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Port clusters as an opportunity for optimizing small-scale LNG distribution chains: an application to the Mediterranean case

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Abstract. Small-scale LNG logistics chains have become more important for delivering LNG via shipping from large supply terminals to customers via satellite terminals. An ideal application of small-scale LNG logistics chains is in the Mediterranean basin, where the maximum distance between two ports is always less than two thousand miles. Focusing on a Tyrrhenian application case, this study develops a modeling tool capable of defining the optimal configuration for a small-scale LNG distribution network serving a set of Tyrrhenian ports organized as a cluster. The aim is to minimize total network costs, including both port entry costs and travel costs. The problem is modelled as a Vehicle Routing Problem with Draft Limits and Heterogeneous Fleet (VRPDLHF). Different network configurations are being tested to explore the transportation cost savings that could result from systemic and integrated management of LNG supply if ports were organized in a cluster. Computational results show that, by acting as an organized cluster, LNG port depots can potentially leverage their increased bargaining power during negotiations to seek reasonable import prices that can benefit from reduced transportation costs and guaranteed volume of LNG to purchase.

Keywords: Small-scale LNG; Draft Limits; Vehicle Routing Problem; Port Coalition

1 Introduction

In the last decades, many nations have faced major challenges related to climate change and environmental preservation. As part of these challenges, many countries have started making substantial efforts to find and adopt cleaner energy solutions [1]. In this

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regard, natural gas is increasingly in demand as an energy source due to its better environmental performance than conventional energy alternatives.

Natural gas can be traded in two ways: through pipelines or as LNG (Liquefied Natural Gas). Before the development of LNG technology, natural gas transportation was limited to gas pipelines [2] with understandable geographic constraints as pipelines are fixed in direction of flow and physically located. The pipeline model typically serves regional markets that involve neighboring countries and are not integrated with the international market. Conversely, the ability to convert natural gas into LNG has made LNG a global commodity that is easily transportable by sea using dedicated ships, thus providing consumers with access to vast natural gas resources around the world and making the world gas market less sensitive to the distance between trading partners [3].

LNG is the cleanest fossil fuel available on a large scale today. In July 2021, the European Commission (EC) presented an ambitious proposal, covering all sectors and all modes of transport, to reduce the EU's carbon emissions by 55% by 2030. For maritime transport, the EC wants to see renewable and low-carbon fuels make up around 6-9% of the bunker fuel mix by 2030 and 86-88% by 2050 [4]. According to the EC, this should be achieved with a combination of electrification, biofuels and other renewable and reduced-carbon fuels, including LNG as a transition fuel.

Traditionally, the LNG supply chains allow supplying large volumes of gas over large distances for which the pipeline delivery model is not viable. More recently, small-scale LNG logistic chains have become more important to deliver LNG by maritime transportation from large supply terminals to customers through satellite terminals [5]. Small-scale LNG supply chains have specific features:

- demands are distributed over short distances (up to few thousand miles)
- ships capacities range from some thousand m^3 up to 50,000 m^3
- ship loads can be split on consecutive receiving ports
- receiving terminals are equipped with storage tanks to be refilled once or a few times a month.

An ideal application of small-scale LNG logistic chains is in the Mediterranean basin, where the maximum distance between two ports is always less than two thousand miles. The ports that make up a small-scale LNG network play a dual role, both as points of use and storage of LNG, and as LNG gateways to the inland areas (which is particularly relevant for areas without methane distribution networks).

Focusing on a Mediterranean application case, this study develops a modeling tool able to define the optimal configuration for a small-scale LNG distribution network serving a set of Tyrrhenian ports.

The proposed modeling tool identifies an optimal small-scale LNG network able to efficiently connect a potential supply port to a set of receiving ports while ensuring minimum transport costs and meeting operational constraints related to draft limits. The latter can prevent ships from entering some ports when they are fully loaded, thus imposing constraints on the sequence of ports visited. Each receiving port is characterized by a demand that must be met in the planning horizon. LNG carriers operating on the network can be chosen from a heterogeneous fleet characterized by different capacities. The problem to be faced consists in selecting how many ships of each type to involve, and providing the route plan for each ship, in compliance with draft constraints. The aim is to minimize total network costs including both port entry costs and travel costs (different for each ship category). The problem is modeled as a Vehicle Routing Problem with Draft Limits and Heterogeneous Fleet (VRPDLHF). Several network configurations are being tested to explore the transport cost savings that could result from systemic and integrated management of LNG supply if ports were organized in coalition. The objective of the application is twofold:

1. define, through the application of an analytical model of network optimization developed ad hoc, the optimal configuration of the distribution network that ensures the lowest transport costs of LNG from a set of alternative supply terminals
2. explore the potential bargaining margin on the purchase price of LNG that would derive from the reduction of transport costs following an integrated management of the supply system by sea.

The paper is organized as follows. Section 2 introduces the rationale behind the study. Section 3 describes the LNG distribution problem at hand while Section 4 proposes its mathematical formalization. Section 5 presents the case study and application data. Section 6 presents the application and its results. Section 7 concludes the paper.

2 The reference context

The cost of shipping LNG has always been an important element to consider in the LNG trade [6] and is believed to have a significant impact not only on LNG trade but also on the commercial scale [7]. For a typical LNG value chain, shipping costs are estimated to represent 20 to 30% of the total LNG cost [8]. Importers and exporters generally negotiate to fix the price of the LNG to be included in the commercial contract. LNG contract prices may vary depending on whether LNG is priced Ex-ship or Free-On-Board - FOB [9]. The former reflects downstream prices minus gasification and other costs of the destination terminal and shipping while the latter considers the prices of LNG delivered to the tanker at the export terminal, in this case shipping and insurance are the buyer’s responsibility. FOB contracts offer buyers greater flexibility with regards to shipping costs and the ability to take advantage of profit opportunities through arbitrage. Contracts nowadays are increasingly of the FOB type and, together with the greater level of integration of the LNG market [3], they are increasing the opportunity for price arbitrage by decreasing transport costs. Indeed, although LNG is now widely considered a global commodity, there is no clear trend towards a single and uniform gas price [10]. The significant development of the LNG market has inevitably led to a corresponding growth in the level of competition among LNG exporters, which has shifted from regional to global competition [10]. Furthermore, the growing demand for LNG is forcing buyers to seek more LNG suppliers, thus encouraging more competitive relationships between exporters.

While in the past LNG was mainly traded on long-term contracts with a small number of exporters supplying specific regional markets, now a larger share of the volumes is traded on short-term contracts, thus further contributing to the liquidity of the LNG market [11]. The short-term market has two main peculiarities [12]:

- sellers can divert the cargo to alternative buyers (flexibility of supply)
- buyers can look for gas from alternative suppliers (quick response to gas demand).

Given this competitive framework, this study investigates the extent to which the transport cost of LNG can be minimized when ports manage their LNG supply as a coalition rather than individually [13].

However, the economic factor is not the only factor at play. The environmental issue also plays an important role in the management of energy supply and can affect the attractiveness of the transport alternative, as well as the energy source itself. LNG is now extensively recognized as the perfect bridge fuel to a world that uses 100% sustainable energy sometime after 2050 [10]. As for Europe, several factors including, among others, the progressive limitation on CO_2 emissions and obstacles to the development of renewable energy sources, seem to force the EU into an increasing dependence on natural gas. Europe is looking for huge imports of natural gas (in the form of LNG) from overseas and clear and effective policies should be developed to support market growth and market liquidity. In recent years, the EU market has been characterized by a continuous decline in local gas production and the continued diversification of gas imports.

In accordance with the "EU strategy on LNG - COM 2016/49” [14], and the international commitments made at the Paris climate conference, this study proposes a new management strategy for LNG distribution in the Tyrrhenian area that can support the implementation of the European recommendations, and at the same time assisting the areas characterized by limited or absent methanisation networks.

3 Problem description

The LNG distribution problem under consideration is a routing problem with draft constraints in which a series of ports must be visited by LNG carriers with different capacities and characteristics. Each port is characterized by a demand that must be served within the reference time horizon and by a draft limit which represents the maximum draft with which a ship can safely access the port. Draft limits can prevent ships from entering some ports when fully loaded, thus imposing constraints on the sequence of ports visited.

The required draft of a ship may depend on several factors that determine the minimum depth of water that the ship can navigate safely. Among the most influential factors we can mention the depth of the water, the tide at a particular moment (of particular importance for some ports), and the load on board. The latter varies according to the sequence of ports visited on the route and can, therefore, impose restrictions on the sequence of visits, as well as restrictions on the ports that can be visited within the same route. If the draft of a ship, when approaching a port, is greater than the draft limit allowed by the port, the ship cannot enter it. The same ship will be able to access that port only after having unloaded part of its cargo in other ports and having reduced the draft to a limit that allows safe access. This also implies that some ports with relatively shallow water depths may still be able to accommodate large ships if they occupy a position within the port sequence visit that allows for low loads.

The fleet is made up of different vessels, each characterized in terms of carrying capacity, port costs, unit transport costs and draft values when empty and fully loaded. The actual draft of a ship at a given time is calculated as the sum of the draft of the empty ship plus a linear function of the load on board at that time. The objective of the problem is to define the optimal configuration of the distribution network that minimizes the total cost of transport over the entire network.

Regarding the related literature, it is possible to find some studies that address the same vehicle routing problem with draft limits investigated in this study, albeit with some differences. Among the closest works we can mention the studies by [15,16]. In these works, the authors deal with fleet sizing for a maritime routing problem with draft limits but consider a fixed draft for each category of vessels, which does not vary with the percentage of load on the ship. The problem faced has an impact on the fleet sizing but does not affect the sequence of visits within a route. Other papers dealing explicitly with load-dependent draft variations, address single vehicle problems with no choice of vehicle size [17-22].

Differently from the works cited above, this study considers a heterogeneous fleet of vessels to choose from and integrates the fleet sizing problem with draft limits and load-dependent draft variations.

The next section proposes a mathematical formulation of this problem that can be solved with a mixed integer programming solver.

4 Formalization of the problem: Vehicle Routing Problem with Heterogeneous Fleet and Draft Limits (VRPHFDL)

This study introduces a Vehicle Routing Problem with Heterogeneous Fleet and Draft Limits (VRPHFDL) in which a set of ports I must be served from a depot. Each port is characterized by a demand to be served Q_i, and a draft limit representing the maximum draft of a ship allowed to enter the port. Draft limits can prevent ships to enter some ports when they are fully loaded, thus imposing constraints on the sequence of ports visited. The fleet is composed by a set of heterogeneous ships, S, each characterized in terms of load capacity, Q_s, fixed costs to enter each port i, r_{is}, unitary sailing costs, c_s, and empty and full load draft values. The actual draft of a ship in a given time is calculated as the draft of the empty ship plus a linear function of the load on board at the time. Based on these data, we can compute, for each ship s and port i, the maximum allowed load, for s, to safely access port i, L_{is}. Sailing time among each pair of ports, t_{ij}, is known. The objective of the problem addressed is to minimize the total network cost given by the sum of fixed costs to access ports and the sailing costs.

In the following we provide the mathematical formulation of the newly introduced problem.

Sets

$I = [1, I_{max}]$ set of ports

$I0 = [0, I_{max}]$	set of ports, included the depot
$S = [1, S_{max}]$	set of ships

Input data

Q_s	ship capacity
q_i	port demand
L_{is}	maximum loading for ship *s* to access port *i*
t_{ij}	sailing time between port *i* and *j*
c_s	hourly sailing cost for ship *s*
r_{is}	access cost for ship *s* entering port *i*

Variables

X_{ijs}	binary variables taking value 1 if arc *ij* is traversed by ship *s*
Y_{is}	binary variables taking value 1 if port *i* is served by ship *s*
l_{is}	loading of ship *s* entering port *i*
u_i	position of port *i* in the sequence of visited ports
p_s	total load for ship *s*

$$min \sum_{i \in I0} \sum_{j \in I0} \sum_{s \in S} c_s t_{ijs} X_{ijs} + \sum_{i \in I} \sum_{s \in S} r_{is} Y_{is} \qquad (1)$$

$$\sum_{s \in S} Y_{is} = 1 \qquad \forall\, i \in I \qquad (2)$$

$$\sum_{i \in I} q_i Y_{is} \le Q_s \qquad \forall\, s \in S \qquad (3)$$

$$\sum_{i \in I0} X_{ijs} = Y_{is} \qquad \forall\, j \in I \quad \forall\, s \in S \qquad (4)$$

$$\sum_{i \in I0} X_{ijs} = \sum_{i \in I0} X_{jis} \qquad \forall\, j \in I \quad \forall\, s \in S \qquad (5)$$

$$X_{0js} \le \sum_{j \in I} Y_{js} \qquad \forall\, s \in S \qquad (6)$$

$$X_{0js} \ge \sum_{j \in I} Y_{js}/|I| \qquad \forall\, s \in S \qquad (7)$$

$$u_j \ge u_i + 1 - |I|(1 - \sum_{s \in S} X_{ijs}) \qquad \forall\, i \in I \quad \forall\, j \in I0 \qquad (8)$$

$$l_{js} \ge l_{is} - q_i - Q_s(1 - X_{ijs}) \qquad \forall\, i \in I \quad \forall\, j \in I0 \quad \forall\, s \in S \qquad (9)$$

$$l_{is} \le L_{is} \qquad \forall\, i \in I \quad \forall\, s \in S \qquad (10)$$

$$l_{0s} = \sum_{i \in I} q_i Y_{is} \qquad \forall\, s \in S \qquad (11)$$

$$X_{ijs} \in \{0,1\} \qquad \forall\, i \in I0 \quad \forall\, j \in I0 \quad \forall\, s \in S \qquad (12)$$

$$Y_{is} \in \{0,1\} \qquad \forall\, i \in I \quad \forall\, s \in S \qquad (13)$$

$$u_i \in N^{+} \qquad \forall\, i \in I \qquad (14)$$

The objective function is reported in (1). Constraints (2) imply that each port is assigned to a ship. Constraints (3) ensure that the maximum load capacity of a ship is never exceeded. If a port is assigned to a ship s it must be visited by that ship exactly once, as stated by Constraints (4) and (5). Each ship must enter and exit the depot once if at least one port has been assigned to it (Constraints (6) and (7)). The position of a port j in the sequence of visits is tracked by Constraints (8), while Constraints (9) track the load of the ship when entering port j. This load must always be lower than the maximum allowed load, as implied by Constraints (10). The load of a ship exiting the depot is equal to the sum of the demands of the ports assigned to it (Constraints (11)). Finally, Constraints (12)-(14) specify variables domain.

5 Case Study and Data

The study considers a small-scale LNG distribution network in the Tyrrhenian area as an application case. The nodes that make up the network are divided into exporting nodes and buyer nodes. The former are the marine terminals used to supply the network while the latter are the marine terminals that acquire the necessary LNG volumes by sea. In particular, the analyzed network includes seven buyer marine terminals and five exporting marine terminals (Figure 1), the latter to be considered for application purposes as alternative sources of supply.

Fig. 1. Analyzed port network. Source: authors

The network in question constitutes an ideal application of the small-scale distribution scheme, with maximum distances between nodes of less than 1,800 nautical miles (nm). Table 1 shows the complete matrix of the nautical distances for the O/D pairs that make up the network in question.

Table 1. Distance matrix [nm].

		Tolone	Genova	Livorno	Bastia	Cagliari	Oristano	Nizza
Buyer nodes	Tolone							
	Genova	163						
	Livorno	195	78					
	Bastia	178	105	61				
	Cagliari	327	349	294	245			
	Oristano	239	304	292	283	142		
	Nizza	82	86	131	126	355	276	
Export nodes	Barcellona	202	352	380	362	370	313	270
	Malta	610	590	532	490	337	491	764
	Skikda	377	460	441	400	174	248	408
	Marsa el Brega	1000	989	895	882	737	1000	985
	Idku	1758	1685	1632	1610	1377	1465	1737

Table 2 summarizes the main features of the buyer terminals examined in terms of nominal and effective storage capacity, nominal and operational draft. The infrastructural data used in this application are taken from the TDI Rete GNL and SIGNAL projects (Interreg IT-FR Maritime Program 2014-2020) and refer mainly to project data. As coastal depots operate according to the "50% always full" principle for safety reasons, the effective capacity is calculated as half of the nominal capacity. The operational draft of the terminal is calculated by subtracting a safety margin from its nominal draft. This application assumes a safety margin of 1.3 m which includes net under keel clearance, dredging tolerances, tidal and weather-marine factors [23].

Table 2. Characteristics of the marine LNG terminals.

	Nominal storage capacity [m^3]	Effective Storage capacity [m^3]	Nominal Draft [m]	Operational draft with a safety margin [m]
Bastia	5,000	2,500	8	6.7
Cagliari	22,000	11,000	8.5	7.2
Genoa	6,600	3,300	5.6	4.3
Livorno	9,000	4,500	9	7.7
Nice	5,000	2,500	7	5.7
Oristano	10,000	5,000	11	9.7
Toulon	10,000	5,000	8	6.7

Each import terminal is characterized by an LNG demand to be served. The demand data used in this application are taken from the TDI Rete GNL and SIGNAL projects (Interreg IT-FR Maritime Program 2014-2020) and refers to some forecasts for the year 2025. These demand data are intended as the sum of three components:

- maritime demand: it considers the volumes of LNG bunkering required by the maritime propulsion market (pleasure craft, commercial ships, ancillary services, public transport services, police, and coast guard)
- port demand: it considers the energy needs generated within port areas (port handling vehicles, energy systems, etc.) which can be met, at least in theory, by using LNG as a fuel for energy production
- terrestrial demand: it considers the demand for LNG bunkering and storage services for industrial and private use that comes from the hinterland and retro-port areas.

Since this application considers a monthly time horizon, Table 3 illustrates the monthly LNG demand that characterizes the eight nodes in the network.

Table 3. Monthly LNG demand (m^3/month). Year of reference: 2025.

Ports	Monthly LNG demand [m^3/month]
Bastia	498
Cagliari	4,842
Genoa	16,062
Livorno	18,255
Nice	794
Oristano	1,014
Toulon	4,524
sum	*45,989*

It is assumed that the network could be served by five categories of LNG carriers with different capacities. Table 4 summarizes the general characteristics of the five ship categories in terms of carrying capacity, full and empty draft and operating cost per nautical mile. The data relating to the capacity and the draft are taken from the information sheets available on the websites of the main LNG carriers, while the operating cost has been estimated with the support of LNG market experts and is to be considered purely indicative.

Table 4. Characteristics of the LNG carriers.

Category	Capacity [m^3]	Full draft [m]	Empty draft [m]	Operating cost [€/nm]
1	3,000	4.3	3.9	17.6
2	7,500	6	5.5	18.5
3	10,000	6.6	5.9	19.3
4	20,000	7.8	6.8	20.4
5	30,000	8	7.5	21.3

6 Application results

The optimization model introduced in Section 4 is applied to different scenarios in order to identify, for each tested scenario, the configuration of the maritime distribution network that guarantees the lowest transport costs.

The following three different network scenarios are considered:

- Scenario 1: the seven buyer nodes procure themselves autonomously and independently (Business As Usual - BAU procurement scenario). The storage capacity and maximum draft of the seven LNG depots reproduce the state of affairs (Table 2). The optimization model is applied considering the seven nodes separately and assuming that each of them alternatively uses one of the five exporting nodes, for a total of 35 instances. The objective is to calculate the minimum transport cost that would characterize the supply of LNG for each of the seven purchasing nodes analyzed if each of them independently managed their own LNG supplies by sea.
- Scenario 2: the buyer nodes procure themselves in a coordinated way by acting in coalition as an organized pool (Project scenario - coalition procurement scenario). The characteristics of the seven marine depots in terms of storage capacity and maximum draft reproduce the state of affairs (Table 2).
- Scenario 3: the buyer nodes procure themselves in a coordinated way by acting in coalition as an organized pool; the characteristics of the marine depots in terms of storage capacity and draft are improved (Table 5) compared to the current state of affairs (Prospective scenario – coalition procurement scenario with improved offer attributes). The minimum draft is raised to 8 meters for all ports, and the capacity of the coastal depots of Livorno and Genoa is set equal to their monthly demand.

Table 5. Improved characteristics of the marine LNG terminals.

	Improved storage capacity [m^3]	Improved draft [m]
Bastia	2,500	8
Cagliari	11,000	8
Genoa	16,100	8
Livorno	18,300	8
Nice	2,500	8
Oristano	5,000	9.7
Toulon	5,000	8

6.1 Scenario 1 – BAU procurement scenario

Tables 6 shows the transport cost for each of the seven buyer nodes according to the export terminal used. For each buyer node, the most convenient transport option is highlighted in bold. The remaining columns of the table detail:

- the total transport cost of the network for each of the five export nodes (calculated as the sum of the transport costs relating to the seven buyer nodes). The most advantageous network option is highlighted in bold
- the total number of miles navigated monthly for each network option
- the cost delta (Δ_{cost}) that characterizes the LNG procurement from each exporting node with respect to the minimum cost network option (shown in the table in bold). Δ_{cost} can be interpreted as the minimum unit discount in terms of €/m^3 that should be applied to the purchase price of LNG at export node *i* so that it can be competitive with respect to the export node serving the minimum cost network.

The Δ_{cost} that characterizes the transport network relating to export port *i* is calculated as:

$$\Delta cost = \frac{(cost\ of\ network\ i - minimum\ network\ cost)}{cubic\ meters\ transported}$$

Table 6. Transport cost of LNG in Scenario 1

	Transport cost of the individual buyer nodes [€/month]							Network cost [€/month]	Distance [nm/month]	Δ_{cost} [€/m3]
	Bastia	Cagliari	Genova	Livorno	Nizza	Oristano	Tolone			
Barcellona	**12742**	13690	**74342**	**66180**	11018	**9504**	**7474**	**194951**	10832	-
Malta	17248	11862	124608	92231	17283	26893	21472	311598	17312	2.5
Skikda	14080	**6125**	97152	72668	**8730**	14362	13270	226387	12578	0.9
Marsa el Brega	31046	25942	208877	153424	35200	34672	35200	524361	29132	7.3
Idku	56672	48470	355872	265864	51568	61142	61882	901470	50082	15.6

6.2 Scenario 2 – Project scenario

Table 7 summarizes the results relating to the project scenario in which the seven buyer nodes manage their own LNG supplies by sea in coalition, and the characteristics of their marine depots reproduce the state of things. The table follows the same organization seen above. For each of the five export nodes, the table lists the corresponding transport cost falling on each buyer node. The share of the transport cost attributed to each buyer node is calculated by dividing the total transport cost of the network in proportion to the LNG demand of the node. Looking at the results, the transport cost of Genoa remains the same as in Scenario 1. The limited draft and capacity of the Genoa depot require six visits per month with a dedicated ship to meet its LNG demand, thus not allowing Genoa to enter a shared route.

Table 7. Transport cost of LNG in Scenario 2

	Transport cost of the individual buyer nodes [€/month]							Network cost [€/month]	Distance [nm/month]	Δ_{cost} [€/m3]
	Bastia	Cagliari	Genova	Livorno	Nizza	Oristano	Tolone			
Barcellona	**587**	**5707**	**74342**	**49635**	**936**	**1195**	**5332**	**137734**	6097	-
Malta	814	7905	124608	69174	1297	1656	7386	212839	9671	2.5
Skikda	597	5800	97152	54501	951	1215	5419	165635	7418	0.9
Marsa el Brega	1333	12953	208877	115068	2125	2713	12102	355171	16112	7.3
Idku	2146	20855	355872	199398	3421	4368	19485	605545	27045	15.6

6.3 Scenario 3 – Prospective scenario

Table 8 summarizes the results relating to the prospective scenario in which the buyer nodes manage in coalition their LNG supplies, and an enhancement of their supply characteristics (draft and storage capacity) is assumed. The table follows the same organization seen before.

Table 8. Transport cost of LNG in Scenario 3

	Transport cost of the individual buyer nodes [€/month]							Network cost [€/month]	Distance [nm/month]	Δ_{cost} [€/m3]
	Bastia	Cagliari	Genova	Livorno	Nizza	Oristano	Tolone			
Barcellona	**427**	**4146**	**13701**	**15413**	**680**	**868**	**3874**	**39109**	1866	-
Malta	581	5645	18655	20987	926	1182	5274	53251	2545	0.31
Skikda	467	4536	14988	16861	744	950	4238	42782	2050	0.08
Marsa el Brega	927	9004	29753	33473	1477	1886	8412	84932	4063	1.00
Idku	1563	15186	50182	56455	2491	3181	14188	143244	6863	2.28

In the prospective scenario that provides for improved infrastructural characteristics in the buyer nodes, the most affordable network option relies on Barcelona, with minimal cost differences compared to the network options served by Malta and Skikda. Given their decentralized geographical position with respect to the study area, Marsa el Brega and Idku are less competitive alternatives.

6.4 Savings in transport costs

Table 9 illustrates the percentage savings on transportation costs that would occur when moving from the BAU procurement scenario (Scenario 1) to the project procurement scenario (Scenario 2). The entry into the coalition, whatever the export node used, involves a significant reduction in costs for all ports, except for Genoa, for which transport costs would remain unchanged. Due to its high demand and infrastructural constraints, Genoa would continue to be served by dedicated ships and to fully bear its procurement cost.

Table 9. Percentage savings on transport costs obtainable in the transition from the BAU scenario to the project scenario

	Savings in transport costs [%]							
	Bastia	Cagliari	Genova	Livorno	Nizza	Oristano	Tolone	Whole network
Barcellona	95	58	0	25	92	87	29	29
Malta	95	33	0	25	92	94	66	32
Skikda	96	5	0	25	89	92	59	27
Marsa el Brega	96	50	0	25	94	92	66	32
Idku	96	57	0	25	93	93	69	33

Table 10 illustrates the percentage savings that would derive from the transition from the BAU procurement scenario to the prospective one with infrastructural upgrading of LNG marine depots (Scenario 3). By bringing the draft of all buyer ports to 8 meters and expanding the capacity of the coastal depots of Livorno (from 4,500 to 18,300 m^3) and Genoa (from 3,000 to 16,100 m^3), it is possible to reduce transport costs by approximately 80%. Thanks to the infrastructural improvements, Genoa could be included in an itinerary that touches various ports of the coalition. Deeper drafts and larger depots would allow all coalition ports to be served using only two LNG carriers, one large and one extra-large. Such a distribution scenario would reduce not only transport costs but also the distances travelled, with environmental benefits in terms of reducing polluting emissions [24].

Table 10. Percentage savings on transport costs obtainable in the transition from the BAU scenario to the prospective scenario with improved infrastructure attributes

	Savings in transport costs [%]							
	Bastia	Cagliari	Genova	Livorno	Nizza	Oristano	Tolone	Whole network
Barcellona	96.6	69.7	81.6	76.7	93.8	90.9	48.2	79.9
Malta	96.6	52.4	85.0	77.2	94.6	95.6	75.4	82.9
Skikda	96.7	25.9	84.56	76.8	91.5	93.4	68.1	81.1
Marsa el Brega	97.0	65.3	85.8	78.2	95.8	94.6	76.1	83.8
Idku	97.2	68.7	85.9	78.8	95.2	94.8	77.1	84.1

7 Conclusion and implications for research and policy

The described application studied to what extent an integrated management of LNG supply between a set of coalition-organized ports could allow a reduction in transport costs. Given a set of Tyrrhenian port depots organized as a cluster, this study identified the network configuration that ensures the minimization of transport costs in compliance with demand and supply requirements. The resulting cost reduction is due to the optimization of the filling coefficients of the ships, to the smaller number of ships to be used for the supply of all the nodes and, clearly, to the reduction in the total number of miles traveled thanks to the optimization of the distribution routes. Significant savings on LNG shipping costs can be achieved by taking advantage of the economies of scale that come from operating as a pool of port depots rather than individually. Acting as an organized cluster, LNG port depots can potentially leverage their stronger bargaining power during negotiations to seek reasonable import prices that can benefit from reduced transportation costs and guaranteed volume of LNG to purchase. Furthermore, the reduction of emissions (due to the reduction of the total distance traveled) and the increase in maritime safety (due to the reduction of traffic) induced by an optimized distribution network, can act as a stimulus for public regulatory bodies in the energy sector for the promotion of similar cluster-based initiatives in support of a more sustainable development of the LNG market. Extensions of the research will concern the economic evaluation of alternative investment scenarios regarding LNG storage infrastructures in the ports analyzed and their effects on the organization of the logistic distribution model.

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References

1. Serra, P., Fancello, G., 2020. Towards the IMO’s GHG goals: A critical overview of the perspectives and challenges of the main options for decarbonizing international shipping. Sustainability, 12 (8), 3220.
2. Kumar, S., Kwon, H.T., Choi, K.H., Cho, J.H., Lim, W. and Moon, I., 2011. Current status and future projections of LNG demand and supplies: A global prospective. Energy Policy, 39(7), pp.4097-4104.
3. Barnes, R. and Bosworth, R., 2015. LNG is linking regional natural gas markets: Evidence from the gravity model. Energy Economics, 47, pp.11-17.
4. European Commission, 2021. https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal/delivering-european-green-deal_en
5. Bittante, A., Pettersson, F. and Saxén, H., 2017, September. A multi-period optimization model for the design of new LNG supply chains. In Proceedings of the 58th Conference on Simulation and Modelling (SIMS 58) Reykjavik, Iceland, September 25th–27th, 2017 (No. 138, pp. 332-342). Linköping University Electronic Press.
6. Rogers, H., 2018. The LNG Shipping Forecast: Costs Rebounding, Outlook Uncertain. Technical report. The Oxford Institute for energy studies.
7. Wood, D.A., 2012. A review and outlook for the global LNG trade. Journal of Natural gas science and Engineering, 9, pp.16-27.
8. Williams, C., 2010. Management 6e. Cengage Learning, 2010. ISBN 0538745975.
9. Maxwell, D. and Zhu, Z., 2011. Natural gas prices, LNG transport costs, and the dynamics of LNG imports. Energy Economics, 33(2), pp.217-226.

10. Chen, Z., An, H., Gao, X., Li, H. and Hao, X., 2016. Competition pattern of the global liquefied natural gas (LNG) trade by network analysis. Journal of Natural Gas Science and Engineering, 33, pp.769-776.
11. Hartley, P.R., 2015. The future of long-term LNG contracts. The Energy Journal, pp.209-233.
12. Wang, S. and Notteboom, T., 2011. World LNG shipping: dynamics in markets, ships and terminal projects. Current Issues in Shipping, Ports and Logistics, pp.129-154.
13. Fancello, G., Serra, P. and Mancini, S., 2019. A network design optimization problem for ro-ro freight transport in the Tyrrhenian area. Transport Problems; 14(4); 63-75
14. COM 2016/49, European Commission (2016). Communication from the Commission to the European parliament, the Council, the European economic and social Committee and the Committee of the regions on an EU strategy for liquefied natural gas and gas storage.
15. Bittante, A., Jokinen, R., Pettersson, F., Saxen, H., 2015. Optimization of LNG supply chain. Computer aided chemical engineering 37, 779–784.
16. Bittante, A., Pettersson, F., Saxen, H., 2018. Optimization of a smallscale LNG supply chain. Energy 148, 78–89.
17. Arnesen, M., Gjestvanga, M., Wanga, X., Fagerholt, K., Thuna, K., Rakkeb, J. G., 2017. A traveling salesman problem with pickups and deliveries, time windows and draft limits: Case study from chemical shipping. Computers & Operations Research 77, 20–31.
18. Battarra, M., Alves Pessoa, A., Subramanian, A., Uchoa, E., 2014. Exact algorithms for the traveling salesman problem with draft limits. European Journal of Operational Research 235 (1), 115–128.
19. Gelareh, S., Gendron, B., Hanafi, Monemi, R. N., Todsijevic, R., 2019. The selective traveling salesman problem with draft limits. Journal of Heuristics Https://doi.org/10.1007/s10732-019-09406-z.
20. Malaguti, E., Martello, S., Santini, A., 2018. The traveling salesman problem with pickups, deliveries, and draft limits. Omega 74, 50–58.
21. Rakke, J., Christiansen, M., Fagerholt, K., G., L., 2012. The traveling salesman problem with draft limits. Computers & Operations Research 39 (9), 2161–2167.
22. Todosijevic, M., Mladenovic, N. abd Hanafi, S., Gendron, B., 2017. A general variable neighborhood search variants for the travelling salesman problem with draft limits. Optimization Letters 11 (6), 1047–1056.
23. PIANC, 2014. Permanent International Association Navigation Congress (PIANC), Report No.121-2014, Harbour Approach Channels Design Guidelines.
24. Serra, P., Fadda, P., & Fancello, G. (2020). Investigating the potential mitigating role of network design measures for reducing the environmental impact of maritime chains: The Mediterranean case. Case Studies on Transport Policy, 8(2), 263-280.