**Optimization of LNG and natural gas supply chains – two models**

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## ABSTRACT

Natural gas is gaining popularity for the production of power and heat because of its lower environmental impact compared to coal and oil, and the production of biogas is also increasing. To study the best way of incorporating such gas sources in the energy systems, two gas delivery problems are tackled as cost optimization tasks. The first is concerned with deliveries of liquefied natural gas (LNG) from a set of supply terminals by a fleet of ships to a number of satellite terminals, where the gas is consumed or transported onward by truck to other consumers. The model is illustrated by a case study in the Gulf of Bothnia. The second task focuses on the development of energy supply to an in-land region, where a gas network connected to an existing LNG terminal and biogas production sites can be built. The problem is nonlinear but it is linearized and tackled by mixed integer linear programming, and is illustrated on a fictitious region in Finland with one LNG terminal, two biogas production sites and a set of consumers, including industrial sites and a power plant. The two case studies demonstrate that the models developed can be used as versatile tools for studying future energy supply concepts.

## 1 INTRODUCTION

Natural gas (NG) is the fastest growing energy source among the fossil fuels: According to the International Energy Agency (IEA), the natural gas consumption is expected to reach 5.4 trillion cubic meter in 2040, replacing coal and becoming the second largest fuel source after oil /1/. Liquefied natural gas (LNG) is today playing a very important role in the supply chain of natural gas, as it can supply energy to very remote or stranded sites for which pipeline delivery is infeasible. LNG is produced by cooling natural gas below –162 °C at atmospheric pressure, which reduces the volume to approximately one six-hundredth of the original one. LNG can be economically transported over long distances by specially designed vessels, which keep the fuel in liquid state. Traditional LNG supply chains deliver large volumes over distances of thousands of kilometers with LNG cargo capacities of 100,000 $m^3$ or more /2/. Recently, small-scale LNG logistic chains have become more important /2/, /3/ and the introduction of sulfur emission control areas serves to increase the popularity of using LNG as fuel in ships /4/.

In a small-scale supply chain, LNG is shipped from larger supply terminals to customers through satellite terminals with a combination of sea- and land-based transport. It is a challenging task to design such supply networks: Tactical planning addresses the vehicle routing problem (VRP, see /5/) while strategic planning deals with decisions regarding location of satellite terminals and size of the optimal fleet. Hoff et al. /6/ reviewed both maritime and land transport routing and found most approaches to be heuristic ones. Some exact formulations based in MILP have been proposed /7/, /8/, /9/ but in a more restricted form than the one presented in this paper, where we apply a model to an emerging gas market in the northern part of the Baltic Sea region.

Optimization and simulation tools have been used to tackle the gas pipeline transportation problems /10/, ranging from deterministic through hybrid to heuristic approaches /11/, /12/, /13/, /14/. The stochastic nature of the demand has also been addressed /15/. Optimizing both parametric and structural variables of the pipeline network yields a mixed integer non-linear programming (MINLP) problem, which is complex and numerically challenging, so many investigators have used stochastic or evolutionary methods /16/, /17/. We propose a model for optimization of a regional gas distribution problem, where the gas sources are an LNG terminal and smaller biogas producers, connected to a local pipeline network, but where LNG from the terminal can also be transported by trucks to the consumers. Linearization yields an MILP model that was applied to a fictitious problem at a coastal region.

## 2 THE MODELS

### 2.1 LNG Supply Chain

The mathematical model tackles a single-period LNG supply chain problem from a set of potential supply ports to inland end customers through a set of potential satellite terminals. LNG is transported from the supply terminals to satellite terminals by ship and from the supply or satellite terminals to the inland customers by truck. Potential satellite terminals and inland customers have given demands for the time horizon considered. If a satellite terminal is built, the total amount of LNG to be delivered from the supply ports is the sum of the satellite terminal's demand and the demands of the customers associated to it in the optimized solution. Alternatively, demands can be fully or partially fulfilled by an alternative fuel, for which transportation costs are neglected. The maritime transportation is performed by a heterogeneous fleet of vessels, with individual capacity, cruising speed, fuel consumption and loading/unloading rate. The ships may or may not return to the same supply port they departed from. Each supply port has a maximum quantity of LNG available for distribution. The land transportation of LNG is carried out by a homogeneous fleet of tank trucks of given capacity and fuel consumption, and every truck is associated to a single supply or receiving terminal; trucks are not allowed to perform split deliveries. When a satellite terminal is activated, a storage tank must be constructed and associated size-dependent investment costs are imposed. Maritime distances between all ports and road distances between terminals and customers are given. The aim is to find the most economical solution of the overall LNG distribution problem, selecting the most appropriate ports, if any, where satellite terminals should be built, the size of the LNG storages, the optimal fleet and routing for the maritime transportation, the number of LNG tank trucks for each port and the port-customer connections to satisfy the inland demand. The overall objective to be minimized is the total costs, including investment in terminals and trucks, renting costs for the ships, operating costs for ships and trucks as well as fuel costs /18/.

## 2.2 Regional Gas Supply

A model is developed for multi-period gas supply to a region considers pipeline transport from an LNG terminal or from biogas (BG) plants, as well as a gas delivery as LNG by trucks from the LNG terminal. The distances between the nodes are given and pipes of different diameter can be used. The gas is transported in steady state between the nodes, but the flow direction is allowed to change between the periods. Compressors maintain the required pressure in the pipeline. Like in the case of the LNG supply chain, an alternative fuel satisfies the remaining energy demand and the task is to minimize the overall costs, considering investment (in the pipes), transportation (compression, trucking) costs and fuel costs /19/.

# 3 RESULTS

This section illustrates the performance of the two model on cases inspired by the conditions in the region of Gulf of Bothnia. Even though the energy demands and some of the costs used here are gross estimates, the examples illustrate the applicability of the models and how they can be used to evaluate options to supply energy in the form of gas during a transition to zero-emission concepts. A brief sensitivity analysis of the two models reveals how the optimal solutions change with respect to changes in the fuel price and in the available quantities of gas.

## 3.1 LNG Supply Chain

In Finland, one LNG terminal has recently been built (in Pori) and another (in Tornio) is under construction, and the possibility of connecting the European and Finnish natural gas networks by a pipeline between Paldiski in Estonia and Inkoo in Finland is being debated. The present study partly re-evaluates these decisions by considering three possible supply terminals distributed in the region (Inkoo, Tornio, Stockholm), seven potential satellite terminals (Turku, Pori, Vaasa, Raahe, Luleå, Umeå, Sundsvall) on the coasts of Finland and Sweden, and 23 inland clusters. The maritime distances and the road distances were collected from a web tools /20/, /21/. Vessel parameters were inspired by information in /22/ using five ship types (5,000–20,000 $m^3$). The optimization was performed for a time horizon of one month. Investment costs of satellite terminals was expressed by a linear expression with a constant (20 M€) and a slope (200 €/MWh).

Figure 1 shows the optimization results for four cases, where the price of LNG at the supply ports is fixed at 30 €/MWh (≈ 9.3 $/MMBtu), and the price of alternative fuel at the consumers is 38 €/MWh, 39 €/MWh, 39 €/MWh or 51 €/MWh, termed Cases 1–4. For all the cases a single ship carries out the maritime LNG delivery in the optimal solution, partly using split deliveries, but the ship size varies. For Case 1, the energy share provided as LNG by the ship (of size 5,000 $m^3$) exceeds 80 %, where about 35 % of the energy demand is satisfied by shipped LNG to and through the satellite terminals, while 44 % is directly trucked from the supply ports. The LNG transportation routes of this solution are presented in Fig. 1a: Three of the seven possible satellite terminals are activated. No satellite terminals are built in Sundsvall, Luleå, Vaasa and Turku; their demands are satisfied by alternative fuel or LNG trucked from Tornio, Pori and Inkoo, respectively. The solution for Case 2 (Fig. 1b) is similar to that of Case 1, but presents the activation of the satellite terminal in Sundsvall. There are maritime LNG deliveries from all three supply ports carried out by the same ship of size 6,500 m$^3$. As the price of alternative fuel further increases by 1 €/MWh (Case 3) a larger (10,000 m$^3$) ship is used. A satellite terminal in Pori is activated and two more inland customers are supplied by LNG (Kuopio and Mora, Fig. 1c). The satellite terminal storages vary from 12,000 m$^3$ in Vaasa to 38,000 m$^3$ in Raahe. Sundsvall, Umeå and Pori are assigned similar capacities of about 20,000 m$^3$. The number of trucks per port ranges from 1 in Vaasa to 25 (the maximum) in Inkoo. Interestingly, as the alternative fuel price exceeds 50 €/MWh, the satellite terminal in Vaasa is suppressed while the one in Luleå is activated (Fig. 1d) and all the customers are supplied, partially or entirely, by LNG; only about 2 % of the energy demand is supplied as alternative fuel. The optimal ship size is the same as in Case 3.

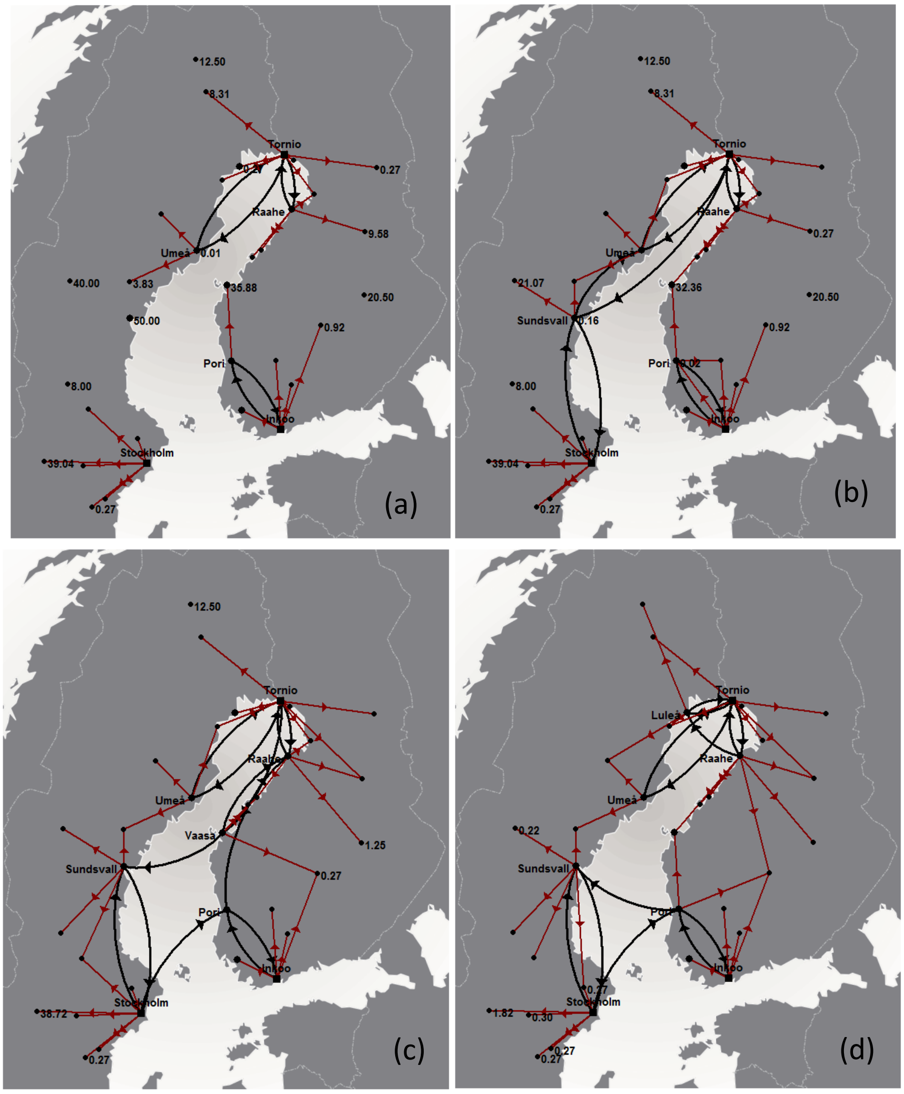


**Figure 1**. Optimal satellite terminals location and LNG distribution from supply ports for Cases 1–4, where the price of alternative fuel exceeds the price of LNG by 8, 9, 10 and 21 €/MWh. Straight arrows: land transport by truck; arrowed arcs: maritime routing; squares: supply terminals; large circles with names: activated satellite terminals; small circles: consumers supplied by LNG (where numbers indicate the quantity of alternative fuel (in GWh) supplied within the 30-day time horizon).

## 3.2 Regional Gas Supply

The model of regional gas supply was evaluated on a case with a local natural gas delivery to a region on the Finnish coast, where an LNG terminal has been built recently close to the harbor. In addition to a power plant providing power and heat to the region, also some industrial companies, larger production sites and gas stations were included as potential consumers. The LNG terminal and the two BG plants can be connected with four pipe diameter options to the 17 consumers via 25 potential pipe connections, as illustrated in Fig. 2. The year was divided into three periods of equal length; for most consumers the energy demand varied with the season. The power plant (indicated by 4 in Fig. 2) is the main consumer (max. consumption 250 MW). The intermediate consumers (5, 6, 14-17) have demands representing 4-20% of the power plant's demand, while the demands of remaining consumers are smaller. The pressure in the pipes is required to be at least 4 bar at the consumers. The higher heating value of the alternative fuel is lower than the value of the LNG and biogas. The fuel prices used in this study are rough estimates: gasified LNG and upgraded biogas supplied by pipe have the same unit price, the price of LNG for truck delivery was 7.5 €/MWh higher and the price of alternative fuel ("at the gate" of the consumers) was 90 €/MWh. An LNG truck transportation cost of 1000 € per load was imposed, with an operation cost of 6 €/km. The investment cost was calculated for a project time of 30 years, using a moderate interest rate (5 %). The influence of the fuel supply rates of LNG from the terminal on the optimal supply chain was studied, using four maximum re-gasification rates (10.0 kg/s, 9.5 kg/s, 9.0 kg/s and 8.5 kg/s, termed Cases A–D), but the maximum supply of upgraded BG was assumed 0.9 kg/s from Biogas plant I (node 2) and 0.5 kg/s from Biogas plant II (node 3).

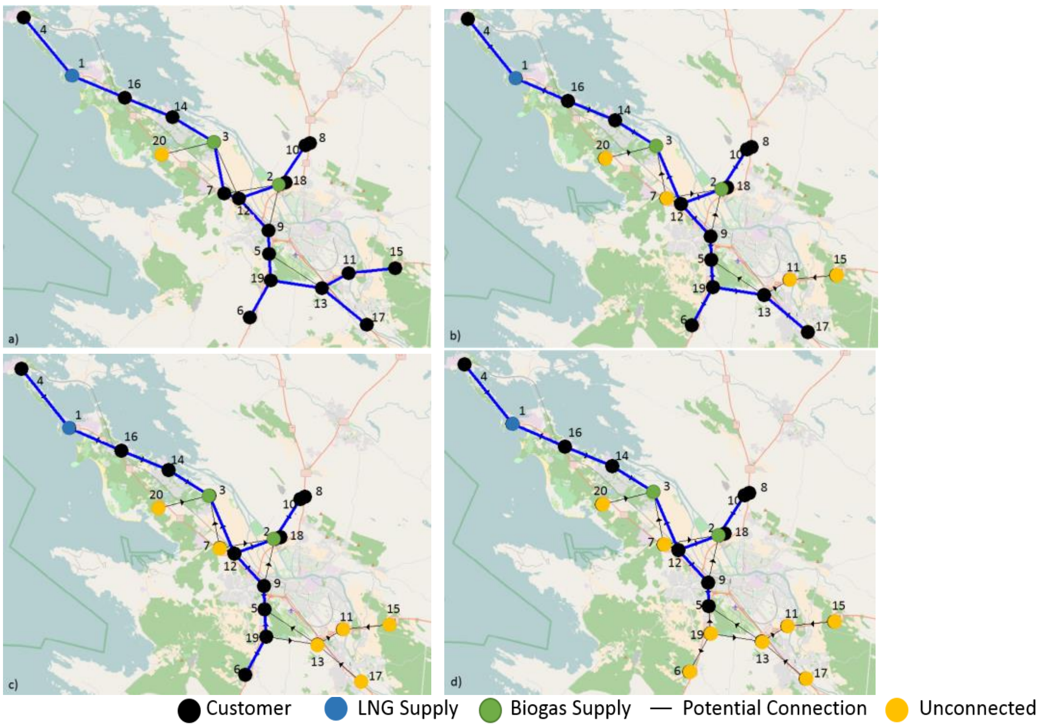


**Figure 2**. Optimal network structure corresponding to a) Case A, b) Case B, c) Case C, and d) Case D. Background map source: © OpenStreetMap contributors.

The optimal pipeline configurations for the cases are depicted in Fig. 2. The construction of an extensive network is economically feasible in Case A (Fig. 2a): All the big consumers and all but one of the small ones (node 20) are connected and supplied by the pipeline. A very small supply of alternative fuel is needed, so LNG and biogas together cover most of the demand. The total annual cost of this network is about 420 M€, with compression costs representing about 11 %. In Case B four customers (nodes 20, 7, 11 and 15, Fig. 2b) are left unconnected by the pipeline, but these are instead supplied by trucks with LNG and alternative fuel. The gas compression costs decrease slightly, but the total annual cost increases above 430 M€ due to a more extensive use of alternative fuel, which is more expensive. The influence of the restricted supply of re-gasified LNG is more obvious for Case C and seen as an omission of a whole branch of the pipeline network (nodes 11, 13, 15 and 17, cf. Fig. 2c). For the lowest LNG re-gasification rate, Case D, the LNG terminal supplies gas predominantly to the large customers along a practically unbranched network (Fig. 2d). The annual cost of the supply chain increases to 461 M€. The BG compressed into the pipeline here comes from BG plant I (node 2). The diameter of the pipes also decreases: the pipeline network constitutes mostly of pipes of 25 cm diameter.

## 4 CONCLUSIONS

This paper has presented models for the optimal design of two energy supply chains related to natural gas, which is a growing energy source in the world. The models have been formulated as optimization problems, where the total cost of fuel procurement is minimized using mixed integer linear programming (MILP). In the first model, the design of a small-scale LNG supply chain is addressed using a single-period formulation, and applied to a test case from the region around the Gulf of Bothnia. The solution provides information about the optimal locations of satellite terminals, fleet configuration, number of tank trucks and the associated distribution network. In the second model, which is developed for a local gas network complemented by truck transportation of LNG to a set of customers, the investment cost in the pipeline as well as the operation cost of it and the associated trucks, are considered. The solution gives the optimal pipeline network and LNG truck transports. Both models can be applied to study the optimal supply chain under different conditions (e.g., varying the price of LNG and alternative fuel, investment cost of terminals or renting costs of ships, etc.). This makes it possible to assess the sensitivity of the arising solutions to changes in the market conditions, which is important in a search for solutions that are robust. In the future work the LNG supply model will be extended to a multi-period formulation with the aim to address variation of the demands and to estimate the optimal storage inventory at the satellite terminals. The regional gas supply model will be augmented to consider investment in LNG tanks at the consumers and to account for costs associated with the use of the alternative fuel with a conversion from one fuel source to another for retrofit problems.

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