Other LNG supply chains could be conceivable; however, one must not disregard their implications. For instance, too many processing steps in the methane supply chain imply lower energy efficiency.

Volvo should be aware of the implications of a fuel quality standard, specifically an LNG quality standard. Our analysis revealed that it would be reasonable to have a standard that apply to the upstream activities (i.e. before liquefaction at the extraction

⁹⁷ This is valid except for L-CNG filling station.

site), as it is currently under development. This would help homogenize LNG composition throughout Europe. However, it would be (almost) impossible to set upstream standards in terms of the requirements for LNG for vehicle use. If the quality specifications are too narrow, they might face strong opposition from gas/oil companies. On the other hand, if the quality standards for vehicle use are set in the downstream activities the current LNG supply chain (i.e. extraction-liquefaction-transportation to the filling station) would drastically change. LNG distributors would have to make great investments to reach these quality specifications; thereby the final fuel price might increase considerably.

In regards to LBM quality standards, it is interesting to see that in comparison to LNG standards, OEMs might have a greater possibility to directly shape them. The possibility to shape the standards is affected by the size and the maturity of the industry. The LNG system is mature and established while the dual-fuel truck system is still underdeveloped. Thus, the dual-fuel trucks have to adapt to the LNG fuel. On the other hand, the LBM market is in an early state of development, therefore there might be a greater opportunity to shape the LBM system and vice versa.

Finally, there are some other strategic issues related to technological discontinuities that are worth mentioning. The transport sector is currently facing a period of technological discontinuities caused, largely, by environmental pressure. Technological discontinuities initiate a period characterized by competing technological alternatives struggling for market acceptance. This is confusing, uncertain, and costly to most of the *actors* involved such as customers and suppliers (Tushman and Andersson, 1986). Under these circumstances, Volvo should consider the implications related to its time of entry and its firm's response capacity.

Volvo is a prime mover in the dual-fuel truck market; as such it should be able to earn positive economic profits, thereby benefiting from first-mover advantages (Lieberman and Montgomery, 1988). Early entry on an uncertain market involves risk, however this is attractive for Volvo as they could influence the way uncertainties are resolved. This resolution leads to various types of advantages. In the case of dual-fuel trucks, setting standards of its complementary technology (i.e. LNG filling stations standards) could be a source of increasing returns to adoption and early mover advantages. Taking into account the interrelatedness of these two technologies is very important, especially when

it comes to filling station and fuel tank pressure compatibility.⁹⁸ In this regard, Volvo needs to work through informal and formal *networks* with filling station owners. However, one must not forget that being the first mover has some disadvantages as well. Volvo must be aware that late-mover firms can benefit from Volvo's ability to resolve technological and market uncertainties (Lieberman and Montgomery, 1988). Furthermore, these firms can "free-ride" on Volvo's investment in buyer's education and infrastructure development.

Furthermore, a firm can strategically handle an uncertain future by adopting an ambidextrous profile (Tushman et al, 1997). In the case of Volvo it means supporting incremental innovation in their diesel technology at the same time as they develop other technologies, which could substitute their own diesel technology.⁹⁹ Thereby, this strategy confers Volvo the ability to manage today's innovation requirements and tomorrow's innovation possibilities. However, ambidextrous organizations might be unstable. Supporting different technologies within the same organization might create disparity in opinions and it is a challenge for the management team to keep coherence and integration of the firm. By being an ambidextrous organization Volvo increases its response capacity to upcoming changes in external factors that are out of the firm's control. For instance, the gap between NG and diesel price may change over time affecting one of the current drivers for customers to adopt the dual-fuel truck. This would guide *direction of search* to other fuels (e.g. DME or hydrogen) and Volvo would have an advantage by having other technologies already available.

7.3. Suitability of the TIS framework for our case study

The TIS framework has been mainly used to derive policy implications; however, in this thesis we used this framework to develop strategy recommendations. Therefore, an indirect purpose of our thesis has been to test the usefulness of this tool for business strategy.

According to our experience, the TIS framework has certain usefulness and limitations to derive business strategy. On the one hand, it helped us guide our research and focus in the relevant factors aiding and constraining the adoption of a new product in the market.

⁹⁸ For instance, Vos Logistic's filling station in Netherlands' is optimized for refueling Mercedes Econic trucks.

⁹⁹ Volvo is already performing as an ambidextrous organization.

Furthermore, it definitively provides a systematic and practical scheme of analysis to identify the main barriers threatening the diffusion of a new product in the market. On the other hand, the TIS framework does not look inside the firm. Some scholars regard this framework as a potential way to connect the micro-level theory of firms' behavior with system dynamics (Coenen and Díaz López, 2009); however, the innovation literature does not provide a practical approach to close the gap between the micro- and the meso-level. Thus, our strategy recommendations need further assessment before their implementation as we suggest in the first part of the discussion (Section 7.1).

Further, we have found out that the TIS framework usefulness for deriving business strategy depends on how much experience the firm has in regards to the new technology. In our case, since Volvo Truck has already materialized the dual-fuel truck, most of the *blocking mechanisms* had been previously revealed. Therefore, we believe that a TIS analysis could be especially interesting for firms that have not materialized their new product. However, we think that the value of this thesis also relies on the compilation of information as there is no comprehensive document illustrating the current state of the LNG/LBM dual-fuel truck.

8. Conclusion

The purpose of this thesis has been to identify the main barriers threatening the successful diffusion of the dual-fuel truck in the European market. In order to address this question we have used the Technological Innovation Systems (TIS) analytical framework. Thus, we have performed a functional analysis of the European dual-fuel truck TIS. From this analysis we drew strategy recommendations for Volvo Truck regarding its new product.

To guide our research we broke down the purpose into three research questions:

RQ1: What is the current state of diffusion of the dual-fuel truck and its complementary technologies in Europe?

RQ2: What are the main barriers hindering the adoption of dual-fuel truck in the European market?

RQ3: How can Volvo speed up the adoption of dual-fuel trucks in Europe?

Based on a literature review and discussions with relevant *actors* around Europe we identified that the system currently goes through a *formative phase*. In particular, the TIS is emerging in four European countries: UK, Sweden, Spain and the Netherlands. In all cases, LNG dual-fuel trucks have its origin in system suppliers. These firms are currently establishing relationship with OEMs and transferring their technology. Since OEMs have resources to scale up the production of these trucks, their entrance may lead to a “change of gears” paving the way to the *growth phase*. However, the existence of *blocking mechanisms* may prevent the TIS from evolving to such *growth phase*.

Five *blocking mechanisms* hindering the development of the system have been identified. These are the lack of European standards and regulations for the dual-fuel truck, lack of experience of and familiarity with the dual-fuel truck, the current small market of LNG for vehicles use, the “chicken and egg” dilemma and concerns about the fossil origin of LNG. All these blocking mechanisms are closely related to the weak functions of materialization, resource mobilization, market formation and legitimation.

For each *blocking mechanisms* we presented a strategy recommendation for Volvo Truck that could help speed up the diffusion of the new truck in the European market.

First, in order to accelerate the creation of standards and regulations Volvo could join existing working groups. Second, in order to alleviate the lack of experience and familiarity with the technology Volvo should prioritize demonstration programs and adopt a clear communication strategy. For instance, Volvo should differentiate the dual-fuel truck from other technologies (e.g. flexi-fuel) and clearly communicate its environmental benefits. Third, in order to raise the interest of oil/gas companies to enter the system, it might be necessary to increase LNG demand from the transport sector. To achieve this, Volvo could support the use of LNG as a maritime fuel. Additionally, Volvo could support the construction of L-CNG filling stations which allows CNG vehicles refill from an LNG storage tank. Fourth, in order to solve the “chicken and egg” dilemma and open market in other countries Volvo should establish formal and informal *networks* with key *actors* at the national level. Finally, Volvo cannot change societal acceptance of LNG as an alternative fuel but they can handle this issue by marketing and public relation strategy.

These strategy recommendations focus only on removing/weakening the key *blocking mechanisms*. Being aware that the TIS analysis also helps highlight other issues, we discussed their implementations for firm strategy. Topics covered include implications of: NG price in Europe, the EU targets, the role of key customers, lack of LBM producers, understanding the fuel supply chain, fuel quality standards, and the fossil fuel lock-in risk. In addition, some strategic issues regarding technological discontinuities such as the prime mover advantage and response capacity were emphasized.

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A. Annex

A.1. Bio-methane trajectories to market.

Bio-methane can be produced by a wide range of technologies. Currently, only first generation technology is commercially available and second generation technology is in an advanced state of research. Thus, we only outline the trajectories *to market* of first and second generation liquid bio-methane (LBM). Third and four generation might be an alternative for bio-methane production in the future.

Bio-methane production starts by biomass collection and transportation to the production facilities. The production plant could be based on first generation technology (represented in yellow in Figure 9) or second generation technology (represented in green in Figure 9). First generation bio-methane is produced by anaerobic digestion of organic matter in landfills or bio-digesters, while second generation is based on thermal gasification of biomass (Johansson, 2008).

In both cases the result is a gas consisting of methane and other compounds that has to be upgraded to increase the methane content and obtain the so-called bio-methane. After upgrading, bio-methane has the same applications as natural gas; therefore the right part of the Figure 9 resembles the natural gas trajectories described above. The trajectories to market of liquid bio-methane to the filling station for first and second generation bio-methane are described below.

First generation bio-methane

First generation bio-methane is based on biogas production (in yellow in Figure 9). Biogas is produced when organic material is decomposed under anaerobic conditions; traditionally it has been produced in landfills¹⁰⁰ (landfill gas) and in anaerobic digesters (digester gas). Both production technologies are commercially available and extensively used in Europe (Pettersson and Willinger, 2009). The organic material used to produce biogas could be sewage sludge, organic fraction of household and restaurant waste, industry and slaughterhouse waste, manure and agricultural crops. Lignin, such woody

¹⁰⁰ Landfilling of organic matter is forbidden in Europe since 2005 which will result in a decreasing landfill gas production. However, the decomposition process in landfills is slow, so they might produce gas for another 30-50 years (Johansson, 2008).

biomass, is not anaerobically degradable (Johansson, 2008).¹⁰¹ The main constituents of biogas are methane (CH₄) and carbon dioxide (CO₂). In addition, it contains a small percentage of other gases such as hydrogen (H₂), nitrogen (N₂) and hydrogen sulphide (H₂S) (Petersson and Willinger, 2009). The feedstock characteristics and production process (landfill or anaerobic digester) affect the yield of biogas and its composition (See Table 3).

The main difference between biogas and natural gas (NG) is the higher level of CO₂ and the absence of other hydrocarbons (HC) in biogas. These differences result in a lower energy content of biogas per unit volume compared to NG.

Table 3. Composition of biogas, landfill gas and natural gas.

	Digester gas	Landfill gas	Natural gas (Dutch, average during 2007)
Methane (vol %)	60-70	35-65	89
Other HC (vol %)	0	0	9.4
Hydrogen (vol %)	0	0-3	0
CO ₂ (vol %)	30-40	15-50	0.67
N ₂ (vol %)	~0.2	5-40	0.28
O ₂ (vol %)	0	0-5	0
H ₂ S (ppm)	0-4000	0-100	2.9
Ammonia (ppm)	~100	~5	0
Lower Heating Value (kWh/NM ³)	6.5	4.4	11.0

Source: Petersson and Wellinger, 2009.

As shown in Figure 9, biogas can be directly used as a renewable energy source in combined heat and power plants (CHP). However, for other applications such as transportation fuel or as raw material in industry, it must be cleaned and upgraded giving as a result a gas consisting mainly of methane (i.e. bio-methane). Depending on the end-use, different biogas treatment processes are needed. The energy content¹⁰² of biogas is an important parameter if it is used as a vehicle fuel; therefore, purification and upgrading processes are required (Persson, et al, 2006).

Biogas is usually cleaned before upgrading in order to prevent corrosion and mechanical wear of the upgrading equipment. During the gas cleaning process, water, hydrogen

¹⁰¹ The production of biofuels from lignin biomass is accomplished with second generation technologies. Wood biomass, residual non-food parts of current crops, such as leaves and stems, as well as other crops that are not used for food purposes, industry waste, such as skins and pulp from fruit pressing, etc, can constitute a feedstock for the production of second generation bio-methane.

¹⁰² An important parameter for bio-methane and natural gas when it is used as transportation purposes is the Wobbe Index (WI). WI is used to compare the combustion energy output of different composition fuel gases in an appliance (fire, cooker, etc.). This index is an indicator of how interchangeable different fuels are for combustion purposes; thus, two fuels that have the same WI could replace each other in a combustion engine.

sulphide, ammonia, siloxanes¹⁰³, oxygen and nitrogen are removed (Petersson and Willinger, 2009). The technology to remove the different compounds is commercially available and includes conventional separation processes such as adsorption on activated carbon, chemical absorption, condensation, filtration, etc. After the gas is clean, the main components of biogas are methane and carbon dioxide, which have to be separated in an upgrading unit in order to obtain bio-methane.¹⁰⁴ There are a number of commercially available upgrading technologies such as Pressure Swing Adsorption (PSA), water scrubbing, chemical absorption and membranes (Petersson and Willinger, 2009). Water scrubber and PSA are the most common technologies in Europe. Upgrading of biogas is still the most important cost factor in the production of liquefied bio-methane (Persson et al., 2006).

An upgrading technology that is especially interesting for production of liquefied bio-methane (LBM) is cryogenic upgrading; it makes possible to upgrade and liquefy in the same process. This technology takes advantage of the differences in condensation temperatures of the different compounds to separate impurities and CO₂ from CH₄ (Johansson, 2008). Thus, clean liquid CO₂ results as a by-product that could be used in external applications, such as refrigeration in the food industry. However, cryogenic upgrading is still under development (Petersson and Willinger, 2009).

Upgraded biogas, or bio-methane, can be injected into the gas grid or compressed to around 200 bars to be used as a vehicle fuel in gaseous form thereby following the same trajectories as pipeline natural gas. However, if the desired product is liquefied bio-methane (LBM) a further liquefaction step is required. After liquefaction, LBM can be transported by truck to the same refueling stations where LNG is supplied as a vehicle fuel.

Second generation bio-methane

Second generation bio-methane, also called bio-synthetic natural gas (Bio-SNG) is based on gasification technology (represented in green in Figure 9). In brief, biomass (e.g. forestry residuals) goes through thermal gasification followed by gas treatment and

¹⁰³ Siloxanes is a common component of biogas from landfills and sewage sludge since it is a chemical that is part of commercial and consumer products such as shampoos and deodorants. When siloxanes (R₂-SiO) are burned silicon oxide is formed. This compound is a white powder that can create deposits and damage the different parts of the internal combustion engine, i.e. pistons heads.

¹⁰⁴ Upgrading consists of removing CO₂ from the clean biogas in order to obtain a gas with high methane content, in particular to reach the percentage of methane specified for the particular application. For instance, methane content must be 95-99% in Sweden for vehicle fuel use (Persson et al, 2006).

methanation. Since any biomass material can undergo gasification this technology is larger in scale than bio-methane production from anaerobic digestion and landfills; thus, it might increase bio-methane availability.

Biomass gasification is an incomplete combustion of biomass using air, oxygen or steam as oxidant agent. The resulting gas consists mainly of CO₂, CO, CH₄, H₂, H₂O and small amounts of C₂ hydrocarbons, tar and other pollutants (e.g. ammonia, hydrogen sulfide). The gas composition depends on several parameters such as gasification temperature, oxidant agent, reactor type and type of biomass (Tunå, 2008). As shown in Figure 9, high temperature gasification leads to high contents of H₂ and CO, gas mixture known as syngas. Syngas can be used directly on heat and power generation or can be further processed to liquid fuels (i.e. such as DME) or other chemicals. On the other hand, low temperature gasification results in a gas with higher content on CH₄ (i.e. raw gas) which is the base for bio-methane production (Tunå, 2008).

Two relevant gasification technologies for raw gas production are pressurized gasification in a circulating fluidized bed (CFB)¹⁰⁵ and indirect gasification¹⁰⁶ (Tunå, 2008). The raw gas produced in the gasification process is further processed through gas cleaning, methanation, and upgrading to produce second generation bio-methane (van der Meijden et al, 2009). A simplified diagram of the overall production process is presented in Figure 8.

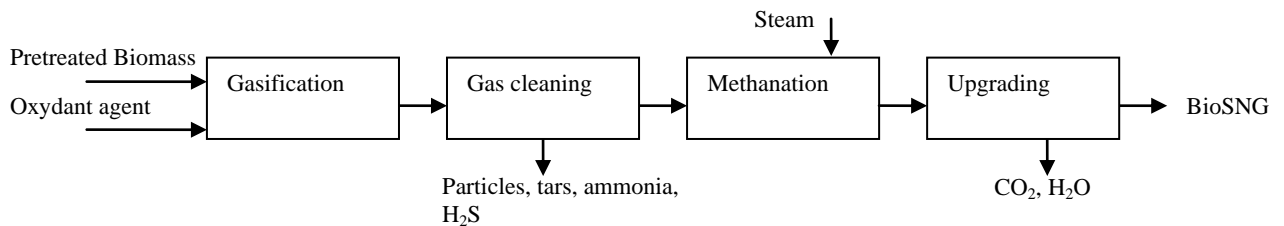


Figure 8. Second-generation bio-methane production process.

The gas cleaning technology consists of commercially available separation technologies such as cyclones, filters and scrubbers (Tunå, 2008). As shown in Figure 8, once the

¹⁰⁵ Pressurized CFB takes place at 20bars and 850-950 °C with oxygen as oxidant agent. The energy required in the process is produced during the combustion of part of the biomass in the gasifier.

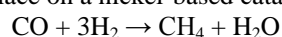
¹⁰⁶ In indirect gasification two reactors are utilized: gasifier and combustion chamber. The gasification takes place at 800-900 °C and atmospheric pressure with steam as oxidant agent. The heat required for the gasification process is produced in the external combustion chamber and transferred to the gasifier in the form of hot sand. It is possible to create a single reactor with two zones –combustion and gasification zones- that follow the same principle as the pure indirect gasification. This configuration is known as fast internal circulating fluidized bed (FICFB).

raw gas has been cleaned it can be used for heat and power generation or can be further processed in a methanation¹⁰⁷ unit to increase the CH₄ content in the gas. The main advantage of producing bio-methane instead of other fuels is the relatively high efficiency of the bio-methane production process. This higher efficiency derives from lower energy requirement in the gasification- it is a low temperature gasification- and the formation of CH₄ in the gasification process, which facilitates the subsequent methanation step. 60-70% energy efficiency can be expected from bio-methane production, while DME reaches 50-60% and biomass to liquid (BtL)¹⁰⁸ processes reach 35-45% (Svensson et al., 2009).

Finally, when the gas leaves the methanation unit it could follow the same trajectories as first generation bio-methane (See Figure 9). The upgrading technologies suitable for second generation bio-methane production are similar to the ones for first generation bio-methane, i.e. pressure swing adsorption (PSA), water scrubbing, chemical absorption, membranes and cryogenic upgrading (Tunå, 2008). After upgrading and liquefaction, the LBM could be transported to a refueling station for its final use as a vehicle fuel to the same types of refueling stations as first generation bio-methane and LNG.

Although LNG and LBM follow two different production processes, they could share part of the infrastructure. In particular, cryogenic storage, distribution trucks and refueling infrastructure are essentially the same for both fuels. Additionally, liquefaction plants could technically be shared by LNG and LBM. However, liquefaction facilities are available mainly in LNG exporting countries such as Qatar and Nigeria (GIE, 2010); therefore it would be required to build such plants in Europe if bio-methane is used in liquid form. The main difference between liquefaction of LNG and LBM would be the scale. In the case of LBM these plants will most likely be small scale liquefaction facilities close to the biogas production site whereas LNG liquefaction has been used in much greater scale for many years by the gas industry (Interview Marhaug, 2011).

¹⁰⁷Methanation is a catalytic process that converts a mix of carbon monoxide and hydrogen in methane and water. The reactions take place on a nickel-based catalyst (van der Meijden et al, 2009).



¹⁰⁸ BtL refers to the production of liquid biofuels through the Fisher-Tropsch synthesis. In practice, the biomass is gasified at high temperature to obtain a mixture of H₂ and CO known as Syngas or synthesis gas. The Fisher-Tropsch process converts syngas in liquid fuels such as bio-diesel.

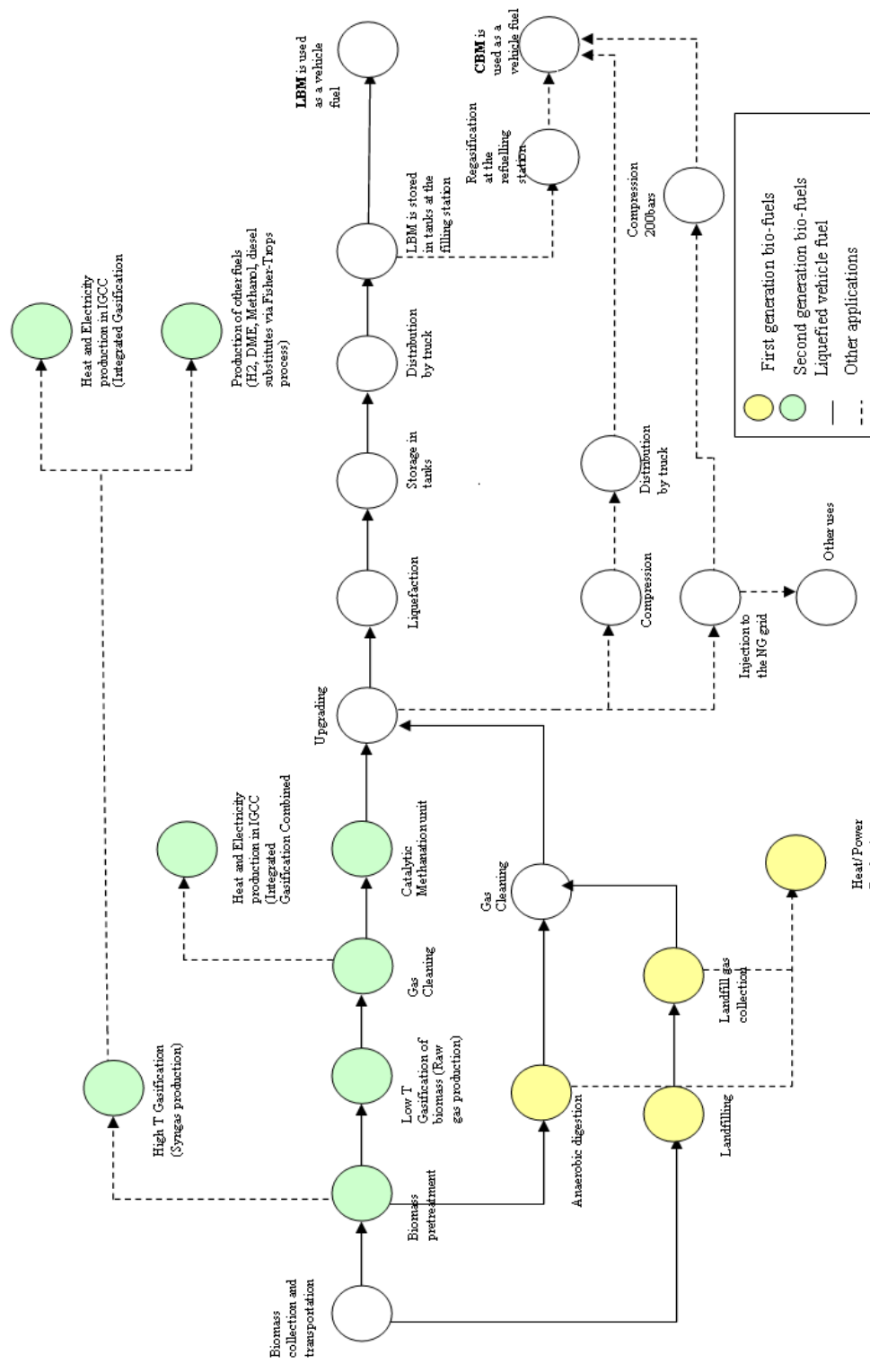


Figure 9. LBM trajectories to market.

A.2. Fuel price and tax in selected countries

Table 4. Diesel price and taxes in selected European countries, average December 2010.

Country	Cost of product plus distribution profit (€ / liters)	Excise duties and other taxes (€ / liters)	VAT (%)	VAT (€/litres)	Price at the Pump (€ / liters)	Tax as a % of total price
Austria	0,631	0,347	(20%)	0,198	1,184	46%
France	0,481	0,428	(19.6%)	0,178	1,087	56%
Germany	0,496	0,470	(19%)	0,183	1,150	57%
Italy	0,466	0,423	(20%)	0,178	1,067	56%
The Netherlands	0,450	0,420	(19%)	0,170	1,040	57%
Spain	0,473	0,331	(16%)	0,132	0,957	48%
Sweden	0,539	0,451 * ¹⁰⁹	(25%)	0,233	1,220	56%
UK	0,436	0,617	(17.5%)	0,159	1,210	64%
EU minimum	-	0,330	According to Annex I of the Directive 2003/96/EC			

Source: ACEA, 2010.

Table 5. Natural gas prices and tax estimation for selected EU countries.

Country	Cost of product plus distribution profit (€ / m ³)	Excise duties (€ / m ³)	VAT (%)	VAT (€/m ³)	Price at the pump (€ / m ³)	Tax as a % of total price
Austria	0,45	0,06	0,20	0,10	0,61	26%
France	0,54	0,00	0,20	0,10	0,64	16%
Germany	0,45	0,14	0,19	0,11	0,70	36%
Italy	0,50	0,00	0,20	0,10	0,61	17%
The Netherlands	0,28	0,17	0,19	0,08	0,53	48%
Spain	0,51	0,04	0,18	0,10	0,65	22%
Sweden	0,89	0,15	0,25	0,26	1,30	32%
UK	0,43	0,25	0,20	0,14	0,81	47%
EU minimum		0,09	According to Annex I of the Directive 2003/96/EC			

Table 6. Natural gas price vs diesel price in selected European countries, December 2010.

Country	Price at the Pump (€ / m ³)	Price at the Pump (€ / diesel liter equivalent)	NG price as a % of diesel price
Austria	0,61	0,63	53 %
France	0,64	0,65	60%
Germany	0,70	0,72	63%
Italy	0,608	0,62	58%
The Netherlands	0,53	0,54	52%
Norway	0,90	0,92	61%
Spain	0,65	0,67	70%
Sweden	1,30	1,33	98%
UK	0,81	0,83	68%

Source: adapted from NGVA, 2011a.

¹⁰⁹ Of which the energy tax is 0,137 € /liters and the carbon dioxide price is 0,313 € /liters.

A.3. Second generation bio-methane projects in Europe.

Table 7. Second generation bio-methane projects in Europe, April 2011.

Location	Description	Size	Current State	Actors
Austria (Güssing)	Demonstration plant for bio-methane production from woody biomass. It includes steam gasification, advanced gas cleaning, methanation and gas upgrading. Integrated in a CHP plant.	8MW _{th} CHP plant from which 1MW is converted to bio-methane	Bio-methane production since 2009	DBFZ, Verbundnetz Gas, TUV, Repotech, Biomasse Kraftwerk Güssing, EdF, CTU, PSI
The Netherlands	Conversion of dry lignocellulosic biomass into bio-methane. The production process is integrated in a CHP plant.	10 MW _{th} CHP plant from which 1MW is converted to bio-methane	First demo operating in 2012	ECN, HVC, Dahlman, EPC
		50 MW bio-methane	Second demo in 2015	
Germany (Göppingen)	Commercial-scale research and development facility for electricity production. The plant will become a research facility for developing bio-methane production process.	No info	Planned	ZSW, Forschung Baden Württemberg
Sweden (Gothenburg)	<i>GoBiGas</i> : large scale co-generation plant to convert low quality cellulosic materials to bio-fuels.	20MW bio-methane	First demo operational in 2012	Göteborg Energi, E.ON
		80MW bio-methane	Second demo operating in 2015	
	<i>Chalmers gasifier</i> : Development of a new design of FICFB gasifier which enables most existing CFB boilers to be retrofitted and turned into a FCIFB unit.	6MW bio-methane	Constructed	Chalmers, E.ON, Göteborg Energi, Metzo, Akademiska Hus ¹¹⁰

Source: DBFZ, 2009; PSI, 2009; ECN, 2009 Gunnarsson, 2010; Thunman, 2010

¹¹⁰ These projects do not incorporate liquefaction.

A.4. First generation liquid bio-methane projects in Europe.

Table 8. LBM plants in Europe, April 2011.

Location		Description	Size	Current state	Relevant <i>actors</i> involved
Sweden	Sundsvall	First LBM production facility in Scandinavia. It treats gas from a sewage treatment plant. It uses the technology GPP®Plus of SGtS	600 000 Nm ³ /year	Constructed	Scandinavian Grastreatment Services (SGtS), Sundsvall Municipal water company Mitt Sverige Vatten, AGA, Fokusera Utveckling Sundsvall
	Stockholm	LBM production from wastewater treatment plant in Loudden, Bromma and Henriksdal	8 600 000 Nm ³ /year	Constructed (In operation since August 31 st 2010)	Scandinavian Biogas AB, Stockholm Vatten
	Lidköping	LBM production from bio-digestion of wastes generated in the food industry in Lidköping and surroundings.	60GWh/year of LBM	Planned to be finished in 2011	Lidköping Municipality, Swedish Biogas Internationa(SBI), Göteborg Energy
	Uppland	Information not available	10 000 000 Mm ³ /year	Planned	Join Venture between Scandinavian Biogas and Uppland Lokaltrafik (UL)
	Helsingborg	The world's largest plant for upgrading of landfill gas. The technology was demonstrated in a pilot project carried out in USA.	15 000 000 Nm ³ /year	Planned to be opened in early 2012	Joint Venture Terracastus (Volvo Technology Trasnfer's subsidiary), Nordvastra Skanes Renhallningsbolag (NSR)
	Klagshamn		Pilot: 20 GWh Planned: 600 GWh		E.ON
The Netherlands	Delfzijl	Located in Delfzijl		In construction	Bio-ethanol Rotterdam BV
	Weert	LBM pilot plant treating biogas from Essent Landfill in Weert since Dic 2008.	7 kg of LBG / hour	In demonstration state	Scandinavian Grastreatment Services (SGtS)
UK	Surrey	LBM production from Albury landfill gas.		LBM production since 2008	Gasrec

Source: Svensson, 2009; BER, 2009; Beyer, and Brown, (2009). Öhman, 2009; NGV, 2008; SBI, 2011; ScandinavianBiogas, 2011.

A.5. Filling stations dispensing LNG in Europe.

Table 9. Identified LNG / L-CNG filling stations currently serving LNG in Europe until April 2011.

Country	Location	Actors involved in operation and/or construction.	Type	Fuel
Belgium	Leuven	NexGen Fueling and Citensy	L-CNG	LNG and CNG
Netherland	Oss ¹¹¹	Cryoenergy Indox , Vos Logistics and Rolande LNG	LNG	LNG
Spain	Terremocha (Guadalajara)	HAM Group	L-CNG	LNG and CNG
	Lerida (Lerida)	Gas Natural		LNG and CNG
	Valencia (Castellon)	Transportes Montfort	L-CNG	LNG and CNG
	Bandalona (Barcelona)	Gas Natural		LNG and CNG
	Olaberria (Guipúzcoa)	Agas 21	L-CNG	LNG and CNG
	Abreira (Barcelona)	HAM Group	L-CNG	LNG and CNG
UK	Tebay	Chive Fuels	LNG	LNG
	Londonderry	Chive Fuels	LNG	LNG
	Castleford	Chive Fuels	LNG	LNG
	Lymm	Chive Fuels	LNG	LNG
	Ilkeston	Chive Fuels	LNG	LNG
	Shepshed	Chive Fuels	LNG	LNG
	Flamsteade	Chive Fuels	LNG	LNG
	Bristol	Chive Fuels	LNG	LNG
	Wolverhampton	Chive Fuels	LNG	LNG
	Carlisle	Chive Fuels	LNG	LNG
	Lesmahagow	Chive Fuels	LNG	LNG

Table 10. LBM filling stations in Europe until April 2011.

Country	Location	Actors involved in operation and/or construction.	Fuels
Sweden	Sundsvall	AGA-Linde and Fokusera Utveckling Sundsvall	LNG and LBM
	Göteborg	FordonsGas	LNG and LBM (planned)

¹¹¹ Refuelling Volvo Truck's dual-fuel truck is impossible in this filling station. It is designed to fill Mercedes Econic Truck.

A.6. The emergence of the TIS in Sweden, UK, the Netherlands and Spain.

Sweden

The commercialization of the dual-fuel trucks in Sweden has been led by Volvo Truck Corporation. They rely on systems suppliers such as Hardstaff, Clean Air Power and Westport for the dual-fuel technology (Interview Franzén, 2011).¹¹² The combination of Volvo's knowledge in diesel engines and the experience of system suppliers with retrofitting diesel engines resulted in the Volvo's dual-fuel truck. Together, they have developed dual-fuel trucks running on CNG/CBM and also running on LNG/LBM.

Westport, a Canadian based company, is a leading global provider of technology that allows engines to operate on CNG, LNG, hydrogen and bio-methane. This company started with research and experimentation of dual-fuel engines (Westport HD-system¹¹³) in the University of British Columbia in 1980 (NGV, 2010b). In 2009, Volvo and Westport committed to a supply agreement where Westport became a Tier 1 development supplier for its heavy duty natural gas engines and associated supply chain. Westport will supply its Westport technology for Volvo heavy duty applications for future commercialization (NGV, 2010b). Besides working with Volvo, Westport works together with Cummins (American engine manufacturer), Weichai Power (Chinese engine manufacturing), Kenworth and Peterbilt. Furthermore, Cryostar is a component supplier in Westport's systems. Westport dual-fuel technology reaches the highest substitution rate available in the market (95%), however due to its small injectors it cannot run entirely on diesel (Westport, 2010).

The dual-fuel truck market developed in Sweden thanks to the BiMe Truck program. In order to introduce LNG as HDV fuel a group of companies joined the Business Region Goteborg (BRG) and applied for subsidies to the Swedish Energy Agency (Interview Pilskog, 2011). The companies involved are Volvo Truck, AGA Gas, E.ON Gas, FordonsGas and Energy Gas Sweden (BiMe, 2010a). The result was a subsidy program for the construction of three filling stations and 100 trucks. It consists of 3,000,000 SEK per station and 170,000 SEK per truck offered by the Swedish Energy Agency (BiMe,

¹¹² For further information about Hardstaff and Clean Air Power activities in relation to the dual-fuel engine see the case of UK.

¹¹³ Westport HD-system has been in commercial development since the middle of the 90's. It has been a proven to work in the Canadian, Australian and Californian markets (Westport, 2010).

2010c).¹¹⁴ The BiMe project coordinated development of the two complementary technologies: fuel and truck, offering customers a commercially viable alternative to diesel-powered HDV in the region of Västra Götaland (BiMe, 2010a).

LNG for vehicles represents a small share of the natural gas consumed in Sweden. Currently, natural gas in Sweden is mainly used in the industry (70%) and residential heating (26%). The rest (4%) is used for vehicles which is to a minor extent imported and stored in liquid form (Svensson, 2009). Thus, most of the natural gas consumed in Sweden comes via pipeline even though there is a limited natural gas grid in the country. This gas grid has a single supply point, the Danish gas grid (Svensson, 2009).

Regarding the LNG filling stations, there are currently two of them in operation (See Table 9). The first is in Gothenburg and is operated by the gas company Fordonsgas Sverige (Interview Berggren, 2011). This project was developed under the BiogasMax European program in coordination with Volvo Truck dual-fuel engine development (Ekengren, 2010). The filling station is currently dispensing LNG from the Norwegian distributor Nordic LNG and is planning to provide LBM later this year (Interview Berggren, 2011).¹¹⁵ The second filling station is located in Sundsvall and it is supplied with biogas from the region. The LBM production facility is a result from collaboration between the municipal water company MittSverige Vatten, Fokusera Utveckling Sundsvall as well as Scandinavian GtS and the gas company AGA, who are all owners of the facility (Kättström, H, 2008; ALTERMOTIVE, 2009).¹¹⁶ The LNG refueling infrastructure is expected to continue growing; at least three more filling stations are planned under the BiMe program (BiMe, 2010b).¹¹⁷ This enlargement will likely reduce the price of construction of LNG refueling stations which is currently rather high due to the need for specific components that have never been manufactured before.¹¹⁸

¹¹⁴ The subsidy for the trucks is given directly to the truck buyer and covers around half of the extra price of the truck in comparison to the conventional diesel truck price (Interview Hammarberg, 2011).

¹¹⁵ The LBM will come from a biogas plant in Lidköping which has a capacity of 60GWh/year.

¹¹⁶ The LBG production facility will produce approximately 600 000 Nm³ LBM, which correspond to approximately 600 000 litre of diesel (ALTERMOTIVE, 2009).

¹¹⁷ The three filling stations under the the BiMe programme will be located in Stokholm, Malmö and Jonköping (BiMe, 2010b). The first one is planned by AGA in collaboration with Volvo and will supply LBM from a biogas plant in Loudden (750 000 Nm³/year). The second one is planned by the energy company E.ON and will probably receive LBM from the production plant in Klagshamn which is currently a pilot plant of 20GWh. The third one is planned for 2012

¹¹⁸ The L-CNG filling station in Gothenburg required an initial investment of 12,000,000SEK (while the BiMe subsidy is 6,000,000SEK/station). An ordinary CNG filling station costs 6,000,000SEK (Interview Berggren, 2011).

The LNG refueling infrastructure is developing closely to the market introduction of Volvo's dual-fuel truck in Sweden. Currently three companies are testing the truck: DHL, Renova and Götene Kyltransporter (Interview Mårtensson, 2011). The companies buy the dual-fuel truck sponsored by the Swedish Energy Agency (SEA). The "field test" consists on returning to Volvo the dual-fuel truck every three weeks for revision (Interview Hammarberg, 2011). These field tests helped gain trust from customers, while Volvo acquires experience about the truck performance in real life operation by feedbacks from its first customers.

Environmental concern is a strong driver for the adoption of low-carbon technologies in Sweden.¹¹⁹ According to Hammarberg (2011), customers are willing to pay more for less polluting transportation of goods. Moreover, logistic firms like DHL have their own environmental targets aiming at reducing emissions in their activity to satisfy customers demand for green transportation (Interview Hammarberg, 2011). Until now there has not been a commercially available alternative option to diesel trucks for long distance transportation¹²⁰ and the dual-fuel truck is considered a real alternative to diesel in the long haulage sector.¹²¹

However, the dual-fuel trucks currently use LNG as a fuel, which is not totally accepted in Sweden (Interview Berggren, 2011). Natural gas, compressed or liquid, might be accepted as a bridge towards bio-methane or to complement biogas to fulfill the gas demand.¹²² Therefore, the adoption of this truck in the Swedish market might depend on the availability of bio-methane in liquid form.¹²³

¹¹⁹ Environmental concerns might be a stronger driver than fuel economy in Sweden since natural gas and diesel have relatively similar prices. According to NGVA statistics, natural gas price was 0,98 times diesel price in December 2010, which represents the lowest gap between gas and diesel price in Europe (NGVA, 2011a).

¹²⁰ Trucks with Otto engine running on CNG/CBM are commercially available; however, truck users do not consider it a solution for long distance transportation due to its low operational range.

¹²¹ It is worth noting that Preem has launched this year the Evolution Diesel which is a perfect substitute for fossil diesel that comes from biomass gasification. This renewable diesel does not require any engine modification and can use the current diesel refuelling infrastructure as it is right now.

¹²² Sweden has implemented the green gas principle, which means that natural gas and bio-methane are both injected into the gas grid and used as a single fuel. Users decide whether or not to pay an extra fee for using green gas. This concept makes sense in a country with high environmental concerns where environmental drivers could be stronger than economic drivers for final users.

¹²³ It is important to know that Sweden does not have import pipelines for natural gas. Thus, the natural gas demand is covered by LNG imports and by biogas produced in the country. In addition, there are plans to build two LNG import terminals in Sweden that will increase the availability of LNG in the country (Interview Andersson, 2011).

According to Svensson (2009), there is a clear trend toward bio-methane use in the transport sector in Sweden since heat and electricity are already well covered by renewable sources (Svensson, 2009). In regards to liquid bio-methane there are currently several production plants planned or under construction that aim at supplying LBM for vehicles. The largest one is the result of a joint venture between Terracasatus Technology and Nordvastra Skanes Renhallningsbolag (NSR). It will be located in Helsingborg and will produce 15 000 000 Nm³/year of LBM (Beyer, J., and Brown, B., 2009).

UK

The use of the dual-fuel truck in the UK has mainly been promoted by system suppliers such as Hardstaff and Clean Air Power (CAP). However, OEMs relationships with these system suppliers have also helped in a successful diffusion of this technology in the market. According the NGVA, in the UK there are around 100 LNG dual-fuel trucks (Boisen, 2011b).

Hardstaff Group, a UK based company, has a patented OIGI® dual-fuel technology that can be adapted to many type of vehicles including heavy duty trucks. Hardstaff has worked closely with Loughborough University to help technologically advance their system for emerging markets (NGVAa, 2011; Interview Landin, 2011).

Hardstaff relationship with OEMs is as follows:

- It worked in conjunction with Mercedes-Benz to develop its Econic, Axor and Actros trucks in a dual-fuel version running on LNG or CNG (Mercedes, 2011).¹²⁴
- It collaborated with Volvo Truck to develop its FE and FL truck in a dual fuel version running on CNG (Interview Landin, 2011).

In regards to filling stations, Hardstaff Group, through its Portal Gas Service business branch, works with technology for LNG and L-CNG station in the UK. Portal Gas Services have an L-CNG station located at their Nottingham headquarters which was the first one proving both LBM and CBM from liquefied bio-methane (Hardstaff, 2011a).

Clean Air Power (CAP), another developer and supplier of dual-fuel system, was initially founded in the USA in 1991; however, it has operational subsidiaries in the UK. Its Genesis Dual-Fuel™ system has received investments of around £40m for its development (CAP, 2008). This system is available as an aftermarket product (no OEMs involvement) for Mercedes's Axor, DAF CF85 (Euro 3) and Volvo FM13 (Euro 5) (CAP, 2006; CAP, 2008). Furthermore, CAP has the following direct relationship with OEMs:

¹²⁴ Hardstaff Group is working with Mercedes-Benz UK to carry out conversions of its engines to run on both diesel and natural gas. As a result the OIGI® conversion does not invalidate the manufacturer's warranty and is supported by a full insurance warranty on the engine and ancillary equipment provided by Hardstaff.

- In 2004, Foden (a division of Paccar UK) offered a dual-fuel variant of their Alpha trucks powered by a Caterpillar engine (Euro IV) (CAP, 2006).
- Volvo offers its FM dual-fuel trucks (Euro 5) using CAP's Dual-Fuel™ technology (liquefied fuel) (CAP, 2008).

During 2003 and 2004 the Energy Saving Trust, a UK governmental founded organization, supported CAP engine technology with 60% grant for truck owners who purchase dual-fuel retrofitting (EST, 2007).

Recently, Clean Air Power opened an R&D facility in Leyland, UK. This facility is used to develop its retrofit Dual Fuel™ Technology and its new OEM integrated engine technology (NGV, 2007). In UK, some users of the Genesis Dual-Fuel™ technology supplied by Clean Air Power include: Sainsbury (the third largest chain of supermarkets in UK) with five retrofitted Mercedes Axor trucks (Euro3) and Robert Wiseman Dairies (one of the UK's leading fresh liquid milk processors) with 22 retrofitted LNG DAF CF85 (Whelan, 2007; NGVA, 2009).

Both Clean Air Power and Hardstaff are strong pioneers of the dual-fuel technology for road transportation in UK. They have taken advantage of governmental incentive programs, fuel prices and environmental concerns to grow their business. With the support of OEMs like Volvo, Mercedes and Foden, these system suppliers have managed, in the past 10 years, to diffuse the dual-fuel trucks in the UK market.

The conventional gas vehicle market is much more developed than the dual-fuel vehicle market. According to NGVA (2010), UK has 220 NG vehicles¹²⁵ in the market, of which 150 are medium and heavy duty vehicles. The availability of conventional (Otto engine) gas vehicles in the UK (from OEMs), is as follows: Volvo offers CNG fuelled passenger cars, Iveco and Daimler offer CNG light good vehicles, Iveco also offers Eurotech gas buses (EEV¹²⁶) and Stralis LNG/CNG trucks.

Both dual-fuel vehicle and conventional gas vehicle availability has helped in the development of the necessary NG filling station infrastructure in the UK. In regards to these stations, the large fleet operators, and particularly those with HDVs, typically have their own fuelling facilities thereby receiving price discounts for the large volumes

¹²⁵ Including Otto or dual-fuel vehicles.

¹²⁶ The engines of these trucks are certified in line with the EEV (Environmentally Enhance Vehicle) standard indicated in the EU heavy duty exhaust emission directive.

of fuel that they purchase (NSCA, 2006; Interview Leaf, 2011). Compared with conventional refueling stations, the number of available CNG and LNG filling stations is extremely limited on mainland Britain. According to the NGVA (2010), there are 16 NG fuelling stations in UK, of which 11 are LNG or L-CNG. All of them are public. Usually, filling stations in UK are associated with a fleet operator.¹²⁷ Table 9 shows the LNG filling stations in UK. The company Chive Fuels supplies all of these stations with LNG fuel (Chive, 2011). This company has ten years of experience in distributing LNG across Europe.

LNG availability in the UK is expected to be plentiful in the near future. UK is the second largest producer of NG in the EU (JES, 2010). Similar to other EU countries, the UK is increasing its demand of NG, particularly for power generation. In 2005, it became net importer of oil and NG. Indigenous supply of NG has not kept pace with increasing demand. Therefore, to address the predicted shortfalls the government started promoting an increase in the domestic production and the establishment of the necessary import infrastructure, such as LNG receiving terminals and transnational pipelines (EIA, 2010).¹²⁸ Consequently, these investments will ensure the continued security of gas supply, the continued availability of NG to the end user and the stabilizations of prices¹²⁹.

An important driver for the use of NG for vehicles in the UK is the price differential between NG and conventional fuels. The price of CNG in December 2010 corresponded to around one half of the price of diesel (including taxes).¹³⁰ However, this differential is not static but affected by the product price and the fuel tax.¹³¹

In the past years the fuel taxes of natural gas and diesel have been increasing. When VAT is included, the tax represents around 65% of the final pump price for natural gas¹³² and around 59% of the final pump price of diesel.¹³³ Traditionally, the UK has charged relatively high duties on road fuels compared to other EU countries, and pump

¹²⁷ And sometimes these filling stations allow third party access.

¹²⁸ In addition, the government has also invested in energy conservation and renewables.

¹²⁹ All of these subject to the political situation in the Middle East.

¹³⁰ In 2010, CNG price in UK corresponded to 0,83 €/litre diesel equivalent while the diesel price was 1.47€/liter (NGVA, 2011a).

¹³¹ The fuel tax is an excise duty imposed on the sale of fuels. Further, VAT is charged on the full selling price of all excisable goods, excised duty included.

¹³² The pump price of NG as of March 2011 in the UK was around 0.75 £ per kg (Interview Leaf, 2011).

¹³³ As of March 2011.

prices have been consistently higher than elsewhere in Europe (Seely, 2011). The following Table 11 shows the fuel tax for NG as a road vehicle during the past years.

Table 11. Fuel tax for natural gas as a road fuel in UK.

Years	Duty on NG as a road transport fuel
2007	0.1370 £ per kg
2009	0.2216 £ per kg
March 2011	0.2400 £ per kg
January 2012	0.2910 £ per kg

Source: Hoben, 2011.

Similarly, the diesel fuel tax in the UK has been increasing over the years. In 2009, this tax was 0.5619 £ per liter of diesel. In 2011, the tax increased to 0.5895 £ per liter. According to James, R. (2011), the price of LNG at Chive's filling station is little less than one pound per kilogram, i.e. 0,93 € /m³.

Liquid bio-methane (LBM) in the UK is scarce. The only company selling LBM is Gasrec. This London based company, is producing LBM in a liquefaction plant at its landfill site at Albury in Surrey (Interview Leaf, 2011; NGV, 2008). In 2002 Gasrec started with R&D for LBM production. By 2008, they became the first commercial producer of LBM in Europe. Gasrec works with BOC, a subsidiary of the Linde Group, who provides the liquefaction technology. Furthermore, Hardstaff's Portal Gas Services (UK natural gas bulk transporter) and Gasrec have formed a partnership to manage the transport logistics and fuel transportation from the landfill (Hardstaff, 2011b). The Surrey plant produces approximately 5,000 tones of LBM per year (capable of fuelling 150 HVDs). Besides producing the fuel and controlling the logistics chain, Gasrec is also controlling the refueling stations at customer's location (Interview Leaf, 2011). However, at the moment Gasrec does not participate in the construction of LBM public filling station because of the lack of LNG/LBM vehicle market (Interview Leaf, 2011). In 2011, the price of LBM is around 48 % of the price of diesel (including tax).¹³⁴ Furthermore, according to Leaf (2011), Gasrec LBM's major competitor is diesel (not natural gas).¹³⁵ The price of natural gas is 82% of the price of LBM, i.e. LBM is around 0,17 €/kg more expensive than NG (Interview Leaf, 2011).

¹³⁴ The pump price of diesel (price for a single customer) is 1,46 € / liter and the pump price of LBM is 0,73 € / liter of diesel equivalent (Interview Leaf, 2011)

¹³⁵ According to Leaf (2011), it does not matter if their LBM is slightly more expensive than LNG. Their intention is to substitute diesel, as long as their LBM prices stay lower than diesel they can show financial savings.

Some users of Gasrec's LBM fuel include:

- Sainsbury's retrofitted Mercedes Axor trucks (NGVA, 2009).
- Hardstaff Haulage, one of the companies of Hardstaff Group, became the first major haulage company in the UK to use liquid biogas from landfill waste (Gasrec's biogas). They serve their fleet with both LBM and CBM from their own station (Hardstaff, 2011b).
- Coca-Cola's Iveco Stralis trucks (NGVA, 2011b).

Furthermore, Tesco has fueled 25 CBM light vans with Gasrec's bio-methane.

An important driver of biofuels availability in the UK is the Renewable Transport Fuel Obligation (RTFO). The RTFO puts an obligation on refineries and importers of fossil fuels such as BP, Chevron, Shell and Total.¹³⁶ In 2009, the obligation was to ensure that 2.5% by volume of the road fuel they supply in the UK is made up of renewables (RFA, 2009).¹³⁷ This instrument was enforced by the Renewable Fuel Agency (RFA); however, this non-departmental public body was dissolved in April 2011 and its duties were transferred to the Department of Transport (Dft). Gasrec supplies bio-methane under the RTFO (Interview Leaf, 2011). The Energy Act 2004 and the Renewable Transport Fuel Obligation Order of 2007 are the two legislations in UK backing up this policy instrument.

In regards to LBM for other applications, the injection of biogas into the natural gas grid in the UK is not permitted (Interview Leaf, 2011). Actually, this forced Gasrec to liquefy its biogas in order to effectively move it from point of production to point of use. According to Doug Leaf (2011), this particular circumstance has moved Gasrec into the liquid bio-methane market. Furthermore, according to our interviewee, at the moment in UK there are no real incentives for the production of electricity from bio-methane. The value of LBM for the transport sector is greater compared to the electricity sector.

¹³⁶ The RTFO puts an obligation on refiners and importers of fossil fuels supplying at least 450,000 litres a year ('obligated suppliers').

¹³⁷ These obligated suppliers must demonstrate that they have met their Obligation by redeeming Renewable Transport Fuel Certificates (RTFCs) to the Renewable Fuels Agency (RFA) at the end of the year. One RTFC is awarded for every litre (or kilogram in the case of biogas) of biofuel reported to the RFA, and an obligated supplier can obtain them either by supplying biofuel itself, or by buying them from biofuel suppliers (RFA, 2009).

The Netherlands

According to the NGVA (2011), in 2010 the Netherlands had a total of 700 HDVs and 2800 light duty vehicles running on gas. In regards to dual-fuel vehicles there are currently no clear statistics in the Netherlands. However, some indicators of the increasing interest in this technology include:

- the dual-fuel test program launched in February 2011 by the Department of Road Transport (RDW, 2011)
- the availability of dual-fuel trucks by OEMs such as MAN and Mercedes (NGVJ, 2011b)
- LNG availability

The “Dual-fuel Test Programme” was initiated by the RDW in collaboration with Ministry of Infrastructure and the Environment (I&M) and the Netherlands Organization for Applied Scientific Research (TNO). The purpose of the program is to gain experience and insight into the emission performance of dual-fuel systems that could contribute to develop emission test procedures in the Netherlands (RDW, 2011).

In 2011, MAN introduced a CNG dual-fuel truck in the Netherlands. This technology runs on 40% natural gas and 60% diesel. Some customers for these trucks include Lekkerland, a chain of convenience stores, and Wim Bosman Group, a 3PL and logistics service provider (NGVJ, 2011b). Mercedes-Benz also offers its Actros truck (retrofitted) in a dual-fuel version in the Netherlands. Besides dual-fuel vehicles, Iveco is present in the Netherlands with its Stralis LNG/CNG truck (Otto engine) as well as Mercedes-Benz with its Econic LNG/CNG trucks (Otto engine). Furthermore, In 2010 IVECO together with Rolande LNG converted an IVECO Stralis CNG to run on LBG (NGV, 2010c).

In regards to LNG availability for vehicles, in 2010, Vos Logistics together with Mercedes-Benz and Rolande LNG opened the first LNG refueling station in the Netherlands.¹³⁸ The LNG is available from nearby terminal in Zeebrugge Belgium (Verbeek, 2006). This project overcame several hurdles such as the lack of legal base for safety and environmental regulation for allowances, both for filling stations and for trucks. Currently, Rolande LNG received a subsidy from the Dutch Ministry of

¹³⁸ Other actors in this project include: LNG Europe, Van Gansewinkel and Indox CryoEnergy Spain.

Economic Affairs to put the entire LNG/LBM (for vehicles) supply chain in place: refueling stations, distribution, purchasing, customers and providing trucks (Rolande, 2011). Thereby, the AgentschapNL (Ministry of Economic Affairs, Agriculture and Innovation) is supporting the development of the infrastructure for this new fuel in the Netherlands. Although the LNG infrastructure is under development, the CNG filling station infrastructure is available and much more extensive. In the Netherlands, there are more than 50 CNG refueling stations for vehicles (NGV, 2010d).

Moreover, the Netherlands is the second largest natural gas producer in Europe. It accounts for more than 30% of EU total annual gas production (EC, 2010). The consumption of natural gas in the Netherlands is about two-thirds of its production. In despite of its abundance of indigenous gas, the Netherlands is also investing in the construction of LNG terminals in Rotterdam and Eemshaven (King & Spalding, 2006).¹³⁹ Electricity in Holland is mainly generated from gas and hard coal (EC, 2010).

In regards to LBM availability for vehicles, some projects for the production of this fuel include:

- Bio-ethanol Rotterdam BV (BER): this Dutch firm expects to secure financing to build a liquefied biogas plant in Delfzijl. Small-scale liquefaction of the resulting bio-methane will be done using the cryogenic technology of Cryonorm (BER, 2009).
- SGtS: this Dutch/Swedish firm has an LBM demonstration plant in Weert. They are testing the production of LBM from Essent landfill. However, it is not commercially available yet (Öhman, 2009).

A contextual aspect affecting the availability of LBM in Netherland is the willingness to pay for this gas. According to Hans Kättström, final users are not willing to pay the high price of this fuel. Therefore, SGtS is considering the exportation of LBM to Northern Europe.

¹³⁹ These terminals are regasification terminals.

Spain

The use of dual-fuel truck in Spain has mainly been promoted by two private companies: HAM Group and Transportes Monfort.^{140,141} HAM Group aims at establishing natural gas as vehicle fuel in Spain, which until now was mainly used as CNG in public transport (i.e. urban busses) and refuse trucks.¹⁴² In particular, the group is interested in LNG for HDVs (Interview Murugó, 2011). Together with the logistics company Transportes Monfort they are the first users of the dual-fuel technology for heavy duty trucks in Spain and also responsible for half of the LNG filling stations in the country.

Already in the 2000, HAM Group bought 10 LNG vehicles in the United States, 5 of which were dual-fuel technology (Interview Murugó, 2011). Currently, they have 10 Volvo's FM trucks that were retrofitted by Clean Air Power.¹⁴³ In 2007, Transportes Monfort converted three trucks, Renault Premium 385/400, to dual-fuel running on LNG (NGVJ, 2011a). HAM's experiences are based on aftermarket conversion, which is currently the only source of dual-fuel trucks in Spain. In addition, other LNG vehicles with Otto engines offered by OEMs such as Mercedes-Benz and IVECO are also available in Spain (Interview Murugó, 2011).¹⁴⁴

Nowadays, there are six public LNG filling stations summarized in Table 9. The first LNG filling station was built in Abrera (Barcelona) in 2000 (NGV, 2010a). At that time, it was a private filling station supplying HAM's LNG fleet; however it became public in 2009 (NGV, 2010a). After that, more firms became interested in LNG as a vehicle fuel and the LNG refueling infrastructure continued to expand. This infrastructure is developing at the same time as the CNG refueling infrastructure, which is almost exclusively related to public transport (e.g. busses) and private companies (e.g. trucks). According to NGV (2011), there are currently 2985 natural gas vehicles in Spain,

¹⁴⁰ HAM Group consists of a number of business branches dedicated to industrial gases including design, construction and maintenance of regasification plants, gas commercialization, filling station operation and transportation services with more than 400 vehicles.

¹⁴¹ Transportes Monfort offers logistics and transport services on road in Europe with more than 100 vehicles in their fleet.

¹⁴² According to NGVA statistics, 46% of natural gas vehicles in Spain correspond to busses and 34% to medium and heavy duty trucks and almost the entire CNG filling infrastructure is private (41 out of 44 filling stations).

¹⁴³ They decided to retrofit 10 more trucks after 12 month trial using a Genesis installation on a Mercedes Axor unit.

¹⁴⁴ The first Mercedes's LNG truck, LNG Econic, was sold to the logistics company Alcotral in 2009.

busses account for 46% and medium/heavy duty trucks (mainly refuse trucks) for 35% of the total number of natural gas vehicles.

Some of the LNG filling stations were co-financed by public institutions such as the regional Energy Agencies and the Institute for Energy Saving and Diversification (IDAE). The size of the subsidies ranges from 30,000€ to more than 200,000€. In the case of the filling station in Castellón (Valencia), it was partially sponsored by the Valencian's Energy Agency (Aven) who awarded more than 200,000€ covering almost the entire initial investment (NGVJa, 2011). The subsidy offered by IDAE for the construction of a filling is considerably lower: 40,000-50,000€ (IDEA, 2008). It covered 20% of the initial investment of HAM's filling station (Interview Murugó, 2011). IDAE also sponsors the uptake of natural gas vehicles under the Energy Saving and Efficiency Strategy. In the case of heavy duty trucks the buyer can receive up to 12,000€ per vehicle from this institution (IDAE, 2008).¹⁴⁵

Spain is one the biggest consumer of LNG in Europe. In January 2011, LNG constituted 70% of the total natural gas imports to the country (CNE, 2011). The country counts with a large LNG import infrastructure and a well developed gas industry.

Further in Spain, natural gas is widely accepted as an alternative fuel due to the lower CO₂ emissions produced in the combustion process compared to diesel. However, the main incentive for Spanish truck owners to use LNG vehicles in general and dual-fuel in particular might be the fuel price. In December 2010, the price of natural gas fuel was 0,58 times the diesel price (NGVA, 2011a). This means that savings in fuel for a Spanish company allows for a short payback time of the truck as well as considerable economic benefits during its lifetime compared to the ordinary diesel truck.¹⁴⁶ This fact encourages firms with intense transportation activities to try this technology. Additionally, HAM Group is encouraging more firms to use LNG vehicles by letting them borrow their LNG trucks to interested firms (Interview Murugó, 2011).

¹⁴⁵ This amount is lower but comparable to the Swedish subsidy under the BiMe programme (175,000 SEK or around 19,600€).

¹⁴⁶ According to HAM Group's experience, the extra cost of a dual fuel truck with 55% substitution rate can be compensated in 2,3 years thanks to fuel savings. Moreover, during the rest of lifetime (1,7 years) the company can save more than 20,000 € in fuel compared to the equivalent truck running exclusively on diesel.

A.7. Blocking and inducement mechanisms in the dual-fuel truck.

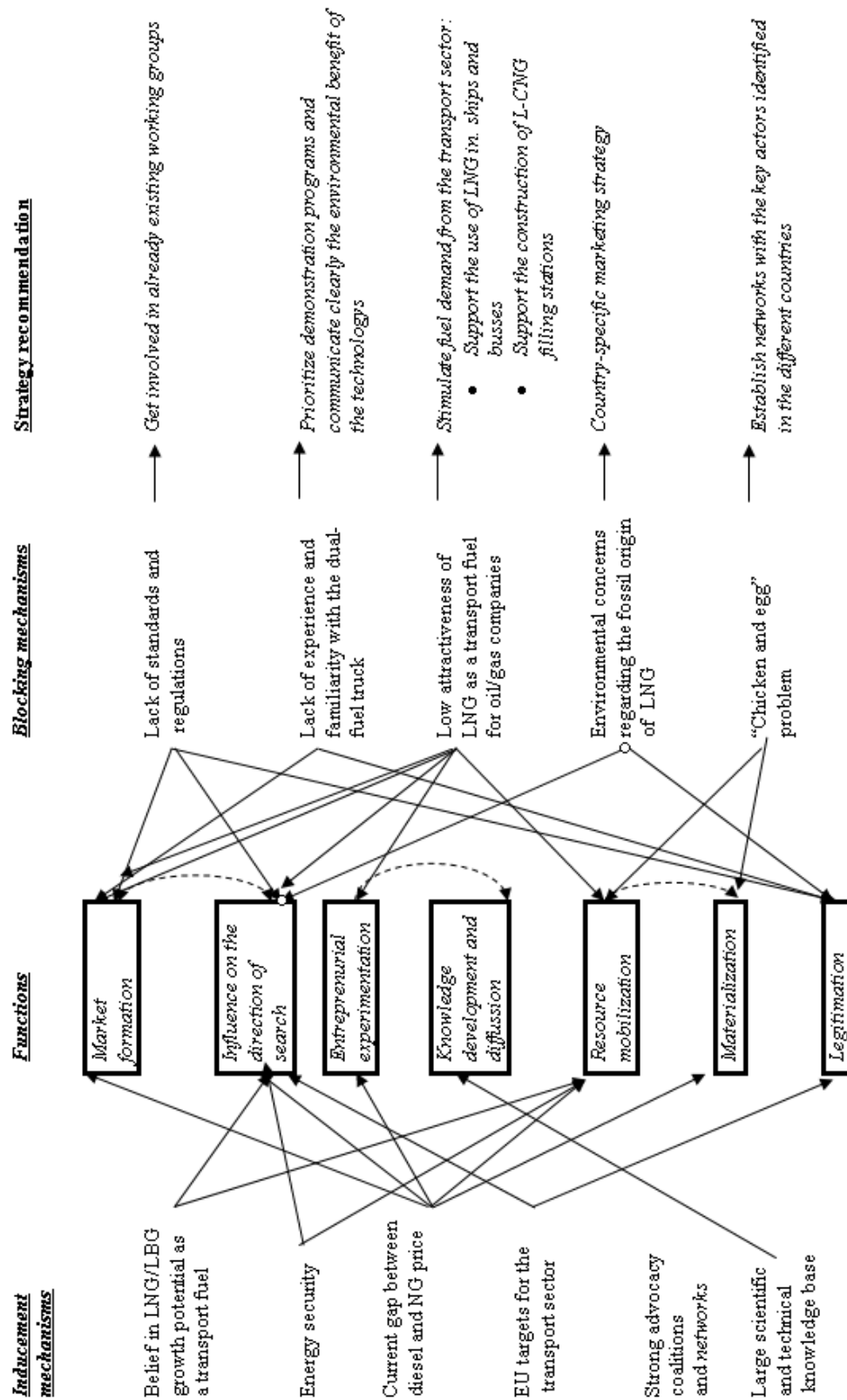


Figure 10. Inducement and blocking mechanism in the dual-fuel truck TIS.

A.8. Contact list

Date	Name	Title/Position	Organisation	Purpose
22/02-11	Lennart Pilskog	Director of Public Affairs	Volvo Truck	Interview: Determinants for Volvo's participation in the development of dual-fuel trucks. Helped us identify further key <i>actors</i> .
24/02-11	Patrik Klintbom	Senior Specialist Energy Resources and Alternative Fuels	Volvo Technology Corporation	Interview: General information about bio-methane environmental benefits. Understanding standards. Helped us identify further key <i>actors</i> .
28/02-11	Roger Andersson	Biogas Responsible	AGA-Linde	Interview: LNG / LBG infrastructure and Sweden and standardization. Helped us identify projects.
02/03-11	Peter Boisen	Board member NGVA Europe Sustainable Mobility	NGVA-Europe	Interview: General overview of NGV market in EU. NGVA role in the TIS. History of the development of the TIS. Helped us identify further key <i>actors</i> .
14/03-11	Josef Pozivil	Consultant technology	Cryostar	Interview: Cryogenic technology maturity. Understand the role of a cryogenic company.
15/03-11	Mats Landin	Hardstaff Sweden	Hardstaff	Interview: System supplier's perception.
16/03-11	Leiv Arne Marhaug	Head of Sales and Marketing department	Gasnor	Interview: LNG market and drivers for the use of LNG in maritime transportation. Helped us identify further key <i>actors</i> and projects.
18/03-11	Toni Murugó	Director Manager	Ham Criogénica	Interview: Spanish infrastructure, LNG and NGV market in Spain. Their experience with dual fuel engines.
21/03-11	Flavio Antonio Mariani	Responsible for Metano per Autotrazione	Eni	Interview: Italian and European LNG market, NGV Italian market. Standards on filling stations and gas quality.
21/03-11	Doug Leaf	Development Manager	Gasrec	Interview: LBM market. Drivers for the use of LBM in England. Helped us identify further key <i>actors</i> and projects.
28/03-11	Marnix Evers	Senior Commercial Advisor and B2B	Shell	Interview: Gas company perception of LNG markets in EU.
28/03-11	Lauran Wetemans	Commercial Road Transport Manager	Shell	Interview: Gas company perception of LNG in the transportation sector in EU.
29/03-11	Anna Berggren	Market Development	FordonsGas	Interview: Fuel infrastructure in Sweden, drivers and barriers. Standards for filling

				stations.
31/03-11	Henrik Gustafsson	EU Regulatory Affairs Manager Volvo Group Representation, EU	Volvo AB	Interview: Pointed out the important landscape conditions, EU context, transport policies and tax uncertainties.
8/04-11	Ulf Hammarberg	Environmental Affairs and Business Development	DHL	Interview: Gave us a user perspective. Explained the drivers, disadvantages, uncertainties and risks of using a dual-fuel truck.
26/04-11	Claes Hillén	Clinic Manager	Volvo 3P	Information about customers views and engine performance
28/04-11	Lisbeth Dahllöf	Sustainability analysis, product development /Engineering	Volvo Technology	LCA on methane diesel truck. Helped us confirm critical issues identified.
05/05-11	Gudrun Rollesfsen	CEO	Barent NaturGass	Confirm information about current state of Norway's LNG infrastructure for vehicles
05/05-11	Stig Olsen	Project Manager	Barent NaturGass	Information about the CNG filling station in Hammerfest.
05/05-11	Alfredo Mostajo	Manager Director	Agas21	Information about the L-CNG filling station in Olaberria (Gipuzkoa), Spain
05/05-11	Peter Hendrickx	Comercial Director	Rolande LNG	Information about the filling station in Oss, the Netherlands.
06/05-11	Manuel Monfort	Manager Director	Transportes Monfort	Information about LNG filling stations and customer perspective on LNG trucks
07/05-11	Roy James	Manager Director	Chive Fuels	Information about LNG filling stations in UK and LNG price
10/05-11	Hans Kättström	Former SGtS's General Manager		Information about LBM in the Netherlands
Continuous dialogue	Lars Mårtensson	Environmental Director Volvo Truck	Volvo Truck	General information and introduction about the subject. Continuous communication.
Continuous dialogue	Mats Franzén	Product strategy and Planning	Volvo Truck	General information about the dual-fuel truck.
Continuous dialogue	Christina Eriksson	Business Manager Alternative Fuel and Hybrid Trucks	Volvo Truck	General information about Volvo's methane diesel business plan.