

TNO report

TNO-RPT-DTS-2011-01124

LNG TTC Definition Study

**Energy/Geological Survey of
the Netherlands**

Stieltjesweg 1
2628 CK Delft
P.O. Box 155
2600 AD Delft
The Netherlands

www.tno.nl

T +31 88 866 20 00
F +31 88 866 06 30

Date	29 June 2011
Author(s)	W. Kuipers E. van Bokhorst F. Driessen B. van den Beemt
Number of pages	64 (excl. appendices)
Project number	033.24725

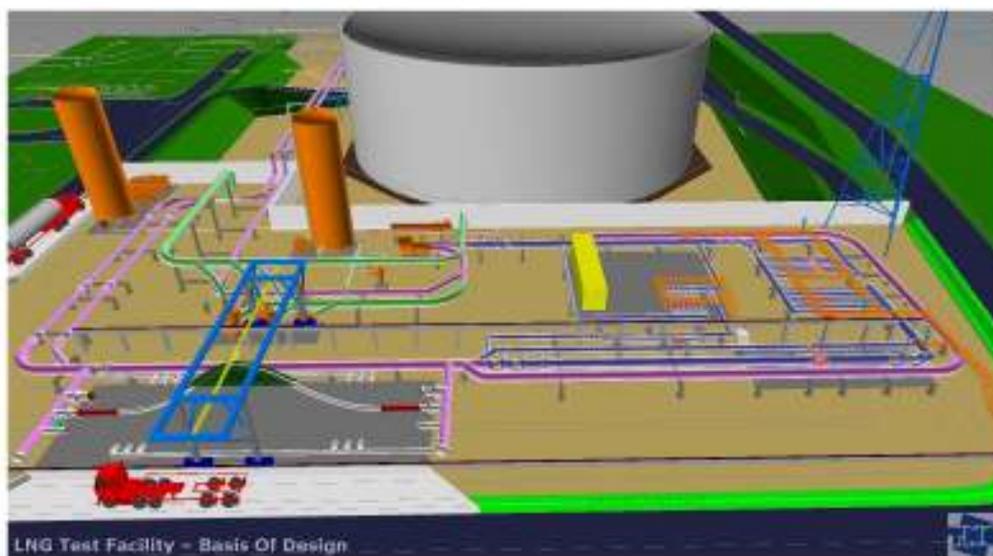
All rights reserved.

No part of this publication may be reproduced and/or published by print, photoprint, microfilm or any other means without the previous written consent of TNO.

In case this report was drafted on instructions, the rights and obligations of contracting parties are subject to either the General Terms and Conditions for commissions to TNO, or the relevant agreement concluded between the contracting parties. Submitting the report for inspection to parties who have a direct interest is permitted.

© 2011 TNO

Management Summary



Mission and ambition

The LNG Test and Technology Centre (LNG TTC) helps to develop the LNG value chain. It provides a level playing field to equipment suppliers and other stakeholders in the LNG chain to test and qualify equipment and to reduce development barriers. The LNG TTC focuses on strengthening the LNG supply chain and development of LNG as a fuel. This includes production, liquefaction, transport & transfer, and regasification. The LNG TTC will provide services to the industry both nationally and internationally.

The LNG TTC supports the Dutch ambition to:

1. strengthen the position of the Netherlands as a major global energy region, i.e. NW European gas hub
2. create a knowledge & technology platform for downstream market applications;
3. strengthen the international position of the Dutch industry;
4. direct the R&D focus on LNG towards the Netherlands.

Background

In 2009 TNO took the initiative to perform a feasibility study for an LNG Test and Technology Centre with input from international industrial parties such as operators, shipping companies, equipment and service suppliers. As a result of the study's recommendations, it was strongly proposed to undertake a "Definition Study" for an LNG Test and Technology Centre. Coincidentally VSL was studying the option to create an LNG calibration facility, and the opportunity to create synergy with the LNG TTC was quickly recognised. A consortium of key Dutch industrial players known as the LNG TTC Consortium (Gasunie, Vopak, VSL, Shell, SBM, Stork, Imtech, Bluewater and TNO) expressed the importance of developing such a centre.

The essential objectives of the LNG TTC are to:

1. Facilitate access to LNG for R&D purposes, without limitations in time, flow rate and quantity;
2. Create an open R&D programme that strengthens the common knowledge base for its subscribers covering topics like safety, metering, systems and materials;
3. Establish and support Joint Industry Projects (JIPs) and Business-to-Business research projects;
4. Provide services like training and education as well as expertise related to cryogenic LNG;
5. Make LNG expertise and knowledge available.

To achieve these objectives both an
R&D Programme and a **Test Facility**
are required within the LNG TTC

The Maritime Innovation Programme supported the LNG-TTC Definition Study aimed at investigating the possibilities of realising the LNG TTC (AgentschapNL project number MAR10903, 22 June 2010).

Scope of the Definition Study

The Definition Study was structured as follows:

- A design of the LNG TTC Test Facility (Basis of Design) including a review of necessary permits and safety requirements;
- Set-up of an LNG TTC R&D Programme, consisting of an open R&D programme, a training & education programme and input for Business-to-Business research activities and Joint Industry Projects.
- A legal and organisational structure for the LNG TTC R&D Programme and the LNG TTC Test Facility.
- A financial plan including an assessment of the necessary investments.

Results

LNG TTC Test Facility

- The feasibility study identified a strong need for large-scale offshore testing as well as a growing need for small-scale testing as a result of growing interest in the application of LNG as a fuel for shipping and trucking. In this downstream process, LNG flow metering is indispensable, but calibration facilities for this are not available worldwide.
- Existing LNG circulation facilities such as Nikkiso Cryo (Las Vegas, USA) and Ebara (Sparks, USA) have a limited flow capacity, limited access and are not suitable for flow meter calibration;
- The validation of models developed in research projects requires an LNG test (flow) facility.
- To create a unique European Centre the LNG TTC needs to facilitate testing on:
 1. Offshore applications with full-scale flow up to 7000 m³/hr, preferably in combination with a sea motion tester;
 2. Small to mid-scale applications in respect of LNG storage, bunkering and distribution;

3. Systems for LNG flow metering, sampling and composition measurement.
- The Basis of Design study provides a basis for the combined LNG test and calibration facility on a minimum footprint of 40 x 100 metres located at the Gasunie Peakshaver or at an alternative location.
 - The Gasunie Peakshaver was the intended location to build the test facility and thus the site for the study, but this location is too close to existing LNG tanks and thus has an unacceptable safety risk. Alternative locations on the site do not seem to be available.

LNG TTC R&D Programme

- Technological Roadmaps have been defined in three areas: Offshore LNG, Small Scale LNG and Traditional LNG. These roadmaps have been used to define the LNG Programme Matrix, which connects the industry's market needs with the relevant fundamental research topics that can be performed at research institutes like TNO and universities.
- A newly developed and unique R&D programme has been defined which focuses on a number of projects related to safety, reliability and process optimisation in offshore and small-scale applications.

Organisational plan

- An LNG foundation is needed to continue the activities after the Definition Study. The intended foundation called LNG TR&D (read: trend), which stands for LNG Test, Research & Development, is expected to start in the third quarter of 2011.
- It is recommended to run the LNG TTC R&D Programme under the supervision of the LNG TR&D.

Financial plan

- In relation to the R&D programme, the Dutch technology foundation STW made a reservation of 1,5 m.euros that will be matched by an equal cash contribution by the industry. It is intended to start a 3 m.euros Partnership Programme LNG in the fourth quarter of 2011.
- An LNG position paper on the LNG TTC and LNG as fuel has been submitted to the Topteam Energy and the Topteam Water, which are advising the Ministers of EL&I and I&M.
- The total CAPEX involved in the basic/detailed engineering and hardware for the LNG TTC Test Facility is dependent on the scope and the operating envelop of the facilities. It is envisaged that a total investment of a maximum 81 m.euros is required to build up the test and calibration facility according to the functional requirements of the partners in the LNG TTC Consortium.
- The 81 m.euros consists of hardware and engineering costs. The CAPEX estimation is accurate to -10/+30 % for the first realisation phase of the test centre . The 81 m.euros break down into:
 - 52 m.euros, for the first realisation phase which covers testing up to 7000 m³/hr;
 - 18 m.euros, for the second realisation phase, which covers testing of process equipment;
 - 11 m.euros, for a Motion Tester which simulates sea motions for offshore testing.
- Based on a cost-benefit analysis, a financial plan has been made for the LNG TR&D Foundation.

Recommendations

LNG TTC Test Facility

- Investigate alternative locations to the Gasunie Peakshaver. Current alternatives under consideration are locations in the vicinity of the Gate Terminal (Rotterdam), near the Euroloop (Rotterdam) or locations in Eemshaven/Delfzijl (Groningen). The partners in this investigation are Port of Rotterdam, Groningen Seaports, Vopak, Gasunie, TNO and VSL.

LNG TTC R&D Programme

- Independent of the establishment of the LNG TTC Test Facility it is highly recommended to start the LNG TTC R&D Programme as soon as possible.
- The objective is to start a full R&D programme with a targeted funding of 15 m.euros in a period from 2011 until 2018. Funding for the R&D programme will be raised by subsidiary funds from participants and local government institutes as well as by contributions from research institutes and universities. A realistic target will be to start up the STW Partnership Programme LNG in the fourth quarter of 2011.

Organisational plan

- Instigate an LNG TR&D Foundation board from the independent organisations TNO, VSL and 3TU with an advisory board composed of members that are active in the LNG industry.
- Run the R&D programme under the supervision of the LNG TR&D Foundation and in close collaboration with industry, universities and research institutes.
- It is strongly recommended that participants in the LESAS project (a Joint Industry Project on legal and safety assessment with respect to using LNG as fuel for small-scale shipping) also join the advisory board and/or steering groups of the LNG TR&D Foundation.

Financial plan

- Perform a capital and operational expenditure (CAPEX/OPEX) study for the selected alternative locations of the LNG TTC Test Facility preferably integrated with small-scale bunkering. This location analysis needs to be finalised before the 30 September 2011.
- Escalate to upper management level among industry partners to obtain commitment for funding (and using) the R&D Programme and Test Facility of the LNG TTC.
- Investigate various funding opportunities for the realisation of the LNG TTC. Besides the ministries of EL&I and I&M, this includes opportunities from Energy Valley, Waddenfonds, Provinces of Zuid-Holland and Groningen, and local organisations like NOM (Investeringsmaatschappij Noord-Nederland) as well as the European Fund for Regional Development (EFRO), and other EU funding opportunities.

List of abbreviations

B2B	Business to Business
BoD	Basis of Design
BOG	Boil off Gas
CAPEX	Capital Expenditure
CMF	Coriolis Mass Flow meter
EFRO	Europees Fonds voor Regionale Ontwikkeling
EL&I	Department of Economic Affairs, Agriculture and Innovation
ERC	Emergency Release Coupling
ESD	Emergency Shut Down
FAT	Factory Acceptance Test
FES	Fonds Economische Structuurversterking
FID	Final Investment Decision
FLNG	Floating LNG
FPSO	Floating Production, Storage and Offloading
FTE	Full-time Equivalent
GAN	Gaseous Nitrogen
HAZID	Hazard Identification
HAZOP	Hazard and Operability
HSE	Health, Safety and Environmental
I&M	Department of Infrastructure and Environment
JIP	Joint Industry Project
LiN	Liquid Nitrogen
LNG	Liquid Natural Gas
MER	Milieu Effect Rapportage Environmental Impact Analysis
OPEX	Operational Expenditure
P&ID	Process and Instrumentation Diagram
PS	Peak Shaver
QRA	Quantitative Risk Assessment
R&D	Research & Development
RAMS	Reliability Availability Maintenance Safety
SME	Small and Medium size Enterprises
SWOT	Strength, Weakness, Opportunity, Threat
TR&D	Test, Research and Development
TTC	Test and Technology Centre
USM	Ultrasonic Flow Meter
UUT	Unit Under Test
VSCF	Variable Speed Constant Frequency
WP	Work Package

Contents

Management Summary	2
List of abbreviations	6
1 Introduction	9
1.1 Background of initiative	9
1.2 Working Plan	9
2 External Analysis	9
2.1 Economical background gas sector.....	9
2.2 Drivers for Floating LNG	9
2.3 Drivers for small scale applications of LNG.....	9
2.4 The need of a unique European LNG Test and Technology Centre.....	9
2.5 SWOT analysis	9
3 LNG TTC R&D Programme	9
3.1 Introduction	9
3.2 Development of a R&D programme	9
3.3 Knowledge management, dissemination, and valorisation	9
3.4 Functionalities.....	9
3.5 Technological Roadmaps LNG.....	9
3.6 Programme Matrix, Scientific Disciplines & Challenges.....	9
3.7 Unique character of the LNG R&D Programme	9
3.8 STW Partnership Programme LNG	9
4 Basis of design of the LNG TTC Test Facility	9
4.1 Introduction to basis of design of LNG TTC Test Facility	9
4.2 Required functionalities	9
4.3 Process descriptions, phases and flow diagrams	9
4.4 Liquid Nitrogen supply	9
4.5 Design criteria and standards.....	9
4.6 Health, safety and environmental aspects.....	9
4.7 Location aspects and alternatives	9
4.8 Recommendations / planned actions for next phase	9
5 Organisation and Financing	9
5.1 Mission of the LNG TTC organisation	9
5.2 Organisational and legal structure of the LNG TTC	9
5.3 Business Model of the LNG TTC.....	9
5.4 The R&D organisation (LNG TR&D Foundation)	9
5.5 Considerations in the realisation of the LNG Test Facility.....	9
5.6 Exploitation of the LNG TTC Test Facility	9
6 Conclusions & Recommendations	9
6.1 R&D Programme	9
6.2 LNG TTC Test Facility	9
6.3 Organisation & Financing	9
7 Acknowledgement	9

Appendices

A LNG Programme Matrix

B Two-Phase surge phenomena

C Combining Pre-processing with Liquifaction

D Overview of natural gas and LNG processes and products

E LNG TTC Test Facility Investment Split-up

1 Introduction

1.1 Background of initiative

A first Feasibility Study showed that knowledge development and the ability to physical testing are indispensable for the development of the LNG value chain. This explains the great (inter)national collective interest in realising this need by means of an LNG Test and Technology Centre (LNG TTC). The entire LNG sector, operators, engineers and builders alike, will be collecting the rewards of such a centre; not only experienced FLNG/LNG producers and builders, but also new entrants. The diversity of stakeholders varies from large scale operators in the energy sector to companies that develop industrial applications and stakeholders in downstream LNG applications such as distribution for the shipping and automotive transport sector (river shipping, trucks).

Definition Study

After the Feasibility Study, the starting sign was given to explore the Definition Study phase of an LNG TTC during a meeting on 2 October 2009. During this meeting a group of key Dutch industrial players expressed the importance of the development of such a centre, being TNO, Gasunie, Vopak, VSL, Shell, SBM and Bluewater. Later also Stork / Imtech SMS joined this group of participants. This group decided to start the joint project that is described in the present document, their roles being:

- TNO: project co-ordinator;
- TNO, Gasunie, VSL: Basic Engineering Design of LNG TTC Test Facility;
- Shell, SBM, VSL, Vopak and Imtech: review of Basic Engineering Design;
- TNO, Gasunie, VSL, Shell, SBM, Bluewater, Vopak, Stork/Imtech SMS: definition of LNG TTC R&D Programme (together with a wide variety of stakeholders).

Taking away innovation barriers

Development of LNG technology is dominated by proving the reliability and safety of new systems under offshore conditions. This means that these new systems need to be qualified under a variety of operational conditions which is only in reach when test facilities and combined knowledge will become available. It is a common opinion throughout the value chain that an investment by individual parties in separate test setups on a case-by-case basis and individual development of fundamental knowledge is highly unprofitable. The lack of these large-scale investments hampers innovation. An integrated investment at Governmental level would greatly strengthen the LNG value chain and take away the innovation barriers.

Open innovation and open access facilities

Key to the LNG TTC is that its access will be open to participation of all stakeholders who wish to contribute to the LNG TTC R&D Programme and that wish to make use of its facilities. The R&D programme will essentially be an (open) innovation platform to share knowledge between all stakeholders.

Mission and ambition

The LNG TTC helps developing the LNG value chain and it provides a level playing field to equipment suppliers with the possibility for testing and qualification of new (offshore) equipment. The LNG TTC will be an independent non-profit organization that focuses on strengthening the LNG supply chain. This includes: production, liquefaction, transport & transfer, regasification and application as well as CO₂ logistics. The LNG TTC will provide services to the (inter)national industry.

The LNG TTC supports the Dutch ambition to:

- 1 strengthen the position of the Netherlands as a main global energy region and may create a platform for downstream market application;
- 2 strengthen the Dutch power base in a NW European gas hub;
- 3 strengthen the position of the Dutch industry;
- 4 direct the R&D focus on LNG towards the Netherlands.

Scope of LNG TTC

The LNG TTC carries out independent qualification of products and calibration of LNG equipment. It will give independent opinions on product specification and design rules from a technological point of view considering the interests of all stakeholders, without being aligned to any stakeholder. It will develop the capability of performing independent design evaluation and troubleshooting and it will develop consultancy for environmental impact assessments. Furthermore it will provide knowledge management of fundamental technical and economical information as an open source to the partners.

In order to achieve its goals the LNG TTC should have an R&D programme and it would be desirable to have a dedicated test facility (LNG TTC Test Facility) to validate research results.

Intended LNG TTC Test Facility location

Essential to the realisation of the LNG TTC Test Facility are:

- Availability of LNG, without limitations in time, flow rate and quantity;
- Availability of LiN and associated facilities (e.g. storage tanks and pumps, LNG safety measures, boil-off compression);
- Well trained personnel to operate and maintain the facilities;
- Sufficient power capacity;
- Attractive location in the Rotterdam area close to potential customers and TNO and VSL locations;
- No (new) MER procedure required.
- The availability of test expertise.

Because of the first precondition, the Gasunie Peak Shaving (PS) plant, located in the Port of Rotterdam was identified as one of the most suitable locations for the LNG TTC Test Facility. This rather unique installation offers a main cost advantage over other locations in Europe where such installations are either not needed or simply not available. At this site there are opportunities to realise the LNG TTC Test Facility against limited capital investments while there are also opportunities for synergy, gains for both Gasunie and the LNG TTC. Therefore, the present Working Plan activities are addressing the Gasunie PS plant as the basic installation, where the LNG TTC Test Facility plant should be constructed.

1.2 Working Plan

The Working Plan is described below :

- WP 200 Basis of Design.
How will the LNG TTC Test Facility look like in terms of hardware investments which is needed to perform tests at the LNG TTC Test Facility; review of necessary permits and safety requirements?
- WP 300 Business Model & Exploitation
What is the added value of the LNG TTC Test Facility and how does this generates revenues for the partners; analysis of type of tests which we will be performed, and what are the cost per testing cycle?
- WP 300 Financing
What is the investment of the government and industry; a financial plan including the assessment of the necessary investments and the LNG TTC Test Facility profitability;
- WP 300 Legal Entity;
Recommendation on the types of organisation to perform tests, to perform R&D programmes, and to perform knowledge transfer.
- WP 400 R&D Programme
Consisting of an open R&D programme, a training & education programme and input for Business-to-Business research activities and Joint Industry Projects.

Relation between Work Packages

The relation between the work packages is shown in figure 1.1, together with the role of the project participants and the output of the work packages that form the results of the project. The project output is to support the Final Investment Decision (FID) into the LNG TTC of the Ministry of EL&I.

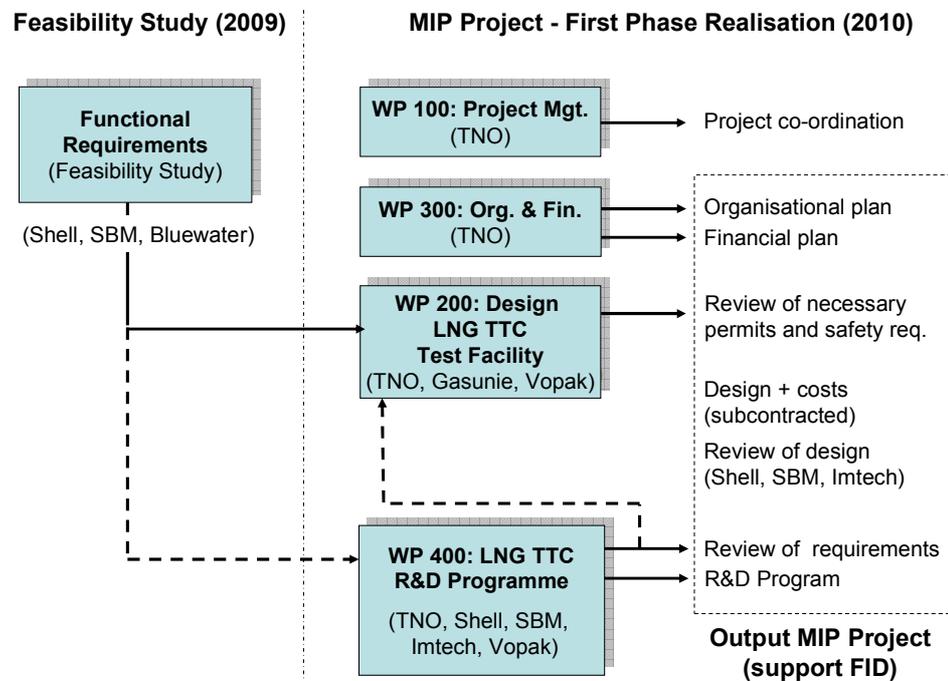


Figure 1.1: Relation between work packages in this MIP project

Input for the design (WP 200) of the LNG TTC Test Facility are the Functional Requirements that have already been drafted by Shell, SBM and Bluewater as part of the Feasibility Study. These participants will also review the design. Gasunie will be responsible for WP 200.

As part of the R&D programme design (WP 400), the functional requirements of the LNG TTC Test Facility will be reviewed (responsibility Stork, later Imtech SMS, SBM and Shell) as a verification step of the indispensable functionalities of the Test Facility.

Costs and planning

The cost of this project is funded by MIP-sub programme 4 (“Innovatiebelemmeringen”). The work has been carried out in the period between September 2010 and June 2011. The subsidy will be used to finance the present initiative with an in kind contribution (hours) by all commercial partners (Gasunie, VSL, Shell, SBM, Bluewater, Vopak, Stork / Imtech). This is the only contribution of the commercial partners covered by this proposal and associated agreement.

The overall timeline of the LNG TTC Definition Study and next steps are described in Figure 1.2.

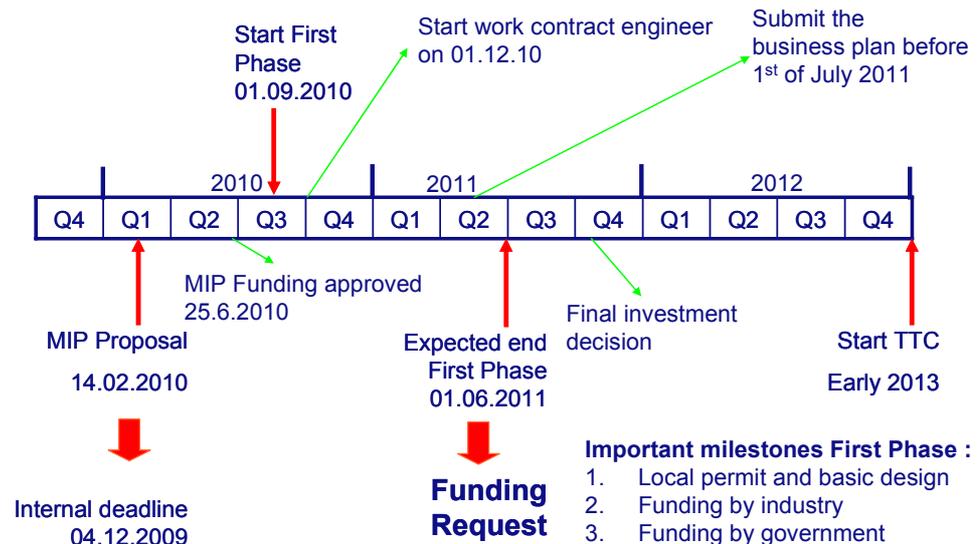


Figure 1.2: Overall time-line of the LNG TTC Definition Study and next steps.

Structure of the report

The structure of the report is depicted in Figure 1.3.

The introduction (Chapter 1.) explains the background and objectives of the study. Subsequently, an external analysis (Chapter 2.) will be described to explain the drivers in the LNG market. Based on this, it will be explained what the LNG TTC Consortium suggests to achieve in terms of a LNG TTC R&D programme (Chapter 3.) and the LNG TTC Test Facility (Chapter 4.. Finally, the key question “how do we get there ?” will be answered by determining what will be the best organisation and financing structure (Chapter 5.), and which recommendations are needed to

achieve the start of the R&D Programme and to start building a financial sound Test Facility (Chapter 6.).

Background of the study	Chapter 1	Introduction
Drivers in the LNG market	Chapter 2	External Analysis
	Chapter 3	LNG TTC R&D Programme
What do we want to achieve?	Chapter 4	LNG TTC Test Facility
	Chapter 5	Organisation & Financing
How do we get there?	Chapter 6	Recommendations

Figure 1.3: Structure of the report

2 External Analysis

2.1 Economical background gas sector

In the period of September 2010 until March 2011, the following companies have been interviewed : Shell, SBM, Imtech, Stork, Vopak, Gasunie, Gaz de France, Statoil, Linde, Siemens, Technip, Exmar, and VSL. Based on these interviews the economical background was determined. At the same time the drivers in the LNG market could be defined.

Global LNG's growth and prospects

Liquefied Natural Gas (LNG) will be playing an increasingly important role the coming years in the global demand for energy supply. The demand for natural gas will be growing exponentially and the availability of new gas supply preserves attention even during the current economic crisis. Security of energy supply is needed.

External LNG supply to Europe will be playing an important role in the future energy mix of the EU. More and more countries are interested to import LNG. Market analysis has shown that LNG trade and production volumes the coming years will increase even further.

At the same time, however, new developments are also showing their own options. Decreasing LNG production costs, in combination with higher oil prices globally, have attracted the interest of new players to set up projects to even explore and produce so-called offshore stranded gas reserves. These largely undeveloped gas reserves however are largely based in instable production regions or places too far from their traditional markets to be economical and commercially viable to be produced and transported via pipeline systems. At the same time, the smaller reserves also are not viable to set up onshore liquefaction projects. However, offshore LNG (also called Floating LNG or FLNG) is now regarded to be a feasible alternative for operators and investors. Main support for this drive has already been given by oil and gas majors, but also by contractors, shippers and utilities on the other side. Offshore stranded gas reserves (or even associated gas production) can now be addressed via FLNG systems.

Position of the Dutch industry

The Dutch Offshore Industry, which already has gained an important role in the global offshore crude oil production, is now assessing its options to enter and target FLNG opportunities. The Dutch shipping sector has a high technology drive, which could be part of a global FLNG drive. Still, challenges are ample; operators, insurers and consultants need to address them at the same time. Until now the underdeveloped knowledge base for cryogenic processes, LNG and specifically FLNG, is a cause of concern. Knowledge of these technology fields is a necessity not only to attract interest but also to expand existing commercial operations in future, taking into account the role the Dutch government wants to play in global gas and LNG developments to come. High-quality know how and infrastructure in the area of LNG energy measurements fits very well with the Dutch position as (gas) trading and distribution nation.

Innovation and removal of entrance barriers

Until now, most developers have taken proven technology or products from the onshore LNG projects to be implemented in the planned FLNG developments. Qualification and security did not gain much interest so far, but has now been put on its plate by investors, legal and insurance companies. To qualify new systems a wide and in-depth knowledge of the specific sector issues is a necessity. The latter is only in reach when test facilities in combination with development of fundamental knowledge are being set up. The ever growing volume of LNG being traded worldwide makes the industry even more aware of the need for innovations in the custody transfer measurement of LNG to obtain higher accuracy and smaller losses. New measurement equipment such as LNG flowmeters or innovative LNG sampling or non-sampling techniques to determine the quality of LNG need to be qualified and calibrated. The calibration facility that is to be part of the LNG TTC will cover this need and thereby stimulate these innovations. The set up of an LNG TTC is seen as a major step forward. The whole LNG sector, operators, engineers and builders alike, will profit from such a centre. Not only experienced FLNG/LNG producers and builders will be benefitting of such a centre, but new entrants can take advantage too.

The main purpose of the LNG TTC will be to remove entrance barriers for new - Dutch and international- suppliers and equipment, with additionally supporting existing parties in increasing their own market powers.

2.2 Drivers for Floating LNG

Mobility of a floating liquefaction plant may reduce commercial and technical barriers to production of stranded gas. Main issues which are currently undergoing a dramatic change are: field development and platform construction; long distance pipelines to shore; land site remediation and plant construction schedules. FLNG projects at present have vast advantages as most onshore LNG projects are constrained by local issues and political-economic factors.



Figure 2.1. A picture of the Shell Prelude Floating LNG factory, that will be built in the next 4 years. The ship will be 488 m x 74 m.

FLNG increases the overall flexibility of the operator, supplier and contractor, as the construction of the whole (or parts) of the FLNG vessel/plant is not constricted to the operational site. For the Final Investment Decision (FID) on an FLNG project, issues such as size, quality and location of the gas resource may have a significant impact.

On 20 May 2011, a positive investment decision was made on the Prelude Project (see Figure 2.1.). This will certainly results in the development of new LNG technologies, for example on Liquefaction in the near future. Also Petrobras is working on the development of a floating LNG projects for the Santos Basin, Offshore Brasil.

It is expected that expenditure on Liquefaction will increase in next years, which is shown in Figure 2.2.. In the last two years there has been a delay in investments due to the global financial crisis. It is expected that in the next years tests are necessary in a unique test center like the LNG TTC Test Facility to validate the results of a newly developed LNG TTC R&D Programme based on Technological LNG Roadmaps (see Chapter 3).

Liquefaction forecast on FLNG in 2010 - 2016

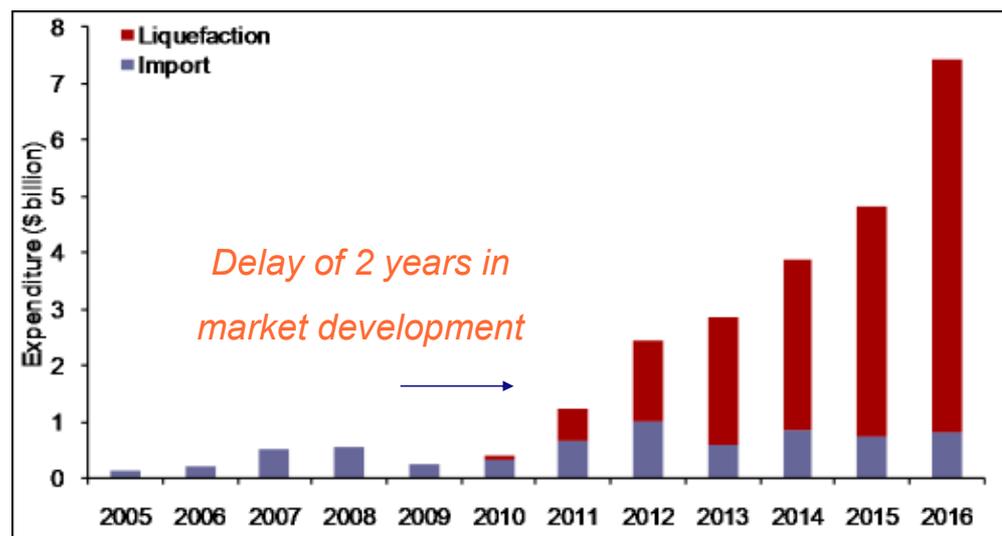


Figure 2.2. Liquefaction expenditure will be 21 bio US\$ in the periods 2010-2016 (Source : Douglas-Westwood 2009).

Safety, reliability and maintenance

Safety, reliability and undisturbed operation are main drivers for equipment qualification and acceptance in the oil & gas industry in general and in the offshore industry in particular. Floating liquefaction and LNG transport as an alternative for pipeline gas transport requires qualification of existing and new LNG technology to safeguard all LNG operations in a sometimes harsh environment. LNG technology from existing onshore installations cannot simply be copied to offshore installations but needs to be qualified with respect to the combination of known forces in onshore operation and additional forces due to wind, waves and motion in the complete Offshore LNG Chain (see figure 2.3.).

Production > liquefaction > loading > shipping > offloading > storage > regasification



Figure 2.3.: Various configurations in LNG transfer.

LNG processing and transfer equipment operates at high flow rates. With a growing potential for floating LNG the undisturbed LNG supply to regasification vessels or offloading from a floating LNG production unit is a demand under all weather conditions. Therefore alternatives to rigid loading arms have been developed, such as flexible cryogenic hoses or pipes, with an additional need for qualification and testing of components and systems. New transfer technologies and methods have to guarantee maximum availability without making concessions to safety, reliability and operability in floating LNG.

The maintainability of liquefaction trains under rough sea conditions and the difference in operating conditions compared to onshore installations should be accounted for during design. So maintenance is a key factor to increase the life-time of the equipment, but at the same time the objective is to reduce the cost involved in maintenance services. The remoteness of the location is also a factor in maintenance as cost increase with distance to shore. At the same time operators are trying to reduce the footprint of FPSO's, though a minimum distance between process equipment may be required to follow the safety rules.

All parties involved in the FLNG value chain are still fighting an uphill battle related to the respective technology consideration. Main issues currently being covered and assessed are refrigeration cycle consideration; the use of aero-derivative gas turbines; LNG transfer for benign and harsh sea states; project economics and safety over efficiency; motion effects; less equipment height and weight; equipment modularization; the synergy of liquefaction plant with other facilities and the issue of LNG storage and hull and mooring.

Controllability & Optimisation of LNG processes

Regarding the development of offshore liquefaction the LNG-TTC could facilitate large scale testing of liquefaction equipment under controlled motion to verify the efficiency and reliability. By providing these tests it provides an independent judgment and develops standard evaluation methods for heat exchangers to be applied offshore. By benchmarking related equipment on its maintainability and performance, the TTC will help (final) end-customers with their equipment selection. With a better understanding of the different components of the liquefaction process the TTC should be able to develop standard evaluation methods for a safe and quick start up and shut down procedures by providing system dynamics simulation.

Although offshore regasification is already being applied, improvement of vaporisation equipment could extend its market potential. By creating an open-access test facility the TTC would not only evaluate system improvements, but it could also provide a market entrance for new suppliers of regasification equipment. With regard to regasification there are also general development issues which should be addressed by the TTC, such as the impact of motion on different types of vaporizer and the environmental impact of different types of regasification. Also related issues such as measurement and control the LNG composition which will allow processing different LNG compositions on a regasification side are subjects for the TTC.

CAPEX reduction

The last decade, FLNG has gradually become financially viable, due to rising oil prices and the fact that there are incentives popping up for the specific operators, such as CAPEX savings and shorter development to market.

It can be concluded that the Floating LNG / Offshore LNG drivers are : Capex reduction, Reliability , Availability, Maintenance , Safety, Controllability & Optimisation of LNG processes. These drivers are mentioned in the Technological Roadmap for LNG Offshore in figure 3.2. in Chapter 3.

2.3 Drivers for small scale applications of LNG

Driven by the increasingly stringent emission regulations and the rising oil prices the interest in using Natural Gas as a fuel for transport grows in popularity. With its relatively high energy density, LNG is a very suitable fuel for heavy duty transportation. This property makes LNG a potential substitute for oil-based liquid fuels such as Gasoil and Heavy Fuel Oil which currently are used for fuelling trucks and ships. Using clean LNG as a shipping fuel fits in with the aim of making ports, inland waterways and short-sea shipping as well as ferrying and fishing more sustainable. LNG used as a transport fuel is relatively new; there is almost no infrastructure for LNG supply in smaller quantities for the use of LNG as a transport fuel.

Traditionally, natural gas has been liquefied only to transport it to the markets, where it is distributed as natural gas after regasification. For over forty years LNG has been shipped by carriers with large cargo volumes from liquefaction plants that have been constructed in regions with large natural gas reserves and less local demand. Until now, the use of LNG as a transport fuel is limited, this mainly being due to the relatively expensive infrastructure such as cryogenic tanks. If LNG prices will stay relatively low against the price of oil, and this seems to be the case observing the potential reserves of Natural Gas, it will appear that the extra infrastructural costs can easily being recovered. Technically there are no obstacles, and while the small scale LNG supply chain is being completed it can count on various outlets such as trucks, trains and even stationary customers such as decentralised power plants.

Several transportation companies and gas suppliers in the Netherlands are currently investing in road transportation with LNG trucks. Primary reasons for using LNG are the lower noise and pollutant emissions levels of the trucks. With respect to ships, in Norway a number of ferries, offshore supply vessels and navy vessels are equipped with LNG propulsion. Furthermore ship owners/operators in the Baltic

Sea are evaluating use of LNG as marine fuel for different vessels. With these developments undertaken, soon further extension of the supplying infrastructure such as small sized LNG tankers will be required to ship LNG from large terminals to break bulk terminals. To realise the targeted expansion in a safe and affordable way, development barriers such as the formation of regulation, codes and standards will need to be broken. These challenges can not reasonably taken by the launching entrepreneurs only.

As of 2005, the Natural Gas- and LNG-price becomes more independent of the oil price (see Figure 2.4.)

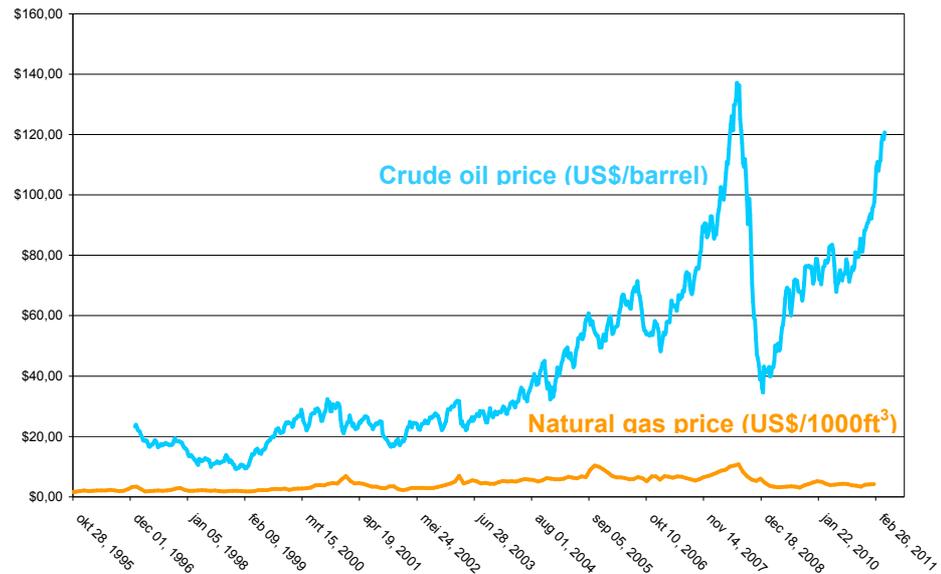


Figure 2.4. As of 2005 the LNG / Natural Gas price becomes more independent of the oil price.

Due to a relatively low price of Natural gas, LNG becomes more attractive as fuel for shipping and trucking. It is expected that the LNG price will increase in the next years, but it is expected that companies will invest in the development of LNG as clean fuel in shipping and trucking. Development of the end-user market is needed, and furthermore Dutch and EU regulations on LNG-usage will be developed by the LNG TTC Consortium in the LESAS-project. The Port of Rotterdam stated that their objective is to replace Heavy Fuel Oil by LNG as Fuel for Container ships.

It can be concluded that following drivers are applicable to Small Scale LNG :

- 1 Economics; low LNG price makes LNG more attractive as fuel;
- 2 Market acceptance ; Not-in-my-back-yard, and safety and legal issues need to be resolved.
- 3 Environment; LNG as fuel contributes to lower emissions of CO₂, NO_x and SO_x.
- 4 Standardisation of LNG Small Scale processes to reduce infrastructural costs;

2.4 The need of a unique European LNG Test and Technology Centre

Based on interviews with the leading LNG Industry partners, the following knowledge gaps and technology needs were identified :

- 1 Motion effects on processes and equipment (multi-phase fluid structure interaction and sloshing);
- 2 Fluid dynamics of LNG, relief and blow down systems;
- 3 Material properties under cryogenic conditions;
- 4 Accidental loads, HAZID technology;
- 5 Qualification of new equipment and suppliers;
- 6 Economising and size/weight reduction of LNG equipment, i.e. liquefaction, regasification, cleaning, drying, process isolation;
- 7 Environmental impact assessments;
- 8 Performance of LNG flowmeters;
- 9 Performance of LNG sampling and non-sampling based quality measurement systems;

It is recommended that investments in large scale validation tests will be made in :

- 1 Initial reliability testing of materials and equipment (using N₂ and H₂O);
- 2 Scaled testing for model developing;
- 3 Full scale test for final validation (using LNG).

The EN Standard EN1474 for qualification of LNG ship-to-ship transfer systems prescribe the baseline of the qualification for components such as loading arms, transfer hoses/pipes but also complete systems such as the Emergency Release System (ERC-ESD)

Major operators wish to encourage competition by having more equipment suppliers qualified. At present there is no existing qualification institute dedicated for offshore LNG, and it is preferred to have a FID on the LNG TTC Test Facility by 31 December 2011 the latest.

On the LNG TTC R&D Programme development two different types of potential competitors can be distinguished:

- 1 Company own R&D or centre of excellence;
- 2 Existing institutes or associations for gas technology & cryogenic research.

Examples of company owned R&D and LNG technology providers are:

- 1 Gaztransport & Technigaz SA: Research on containment systems. Operates as a naval engineering company. It owns a fleet of liquid natural gas tankers. The company is based in Saint-Rémy-les-Chevreuse, France (Comparable with, Hyundai, Samsung, GTE, Hamworthy);
- 2 Bechtel: Has an LNG centre of excellence. Contractor for onshore LNG plants (comparable: Technip, KBS, JGC);
- 3 Air Products: Has experience and own developed solutions for LNG processes. Provider of technology and equipment (comparable: Nikkoso (pumps), Ebara (pumps), Linde (new in LNG processing), FMC (loading arms));
- 4 Shell Global Solutions: Has developed its own LNG process and has years of experience with LNG plant operating (comparable: Conoco Phillips, Statoil Hydro (new in LNG));
- 5 Expertise centres related to the classification societies (BV, LR, DNV, ABS).

It has also become clear that Company Owned R&D Centers cannot cover every fundamental research topic they would like. That has been a clear basis to start the initiative by the LNG TTC Consortium on developing the LNG Partnership Programme with the STW institute (see Chapter 3).

2.5 SWOT analysis

Based on the external analysis and interviews with the partners in the LNG TTC Consortium a SWOT-analysis was determined in two categories, see Figure 2.5. and 2.6.. The first category refers to the LNG TTC R&D Programme and the second category refers to the LNG TTC Test Facility.

The Strength and Weaknesses reflects the capabilities of the LNG TTC Consortium which consists of Industry, Research Institutes and the Universities which become more and more part of the Consortium. This is shown by the co operation with the universities by creating an unique R&D programme (see chapter 3.)

For instance, the Universities do not have the capability to perform Business Development on LNG, and could therefor be referred to as a weakness. However, TNO as Research Institute has strong link towards the LNG Industry, and that means that Business Development (e.g. creating Joint Industry Projects) is a Strength of TNO.

A good example of an Opportunity in the LNG R&D Programme, is the fact that STW made a reservation of 1,5 m.euros to start a STW Partnership Programme LNG (see Chapter 3.)

<p style="text-align: center;">Strengths</p> <ul style="list-style-type: none"> • LNG knowledge base at industry,TNO and universities • Consortia like LNG TTC, Chain Analysis and LESAS were created • Unique LNG R&D Programme initiated by LNG TTC Consortium • Expertises and strengths of industry, universities and TNO are complementary 	<p style="text-align: center;">Opportunities</p> <ul style="list-style-type: none"> • Creation of more jobs in NL • Continue the consortia in the LNG TR&D Foundation or large LNG Consortium • Long term ;LNG TR&D could combine EU LNG activities in one Foundation • No entry barriers for new players • Removal of innovation barriers • STW made a reservation of 1,5 m.euros in Partnership Program
<p style="text-align: center;">Weaknesses</p> <ul style="list-style-type: none"> • Insufficient knowledge on LNG applications in The Hague/ Brussels; • Level of co-operation between industry, research institutes and universities 	<p style="text-align: center;">Threats</p> <ul style="list-style-type: none"> • Insufficient support for joint R&D programme • LNG initiatives in other European countries;

Figure 2.5. SWOT of LNG TTC R&D Programme

A threat to the LNG R&D Programme might be that there will be insufficient support by the foreign LNG Industry. It is recommended to organise an LNG Customer Event in the Netherlands by the newly founded LNG Consortium (e.g. LNG TR&D Foundation).

On the LNG TTC Test Facility (see Chapter 4.) there are many Opportunities in favour of creating this facility, like creation of (see figure 2.6.):

- 1 more jobs in the LNG Industry, Universities and Research Institutes.
 Conclusions of Gas Hub Report to department of EL&I by Brattle Group (UK), November 2010, show that extra employment created is by 13600 FTE, and extra economic output of Euro 21.4 billion.
 The LNG TTC will also create extra employment and economic output, and this needs to be defined.
- 2 the use of LNG as clean fuel by reducing emissions of CO₂, SO_x and NO_x, and
- 3 the removal of innovation barriers.

Strengths	Opportunities
<ul style="list-style-type: none"> • LNG knowledge base at industry, TNO and universities • Unique LNG Test facility in Europe • Location analysis study was started and will be finalised on 30 September 2011 • Exploitation and ownership by an entity which has low profit level objective 	<ul style="list-style-type: none"> • Synergy with small scale bunkering in Rotterdam or Eemshaven; • Creation of more jobs in NL • Promotion of LNG as clean fuel (= Reduction of CO₂, SO_x, NO_x) • No entry barriers for new players • Removal of innovation barriers
Weaknesses	Threats
<ul style="list-style-type: none"> • Insufficient knowledge on LNG applications in The Hague/ Brussels • Level of co-operation between industry, research institutes and universities • Market development of LNG flowmeters is partly depending on start of test facility; 	<ul style="list-style-type: none"> • No funding for Test facilities • 50% occupancy level might be too optimistic; • LNG initiatives in other European countries • Legal barriers for LNG application • Calibration of LNG Flow meters with water can be extrapolated to LNG

Figure 2.6. SWOT of LNG TTC Test Facility

A pre-investment (estimated level approx 0.5 m.euros) into a small/mid scale LNG flowloop up to 150-200 m³/h can be used to proof or disproof the possibility to extrapolate from water to LNG calibration. About 100 k.euros is available from VSL research budget to build the small/mid scale calibration skid. The additional investments are foreseen for a tie-in to an existing LNG installation, and auxiliary equipment/piping for supply and exhaust of the LNG flow. This small/mid-scale facility has the advantage that it could be realised relatively soon compared to the phase 1 of the LNG TTC and can directly be used for calibrations and testing of equipment for the small and mid-scale application and pave the way for the large scale TTC.

A Threat might be that an occupancy level of 50% at the projected LNG TTC Test Facility, is too optimistic (see Chapter 5), and the that Brussels / EU is not enough aware of the advantages of LNG. Last but bot not least, the flow meter calibration facility might already in the first year demonstrate whether an extrapolation model from water to LNG calibration can be validated with sufficient accuracy. If that proves to be the case, the LNG calibration facility will lose much of its attractiveness because the added value of creating realistic testing circumstances may not outweigh the additional costs compared to water calibrations.

3 LNG TTC R&D Programme

3.1 Introduction

The mission and ambition of the LNG TTC is developing the LNG value chain, being production, liquefaction, transport & transfer, regassification and applications. With onshore LNG production coming under pressure and demand for LNG continuing to increase, there is a need for new suppliers and equipment. The LNG TTC Test Facility expects a continuous stream of requests for engineering, small scale validation tests and development of test methods and fundamental research for which a long term relation funding possibilities is considered as crucial.

The LNG TTC activities should cover the industrial needs of its participants:

1. an open innovation R&D programme that strengthens the common knowledge base for its subscribers that covers topics like safety and reliability in offshore and small scale applications, and custody transfer flowmetering;
2. the possibility to provide services like training and education and to provide expertise related to cryogenic LNG;
3. the possibility to establish and support Joint Industry Projects (JIPs) and Business-to-Business (B2B) research projects.

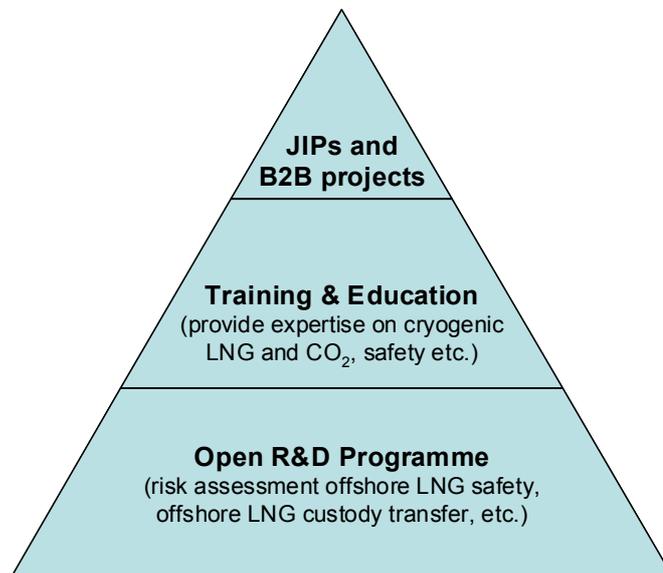


Figure 3.1. commercial training & education services and provide the structure to initiate B2B research projects and JIPs.

3.2 Development of a R&D programme

In order to develop a well-balanced R&D programme it was concluded that first individual interviews needed to be conducted by TNO in the fourth quarter of 2010 and first quarter of 2011 with each industry partner in the LNG TTC Consortium.

The results of these interviews have been presented to the LNG TTC Consortium in a workshop and was used as a basis to develop the Technological LNG Roadmaps. Based on this input the final Technological Roadmaps have been developed in the first quarter of 2011. All partners of the LNG TTC Consortium acknowledge that fundamental research and applied research is required to solve the current demands in the LNG industry for :

- 1 Offshore LNG;
- 2 Small Scale LNG;
- 3 Traditional LNG;

3.3 Knowledge management, dissemination, and valorisation

As part of Work Package 400, special attention was given to knowledge management, dissemination, and valorisation. This comprises the following aspects and activities:

- 1 building up a know-how and technology base from its R&D programmes supporting its services to industry;
- 2 collecting information that is available in the public domain and maintain a web-based service to enable access to this information;
- 3 where needed necessary IPR protection can be vested on results from its R&D programme.

These aspects are mentioned as well in the business model (see Chapter 5).

IP issues with respect to foreground and background knowledge was given special attention. In order to become an independent accepted centre of excellence, the LNG TTC should be able to work under strict confidentiality rules regarding information that is treated for individual clients.

It has become clear that the diversity of stakeholders in the LNG supply chain, results in quite a variety of requirements. The objective to have the centre accepted as an independent internationally recognised centre of excellence, implies that it should be adequate to carry out a multitude of tests in large offshore and small scale projects and include a vast range of functionalities.

3.4 Functionalities

Collective functionalities

The major group of functionalities that are required by the stakeholders in the offshore LNG supply chain have a dominant collective character. Creating an open-access test facility for the industry will address a growing industry demand to test large components dedicated to applications in the offshore LNG supply chain. It has become clear that there is no availability of such an independent facility in the world. Besides generating general acceptance for offshore LNG technology, this facility could enhance competition for end users and at the same time lower the entry barriers for equipment suppliers.

Services such as training and management of a collective R&D programme will reinforce the centre's functionality to transfer and develop LNG knowledge, inclusive the information management. The centre should also be able to cover its role as a promoter of the development of the LNG supply chain and the application

of LNG in the society. It will increase its acceptance by promoting development of standards and best practices.

Individual business to business functionality

Besides its collective functionalities, there is a vast amount of business to business consultancy services to be performed by the centre. The centre should make its facilities available for company in-house R&D projects, and Factory Acceptance Tests (FAT's) for manufacturers or system integrators. Additional commercial services such as performing environmental impact studies, design evaluation, troubleshooting (e.g. root cause analysis) and risk assessments are matching with the technical expertise already available or to be developed within the framework of the centre.

Important conditions to preserve the centre's acceptance, in spite of the performance of commercial services by the LNG TTC, are the protection of intellectual property and guarantee to be independent. Protection of intellectual property can be guaranteed when performing independent research, even on a commercial basis.

3.5 Technological Roadmaps LNG

The Technological LNG Roadmaps have been defined by the LNG TTC Consortium. Many aspects of LNG onshore are known, but the LNG processing offshore has still many unknown factors and need to be determined by fundamental research. Secondly, the small scale production and supply of LNG becomes more attractive due to a relative low price of LNG. The market acceptance of LNG needs to increase because LNG is a clean fuel with low CO₂ emission and therefore contributes to a more sustainable society and economy.

Technological Roadmap LNG Offshore

Offshore LNG will be the core technology subject for the LNG TTC. In general the offshore LNG development is focusing on adopting onshore technology for offshore instead of applying new technology for the first time offshore. It has become clear that technology development for offshore LNG will have an evolving character instead of being a one-off development. Although the acceptance will immediately increase after a successful commercial market introduction, further improvement of efficiency and availability will be needed for further commercialisation and optimisation of these technologies.

The LNG-TTC needs to strengthen the offshore LNG development by independently supporting the offshore drivers. Typical offshore drivers are described in Chapter 2 :

- RAMS stands for Reliability, Availability, Maintenance and Safety
- Controllability / optimisation LNG processes
- CAPEX reduction
- Remoteness of location

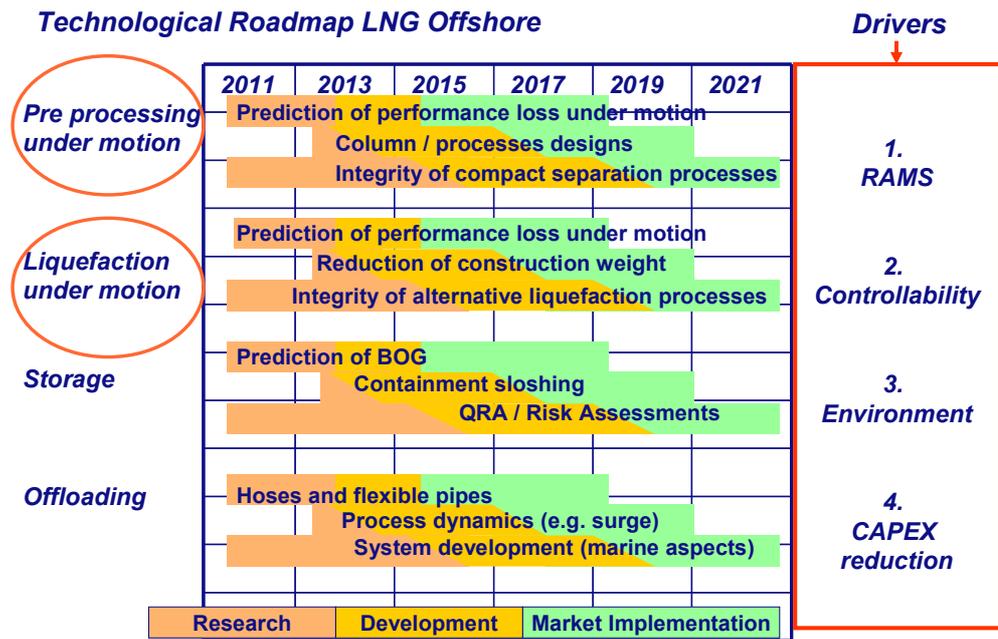


Figure 3.2. Technological Roadmap LNG Offshore with subjects and drivers

The offshore technology development can be divided into four main development topics: 1) Liquefaction and preprocessing under motion, 2) Storage / off loading / transfer systems 3) Regassification and 4) Fundamental research on multi-phase, multi-component fluid flow under motion.

Liquefaction and preprocessing under motion

Regarding the development of offshore liquefaction the LNG TTC Test Facility will facilitate large scale testing of liquefaction equipment under controlled motion to verify the efficiency and reliability. By providing these tests it provides an independent judgment and develops standard evaluation methods for heat exchangers to be applied offshore. By benchmarking related equipment on its maintainability and performance, the LNG TTC will help end-customers with their equipment selection. With a better understanding of the different components of the liquefaction process the LNG TTC should be able to develop standard evaluation methods for a safe and quick start up and shut down procedures by providing system dynamics simulation. In general the LNG TTC could assess many technological issues related to offshore LNG from the risks of offshore LNG operations to the fundamental behaviour of LNG.

Storage, offloading / transfer systems

The development of offshore transfer systems is crucial for applying offshore liquefaction in harsh environments. The LNG TTC Test Facility will accelerate the development of transfer systems by providing a possibility to test transfer systems such as flexible hoses , pipes or transfer arms on a full scale. This will allow different suppliers to test their transfer solutions and will finally help to accelerate the time to market of these systems. The LNG TTC will also cover fundamental development issues, such as system dynamics simulation in case of emergency release, determination of new material requirements for cryogenic application, prediction of flow and mechanical behaviour of flexibles. All these issues are

essential for the acceptance of transfer solutions and will make the LNG TTC an important source for the development of standards, such as the EN1474.

Offshore regas systems

Traditional methods for regas systems like ambient air evaporation or water heated evaporator systems prove to have significant drawbacks. Active cycle regas systems have better operational features, can be used for regas as well as recondensation and have a better weight to performance ratio.

Fundamental research topics

The possibility of optimising offshore facilities require a fundamental knowledge on the behavior of LNG mixtures under motion. This ranges from sloshing in storage and related problems as increased evaporation to the stability of flow components as heat exchangers and distillation under motion and the control of these processes.

Technological Roadmap Small Scale LNG

In the technological roadmap Small Scale LNG the following topics have been identified :

- 1 Production; for instance how can cryogenic pre-processing in small scale offshore and onshore application be improved and optimised (e.g. Shell’s topic in the STW Partnership Programme);
- 2 Transport; use of LNG in trucking and shipping;
- 3 Storage; improvement of QRA legislation;
- 4 LNG as fuel, in heavy duty transport applications;
- 5 Metrology; LNG calibration in flowmeters;

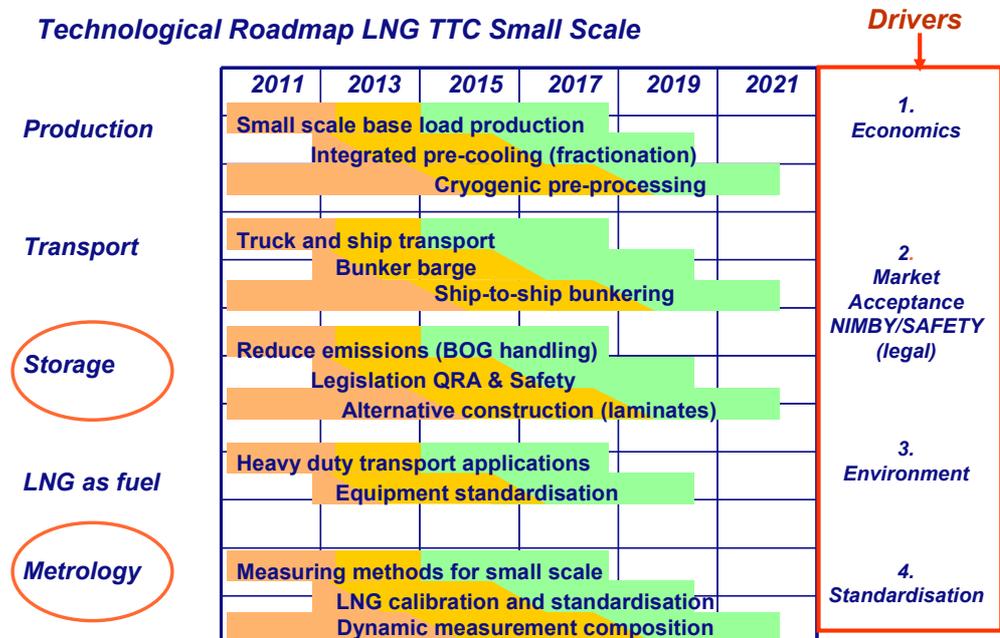


Figure 3.3. Technological Roadmap Small Scale LNG with subjects and drivers

The drivers in the technological roadmap Small Scale LNG have been defined in Chapter 2 and are covering the following issues :

- Economics; Availability of an LNG infrastructure in a country will enhance other possible applications than just generating electricity and fuelling household appliances. The combination of energy density, price and efficiency makes LNG a legitimate choice for heavy duty transportation (trucks, boats, etc.). This increases the total application options for natural gas. In addition, gas is a relatively clean fuel. On the short-to-middle long-term, challenges can be found in developing standards for small scale transport and storage (distribution and logistics), commercial transfer and the economics of the chain.
- Market acceptance ; Not-in-my-back-yard, with safety and legal issues that need to be resolved.
- Environment; see Chapter 2.
- Standardisation; see Chapter 2.

Technological Roadmap Traditional LNG

The defined subjects in the Technological Roadmap Traditional LNG are :

- 1 CO₂ reduction; for example, what will be the best way to recover energy from temperature differences during regasification processes;
- 2 Development of new standards;
- 3 Biogas; until sofar this is a niche market;

The drivers in the Technological Roadmap Traditional LNG are : Environment, Efficiency, Flexibility, and determining New Markets.

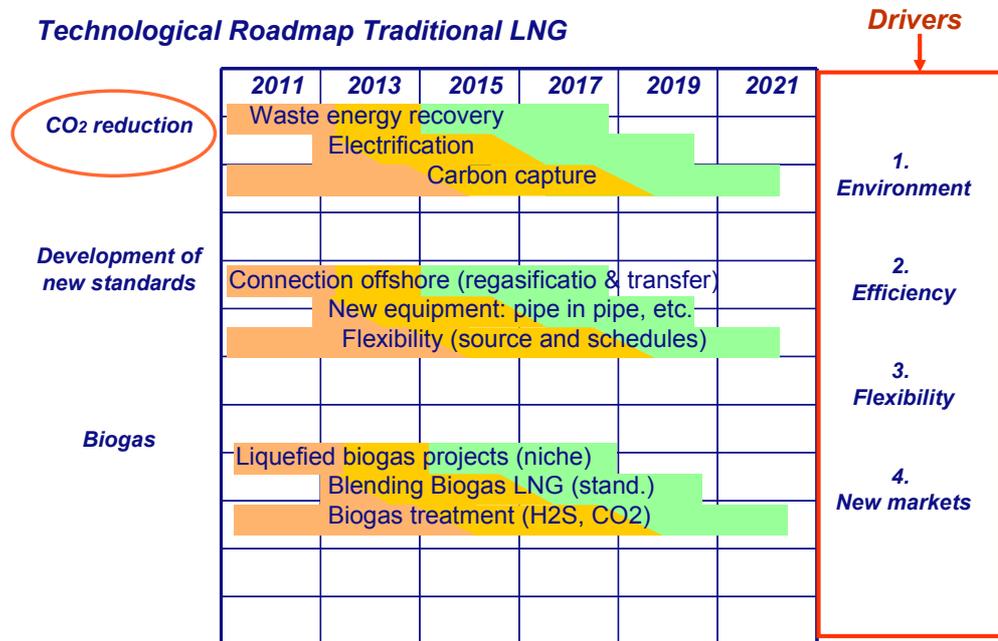


Figure 3.4. Technological Roadmap Traditional LNG with subjects and drivers

It is recommended to explore further the market needs in the traditional LNG.

3.6 Programme Matrix, Scientific Disciplines & Challenges

The fundamental research topics are described in the LNG Programme Matrix (see Appendix A). The matrix contains the following scientific disciplines:

A) Fluid Structure Interaction for Structures under Motion;

The scientific challenges are in the accurate efficient calculation of LNG mixture flow at high Reynolds numbers. LNG Fluid Wall Interaction with high wall heat load, non-stationary walls and (variable) wall geometry due to motion, flexibility and so on. This research is important for predicting the thermal/hydraulic properties of LNG flow under operational conditions as well as the behavior of the LNG flow under fault conditions and/or transient conditions.

For example, in the MIP-IOP project Fluvawint it becomes clear that with a growing potential for floating LNG the undisturbed LNG supply to regasification vessels or offloading from a floating LNG production unit is a demand under all weather conditions. Therefore alternatives to rigid loading arms have been developed, such as flexible cryogenic hoses or pipes, with an additional need for qualification and testing of components and systems. New transfer technologies and methods have to guarantee maximum availability without making concessions to safety, reliability and operability in floating LNG processes.

B) Thermodynamic Process Flow Optimisation for Cryogenic Fluid Mixtures;

This area of research involves nucleation processes in LNG under process conditions. Nucleation (the formation of bubbles or crystals) and their behavior in the LNG flow and thus on the transport properties is not well defined. This research is important not only for the prediction of blockages in the LNG flow but also for QRA calculations .

C) The last area of research to mention concerns the development of alternative processes for themes as Cold Energy Recovery or process control and optimisation under transient conditions.

Other scientific disciplines in the programme will be :

- Evaporation of a Cryogenic Fluid Mixture at a non-stationary boundary.
- Dispersion of an evaporating, cryogenic fluid mixture.
- Fast, efficient process optimisation flow solver development.
- New Materials for use in an LNG environment.

3.7 Unique character of the LNG R&D Programme

The unique character of the LNG TTC R&D Programme is an international group of LNG Industrial partners (LNG TTC Consortium) and the Dutch 3 Technological Universities Federation (3TU), are working closely together to solve fundamental research topics in order to remove innovation entrance barriers. It is recognised that this partnership, solving in a generic way rather than in a application specific way, is beneficial for all partners providing a solid basis for further, company dependent, developments.

The programme provides the knowledge, calculative and experimental tools in an area in which the cost of an experimental driven approach is a barrier for further developments.

Funding for the programme will be raised by subsidiary funds, funding by participants, and in-kind contributions of the Universities. The full R&D programme requires funding of 15 m.euros in a period ranging from the fourth quarter of 2011 to 2018.

3.8 STW Partnership Programme LNG

The objective is that the LNG TTC R&D Programme will run under the supervision of the LNG TR&D Foundation and will be executed in close collaboration with the LNG TTC participants and the Dutch universities. For a typical programme, the project group typically consists of one Ph D student, one University staff member, one participant staff member and one member of the LNG TTC.

In this stage the first programme has been identified for a total of eight Ph D students, which is this application for the STW Partnership Programme of 3 m.euros, within a timeframe of 5 years. The start of the projects will be in the fourth quarter of 2011 or the first quarter of 2012. The funding for the programmes will be divided between the LNG TTC partners and third party commitments (50%) and STW (50%).

The objective is to launch a second set of projects of similar magnitude in about 3 years from now. If possible, and pointing at our intention for a long partnership with STW, we would like to launch them as an add-on to the current partnership proposal. Continuation of the partnership proposal would also be beneficial for the Universities to make the LNG market related cryogenic flow, material and safety issues to a core research topic in their energy institutes.

Programme Committee

The programme committee will be appointed by the STW Board. The committee consists of two industrial members from the LNG TR&D Foundation and two independent, foreign expert, academic members. Scientific quality and utilisation perspective will carry equal weighting in the committee's evaluation of the proposals. The fit into the programme will also be taken into account.

Industry partners like SBM, Imtech and Shell described market applications of fundamental research topics.

Major Research Areas linked to the Market needs

The LNG Programme Matrix (see Chapter 3.6 and Appendix A) contains topics of fundamental research, technology development and experimental research. Only programmes that have an appropriate fundamental level, to be decided by Scientific Board (as defined in Figure 5.3. Organisation Chart Foundation LNG TR&D), which is part of the LNG TR&D Foundation, and will be submitted to the STW partnership programme. Based on the LNG Technological Roadmaps as compiled by the LNG TTC partners the following major research areas have been determined.

Examples of the market applications and the connected research areas, are :

Market Application 1 : Two-Phase surge phenomena (see also Appendix B)

High transfer rates as applied in LNG transfer in combination with fast closing valves in case of emergency may lead to high amplitude shock waves or pressure

surges. Generally thinking surge phenomena are considered more critical upstream of the valve, in case of valve closure. However if cavitations occurs downstream the valve creating locally a pocket of gas, a huge peak of pressure (comparable to a slam shut) may occur. Such surge phenomena may occur at a certain time after the total valve closure, depending on the downstream piping configuration.

Based on a significant test campaign, a researcher or Ph D student has to establish an LNG surge test database (considering flow rate, valve closure time, valve configuration, type, downstream pipe, etc.) and develop a suitable algorithm for predicting surge pressures in LNG service. The database can then be used by software developers to improve the accuracy of existing dynamic (LNG) flow software.

This topic that has been suggested by SBM Offshore. Possible companies that could join this research area are operators like Shell, Total, Statoil and Trelleborg and equipment suppliers of ERC systems (KLaw, MIB, Arta, etc.). Also shipping companies involved in offshore LNG transfer as Exmar-Excelerate are potential partners.

Market Application 2 : Combining Pre-processing with Liquefaction (see also Appendix C)

Fundamental research on how the pre-processing step can be combined with the liquefaction step. This means how can components like CO₂ be removed from the methane, for example in a crystallisation process. Subsequently the methane gas will be liquefied and becomes LNG. This integration step would be a huge step forward in the LNG processing. This topic has been suggested by Shell. Possible companies that could join this research area are BASF, Gaz de France, Fives Cryogenie and SBM Offshore.

Market Application 3: Cold Energy Recovery

Cold Energy Recovery and LNG re-condenser/production processes are an alternative for the traditional regas method using water-bed evaporator/heaters. As the technique under evaluation, is also suited for offshore applications and is a promising technique for reduction of environmental impact and reduction of energy intake in the LNG process. It is the intention that the fundamental research required for this process will be a topic for the partnership programme. This topic has been suggested by Imtech SMS.

4 Basis of design of the LNG TTC Test Facility

4.1 Introduction to basis of design of LNG TTC Test Facility

TNO and partners are active in Business-to-Business research projects and Joint Industry Projects on reliable and safe operation of LNG equipment in offshore floating and onshore small scale applications. Test facilities are indispensable in these projects and also play a role in model validation in a joint R&D programme to be defined by the LNG TTC partners.

VSL's aim for the project is to come to a test facility to develop a standard for calibration of custody transfer flow meters, and if developed, to use it for calibration purposes of LNG flowmeters for custody transfer on a regular basis.

At current custody transfer flow metering of LNG is based on static metering merely by tank level gauging. Dynamic in line flow metering is preferred, however, accuracy and repeatability are so far based on water calibration as facilities for LNG flowmeter calibration are not available worldwide. The calibration facility could also accommodate a test and calibration area for LNG quality measurement systems to benchmark their performance and support innovations in design.

As part of the LNG TTC Definition Study the functional requirements of the LNG cryogenic test and calibration facilities as defined by the LNG TTC partners are described. The functionalities are required for the Basis of Design study, which is the first step in the engineering design of the facilities. For this design and the estimate of the CAPEX cost (-10/+30%) involved in the engineering and construction phase, the scope of the test facilities and operating envelope should be well defined. This includes flow, temperature and pressure range, diameters of piping, sizes of the equipment, static and flow dynamic testing possibly including sea motion. In the next phase the (detailed) engineering will result in a more accurate estimate of the CAPEX cost ($\pm 10\%$).



Figure 4.1. Location of LNG TTC Test Facility projected at Gasunie Peakshaver in yellow area.

The proposed location for the LNG TTC Test Facility in this study is at the Gasunie Peak Shaver at Rotterdam Maasvlakte, The Netherlands (see figure 4.1.). The Basis of Design Study has been performed by KH Engineering and Cryonorm Projects (CNP), Alphen a/d Rijn. Cryonorm was involved as Technology Provider and Mechanical Engineers, KH were involved with Process, Piping & Layout, Electrical, Process control & Instrumentation and Civil / Structural. As it concerns a test and a calibration facility, the partners involved in the design are VSL (Dutch Metrology Institute), TNO and Gasunie. Also the other industrial partners Vopak, Shell, SBM Offshore Services and Imtech attended some of the Basis of Design study progress meetings.

The aim of this Basis of Design (BoD) is to define the required functionality and a base concept with an assumed feasibility and an indicative cost estimate (+/- 30% accurate). The Basis of Design study is reported in the KH report 62249-01-10-27A-001 rev 1 of 6 April 2011 and has been issued to all partners in the LNG TTC Consortium including a package containing:

- Overall plot plan of the facility
- 3D snapshots
- Process Block Diagrams
- Electrical Diagrams
- Equipment description/ data sheets/general arrangements
- Process Flow Diagrams and preliminary P&ID
- HAZID and coarse HAZOP analysis
- Cost information per Scope of Work

The package starts with an introduction of the project considered (Chapter 1), followed by a qualitative description of the process (Chapter 2). Chapter 3 defines the Design Criteria applicable and includes for the Process Design basis. Chapter 4 handles the material selection.

Health, Safety & Environmental aspects are addressed in Chapter 5, followed by the description of the Scope Of Work. The Scope of Work per Chapter 6 forms the basis for the cost estimate, and clarifies the Estimate Assumptions made. The last chapter is Chapter 7, which addresses the attention points for next project phases. Important aspects and results are briefly discussed and presented in the following chapters.

4.2 Required functionalities

The LNG test and calibration facility should be able to cover a wide operating range in flow to cover small scale and large scale (offshore) flow applications for LNG transfer, storage and process operations.

A summary of applications in the 100% liquid phase with minimum boil-off gas are summarised below:

- Flow meter calibration of small scale and mid scale sizes, from 25-1000 m³/h at low-pressure;
- Static and flow dynamic testing of : cryogenic materials, equipment used in small scale LNG storage, distribution by trucks/ships, fuel for shipping: storage tanks, valves, flexible hoses, piping, couplings, safety valves in applications up to 10 barg and a maximum flow of 1000 m³/h;
- Flow meter calibration in a large operating range from 25 up to 7000 m³/h, at medium pressure up to 24 barg with a maximum diameter of 24-inch;

- LNG circulation in test loop: from 100-7000 m³/h maximum working pressure 24 barg for testing of mechanical integrity and efficiency (pressure drop, heat flux, pulsations, vibrations, cavitation, vortex shedding, impact of fast closing valves, pressure surges , transient loads) in large flow (F)LNG such as large flexibles hoses/pipes from 8 up to 20-inch, ESD valves, ERC couplings;

Next there are also applications, which produce large amounts of boil-off gas , for which (additional) boil-off gas compressor capacity would be required. Typical applications are process equipment, such as:

- Boil-Off Gas Compressor Package testing required through 10 tph and 80 bar;
- Compressor/Expander testing on nitrogen up to a liquefaction rate of 50 tpd;
- HP Pump/Liquid expander testing up to 1000 m³/h at 100 barg;
- Spiral-Wound and Plate Fin Heat-Exchangers to check integrity and optimisation of performance;

Finally the possibility of testing floating hoses for LNG transfer or LNG processing equipment under simulated sea motion would offer extended possibilities for floating LNG technology to the test facilities and is therefore briefly considered to enable a rough estimate of the cost involved in a motion testing facility.

The Gasunie Peak Shaver location is considered as the primary project location in the BoD study and therefore possible synergy effects are considered. Benefits are:

- 1 the presence of LNG and LIN;
- 2 Gasunie's focus on LNG development;
- 3 Gasunie's well equipped personnel and a permit regime available for LNG.

4.3 Process descriptions, phases and flow diagrams

4.3.1 General Process Description

Process description Test Area

The Test Area is a rectangular area of approximately 30 by 10 meters. This area is bordered with a number of connections that can be used for supply- and return of LNG. There are two 24-inch connections, two 16-inch connections and two 8-inch connections and twelve 4-inch connections. A small LiN-fed cooler E-13 can be used to sub cool LNG prior to storage in Dewar-vessels. The 4-inch connections are located on "working-height". The 24-inch connections are located on an "elevated position", this to enable suspension of e.g. loading hoses.

Process description VSL Facilities

The VSL facilities mainly comprise the following:

- Three racks of so-called "Reference Meters" mounted in series. Each rack holds six coriolis-type meters mounted in parallel. The size and capacity of the upstream flow meters is larger than the size and capacity of the downstream flow meters. A single flow meter of the upstream rack can be calibrated with six flow meters of the downstream rack. The same applies to the Master Meters, see next;
- Four metering-runs holding the so-called "Master Meters" . These ultrasonic-type meters considerably differ in size in order to cover the whole operating envelope of the test facility.
- Three metering-runs holding the so-called "Meters Under Test" .These ultrasonic-type meters considerably differ in size in order to cover the whole operating envelope of the test facility;

- A Sampling System. Within an “Abri-type” shelter the LNG flow can be sampled, evaporated and analysed; This area should also allow testing and calibration of LNG quality measurement;
- The so-called “VSL primary mass flow standard”. A relatively small container holds the primary standard for realising traceability to the Systeme Internationale (SI). This is an existing container, owned by VSL;
- A large space is reserved for future installation of an LNG Meter Prover.

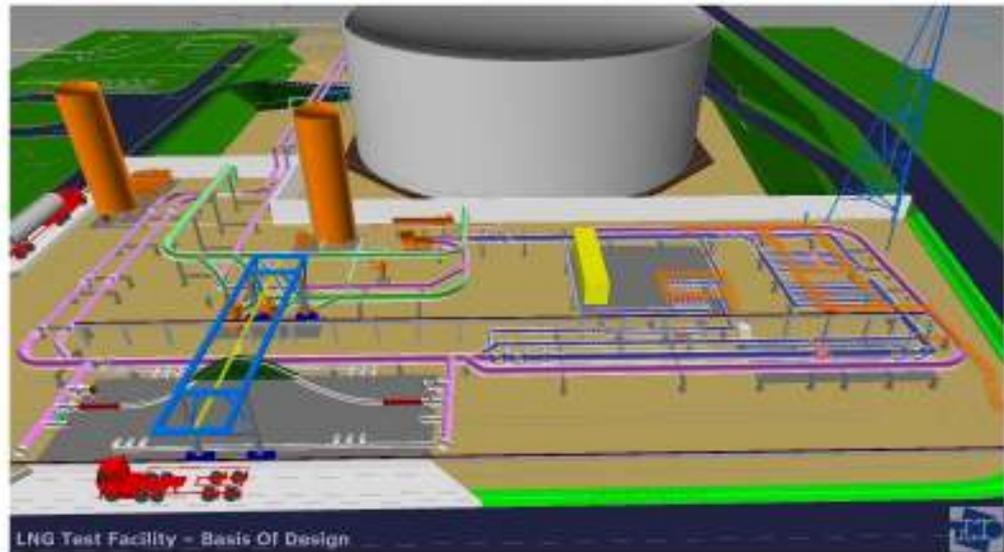


Figure 4.2. LNG test and calibration facility at Gasunie Peakshaver

4.3.2 *Process description Phase 0*

For Phase 0, the objective is to minimise investment cost, by making maximum use of the existing equipment at the Gasunie Peak Shaver facility.

Basic Process specifications are :

Flow:	25 - 2000 m ³ /h.
Pressure:	not specified.
Temperature:	none specified.
Sub cooling:	>0 °C.
Boil off gas:	minimum.
Pressure stability:	+/- 4%.
Flow stability:	+/- 1%.

LNG supply

Two flat-bottom existing Gasunie LNG tanks D-302 and D-303, both with four submersed LNG pumps, provide the LNG for the test facility. The tie-in point for the new facility is located at the inlet of the high pressure (HP) Main LNG Pumps (P-302-1/2/3 & P-302-1/2/3). These two LNG feed lines are combined and sent to the Master Flow Meters, so the exact amount of flow sent to the test facility is known.

Testing

From the master flow meters, the LNG is run to the test area, where a certain pressure drop may be taken, and/or heat may be put into the flow (for example by removing pipe insulation). 300 kW of heat losses in the test facility are considered. The flow control is set manually, by opening the flow control valves to the inlet of each tank. In this case, a manual set point is preferred over automatic control, because it will give a more stable flow through the facility. The operator may set each of the two valves at a desired position.

This will enable setting of the total flow, as well as the individual return flow into each tank. To prevent reaching high level in one of the tanks, it is required to bring the same amount of liquid back into each tank, as is taken out. This can be measured by comparing the inlet and outlet flow of each tank.

Pressures

The pressure during the test is determined by the suction pressure of the pump (liquid level in the storage tank), the pump curve, and the height of the tank. All three variables remain constant during the test. Figure 4.2. shows how the pressure during the test can vary with different operation modes of the pumps. Scenarios 1 and 3 will give the higher pressure numbers, in scenario 2 the pressure is somewhat lower. Lower pressures in the test area can not be realised. At lower pressure, it would not be possible to return the liquid back into the main storage tanks.

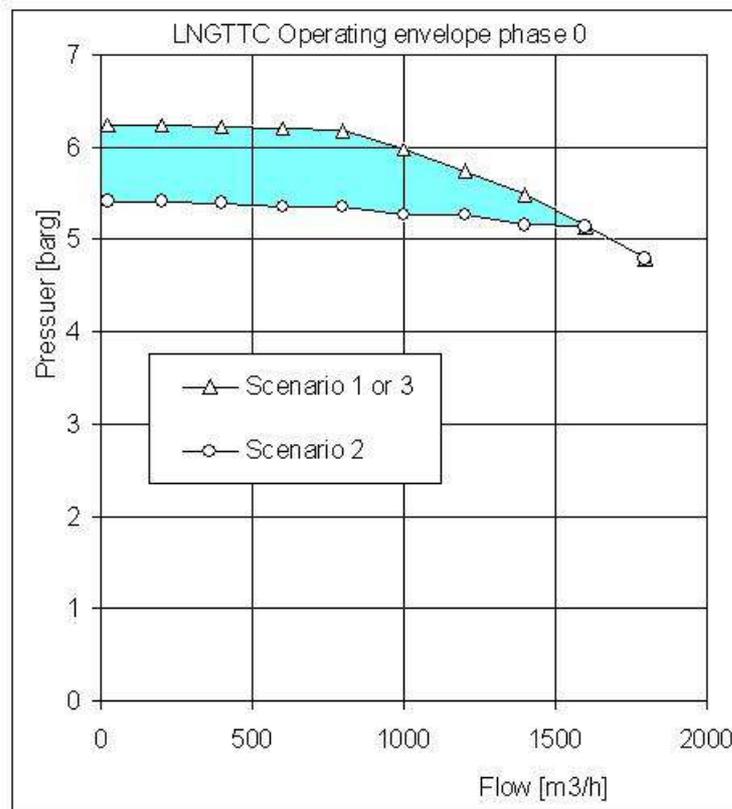


Figure 4.3. Operating envelope for LNG TTC Test Facility Phase 0

4.3.3 *Process Description Phase 1*

For phase 1, the objective is to reach a higher flow and higher pressures. As in Phase 0, boil off gas shall be minimised. Test objects are flowmeters for the VSL calibration facility, and other LNG equipment at the test facility.

Basic Process specifications:

Flow:	25 - 7000 m ³ /h.
Pressure:	4 bar through 24 bar
Temperature:	not specified.
Sub cooling:	>0 °C.
Boil off gas:	minimum.
Pressure stability:	+/- 4%.
Flow stability:	+/- 1

LNG supply

In Phase 1 of the project, a storage tank V-01 is filled with LNG coming from existing storage tanks D-302 and D-303. The pressure in V-01 is controlled by a pressure builder E-07. If the pressure, measured at the pressure transmitter (PT), is too low, it allows a pressure-controlled control valve to open and allow liquid to E-07. This liquid flow is driven by the liquid head in V-01. LNG is vaporized (with 28 °C of superheat), and the gas is sent back to the top of V-01, resulting in an increased tank pressure. Also, sub-cooled liquid through the recycle flow line, can be injected in the tank through both top- and bottom filling. This also allows a regulation of the tank pressure. This way, V-01 pressure may be controlled between 2 and 8 bar(g).

The LNG is pumped through jockey pump P-03, where it enters the test loop to the suction of the loop pumps (P-01, P-02A and P-02B). P-01 has a smaller capacity (200 m³/h) than P-02A/B (3500 m³/h). All three pumps have a 5 bar differential across it at design flow. These pumps cannot run all three at the same time. Possibilities are: only P-01 is running, only P-02A, only P-02B or P-02A/B at the same time.

Testing

From the loop pumps, the LNG flow is sent to the Master Flow Meters, to have an accurate recording of the amount of flow being sent to the test facility. No control is performed from this signal.

Subsequently, the LNG flows either through the Test Area or the VSL Test Facility. In the Test Area, a small sub cooler is foreseen to enable filling of Dewar-vessels at the facility.

Cooling

At the outlet of both test facilities, the returning liquid flow is sent to heat exchanger E-02, where the LNG is cooled to remove the heat of the system, resulting from the testing and the energy of the pumps. This flow is sent back to the suction of the LNG pumps.

The temperature of the test loop is controlled by E-02.

The flow of the test loop is controlled by two (manual: HC) flow control valves at the inlet and at the outlet of the test facility. One or both of the control valves can be manipulated to take the pressure drop that is required to maintain the required amount of flow. Using the inlet control valve allows less sub-cooling in the liquid; using the outlet control valve allows the maximum amount of sub-cooling in the liquid; when both control valves are used, the amount of sub-cooling can be adjusted between minimum and maximum.

A minimum flow through the pumps is necessary to keep the pumps operating at their pump curves. A minimum flow loop, that bypasses the test facility, allows to turn down the flow to the test facility to the required range (25 – 7000 m³/h), while allowing the pumps to operate at a stable condition.

The pressure of the test loop is controlled by means of jockey pump P-03 and the pressure control valve. The jockey pump pumps a constant flow into the test loop. If no pressure change is required, this extra amount of liquid flow is sent back to V-01 through the pressure controlled valve. If a higher pressure in the test loop is required, the opening of this valve will decrease, so less liquid is sent back to V-01 and more liquid remains in the test loop. Since the test loop is a closed loop, this addition of liquid will result in an increase of the loop pressure.

Flows

For the static and flow meter testing with a maximum 2.0 bar pressure drop across the test area it is possible to achieve the required flows of 25-7000 m³/h. The accuracy/stability of the flow is based on the sizing of the flow control valves and the required stability of 1% should be achievable using properly sized flow control valves. The flow controls are based on automatic valves with a hand controller (HC). This arrangement will minimize instability in the system due to loop tuning parameters.

Pressures

The pressure during the test is determined by the suction pressure of the LNG loop pump and the pump curve. The pressure at the test inlet is controlled by adding/removing liquid from the loop via the LNG jockey pump and the pressure control valve that returns liquid to the LNG storage tank V-01. The pressure stability of the system is based on the control dynamics of the pressure valve and a good engineered piping system in respect to gas traps and dead end boiling.

Figure 4.4. below shows the possible operating envelope for phase 1. The minimum stable pressure in the loop is given when V-01 at its lowest stable pressure (2 barg), the jockey pump at lowest stable pressure rise (2 bar), and the pressure rise of the loop pumps (approximately 5 bar), which makes an inlet pressure at the facility of 9 barg.

The maximum pressure is the design pressure of the system, which is 24 bar. This pressure can be maintained over the full flow range. The dark blue area shows the stable envelope.

It is possible that the system can be operated with the tank at lower pressure and the jockey pump at lower head, or even off. In that case, the operating envelope would be extended as shown by the light blue area in Figure 4.4. (best case).

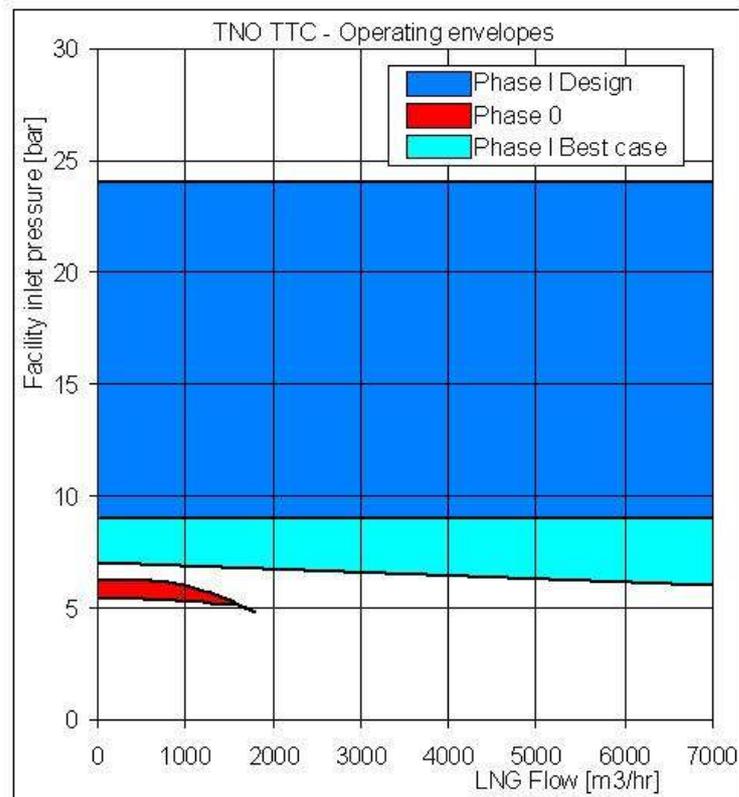


Figure 4.4. Operating envelope for LNG TTC Test Facility Phase 1
(The envelope for Phase 0 is shown for comparison)

4.3.4 Phase 2 - Process Description and Mass and Heat Balance

Phase 2, a variety of equipment is foreseen to be tested, each requiring its own design of the test facility. The equipment foreseen is summarized below, and for each design a brief introduction is written.

Boil off Gas Compressors

The BOG compressor test area will provide a means to test LNG boil off gas compressor up to 10 tph and 80 barg discharge pressure using existing BOG from the Gas Unie peak shaving facility. The BOG compressor along with the required auxiliaries will be supplied as part of the unit under test (UUT). The motor and required test equipment will be permanently installed at the test area.

The major pieces of equipment include:

Inlet knock out drum V-21, BOG liquefier E-21, BOG suction de-super heater TV-21 and the BOG compressor UUT.

A slave motor to drive the compressor will be available, similar to other compressor test facilities.

The BOG for the test is supplied from the Gas Unie BOG system which enters the test loop via the suction pressure control loop. The BOG is only used to inventory the test loop and the quantity is determined by the volume of the piping and equipment of the test loop along with the test pressure of the compressor. During normal steady state operation the only BOG required is to make up for seal losses and/or piping leaks. The gas then enters the inlet knock out drum V-21 to eliminate

the possibility of any entrained liquid in the compressor suction. From there the gas enters the compressor where it is compressed and cooled using test compressor and auxiliaries. The gas leaves the compressor at required test pressure and temperature. The gas is split into two streams, one stream goes to BOG liquefier E-21 where it is liquefied against a liquid nitrogen (LiN) stream and combined with the second stream to maintain the desired inlet gas temperature for the test. The liquefied BOG is injected into the relatively warm stream by using a de-super heater which sprays the liquid into the warm stream and cooling the suction stream. The temperature is controlled by an inlet temperature control loop. The gas is then returned to the inlet knock out drum where the loop is repeated. During the test a change in suction pressure or discharge pressure will require gas to be removed or added to the system. Gas will be added by inlet pressure control system or removed by a discharge vent valve. The discharged BOG would be returned to the Gas Unie BOG system.

The utilities required for this test facility include: BOG, cooling water, LiN, instrument gas, and electricity.

Compressor/Expander or Componder

The Nitrogen compander test area will provide a means to test a nitrogen compander up to an LNG liquefaction rate of 50 tpd using gaseous nitrogen (GAN) from the Gas Unie peak shaving facility. A standard nitrogen compander consists of a three stage nitrogen compressor and a single expander mechanically connected on a common bull gear driven by a motor.

The Nitrogen compander along with the required auxiliaries will be supplied as part of the unit under test (UUT). The motor and required test equipment will be permanently installed at the test area.

The major pieces of equipment include:

Main heat exchanger E-31, GAN super heater E-32, and nitrogen compander UUT.

The GAN for the test is supplied from the Gas Unie GAN system which enters the test loop via the suction pressure control loop. The GAN is only used to inventory the test loop and the quantity is determined by the volume of the piping and equipment of the test loop along with the test pressure of the compressor. During normal steady state operation the only GAN required is to make up for seal losses and/or piping leaks. The gas then enters the compressor where it is compressed and cooled using test compressor UUT and auxiliaries. The gas leaves the compressor at required test pressure and temperature. The compressed GAN goes to the main heat exchanger E-31 when the gas stream is cooled to the desired test temperature and fed into the inlet of the expander. The outlet gas of the expander is split into two streams. One stream is fed into the cold end of the main heat exchanger to cool the incoming (expander inlet) stream. This flow is controlled to achieve the desired inlet temperature to the test expander.

The second stream is fed into GAN super heater E-32 where it is warmed back to compressor inlet temperature. After the outlet of heat exchangers E-31 and E-32 the GAN stream are combined and fed to the inlet of the nitrogen compressor where the loop is repeated. During the test a change in suction pressure or discharge pressure will require gas to be removed or added to the system. Gas will be added by inlet pressure control system or removed by a discharge vent valve. The discharged GAN would be vented to atmosphere.

The utilities required for this test facility include: GAN, cooling water, instrument gas, and electricity.

HP LNG send out pump

The HP LNG send out pump test area will provide a means to test an LNG high pressure pump up to 1000 m³/h at 100 barg from the Gas Unie peak shaving facility. The HP pump and motor along with the required auxiliaries will be supplied as part of the 'Unit Under Test' (UUT). The required test equipment will be permanently installed at the test area.

The major pieces of equipment include:

LNG storage tank V-01 (existing from Phase 0/1), LNG heat exchanger E-41, and HP LNG pump UUT.

The LNG for the test is supplied from the LNG storage tank V-01. The LNG is used to inventory the test loop and the quantity is determined by the volume of the piping and equipment of the test loop along with the BOG produced during the cool down and testing. During normal steady state operation the only LNG required is to make up for BOG losses. The LNG enters the UUT pump where it is discharged at test pressure and flow. The pressure and flow are controlled by a back pressure control valve which will control the pump along its required pump curve. After the pressure drop across the control valve the LNG warms up and is sent to LNG heat exchanger E-41 where the heat of the test loop is removed against evaporating LiN. The LNG is cooled to the desired test temperature and fed into the inlet of the LNG storage tank V-01. The amount of produced BOG can be controlled, since the temperature of the LNG returning to the storage tank can be controlled.

The utilities required for this test facility include: LNG, LIN, instrument gas, and electricity.

LNG liquid expander

Refer to attachment 6.15 which includes for the PFD and M&H balance summary.

The LNG Liquid expander test area will provide a means to test an LNG liquid expander up to 1000 m³/h at 100 bar differential from the Gas Unie peak shaving facility. The liquid expander and generator brake along with the required auxiliaries will be supplied as part of the 'Unit Under Test' (UUT). The required test equipment will be permanently installed at the test area.

The major pieces of equipment include:

LNG storage tank V-01 (existing from Phase 0/1), HP LNG pumps P-41A/B, LNG heat exchanger E-41, and LNG liquid expander UUT.

The slave motor as available for the compressor package tests can be included as load to the generator.

The LNG for the test is supplied from the LNG storage tank V-01. The LNG is used to inventory the test loop and the quantity is determined by the volume of the piping and equipment of the test loop along with the BOG produced during the cool down and testing. During normal steady state operation the only LNG required is to make up for BOG losses. The LNG enters the hp pumps P-41A/B where it is discharged

at test pressure. The discharge pressure of the pumps is controlled by utilising variable speed drives to match the required pressure. The flow of the liquid expander is controlled by either a set of inlet variable geometry nozzles or a variable speed constant frequency controller (VSCF). There is a control valve installed in parallel to the expander to increase the operating envelope of the test and also to assist in the cool down of the system. After the pressure drop across the expander the LNG is sent to LNG heat exchanger E-41 where the heat of the test loop is removed against evaporating LIN. The LNG is cooled to the desired test temperature and fed into the inlet of the LNG storage tank V-01. The amount of produced BOG can be controlled, since the temperature of the LNG returning to the storage tank can be controlled.

The utilities required for this test facility include: LNG, LIN, instrument gas, and electricity.

LNG evaporator

Refer to attachment 6.15 which includes for the PFD and M&H balance summary.

The LNG evaporator test area will provide a means to test an LNG evaporator up to 20 m³/h at 100 barg from the Gasunie peak shaving facility. The LNG evaporator along with the required auxiliaries will be supplied as part of the 'Unit Under Test' (UUT). The required test equipment will be permanently installed at the test area.

The major pieces of equipment include:

LNG storage tank V-01 (existing from Phase 0/1), HP LNG pumps P-41A/B, LNG heat exchanger E-41, CNG liquefier E-42 and LNG evaporator UUT.

The LNG for the test is supplied from the LNG storage tank V-01. The LNG is used to inventory the test loop and the quantity is determined by the volume of the piping and equipment of the test loop along with the BOG produced during the cool down and testing. During normal steady state operation the only LNG required is to make up for BOG losses. The LNG enters the hp pumps P-41A/B where it is discharged at test pressure. The discharge pressure/flow of the pumps is controlled by utilising variable speed drives to match the required pressure/flow. The flow into the test evaporator is controlled by flow control valve. There is also a control valve installed in parallel to the evaporator test to increase the range ability of the test and also to assist in the cool down of the system. After the LNG has been vaporized the gas is sent to the CNG liquefier E-42 where the gas is reliquefied.

The reliquefied LNG is combined with the LNG that has bypassed the evaporator and sent to the LNG heat exchanger E-41 where the heat of the test loop is removed against evaporating LIN. The LNG is cooled to the desired test temperature and fed into the inlet of the LNG storage tank V-01. The amount of produced BOG can be controlled, since the temperature of the LNG returning to the storage tank can be controlled.

The utilities required for this test facility include: LNG, LIN, instrument gas, and electricity.

4.4 Liquid Nitrogen supply

The prevention of excessive boil-off of natural gas is by means of cooling the flow with liquid nitrogen. This nitrogen will be evaporated and vented to atmosphere via a vent-stack. To prevent having large vapor clouds over the existing plant and its surroundings, this gaseous nitrogen is warmed to almost ambient temperature through heat exchanger E-12.

To have some independency, a dedicated nitrogen storage (V-11) is foreseen, having 200 m³ of liquid available.

In Phase 2 of the facility, when large equipment is tested, the required nitrogen needs to come from the existing liquid nitrogen storage at the peak shaver (D-301). After a test, the inventory of D-301 may then be replenished using trucks from the local gas supplier. Pump P-11 is installed to bring the liquid from the main storage to V-11. A pressure control valve is installed for start up and to keep the pump from cavitation once the required flow is less than the pump minimum flow.

For Phase 0 and Phase 1, smaller scale tests may be performed that do not require such a large amount of nitrogen. For this case, V-11 may be filled by trucks. During a test, the tank may be refilled to enable longer tests.

The pressure in V-11 is regulated by pressure builder E-11 and the pressure controlled vent valve on the top of the vessel. During filling, pressure may be controlled by choosing top or bottom filling.

4.5 Design criteria and standards

Since the location is owned by Gasunie, the Gasunie Standards form the basis for the design. For LNG application the standard has been challenged by other standards (ref memo 62249-01). The following standards are mentioned and applicable in view of the Basis of Design:

- European Guideline 97/23/EG (PED)
- EN 1473 – Design of onshore installations for LNG
- ASME B31.3 Process piping
- Gasunie Technical Standards
- Gasunie Piping specifications

4.6 Health, safety and environmental aspects

HSE Philosophy

The LNG TTC Test Facility HSE philosophy is to comply with the applicable National and European safety, health and environmental regulations and directives and to do the utmost to prevent injury to persons, damage to property or harm to the environment.

The methods applied to the Basis Of Design are HAZID and Coarse HAZOP

A Quantitative Risk Assessment (QRA) is required for endorsement of the project location, at current North of D-302. The QRA is intended to be performed under direction of TNO / Gasunie, upon completion of the Basis of Design.

Due to an LNG TTC Test Facility location close to the LNG tank D-302, the Basis Of Design includes for a blast wall between D-302 and the test facility in view of HSE. The bund walls around the test facility will be demolished to allow for natural ventilation. The remaining bund walls will be increased to keep the same retention volume for D-302 and D-303.

The method to verify on safety distances for the test facility, a Process Safety Review on Project Location has been performed (ref. Memo 62249-03 & 05).

Risk Analysis

A **HAZID** (HAZard IDentification) has been performed in a session with a HAZID facilitator, engineering representation and Plant Owner representative. The HAZID provides early identification and assessment of the critical HSE hazards, being essential input to project development decisions. A report is enclosed per attachment 6.1, and includes for an introduction of the method applied.

Since this is the first HAZID during the Basis of Design phase of the project, a simplified risk ranking (Low/Medium/High) has been applied.

The HAZID findings are reported, indicating mitigation actions appropriate to this project stage. These actions are defined under responsibility of the KH Project Manager, who completed the actions for 'Basis of Design'.

Area Classification

Please refer to the Area Classification drawing per attachment 3.8.

Since the test facility comprises LNG, a zone 2 is considered. Zone 1 occurs at emergency venting, at a height of 35 m.

The effect on emergency venting as close to the LNG tank D-302 is to be considered in a next project phase and to be integrated in the TNO/Gasunie's QRA as mentioned in Chapter 5.1, if applicable.

4.7 Location aspects and alternatives

The basic assumption with respect to the location of the LNG TTC Test Facility was the Gasunie PeakShaver site. The Basis of Design analysis of the test facility has been performed independent of this site as much as possible.

As a result of the Basis of Design Study by KH-Engineering/Cryonorm and the discussion on 3 March 2011 in the LNG TTC Consortium it was concluded that the intended location at the Gasunie Peakshaver site was not feasible from safety point of view. In spite of the advantages of locating the LNG TTC Test Facility at the Gasunie Peakshaver the available location is too close to the existing LNG tanks and offers a potential risk concern as expressed by several partners in the consortium.

The intended location of the LNG TTC Test Facility on the site of Gasunie Peakshaver obviously has a number of advantages:

- Availability of LNG, LIN and associated facilities (e.g. storage tanks and pumps, LNG safety measures, boil-off compression);
- Well trained personnel of Gasunie to operate and maintain the facilities;
- Sufficient power capacity;
- Attractive location in the Rotterdam area close to potential customers and TNO and VSL locations;
- No (new) MER procedure required.

Though also a number of disadvantages of the intended location are addressed:

- Objections with respect to safety as the intended location is too close to existing LNG tanks as expressed by LNG TTC partners;
- Combination of present activities of Gasunie PS in combination with LNG TTC Test Facility and possible future extension of Gasunie activities like Small Scale LNG bunkering and LNG Filling station for trucks. Combination of all these activities should be considered in a QRA by an external party;
- Future activities of Gasunie at the PS are not yet decided, though alternative locations on the site are not available at present; at this moment a QRA can only be performed for the present activities;
- Continuous operation may be interrupted during short periods (some weeks) in winter when Gasunie PS is in the send out mode in cold winter periods. It is assumed that operation is not interrupted in Phase 1 (LNG TTC Test Facility pumps required) when the PS is in the liquefaction mode (3-4 months);
- Possibilities for extension (motion testing and 2-phase flow testing) of the LNG TTC Test Facility are limited due to the limitations of the presents location (40 x 100m);

As a result of the conclusions regarding the location of the LNG TTC Test Facility a meeting has been organised with Gasunie (present; Ulco Vermeulen, Piet Kager and Klaas Hoving), Vopak (Dirk van Slooten and Guus Vogels) and TNO (Rene Peters, Willem Kuipers, Bas .v.d. Beemt and Evert van Bokhorst) on 5 April 2011 at TNO Utrecht. Gasunie has confirmed that there is no alternative at the Gasunie Peakshaver site in view of the planned extension of Gasunie activities, like the cryogenic pipeline from GATE, small scale bunkering, truck loading and possible additional LNG Tank.

It was concluded by all partners in this meeting that alternative locations need to be investigated as a result of safety requirements and limited operation possibilities at the Gasunie PS site. Possible alternatives, which need to be investigated further are:

- 1 Location combined with bunkering site for small scale LNG supply for shipping in the Rotterdam area, which is at present under investigation.. Possibly the location near the Gate Terminal in combination with extension LNG tank 5 of Vopak;
- 2 Stand-alone location like the "Driehoek" or Noordwesthoek on the Maasvlakte close to the GATE terminal;
- 3 Location at or close to Euroloop natural gas/oil calibration facilities of VSL;
- 4 Alternative location in the northern part of the Netherlands near Eemshaven / Delfzijl.

An overview of the results obtained so far (status as per 17 June 2011) is given below in the table summarising the requirements and results of the alternative locations.

Table 1: Requirements for LNG TTC Test Facility to cover Phase 1 (single phase LNG liquid loop up to 7000 m³/h) and Phase 2/3 (including BOG production)

Requirements	Location combined with LNG and/or small scale hub e.g. GATE terminal	Stand alone location e.g. "Driehoek" Maasvlakte	Location at or close to Euroloop*) – Rotterdam (based on info via VSL)	Eemshaven Delfzijl
<i>Available for footprint 50 x 100m (excluding control room)</i>	Combination with GATE LNG and bunkering site needs to be verified including option Euromax . Discussion PoR-Vopak and PoR-TNO	Possible options according VOPAK 1) Triangle 0.6 ha 2) South of GTS 3) NW corner Need to be discussed PoR-TNO planned 30-06-2011	Not at Euroloop site but possibly west of Euroloop – contact with PoR and curator Renestate via VSL. No alternative due to high cost of site inclusive existing buildings	Available/ to be verified
<i>Power required 2 MW</i>	To be verified	1) near MOT 2) near MOT and Euromax 3) not available.	Contact STEDIN via VSL (Peter Lukas)	To be verified
<i>LNG supply/ storage capacity 220 m³ minimum</i>	Via pipeline from GATE	1) close to GATE 2) close to GATE 3) 400m to GATE	No LNG storage available or close	Not available
<i>LiN storage capacity 220 m³</i>	Not required	Not required	Not required	Not required
<i>Control and data acquisition room 5x10 m</i>	Not available, possible integration with small scale hub	Not available	Not directly available at Euroloop control room	Not available
<i>Qualified personnel for control and data acquisition</i>	Maybe if combined with small scale hub	Not available	Possibly NMI Euroloop – needs further investigation	Not available
<i>Supply of LNG by pipeline , ship or truckloading</i>	Pipeline direct from LNG storage	Pipeline from GATE	By ship or truck	By ship or truck
<i>Supply of LIN by truck</i>	Possible	Possible	Possible	Possible
<i>Safety requirements HAZID, HAZOP and QRA</i>	Possibly in combination with small scale hub	Safety distances to MOT and Euromax to be verified	To be verified	Location dependent Safety distances to be verified
<i>Legal permits MER required</i>	Possibly in combination with	To be verified	To be verified	To be verified

	small scale hub			
<i>Presence of local partners</i>	GATE (Vopak Gasunie) and PoR	Vopak and Rotterdam Havenbedrijf (PoR)	NMI (Euroloop)	Gasunie/VOPAK
<i>Presence of local innovation clusters, R&D facilities, testfacilities</i>	Relatively close to TNO and VSL	Relatively close to TNO and VSL	Next to Euroloop (NMI) and close to TNO and VSL	To be verified: -Energy Valley -TNO Groningen -Energy Academy (Education)
<i>Possibilities for regional and/or local funding</i>	To be verified	To be verified	To be verified	++ Energy Valley Delfzijl
<i>Possible integration with existing facilities</i>	Yes, if combined with GATE and/or small scale hub	No	Euroloop: needs further investigation	No
Additional requirements for Phase2/3: BOG :				
<i>BOG compressors and gas pipeline</i>	--	-	+: Existing pipeline To be verified	-
<i>Motion tester</i>	-	-	-	-
<i>Additional power requirement 3 MW</i>	To be verified	To be verified	To be verified	To be verified

*) Existing Flow calibration facility NMI at Europoort

4.8 Recommendations / planned actions for next phase

The BoD report of KH Engineering contains a Chapter 7 referring to attention points for the next phase.

5 Organisation and Financing

5.1 Mission of the LNG TTC organisation

From the mission statement the following roles and business model of the LNG TTC can be determined:

- 1 Facilitating: operator of test facilities and test analysis and evaluation;
- 2 Consultancy: independent advising on for example product specification, design rules, performing design evaluation and troubleshooting, environmental impacts;
- 3 R&D Management: managing open source research and development programmes and knowledge management.

5.2 Organisational and legal structure of the LNG TTC

The organisational and legal structure of the LNG TTC is shown in Figure 5.1.. Please note that this structure is not to be seen as an organisation chart. The activities to be performed in the LNG TTC are to be splitted into two separate clusters: the LNG TTC R&D Programme and the LNG TTC Test Facility.

For the development of the LNG TTC a consortium agreement has been signed in December 2009 by key Dutch industrial players known as the LNG TTC Consortium (Gasunie, Vopak, VSL, Shell, SBM, Stork, Imtech, Bluewater, and TNO). The consortium agreement will be terminated at the closure of the Definition Study.

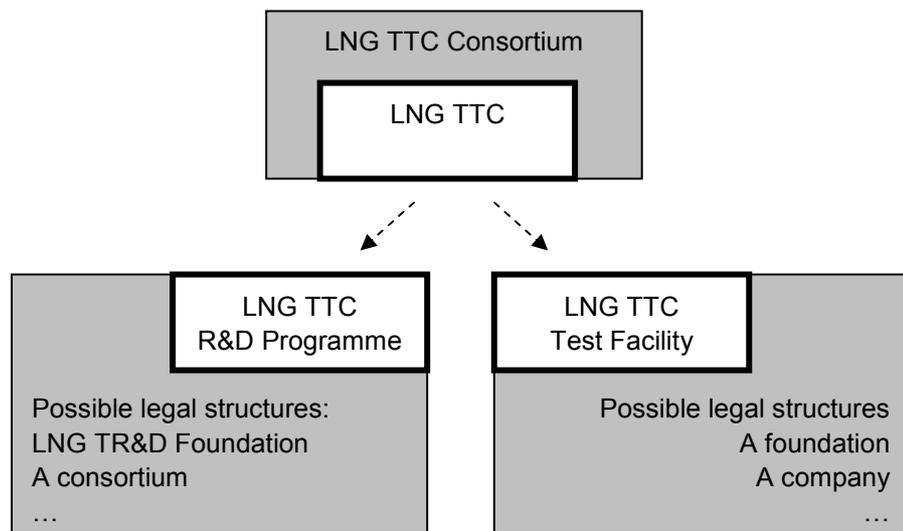


Figure 5.1. Organisational structure of the LNG TTC

It is advised that the activities of the LNG TTC R&D Programme (see also Chapter 3) are to be run under the supervision of the LNG TR&D Foundation (see later on in this chapter). However, other legal structures such as a consortium,-not necessarily the same as the LNG TTC Consortium-, are possible as well.

The LNG TTC Test Facility should have its own legal structure, such as a foundation,-not necessarily the LNG TR&D Foundation-, or a company (e.g. Ltd.).

5.3 Business Model of the LNG TTC

The concept Business Model of the LNG TTC -as assumed at the start of the Definition Study- is described in Figure 5.2.. This business model became more complete, based on the LNG drivers and SWOT analysis of Chapter 2, which were linked to the Technological Roadmaps of Chapter 3.

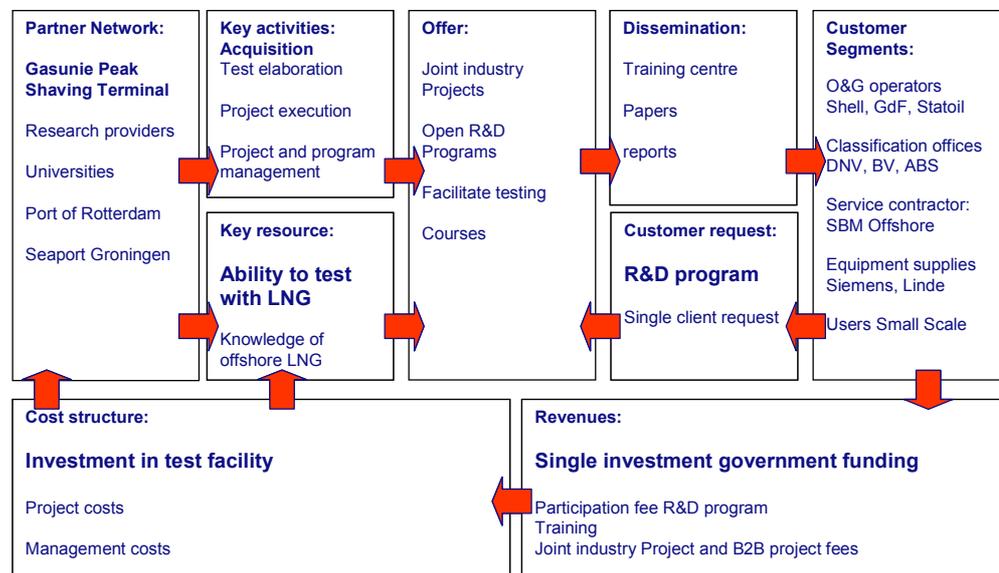


Figure 5.2. Concept of the preliminary Business Model of the LNG TTC and how this generates revenues for partners

The LNG TTC should offer the following general services:

- 1 Independent analyses for new and enhanced LNG technology, for support to regulations development, to carry out environmental impact studies and to support the development of an offshore LNG supply chain;
- 2 An independent quality-assessment system (or benchmark system) in which no commercial criteria will be used, to compare and qualify LNG cryogenic system components and equipment;
- 3 Support to or enabling of development of new technology and equipment innovations, within Joint Industry Projects or other co-operation structures;
- 4 Provide information and organise seminars and conferences, to support the Dutch industry (incl. Dutch SME and new entrants) to reach the necessary LNG technology levels demanded by market;

A description of functionalities is given in Chapter 3.

The key financial aspects are :

1. capital investment needed to build the LNG TTC Test Facility (input from WP 200);
2. income and operational costs from the LNG TTC Test Facility activities;
3. development of cash flow from external financing, capital investment, income and operational expenditure;

Generated revenues need to be sufficient to cover the exploitation costs. Capital and income will be generated from:

1. subordinated loans by participants to the LNG TTC R&D Programme and building of the LNG TTC Test Facility;
2. the yearly contributions of the founding organisations and the participants to the LNG TTC R&D Programme;
3. income from rent of the LNG TTC Test Facility to LNG TTC projects (Business-to-Business research projects, Joint Industry Projects);
4. income from rent of the LNG TTC Test Facility to third parties;
5. income from training and education courses;
6. income from other activities.

It is recommended to redefine the Business Model and its financial implications according to the outcome the organisational and legal structure.

It is also recommended to describe the expected exploitation of the LNG TTC on a balance sheet level, including the Test Facility and other activities such as organising workshops and trainings, and project management.

5.4 The R&D organisation (LNG TR&D Foundation)

The LNG TTC R&D Programme and the organisation has been discussed in Chapter 3. The LNG Industry and 3TU are gathered in the LNG TR&D Foundation (read: trend), which stands for LNG Test, Research & Development.

The mission of the LNG TR&D Foundation is:

- To remove innovation barriers;
- To increase competitive strength in the Industry, Universities and Research Institutes in the LNG market;
- To achieve a cleaner environment by using LNG as fuel, which helps to lower the emission levels of CO₂, particulates, SO_x- and NO_x.

The objectives of LNG TR&D Foundation are:

- To improve innovation, fundamental research, testing of new LNG technologies by the Dutch and European LNG industry, in cooperation with universities, TNO and governmental institutes;
- To increase the employment related to LNG in industry, universities and research institutes;
- To establish a better understanding of the advantages of LNG as a relatively clean fossil fuel in the Netherlands and in Europe;
- To communicate the advantages of LNG as fuel for the shipping and trucking industries;
- To establish synergies between the LNG TTC Test Facility, the creation of small scale LNG storage hubs, and LNG as fuel in the transportation sector;

- To establish a joint R&D programme on LNG of at least EUR 15 million in the period of 2011-2018;

The organisation of the LNG TR&D Foundation is shown in Figure 5.3. The four Steering Groups will develop and increase the specific R&D programmes further, by acquisition of more international LNG Industry partners. Also more international funding possibilities will be explored.

Funding for the programme will be raised by subsidiary funds, funding by participants, and in-kind contributions of the Universities. The full LNG TTC R&D Programme requires funding of 15 m.euros in a period ranging from the fourth quarter of 2011 to 2018.

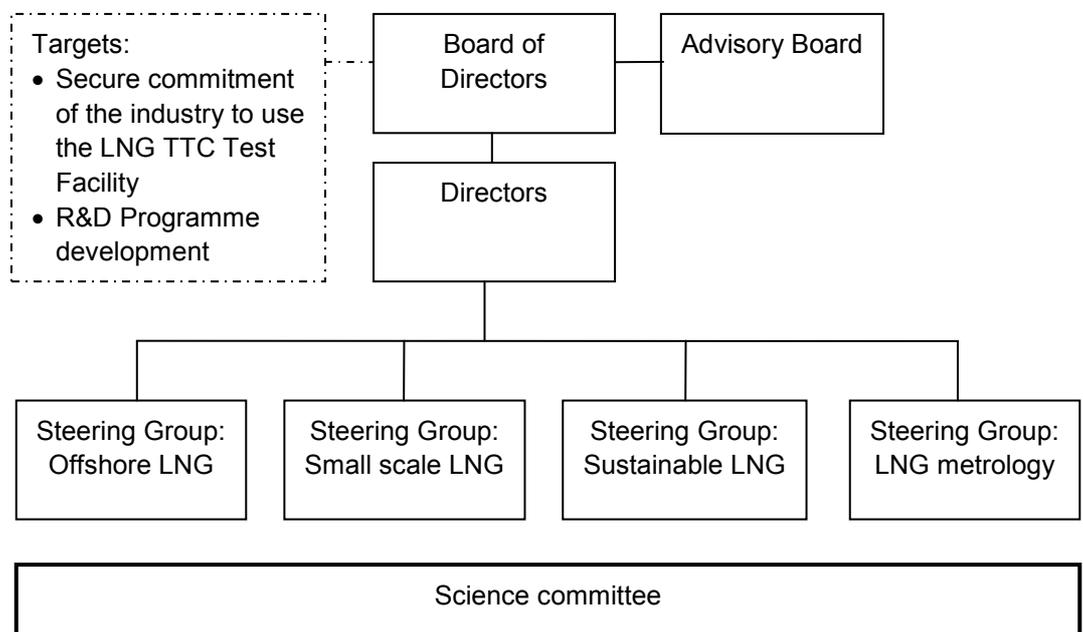


Figure 5.3. The organisation structure of the suggested LNG TR&D Foundation

The groups in the LNG TR&D Foundation organisation are:

- Board: TNO, Holland Metrology (VSL is a company within the HM holding) and 3TU.
- Directors : TNO, Holland Metrology (VSL) and 3TU.
- Council Board: Companies from the LNG Industry.
- Steering Groups: Companies from the LNG Industry.
- Science committee: 3TU and TNO

The objectives, tasks and responsibilities of the Advisory Board and the four steering groups are expected to be finalised in the third quarter of 2011.

5.5 Considerations in the realisation of the LNG Test Facility.

Part of the investigation into the development of the LNG Test-Technology Centre is the basic design of the flow facilities in WP200. The design, based on functional requirements from the feasibility study and further discussion with the LNG TTC

partners during the project, is realised by KH Engineering and Cryonorm under supervision of TNO and VSL.

Important considerations in the realisation of full scale LNG test facility are:

- 1 LNG flow facilities are not available in Europe;
- 2 Existing LNG circulation facilities such as Nikkiso Cryo (Las Vegas US) and Ebara (Sparks US) have a limited flow capacity, limited access and are not suitable for flowmeter calibration;
- 3 There is a growing need for LNG flowmeter calibration facilities, which are not available worldwide.
- 4 There is a need for an open-access test and flow facility run by an independent party, which offers access to industrial partners and universities for joint research, Business-to-Business research projects, training courses and education.
- 5 Qualification of systems and components (EN-1474) for LNG transfer, storage and processing in offshore and small scale applications becomes more and more important and cryogenic facilities are actually indispensable for these qualifications.
- 6 Validation of models developed in research projects requires an LNG flow facility.

Potential users of the LNG flow facilities are equipment manufacturers of LNG transfer, storage and processing equipment and systems like cryogenic hoses, pipes, valves, ERC systems and loading arms. Qualification projects on flow aspects have been carried out in the period 2008-2010 for Gutteling/Exmar, SBM Offshore Services and Bluewater Energy Services. In these qualification projects for 8 to 18-inch LNG hoses facilities of Deltares Flow laboratories have been used for ambient testing, which are however no longer available. Cryogenic flow tests have been performed on facilities of Nikkiso Cryo (Las Vegas) for the 8-inch hose and at Ebara (Sparks U.S.) for the 18-inch hose up to a (limited) capacity of 4000 m³/h, which is about 60 % of the required maximum capacity.

The cryogenic facilities in the US have a limited availability, are not feasible for extended testing at large flows and involve relatively high costs.

The design of the LNG TTC Test Facility is at present based on the location of the Gasunie Peakshaver (Maasvlakte Rotterdam) and is presented in the final report of KH Engineering entitled: Basis of Design Package LNG TTC – doc. Nr 62249-001-10-27A-001 rev 1 date 6 April 2011.

The design consists of three successive phases 0, 1 and 2, which is shown in Figure 5.4.

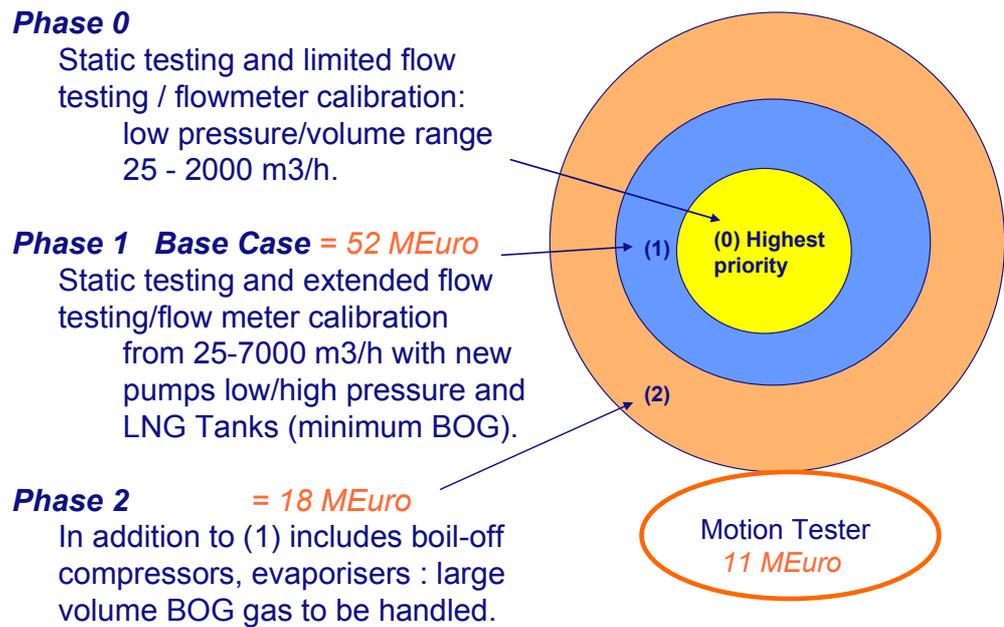


Figure 5.4.: The design phases of the LNG TTC Test Facility

Phase 0 of the LNG TTC Test Facility project enhances existing pumping capacity of the Gasunie Peak Shaver. The intended application for the LNG TTC Test Facility is:

- Flow meter calibration of mid scale sizes, from 5-2000 m³/h at low-pressure;
- Qualification of sampling and non-sampling based quality measurement systems;
- Static and flow dynamic testing of : cryogenic materials, equipment used in small scale LNG storage, distribution by trucks/ships, fuel for shipping: tanks-valves, flexible hoses, couplings, safety valves etc.

Phase 1 of the LNG TTC Test Facility project enhances new pumping capacity, dedicated to the LNG TTC Test Facility. The test loop will be separated from the Gasunie Peak Shaver installation, except for the charge of LNG. Higher pressures and higher flows can be achieved. The intended application for the LNG TTC Test Facility in phase 1:

- Flow meter calibration in a large operating range from 5 up to 7000 m³/h, at pressures up to 24 barg
- LNG circulation in test loop: from 100-7000 m³/h maximum working pressure 24 barg for testing of mechanical integrity and efficiency (pressure drop, heat flux, pulsations, vibrations, cavitation, vortex shedding, impact of fast closing valves, pressure surges , transient loads) in large flow (F)LNG for testing of mechanical integrity and efficiency (pressure drop, heat flux, pulsations, vibrations, cavitation, vortex shedding, impact of fast closing valves, pressure surges , transient loads): large flexibles hoses/pipes from 8 up to 20-inch, ESD valves, ERC couplings, etc.

Phase 2 of the LNG TTC Test Facility allows for testing of equipment like BOG compressor packages, companders and HP Pumps / Liquid expanders.

The intended application for the LNG TTC Test Facility with Phase 2 is:

- Boil-Off Gas Compressor Package testing up to 10 tph and 80 bar;
- Compander testing on nitrogen up to a liquefaction rate of 50 tpd;
- HP Pump/Liquid expander testing up to 1000 m³/h at 100 barg;
- Flowmeter performance test under dual phase conditions;

On the 3 March 2011 the plans on the Motion Tester have been presented to the LNG TTC Consortium.

The moving platform will be used to simulate the offshore sea motions, in order to test floating hoses, ship-to-ship hoses, heat exchangers, fractionating columns and to test sloshing. The surface area to implement the moving platform is 8 m x 8 m. The platform will consist of 6 degrees of freedom which is reflected in Figure 5.5..

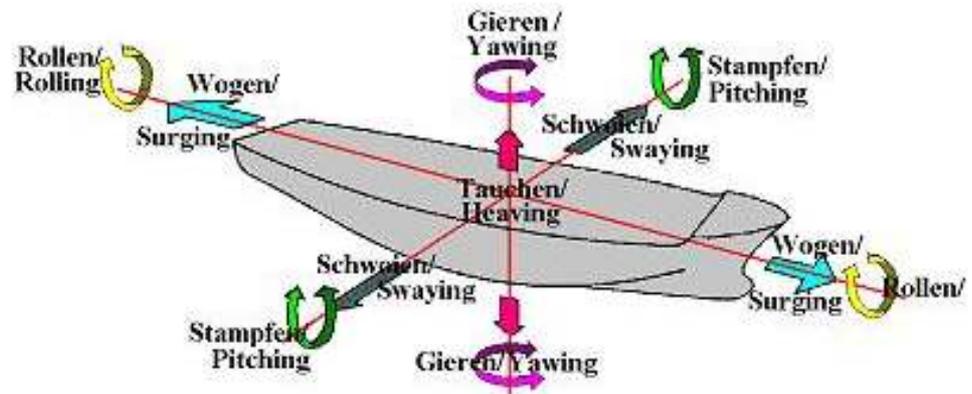


Figure 5.5. Six degrees of freedom in sea motion testing.

Estimation on the cost of the Motion Tester is 11 m.euros, including a CAPEX- mark up of 50% (see Appendix E).

5.6 Exploitation of the LNG TTC Test Facility

Benchmark / competition :

The commercial price of the existing facilities is about € 50,000 per day for an LNG flow facility with a maximum flow of 7000 m³/h (Nikkiso Cryo Offer 2009), when performing a test of 3 hr per day with a 16/18-inch LNG Hose at 7000 m³/hr including cooling.

Assumptions in the calculation of testing at the LNG TTC Test Facility:

1. Depreciation of equipment in a period of 20 years.
2. Full scale test and flowmeter calibration test cannot be done in parallel.
3. Level of occupancy is 50%, which means 100 testing days of 8 hours.
4. Invested money is calculated with 9% interest.
5. Annual exploitation cost : € 1,400,000 (rental cost on site € 200,000 ,personnel € 500,000, energy € 200,000, cryogenic liquids € 400,000, other € 100,000)

Two scenarios are described in Figure 5.6.

- 1 phase 1: contains different combinations of funding and investment, which totals 51 m.euros.
- 2 phase 2: contains different combinations of funding and investment, which totals 81 m.euros.

			Number of tests in parallel					Depreciation			Income		Total		Result
Investment	Funding	Interest	1	5	1	Days	Meuro/ year	Full scale	Small scale	VSL calibration	Income				
Meuro	Meuro	%													
51	0	9.00%	3	50	108	108	20	1.566	1.958	3.524	7.048	0.522			
51	0	9.00%	3	50	108	108	30	1.429	1.786	3.215	6.431	0.476			
10	41	9.00%	3	50	108	108	20	0.577	0.722	1.299	2.597	0.192			
26	25	9.00%	3	50	108	108	20	0.963	1.204	2.167	4.334	0.321			
35	16	9.00%	3	50	108	108	20	1.180	1.475	2.655	5.311	0.393			
0	51	9.00%	3	50	108	108	20	0.336	0.420	0.756	1.512	0.112			
81	0	9.00%	3	50	108	108	20	2.290	2.862	5.152	10.304	0.763			
20	61	9.00%	3	50	108	108	20	0.818	1.023	1.841	3.683	0.273			
40	41	9.00%	3	50	108	108	20	1.301	1.626	2.927	5.854	0.434			
53	28	9.00%	3	50	108	108	20	1.614	2.018	3.632	7.265	0.538			
0	81	9.00%	3	50	108	108	20	0.336	0.420	0.756	1.512	0.112			

Figure 5.6. Possible Positive Exploitation Scenarios of the LNG TTC Test Facility. Phase 1: 51 m.euros (yellow), and Phase 2: 81 m.euros (green), with expected turnover (income) to achieve a positive financial result (profit).

The exploitation of the LNG TTC Test Facility is based on static and dynamic flow tests in combination with flowmeter calibration.

The operating envelope of Phase 0 (maximum 1000 m³/h) is not covering the requirements for most of the clients applications and is also location (Gasunie Peakshaver) dependent. For the actual exploitation we consider the operating envelope of Phase 1 to be the scope required for full scale flow testing in the liquid phase.

The CAPEX cost for Phase 1 are € 40,000,000 (-15 to +30% margin) according to the best estimates from the Basic Design study of KH Engineering/Cryonorm. Total annual cost involved are approximately € 2,800,000

If we assume breakeven and in total about 100 days (50%) actual flow testing in the facilities (excluding preparation, which can take place in parallel on another part of the facility) the daily price for testing is approximately € 30,000 for a full scale test day or a calibration day excluding the cost for installation of the test object and chilling down of the installation. It could be feasible to have a fixed price per day and include an additional price per running hour for energy.

Exploitation costs need to be covered by tests (e.g validation, qualification, research and calibrations). VSL has developed three possible scenarios for the market development of LNG flowmeters for large scale custody transfer (small and mid-scale application to be investigated). The variables considered in these scenarios are:

- 1 Transition rate at which the industry will convert to flow metering.
- 2 Positions in the LNG train where LNG flow meters will be installed, i.e. LNG loading port, offloading port and carriers themselves.
- 3 Growth assumption for global trade and the increase of production, transport and regasification capacity.
- 4 Technical implementation of flow metering; for example using a number of intermediate sized flowmeters in parallel for a certain throughput capacity or using two or three large diameter flowmeters in series.
- 5 Type of flowmeters installed. Ultrasonic flow meters (USM) can measure volume up to very large flowrates. Coriolis massflow meters (CMF) have the advantage of measuring the mass directly making density measurements (and the associated inaccuracy) obsolete. However a single maximum size CMF measures at half the flow rate of a similar sized USM doubling the amount of flowmeters to be installed.

The minimum scenario predicts either 60 USM or 120 CMF to be installed each year.

The base scenario predicts either 170 USM or 340 CMF to be installed each year. The maximum scenario predicts either 225 USM or 450 CMF to be installed each year.

The market for calibration of LNG flowmeters will grow together with the expected increasing application of LNG flowmeters in the field but this is not a one-on-one relationship. There are two factors to be considered:

- 1 LNG flowmeters which periodically return for recalibration after initial calibration and installation in the field;
- 2 Water calibration be an acceptable alternative for real LNG calibration; it is recommended to find out what the chance it is that this occurs, since this might be a show-stopper for the Flowmeter Calibration business case in the LNG TTC test facility;

The following example calculation is based on the base scenario with an assumed preference (not representing a preference by VSL) for an USM solution. It is furthermore conservatively assumed that flowmeters will not return for recalibration. The calculation is based on the optimistic assumption (see SWOT analysis in chapter 2) that water calibration facilities do not compete with the LNG calibration facility. The calculation is also based on a fully developed market which will take several years.

An analysis was made of the sequence of activities for a flow meter calibration. The actual calibration run will take between 4-5 hours. The mounting, flushing, precooling, warming up and unmounting total up to 30 hours for a moderate sized flow meter. These steps can be carried out partly in parallel in case there are several flow meters ready for calibration by implementing a revolving procedure. This leads to a maximum (practical limit) of two flow meters that can be calibrated per twenty-four hours.

If a daily rate for rental of the LNG TTC Test Facility of € 30,000 is assumed and additional costs for the calibration analysis are taken into account the costs for calibration would be approximately € 18,000 per flow meter. This is on the high side

of what may be accepted by the market (if compared with water and high pressure natural gas calibrations). Nevertheless this would result in a yearly income (after several years) for the LNG TTC Test Facility of $170 \times \text{€ } 15,000 = 2.6 \text{ m.euros}$. A more realistic price level of € 12,000 for the calibration of an intermediate sized flow meter allows for a rental rate of € 9,000 per flow meter and € 18,000 per 24-hours of using the LNG TTC Test Facility. This would result in an income for the LNG TTC Test Facility of $170 \times \text{€ } 9,000 = 1.5 \text{ m.euros}$.

Based on this, an average of the above mentioned 2.6 and 1.5 m.euros means an expected VSL turn over of 2.0 m.euros. Once we project this value in the table of Figure 5.6., it becomes clear that this fits in the 51 m.euro scenario (yellow) with a (50% / 50%) breakdown of 26 m.euros investment and 25 m.euros funding.

It can be concluded that :

- 1 based on present expectation we foresee that about 50% of the (financial and exploitation) should be covered by VSL Flowmeter calibrations and 50% by full scale and small scale testing of LNG equipment
- 2 based on TNO and VSL experience we believe that about 70-80% of the time is needed for installation of the equipment under test, sensor installation and preparation for data acquisition, cooling prior to the test and heating up after the test and uninstalled equipment. Only 20-30% is needed for actual flow testing dependent on the equipment and the test programme.

In Appendix D we have adressed natural gas and LNG processes and products for potential evaluation and qualification in both small scale and offshore LNG. It is recommended that this list has to be completed with companies, which are active in (F)LNG equipment and small scale LNG applications and have shown interest in the LNG facilities for qualification of specific LNG equipment.

An assumption will be made about which international companies will use the facilities for which kind of tests. An example is the full scale test that SBM could perform. It is recommended that as next step, the exploitation assumptions will be included in Appendix D.

Scenarios of funding the LNG TTC Test Facility

The funding can be realised by a combination of the following options :

- **Government**
In the past FES was an option, which for example was used for the Holst Centre. The government however has decided to stop the FES funding.

Opportunities will be revolving funds with low level of interest.

The government can also be supportive in creating low levels of tax to the users of LNG as fuel in shipping and automotive industry.

Condition by the government for funding will be that the industry shows commitment by investing in the LNG TTC Test Facility.

- **Industry**
The Stakeholders Association Model (e.g. subordinated loan by Industry) could also be used in partly funding the test facility.

The funding is a chicken and egg situation, of whom will be making the first step, the government / or the industry. It will be one of the main objectives of the LNG TR&D Foundation in the third and fourth quarter of 2011 to secure funding for the realisation of the LNG TTC Test Facility.

- **Funding by regional funding institutes**
The LNG TTC Consortium and in the near future the LNG TR&D Foundation will explore further the regional funding opportunities at
 - 1) the province of Zuid Holland
 - 2) Energy Valley
 - 3) Waddenfonds

6 Conclusions & Recommendations

6.1 R&D Programme

It has also become clear that Company Owned R&D Centers cannot cover every fundamental research topic they would like. That has been a clear basis to start the initiative by the LNG TTC on defining the LNG Technological Roadmaps and the LNG R&D programme.

Technological Roadmaps have been defined on 3 areas, which are Offshore LNG, Small Scale LNG and Traditional LNG. These roadmaps have been used to define the LNG Programme Matrix, which connects the industry's market with the fundamental research topics which can be executed at institutes like TNO and the universities (see Appendix A).

It is recommended to explore further the market needs in the traditional LNG.

In 2011, the LNG TTC Consortium and the Universities decided that cooperation was needed to:

- remove innovation barriers;
- improve the competition strength of the Dutch industry, university and research institutes, in Europe;
- improve the market acceptance of LNG, and it's contribution to lowering the CO₂ and NO_x emissions.

It is recommended that the LNG TR&D Foundation will be established, and that a contract will be set up between the foundation and STW on a Partnership Programme LNG. STW made already a reservation of 1,5 m.euros which will be matched with 1,5 m.euros cash-contribution by the industry.

The unique character of the LNG TTC R&D Programme is an (inter)national group of LNG Industrial partners and the Dutch 3 Technological Universities Federation (3TU), working closely together to solve fundamental research topics in order to remove innovation entrance barriers.

The objective is that the LNG TTC R&D Programme will run under the supervision of the LNG TR&D Foundation and will be executed in close collaboration with the LNG TTC participants and the Dutch Universities. Funding for the programme will be raised by subsidiary funds by participants, and in-kind contributions of the Universities. The full LNG TTC R&D Programme requires funding of 15 m.euros in a period ranging from 2011 to 2018.

It is recommended that more European LNG Industry partners will join the LNG TTC R&D Programme. TNO has good contacts with the International Industry and will be supported by other members in the LNG TR&D Foundation to increase the number of members in the LNT TTC R&D Programme.

Even when the LNG TTC Test Facility will not be built on the short term, it will be important to start the unique LNG R&D Programme.

6.2 LNG TTC Test Facility

Important considerations in the realisation of full scale LNG test and flow facilities are:

- LNG flow facilities are not available in Europe;
- Existing LNG circulation facilities such as Nikkiso Cryo (Las Vegas, USA) and Ebara (Sparks, USA) have a limited flow capacity, limited access and are not suitable for flow meter calibration;
- There is a growing need for LNG flow meter calibration facilities, which are not available worldwide. To create a unique European Centre it needs to facilitate test on : 1) LNG flow meters, and 2) Offshore testing with full scale flow up to 7000 m³/ hr in combination with a sea motion tester, 3) small scale / mid scale testing.
- There is a need for an open-access test and flow facility run by an independent party, which offers access to industrial partners and universities for joint research, Business-to-Business research projects, training courses and education.
- Qualification of systems and components (EN-1474) for LNG transfer, storage and processing in offshore and small scale applications becomes more and more important and cryogenic facilities are actually indispensable for these qualifications.
- Validation of models developed in research projects requires an LNG flow facility.

The Basic of Design study as performed by KH Engineering / Cryonorm provides a basis for the combined LNG test and calibration facility on a footprint of 40x100 meter located at the Gasunie Peakshaver Facility, which however can also be used for alternative locations.

The intended location on the site of Gasunie Peakshaver has the advantages of availability of LNG and Liquid Nitrogen, well trained personnel of Gasunie to operate and maintain the facilities, sufficient power capacity. Besides it is an attractive location in the Rotterdam area close to potential customers and TNO and VSL locations and requires no new MER procedure.

The capacity of existing LNG pumps at Gasunie PS is very limited and would only therefore offer restricted applications for small scale testing and not for large scale Offshore LNG Qualifications and calibration of large flowmeters. Continuous operation may be interrupted during short periods (some weeks) in winter when Gasunie PS is in the send out mode. The intended location is also too close to existing LNG tanks and has a safety risk which is not acceptable and alternative locations on the site are not available.

Total CAPEX involved in the basic/detailed engineering and hardware for the facilities is dependent on the scope and the operating envelop of the facilities. It is envisaged that a total investment of maximum 81 m.euros is required to build up the test and calibration facility according to the functional requirements of the partners in the LNG TTC Consortium. The LNG Test Facility would be a unique cryogenic facility which includes the possibility to test and qualify components and equipment for offshore LNG in actual flow conditions under sea motion.

Alternative locations need to be investigated as a result of safety requirements and limited operation possibilities due to Gasunie PS activities. Possible alternatives which are being investigated are:

- Port of Rotterdam (e.g. a bunkering site for small scale LNG supply for shipping);
- Sea Ports Groningen

Conclusion and recommendation of the location analysis will be reported to the LNG TTC Consortium.

6.3 Organisation & Financing

There are several Critical Success Factors for the realisation of the LNG TTC Test Facility.

- When it is absolutely sure that LNG TTC Test Facility will not be built at the Gasunie Peak Shaving Plant, alternatives are needed as fall-back scenario. An analysis of alternative locations is in process.
- Funding by government : position paper LNG has been submitted to Topteam Energy of the Department EL&I. Business Cases LNG at Sea and LNG as Fuel have been submitted to Department of I&M.
- Funding by industry : Escalation to higher management at industry partners to obtain commitment.
- It is believed that the key to the realisation of the funding is in Energy Valley and EFRO (European Funding on Regional level)
- Commitment from international companies to perform tests at the LNG TTC Test Facility This will be one of the objectives of the LNG TR&D Foundation to have this accomplished.
- Testing costs per day needs to be market conform.
- Start with LNG TTC R&D Programme as soon as possible. STW has made a reservation for 1,5 m.euros.

Realisation of the LNG TR&D Foundation, which supports the Topsector objectives:

- To improve innovation, fundamental research, testing of new LNG technologies by the Dutch and European LNG industry, in cooperation with universities, TNO and governmental institutes;
- To increase the employment related to LNG in industry, universities and research institutes;
- To establish a better understanding of the advantages of LNG as a relatively clean fossil fuel in the Netherlands and in Europe;
- To communicate the advantages of LNG as fuel for the shipping and trucking industries;

It is recommended to further develop the Business Model of the LNG TTC according to the organisational and legal model to be chosen, and to understand how much money will be generated by each activity in the Business Model. This will be again one of the key objectives of the LNG TR&D Foundation in the third and fourth quarter of 2011.

It is also recommended to describe the expected exploitation of the LNG TTC on a balance sheet level (including the Test Facility and other activities such as organising workshops and trainings, project management).

7 Acknowledgement

We would like to thank everyone who made a contribution to this LNG TTC Definition Study report.

In alphabetical order:

- Albert Aalbers (MIP)
- Michiel van Aken (Shell)
- Joe Andrukaitis (Cryonorm Projects)
- Jacques Dam (Imtech)
- Klaas Hoving (Gasunie)
- Stephan Huisman (Vopak)
- Oswin Kerkhof (VSL)
- Gerard van der Laan (Shell)
- Frits Lagers (Gasunie)
- Edwin van Leeuwen (Cryonorm Projects)
- Sander Lemmers (Vopak)
- Erik Smits (VSL)
- Guus Vogels (Vopak)
- Jeroen Wagenaar (KH Engineering)
- Chris Wulffers (DeMaCo)
- Wim van Wijngaarden (SBM Offshore)

A LNG Programme Matrix

Forced flow	Pool Boiling	Numerical strategy development	Results	
Thermodynamic process flow optimization for cryogenic fluid mixtures. <ul style="list-style-type: none"> • Effects of Pressure and Temperature transients. • External heat load. • Cryogenic cycles for: <ul style="list-style-type: none"> - Re-gasification - Re-condensation - LNG production - LNG transfer • Effects of non-equilibrium mixtures. 	Evaporation of a cryogenic fluid mixture at a non-stationary boundary. <ul style="list-style-type: none"> • Moving solid wall (as floating storage) • Moving fluid wall (as spill in water) • Fluid-wall interaction model 	Fast, efficient process optimization flow solver development. <ul style="list-style-type: none"> • Multi-disciplinary process optimization • Dynamic and transient cases • Non-equilibrium mixtures 	Optimized flow process transients under motion	
		Model order reduction for detailed dynamic design of FSI coupled systems		
		SPH calculation techniques for LNG pool boiling and spill at disturbed interfaces		
FSI for structures under motion: <ul style="list-style-type: none"> • Coupling of multi-disciplinary systems. • Effect of moving wall geometry on: <ul style="list-style-type: none"> - Hydraulic properties - Thermal properties - Mechanical loads - Combustion 	Dispersion of an evaporating, cryogenic fluid mixture. <ul style="list-style-type: none"> • Restricted environment • Open environment • Fluid pool dispersion (LNG in water) • Multi-phase evaporation dispersion in air • Poolfire modeling 	Coupling to generic process design tools as Aspen Hysys (TBD) and structural design tools as NX, ProE or Catia (TBD) for. <ul style="list-style-type: none"> • Dynamic system represented by differential-algebraic equations (DAE) • Dynamic system represented by ordinary differential equations (ODE) • Dynamic system represented by discrete events 	Quantification of effect, Extension of spill model applicability	
		Development of a GUI for the TBD process design tool.		Enhanced structural design integrity and residual life prediction
		Fast, stable d-base for fluid mixtures and material properties. <ul style="list-style-type: none"> • Extension to cryogenic temperature range • Based on industrial standard fluid property d-base • Parallel and predictive calculation techniques 		Model and sensor based control and predictive maintenance (hybrid control)

GUI: Graphical User Interface

FSI: Fluid Structure Interaction

B Two-Phase surge phenomena

STW Partnership Programme Proposal based on application by SBM

Due to the global increase of demand for natural gas the interests in offshore liquefaction, transport and re-gasification grow rapidly. The installations that are presently developed are in essence copies of the onshore systems that are already many years in operation. However, the fact that the installation is installed on a ship imposes limitations and leads to special system requirements. A critical link in the chain is the ship-to-ship transfer system, also called the offloading system. An important issue is that offshore offloading systems, in contrast to ship-to-shore offloading, have to function under harsh sea conditions. Systems should be flexible to deal with the ships moving relative to each other and extreme cases may require instantaneous disconnection. Besides, the offloading system has to transfer LNG at the highest possible rate, which requires that the equipment has to withstand high flow velocities and pressures. At the same time the system integrity has to be safeguarded effectively so that a spill of LNG is excluded.

At present ship-to-ship transfer systems are being developed that apply loading arms or flexible pipes and hoses. Such systems have already been successfully operated in a number of cases. A question that remains appropriate continuously is whether the integrity of such a system can be guaranteed under all circumstances and in all configurations, for instance for all hose lengths. That means that all static and dynamic loads that can act, should be carefully analyzed. It is known from the existing offshore oil offloading systems that fast transients, also known as water hammer, may cause large pressure shocks and dynamic loads, leading to failure and spills. An example of a large oil spill, caused by unexpectedly large pressure surge, is presented in reference [1]. Similar incidents may happen with LNG offloading systems with, because of the explosion hazard, even more disastrous consequences.

The effect of water hammer during loading and offloading has already been recognized by the organization SIGTTO and guidelines have been published. See reference [2] and [3]. In ship-to-ship transfer water hammer can occur when the flow is suddenly stopped, for instance due to an emergency shut down (ESD), and there is no time to run down the pumps properly. In that case the emergency release coupling (ERC), which closes quickly to minimize the spill of LNG, will stop the flow almost instantaneously causing a large pressure surge in the upstream and downstream system. The combination of a high transfer rate, which means a high flow velocity and a fast closing valve, may lead to high amplitude shock waves. Though water hammer can be avoided by first running down the pumps and delay the release of the coupling until the flow has stopped, in practice it may occur that the coupling has to be released at full flow.

In the standard EN 1474-2 (reference [4]) a simple design rule is given to avoid water hammer. Unfortunately in most cases this design rule does not apply, because the key parameters, such as closure time and system length, are out of range. Therefore it is in general required to make a complete water hammer analysis, which is often part of the design of all kinds of systems carrying liquids.

However, because LNG is close to its boiling point, cavitation and column separation can occur, which may cause larger pressure shocks than the initial water hammer shocks. Cavitation and column separation therefore complicates the analysis. More sophisticated models are required to include this phenomenon in the analysis.

In order to be able to analyse new system designs numerical models are required that are carefully validated.

Proposal

For the calculation of transients in pipelines (so called water hammer) various numerical models have been developed and are successfully applied for pipelines transporting water, oil and other liquids. A complication is that depending on the local pressure in the system a vapour bubble may develop that, when it collapses, will cause very large pressure shocks. This phenomenon is known as “column separation”. As LNG is often transported close to boiling conditions, column separation can be expected to occur in LNG transportation more often.

Models that describe column separation have been developed and are in use in various commercial codes; examples are HALT, Flowmaster and PULSIM.

Further R&D is required for LNG applications, which includes:

1. Improvement and validation of the present models. At present the Discrete Vapour Cavity Model (DVCM) and the Discrete Gaseous Cavity Model (DGCM) are used in various forms. It should be investigated for the application on LNG how accurate these methods are and what improvements are necessary. Especially the effect of non condensable gases should be investigated.
2. The propagation of pressure waves through pipes and hoses depends to some extent on the properties of the wall. Especially the properties of flexible hoses under cryogenic conditions is unknown. Therefore the wave propagation in hoses filled with LNG should be investigated.
3. In ship-to-ship transfer systems an Emergency Release Coupling (ERC) is applied that allows quick decoupling when necessary. Common in the designs is that all ERCs are at the upstream and downstream side equipped with valves that close in a very short time in order to minimize the amount of LNG that is spilled. As the transients depend on the closure time and valve characteristic, the closure dynamics of ERC's should be investigated.
4. The above subjects require experimental validation with LNG or a very similar liquid. This requires a test set-up that can be realized at the LNG TTC Test Facility.

STW project application

An STW project proposal should address topics that are an academic challenge, but on the other hand should generate applicable knowledge. Therefore a balance should be found between academic interest and immediate applicability. In this case the project should result in technology that still needs to be developed one step further to be applicable by the interested partners. Therefore all partners will equally share the knowledge developed in the STW project and should be aware that the project does not deliver any directly applicable results. With respect to the R&D topics discussed in Chapter 2 the following remarks can be made:

1. Models for column separation in transient flow will result in physical mathematical and numerical models that are not implemented in a specific

software such as HALT, PULSIM, Flow Master or any other. The integration will be the responsibility of the interested partners. Nevertheless the PhD student will need some software to implement and validate new models and numerical models. For this an independent academic software platform has to be used. The ultimate result will be a library of modules that can be distributed amongst the partners.

2. The second and third topic concern components for which competitive interests can play a role. Therefore, in order to be general, models should be developed that are independent of a specific product. For the pressure drop in corrugated hoses this already has been achieved in the FLUWAWINT project that is presently in progress. Similarly the topic of wave propagation in flexible hoses could be investigated resulting in generalised models and test methods to determine the relevant parameters. This also holds for the ERC's. In the project general models of ERC dynamics should be developed and a method to experimentally determine the parameters that are required for the model.
3. The experimental validation, i.e. point 4, is extremely important. At first laboratory scale test facilities will be used to validate the models. An inventory has to be made of existing facilities that can be used. However, finally full scale testing will be required. It should be decided if full scale testing will be part of the STW project or if it should be a separate project.

Project organisation

For the project at least one Ph D student will be required. For some topics the support of a postdoc may be required.

The coordination of the project will be done by LNG TR&D Foundation in cooperation with STW. At least twice a year a progress meeting will take place during which the progress is presented. This is also the opportunity for the participants to bring in questions from practice.

In order to promote knowledge transfer specific parts of the research will be executed at universities & TNO.

Universities & TNO will be responsible for developing the required test facilities, i.e. explore existing test facilities and developing a plan for experimental testing. Laboratory scale testing will be part of the STW project. Eventual full scale testing will not be part of the project unless a very convenient opportunity is found.

Results and applications

The results of this project are in fact models and numerical solvers. The deliverable will be a report describing the physical mathematical models and the numerical models and an implementation in software. To make the models operationally applicable it will be necessary to integrate the models in existing programmes. TNO will distribute the software as is between the participants and can assist in integration in a software tools as required. TNO will integrate the software in their proprietary simulation tool PULSIM.

References

- [1] Erik D. Nennie, Harry J.C. Korst, Knud Lunde, Rune Myklebust, "Water Hammer Likely Cause Of Large Oil Spill In North Sea", PVP2009-77770, Proceedings of the ASME 2009 Pressure Vessels and Piping Division Conference, July 26-30, 2009, Prague, Czech Republic
- [2] "Ship to Ship Transfer Guide (Liquefied Gas)", 2nd Edition 1995, International Chamber of Shipping, Oil Companies International Marine Forum, Society of International Gas Tanker and Terminal Operators.
- [3] "Guidelines for the Alleviation of Excessive Surge Pressures on ESD", SIGTTO 1987, ISBN: 0 948691 40 9
- [4] Standard EN 1474-2: "Installation and equipment for liquefied natural gas - Design and testing of loading/unloading arms". Annex C "Surge pressure considerations for LNG hoses"
- [5] Bergant, A., Simpson, A.R., Tijsseling, A.S. (2006). "Water hammer with column separation: a historical review". *Journal of Fluids and Structures*, 22(2), 135-171.
- [6] Li, W.H., Walsh, J.P., 1964. Pressure generated by cavitation in a pipe. *ASCE Journal of the Engineering Mechanics Division* 90(6), 113 - 133.

C Combining Pre-processing with Liquefaction

STW Partnership Programme Proposal based on application by Shell

For transport over large distance LNG is the preferred method of transport. Prior to liquefaction impurities have to be removed from the natural gas stream as they may condense, block or corrode the cryogenic equipment, especially heat exchangers are susceptible to impurities.

Typical values for upper limits of the impurities are: CO₂ 50 ppmv, H₂S 4 ppmv, H₂O 1 ppmv, Hg 10 nanogram/m³. Traditionally an absorber column is used to remove the CO₂. Gas treatment based on absorption involves large columns, which are susceptible to motion, and require large stocks of fresh water and solvents. Especially for FLNG this is an issue.

In the literature some alternatives are discussed for the removal of CO₂, such as Cryogenic Carbon Capture (CCC), which may simplify the overall process [1]. Also, these units may relatively easy be combined with the already available cryogenic liquefaction equipment.

In this proposal an inventory will be made of the possible preprocessing steps at cryogenic conditions, and how these processes can be integrate with liquefaction using (cryogenic) plate fin heat exchangers (PFHE). Special attention will be paid to the description of the phase behavior of natural gas at cryogenic conditions for different impurities, and how the phase behavior can be used to design a more efficient LNG process.

Virtually all LNG facilities, large as well as small units, comprise several gas treatment steps to remove impurities present in natural gas, prior to the actual liquefaction. Traditionally, tight specifications of impurities in LNG have to be met in order to comply with international LNG Sales and Purchase Agreements. Removal of impurities has also a very practical reason. Since too high concentrations of for example water, CO₂ or benzene in natural gas will result in fouling and partial blocking of cryogenic heat exchange equipment, resulting in a loss of performance. Gas treating equipment itself has usually a relatively low, as compared to liquefaction, capital cost. Although, the actual capital cost depends the concentration of contaminants or impurities. Also, the various gas treatment facilities add complexity, require utilities and chemicals, affect the overall plant reliability, and need significant operator attention and maintenance. Gas treating equipment is usually also exposed to corrosive and potentially fouling fluids, which increases maintenance intensity. The chemical solvents, like amine solvents, and the desiccants have to be replaced regularly due to ageing and fouling. The disposal route of by-products (e.g. hydrocarbon condensate) and in particular the waste streams (CO₂, elemental sulphur, sulphur compounds, mercury, etc.), resulting from the gas treatment is another aspect getting more attention.

Last but not least; small or micro LNG units are becoming more and more commercially attractive. To make these relatively small units viable, the liquefaction process is usually simplified by applying a single (but less efficient) refrigerant loop instead of several integrated refrigerant loops as with large base load LNG plants.

However, such a simplification resulting in less complex equipment is not possible with the gas treatment units, assuming that the same (tight) LNG specifications apply. One of the main questions is, how relevant are the 'traditional LNG quality specifications', which exist for more many years, and what is the physical basis? What are typical 'comfort' margins between the concentration of impurities where 'actual freeze-out' can occur and the LNG specification?

A main part of the research activities will be focused on the description of the liquid/solid equilibrium freeze point for different species present in natural gas. Only limit data is available for the most important species, like CO₂ and hydrocarbons (other than methane) [2,3].

Another question is, is it possible to significantly relax these LNG specifications and would this allow for a simpler design of the preprocessing and gas treatment units. This is especially relevant for small-scale LNG applications.

Finally, is it feasible to do without any gas treatment? For example; impurities can intentionally freeze-out on cryogenic equipment and are subsequently removed by a "regenerative process" based on temperature increase/swing. This concept is currently being developed by company Chart (Tango unit) [2]. A more elegant alternative can be envisaged where a continuous process is used to prevent any freeze-out by novel equipment design (e.g. non-sticky materials). In this concept, crystals nucleate, grow and stay in the gas-liquid phase and are finally removed from a "LNG slurry", followed by separation of waste and valuable by-products. Note that the "heavies (C5+) removal" step is normally integrated with the liquefaction unit, because of the required low temperatures. "Heavies removal" is not considered to be part of the gas treatment, which takes place at about ambient temperature. The "freeze-out" concept does not require "heavies removal", which is normally done in a scrub column, followed by distillation and possibly LPG re-injection into the main gas stream, prior to liquefaction.

In the research programme different activities will be studied, ranging from the thermodynamics of CO₂ freezing, equipment and process design, and lab-scale testing of various concept for cryogenic CO₂ capture. The main activities of the Gas Treatment Group of TNO focus on CO₂ removal for various applications. Dedicated equipment, both lab-scale and bench-scale, is available to evaluate absorption processes and membrane gas separation. The main focus is on removing CO₂ from flue gases and on acid gas (CO₂ and H₂S) removal from natural gas.

Lab-scale equipment is available to study basic chemical-physical properties for both absorption and membrane processes. Different properties are studied, like vapor-liquid equilibrium (VLE) for CO₂ for absorption liquids, kinetics of CO₂ uptake in absorption liquids, and the permeation and separation behavior for membranes.

The chemical-physical properties serve as input for the process modeling (using Aspen or Matlab). The modeling tools are used for scale-up and techno-economic evaluation of the various capture and separation processes.

Bench-scale set-ups are available to evaluate the scale-up studies of the absorption processes for the removal of CO₂ from flue gas. Examples of recent studies include solvent testing and optimization for CO₂ removal from flue gas using high-throughput experimentation, flow sheeting and optimization of absorption-desorption process for CO₂ removal from flue gas, bench-marking of a number of membranes for the removal of high concentrations, up to 20%, of CO₂ from natural gas.

STW project application

The following approach is being proposed, in order to assess the feasibility of liquefaction of natural gas, with limited or no gas treatment at all and no heavies removal.

- 1 Thermodynamic of crystallisation
Study the crystallisation behavior of impurities in natural gas and liquid at cryogenic temperatures. The main objective is to determine the freezing point for different mixture, and develop an accurate description of solid-liquid equilibrium and of the solid crystallisation process. What are typical saturation concentrations of components like CO₂, benzene and heavy components in LNG. How do layers of different crystals grow on cryogenic heat exchanger surfaces; so-called “plating”? Are there different temperature zones where specific components crystallise?
- 2 Equipment design
What are the alternatives to develop cryogenic heat exchange equipment which is not or less sensitive to fouling due to crystallisation on heat exchanger surface ? This can be related to anti-icing materials but also the type of exchanger. For example; operational experiences seem to indicate that plate fin heat exchangers are less sensitive to fouling due to heavy hydrocarbons than coil wound exchangers.
- 3 Process development and process modeling
Develop process schemes, based on removal of “crystallised impurities” downstream of liquefaction; or so-called “cryogenic slurry processing”. What are the disposal routes of waste streams and how can valuable hydrocarbons be separated from for example CO₂. Would it be possible to produce a high purity, high pressure CO₂ stream? This will be extended to flow sheeting for integration of the various separation steps and liquefaction. What are the best conditions to combine a cryogenic separation step for CO₂ removal with a PF heat exchanger? These models will be used to evaluate to establish the best solutions for the various applications. What are the best options for small-scale LNG (including bio-LNG), standard LNG plants, and Floating LNG (FLNG).
- 4 LNG quality
A new and a fundamentally different way of producing LNG will also have a significant impact on product quality and will result in a different “LNG grade”. In particular, the LNG will be saturated with several components. Aspects around the different LNG grade have to addressed, with small scale LNG applications in mind; what is the potential impact on further downstream equipment like storage tanks, pumps, vaporisers and burners?

References

- [1] A Hart, N Gnanendram, Cryogenic CO₂ Capture in Natural Gas. Energy Procedia 1 (2009) 697.
- [2] C Emmer, TK Drube, Sacrificial Cryogen Gas Liquefaction System. US patent 6598 423.
- [3] LF Ayala, JE Fernandez, Evaluating Crystallization Risks in Liquefied Natural Gas (LNG) Production. SPE paper 110391.
- [4] T Eggeman, S Chaifin, Beware the Pitfalls of CO₂ Freezing Prediction. Chemical Engineering Progress, page 39, March 2005.

D Overview of natural gas and LNG processes and products

30	Refrigeration and liquifaction			
	31	Pre-cooling (NGL extraction)		
	32	Liquefaction		Linde, Chart, Cryogenic Industries CB&I, Conoco Phillips, Ferox
	33	Sub-cooling		Linde, Chart, Cryogenic Industries Ferox
	34	N2 and O2 separation		
	35	Pressurisation		
	36	Treating and liquefaction combined		Shell, Chart
40	Storage and loading			
	41	Large storage tanks		
	42	Jeties		Vopak
	43	Transfer system	Qualification of hoses, ESD valves, ERC couplings, waterhammer analysis	Gutteling, Exmar, SBM Offshore, Bluewater, Technip, Nexans, Trelleborg
	44	Flow measurement systems	Custody Transfer LNG Flow meter Calibration	Krohne, GE, Elster-Intsromet, Caldon, Micromotion
50	Shipping			
	51	Containment system		Chart,
	52	BOG system	Impact of BOG gas in LNG Hoses (FLUVAWINT)	Shell, Exmar, Anthony Veder
	53	Gas ship propulsion		Wartsila, Rolls-Royce, Damen, Antony Veder
60	Ship-to-ship offloading			
	61	Hose or flexible pipes	Qualification acc EN1474, flow testing incl motion Up to 20-inch	SBM Offshore, Bluewater, Technip
	62	Marine operation	Impact on flow regime (integrity, efficiency) on heat-exchangers	Shell, Chart, Linde
	63	Transfer system and ship configuration	Application of aerial and floating hoses: integrity, ship/wavemotion, pressure loss, cavitation	SBM Offshore, Bluewater, Technip
	64	Couplings	ERC couplings: leakage, thermal shock, dp, waterhammer	Klaw GB, MIB Italy, Arta, Exmar, KSB
	65	Valves	ESD valves	Klaw GB, MIB Italy, Arta
	66	Emergency systems	Qualification of system acc EN1474; waterhammer analysis, shock loads on hoses	SBM Offshore, Bluewater, Technip
70	Regasification			
	71	Storage tanks		
	72	BOG management systems		
	73	Pipelines (e.g. cryogenic pipe-in-pipe)		SBM Offshore, Nexans
	74	Connection to small scale (e.g. truck loading fac.)	Standardisation, legislation and qualification of systems	Gutteling Trelleborg
	75	Cold recovery systems		
	76	Flow measurement		

		systems		
	77	Injection (N2)		
80	Truck loading stations			
	81	Small scale storage		LNG Europe
	82	Small scale flow measurement systems		Krohne, GE, Elstar-Intsromet, Caldon, Micromotion, Endress&Hauser, Yokogawa
	83	Small bore transfer lines (incl. compensators, insulation etc)		Gutteling, Trelleborg
	84	Process equipment (pumps, valves, connections)		
	85	Flexible transfer lines		Gutteling
	86	Safety systems (ESD)		Klaw, Arta, MIB
	87	Fiscal metering for mid/small scale, samplers	Calibration of in-line LNG flowmeters	Krohne, GE, Elstar-Intsromet, Caldon, Micromotion, Endress&Hauser, Yokogawa
90	Bunkering			
	91	Small scale ship containment systems		
	92	BOG handling at bunker ship		
	93	Transfer connections (couplings)		KSB, Arta, MIB
	94	Offloading system		
	95	Small bore transfer lines		Gutteling
	96	Marine operation		Anthony Veder
100	direct consuming of LNG			
	101	ship tank systems		
	102	ship propulsion		
	103	truck tanks		
	104	truck engines		
	105	BLEVE prevention		
	106	Safety systems		
	107	BOG handling		
	108	Gasturbines in combinatie met tankstation		
	109	Boil-off free tanks d.m.v. brandstofcellen.		

E LNG TTC Test Facility Investment Split-up

LNG TTC testfacilities Investment cost	Phase 0	Phase 1	Phase 2	Phase 3 Motion test
(from BoD report KH Engineering)	LNG Flow up to max. 2000 m3/hr	LNG Flow up to 7000 m3/h	LNG Flow up to 7000 m3/h	Motion test of equipment included
28-03-2011 -EvB	with existing Gasunie pumps	stand alone facilities	and 2-phase flow	
		LNG supply by Gasunie	substantial BOG	
Accuracy of cost estimates	- 15% / + 30%	- 15% / + 30%	- 15% / + 50 %	- 15% / + 50 %
Site preparation incl blastwall (location dependent)	€ 1,660,000			
Feed&return, vent-headers	€ 7,980,000			
TNO Test area	€ 770,000			
VSL Facilities (Flowmeters&sensors)	€ 7,830,000			
Nitrogen system	€ 1,040,000			
Common items (crane, process control, electrical etc)	€ 3,560,000			
Allowances (known unknowns)	€ 2,180,000			
Engineering and Inspection	€ 4,540,000			
Contingencies (unknown unknowns)	€ 4,740,000			
Total cost Phase 0	€ 34,300,000			
Vessel V01 and Jockey Pump		€ 1,100,000		
Pumps P-01 and P02 A-B		€ 2,700,000		
Common Items		€ 350,000		
Engineering and Inspection		€ 800,000		
Contingencies (unknown unknowns)		€ 750,000		
Total additional cost Phase 1		€ 5,700,000		
Total cost Phase 0+1		€ 40,000,000		
Maximum + 30 %		€ 52,000,000		
BOG Compressor Package			€ 3,000,000	
Comander Package			€ 1,000,000	
HP Pumps+ Liquid expander			€ 7,000,000	
Additional cost estimate (TNO)			€ 1,000,000	
Total additional cost Phase 2			€ 12,000,000	
Maximum + 50 %			€ 18,000,000	
Additional cost motion tester + 50 %				€ 11,000,000
Total cost Phase 0+1+2+3				€ 81,000,000