Multiple approaches to exploit ferulic acid bio-based epoxy monomer for green thermoset

AN ENVIRONMENTAL PERSPECTIVE ON NATURAL GAS TRANSPORT OPTIONS: PIPELINES VS LIQUEFIED NATURAL GAS (LNG)

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ABSTRACT

The environmental impacts of all supply chains are of great importance for the current climate change mitigation goals. Among the key supply chains is that of natural gas (NG), which has been envisaged as an enabler for the transition into future scenarios where dependence on fossil fuels is reduced or completely eliminated. Within the NG supply chain, the transport phase plays a fundamental role. It determines the required frequency, infrastructure and investments (among other factors) that make it possible to guarantee the societal NG supply and allows energy services to be covered. This study seeks to make a preliminary comparison between different options for NG transport from an environmental perspective. For this, four transportation options are analysed (over a distance of 1000 km): onshore gas pipeline, offshore gas pipeline, liquefied natural gas (LNG) tankers, and a combination of LNG and onshore pipeline. General proxy data present in the Ecoinvent v3.8 databases and the CML method are used, employing the transported MJ as the functional unit. The results suggested that NG pipeline transport generates greater depletion of the ozone layer, but it has an advantageous environmental footprint in terms of (eco)toxicity (in humans, on water bodies and terrains) compared to LNG. In terms of energy expenses (abiotic depletion - fossils), transport by pipelines represents around 2.0-2.5% of the transported energy, while LNG can reach up to 18.7%. In terms of global warming, LNG only had a 12% higher footprint than onshore NG pipeline transport, and overall these footprints are equivalent to 0.5-0.6% fugitive methane in the systems. Finally, general recommendations are provided concerning the different studied transport options and their environmental footprints.

Keywords: natural gas (NG) pipeline, Liquefied Natural Gas (LNG), transport NG, environmental analysis

1 INTRODUCTION

Among the fossil fuels that are currently used to cover societal needs, natural gas (NG) represents at least 20 % of the global primary energy consumption [1]. NG has drawn considerable attention from different stakeholders in academia, commercial and policymakers sectors since it is a versatile energy carrier that can be used for heat and power (co)generation and as a transportation fuel. NG plays (and will probably continue to have) an important role in the worldwide energy market; however, the NG supply is often in the midst of complex geopolitical tensions, which can affect different regional and global production chains. Ultimately, the destabilization in the supply and high price fluctuations can jeopardize societal welfare by preventing some (basic) needs from being covered (especially for the most vulnerable populations) and by increasing intragenerational inequity.

NG has been envisaged as a key facilitator for the transition towards low carbon economies, due to the lower direct CO_2 emissions compared to other fossil fuels and due to the adaptability of its supply chain that could be potentially exploited by other renewable fuels (e.g., syngas, biogas and bio-methane). NG is produced either in onshore or offshore facilities, depending on the location of the reservoirs. After the production phase, NG is sent to the processing stage, which includes a set of operations aiming at removing the main impurities present in the reservoir fluids. For this, phase separations are first conducted (G-L and G-L-L) and after the main gas stream is obtained, it undergoes different dedicated treatments. These treatments seek to bring natural gas to the required specifications for transport and end-users. Specifications for NG vary on regional and seasonal bases [2]. Typical quality specifications include the heating value of NG (based on LHV and/or the Wobbe Index), the amount of allowed acid species (CO_2 and H_2S), total sulphur compounds

(total S), the limits of other trace gases (O_2 and N_2), and the residual content of hydrocarbons and water (HC and H_2O dew points). Depending on the NG transmission method, there might be also differences in terms of specifications (i.e., the content of H_2S, total sulfur, CO_2, water, nitrogen, mercury). In general, NG whose transmission is through pipelines tends to have less strict impurity limits compared to Liquefied Natural Gas (LNG). LNG has been recently gaining ground, accounting for more than 10 % of the global production in 2020 [3]. It is a form of natural gas that has been liquefied (at cryogenic temperatures, usually below -160 C) for transport and storage purposes since in the liquefied form its volume significantly reduces (over 600 times). However, LNG requires additional processing steps in the supply chain, such as liquefaction, regasification (and their dedicated infrastructure) and the management of boil-offs (the evaporation that occurs during the transport of LNG). Indeed, these differences represent a greater consumption of chemicals and materials, as well as a reduction in the capacity of the plants, to comply with the more stringent specifications (e.g., greater consumption of glycol for dehydration, consumption of absorbent for the removal of acid gases, greater use of precious metals such as silver for the removal of mercury).
NG transport through pipelines often establishes a close interdependence between the provider and consumers, which can become coercive and affect the societal supply of NG. On the other hand, LNG offers more versatility and decentralization in the supply (although pipelines might also be required to reach end-users), hence the possibility to resort to multiple providers if interruptions in the supply chain are encountered. Trade-offs between the two modes of supply are a topic of great current interest. For example, in [4] a strategic perspective between NG pipelines and LNG is presented. A preliminary study of the LNG life cycle for the UK can be found in [5]. More recently, a study evaluated the environmental footprint of the two transport options for the supply chain in Norway [6]. However, more research is required on global perspectives on NG transport options. In particular, it is of interest to understand the additional phases required for LNG, the infrastructure that must be built and maintained, and to mitigate possible environmental impacts using the so far collected data.
This article aims to perform a preliminary comparison of the environmental footprint of the above-mentioned NG supply chain options, using as the case study a distance of 1000 km. For this, a life cycle assessment (LCA) is performed, using the secondary data present in LCA databases. The case study is centred on the transport phase of the NG supply chain, and it includes four transport options (onshore pipelines, offshore pipelines, LNG tankers, and a combination of LNG and onshore pipelines). The results shed light on the environmental performance of each transport method and they can help in planning for NG provisioning, as well as identifying critical impact categories that require special attention in the trade-off between NG pipelines and LNG.

2 METHODOLOGY

2.1 THE CASE STUDY: the midstream phase in NG supply chain

The focus of the study is the midstream phase of the NG supply chain. As shown in Figure 1A, the traditional NG pipeline transport includes the initial compression stage, which is necessary for the high-pressure transmission in pipelines. However, (eventual) compression stations are required for long-distance pipelines (each 100-200 km for onshore NG pipelines). Finally, gate stations are required to carry out the pressure reduction (if required) for the distribution to end-users.

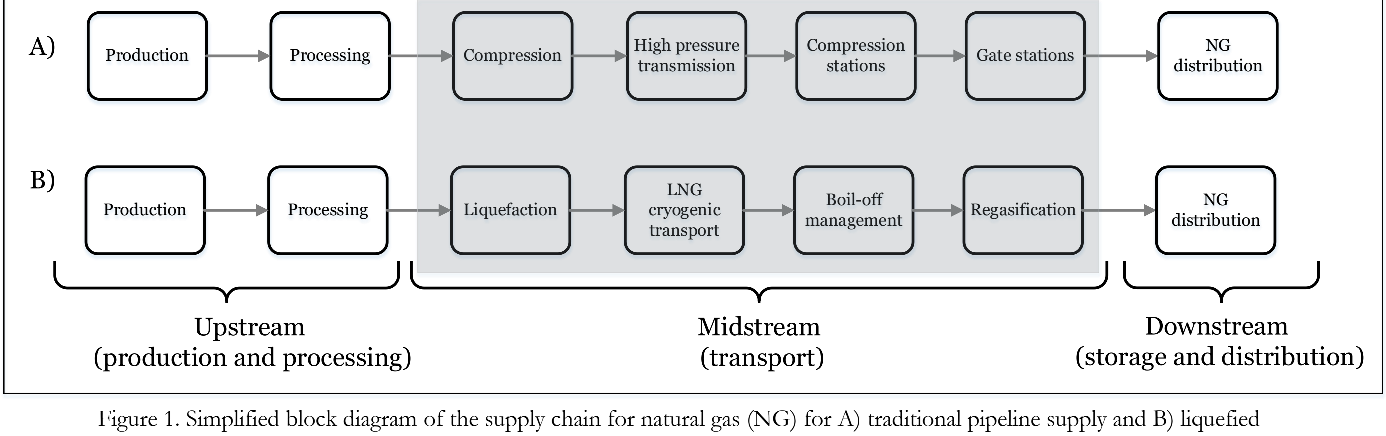

Figure 1. Simplified block diagram of the supply chain for natural gas (NG) for A) traditional pipeline supply and B) liquefied natural gas (LNG).

As noted before, the LNG upstream phase (the processing stage) might be more energy-intensive (due to the differences in quality specifications); however, these operations are considered out of the scope of the present analysis. For the transport phase of LNG, a liquefaction phase is first required (up to -162°C, and close to atmospheric pressure). Once LNG has been obtained, it is loaded into cryogenic tankers for off-shore transport. Although cryogenic tankers tend to be adequately (thermally) insulated, even (inevitable) small amount of heat exchanges causes a fraction of the LNG load to evaporate (i.e., boil-off gas). This boil-off gas requires an adequate management strategy in order to avoid overpressure within the vessels and to optimize the energy consumption of the ships. Upon arrival at onshore terminals, the LNG carriers berth and unload the LNG, which is then sent to the regasification stage.

In the present study, the aim is to shed light on the environmental footprint of the different NG transport options. For this, pipeline transport of NG is compared with LNG. A transported distance of 1000 km is used as a calculation basis, and the following cases are evaluated:

i) onshore NG pipeline,
ii) offshore NG pipeline,
iii) LNG tankers,
iv) combined transport: 800 km LNG tanker + 200 km onshore NG pipeline.

For the comparison among these options, the direct and indirect energy, chemicals and materials requirements are taken into account, as well as the required infrastructure. For onshore pipeline transport, compression stations were considered (every 150 km), while for offshore pipelines a single compression phase was considered (the initial one, at higher pressures). For LNG, the liquefaction and regasification operations were included, as well as the fuel consumption of the tankers (assumed LNG tanker capacity of c. 67500 tons, 150 000 m^3, ρ_{LNG}=450 kg/m^3). The last case sought to present a more realistic perspective, since after the LNG is transported and it reaches the mainland again, in many cases it is fed into the national NG pipeline systems (before reaching the gate stations and/or distribution to end users).

2.2 Life cycle assessment (LCA) for NG transport alternatives

In order to evaluate these NG transport options, a life cycle assessment (LCA) was performed. The objective of this LCA was to evaluate four different NG transport options from an environmental perspective. The approach was *gate-to-gate*, and the analytical boundaries are depicted in Figure 1. That is, within these boundaries NG was considered to be already produced and treated (production and processing - upstream operations of the O&G industry) and after the transport phase, it was considered to be delivered to the distribution phase (beyond the analytical boundaries). Since NG mainly serves to cover different societal energy services, the MJ of transported energy was chosen as the functional unit of the LCA. The inventory was carried out by compiling secondary data for each case, including direct and indirect consumption (materials, chemicals and energy), in addition to the key infrastructures in each case. Datasets were obtained from the Ecoinvent v.3.8 databases (in the SimaPro 9.4.0.2 software) and global representative processes or for the rest of the world (GLO and RoW) were selected. For the impact analysis, the CML-IA baseline V3.08/EU25 method was used, which includes the following eleven categories: Abiotic depletion (non-fossil), Abiotic depletion (fossil fuels), Global warming (GWP100a), Ozone layer depletion (ODP), Human toxicity, Freshwater aquatic ecotoxicity, Marine aquatic ecotoxicity, Terrestrial ecotoxicity, Photochemical oxidation, Acidification and Eutrophication. Although the impact analysis was carried out in characteristic terms of each category and without normalization, it was sought to contextualize the results of each case by reporting the impact of fugitive NG emissions. For this, fugitive emissions of 1% of the transported NG were used as a reference and it was contrasted against the four evaluated NG transport options.

3 RESULTS

3.1 Abiotic depletion (non fossil) and Ozone layer depletion

The comparison in terms of abiotic (non-fossil) resource depletion suggested that pipeline transportation of NG tends to require fewer resources overall than the options that include LNG (Figure 2A). This is probably due to the greater quantity and variety of materials required for this type of transport (including dedicated alloys for cryogenic conditions). For the Ozone layer depletion category (Figure 2A), that transport through pipelines resulted in a more polluting footprint than LNG, due to the type of emissions tabulated for each case. While the transport phase for LNG is characterized by CO_2, NO_x, SO_X and CO emissions (mainly derived from the combustion of fuels for navigation), in NG pipeline transport, the flows to the biosphere include hydrocarbons such as methane, ethane and traces of (hydro)chlorofluorocarbon compounds. This latter group had an important weight in this impact category, therefore the obtained results.

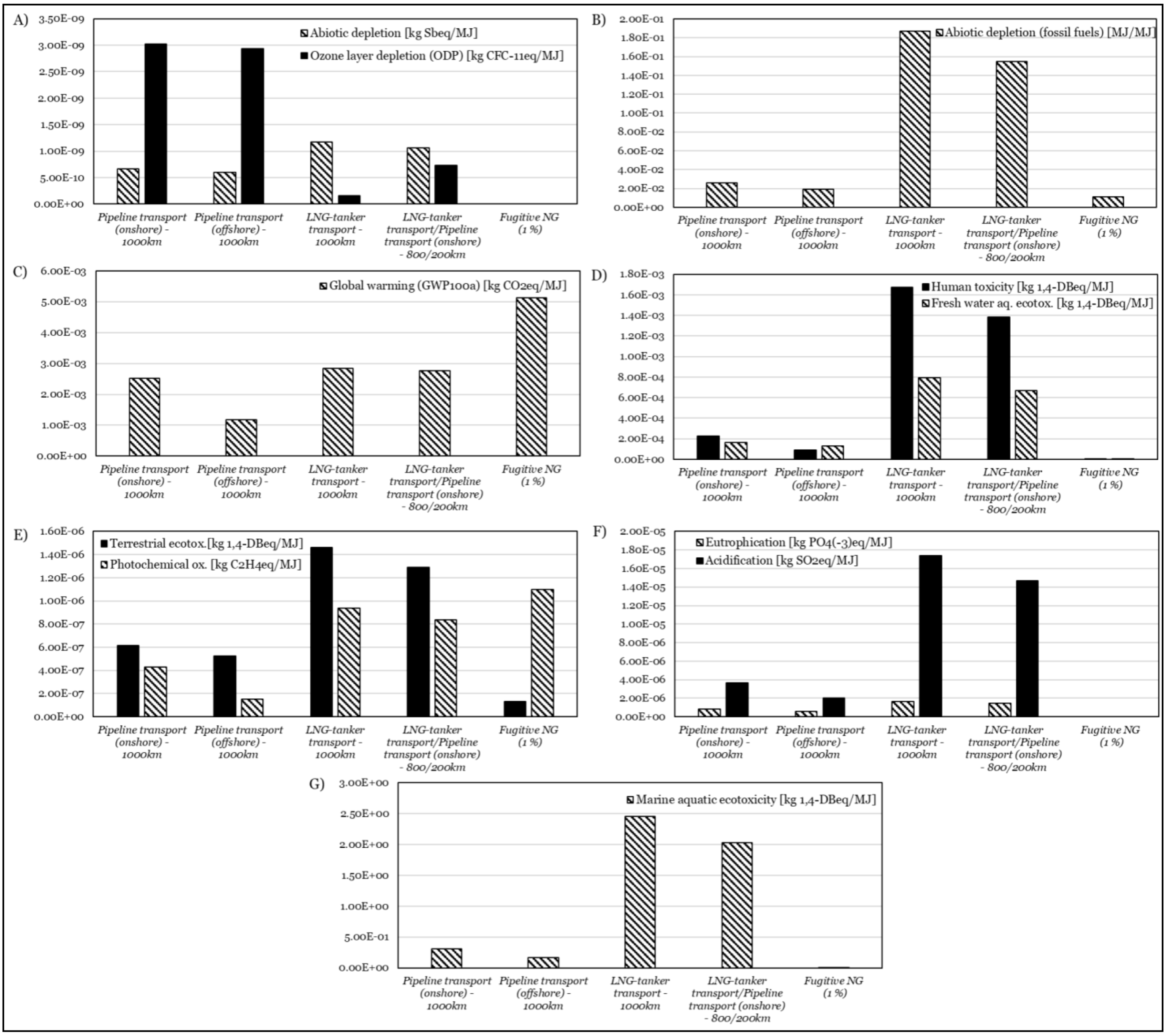

Figure 2. The life cycle assessment (LCA) results of the four evaluated transport options for natural gas (NG), following the CML-IA baseline method.

3.2 Abiotic depletion (fossil) and the Global warming

The fossils depletion category can be interpreted as the energy consumption for each NG transport option (Figure 2B). The results showed that LNG transport is more energy intensive than pipeline options. This is due to LNG tankers' fuel requirements (e.g., heavy fuel oil and/or NG), in addition to electricity costs for liquefaction and regasification [7]. On the other hand, NG pipeline transport options included the energy cost of compression (electricity). Hence, the lowest energy expenses (in terms of $MJ_{invested}/MJ_{transported}$) were obtained for the offshore pipeline option amounting to c. 2.0% compared to 2.5% for onshore pipelines. For LNG transport, the resulting footprint was almost nine times more (18.7%) and the combined case yielded proportional results of 6 times more than onshore pipelines (15.5%). For the global warming category (Figure 2C), a similar trend was obtained, although the differences are less marked between the transport options being evaluated. The obtained values were: 2.51 (onshore pipeline), 1.18 (onshore pipeline), 2.83 (LNG) and 2.76 (combined) $gCO_{2eq}/MJ_{transported}$. The offshore pipeline CO_2 footprint is much lower than onshore pipelines, as the former supply chain was modelled with fewer gasification stations, which is one of the largest sources of emissions for NG pipeline transport. In contrast, the differences found between onshore gas pipelines and LNG were only about 12%. Interestingly, if these emissions are compared to the fugitive NG footprint, it is observed that fugitive NG reaching 0.6% of the transported amount can surpass the global warming potential of all studied transport options.

3.3 Human toxicity, terrestrial ecotoxicity, fresh water and marine aquatic ecotoxicity

The human toxicity category was higher for LNG transportation, almost one order of magnitude higher than the pipeline options (Figure 2D). This is probably due to the higher emissions from the combustion of tankers and the materials used in that case, while for pipelines *in-situ* combustion is not included (grid electricity feeds the pipelines' compressors and instruments).

For the terrestrial ecotoxicity category, similar results were obtained, but with a footprint that is 50% higher for LNG (Figure 2E). For the aquatic category, NG offshore pipeline had the lowest ecotoxicity either in the freshwater (Figure 2E) or marine (Figure 2G) categories, followed by onshore pipelines (although the difference in freshwater is very low compared to offshore pipelines) and, finally, the LNG option. It was also noted that in absolute terms (using the reference units of both impact categories), the footprints on fresh waters are much smaller (by at least three orders of magnitude) than on seawaters. However, the environmental footprint of NG transport in terms of ecotoxicity on the studied environmental matrices suggested a much more pronounced impact than the reference fugitive methane emissions (more than four orders of magnitude for water bodies and between 5-10 times more for the terrestrial ecotoxicity).

3.4 Photochemical oxidation, eutrophication and acidification

For the photochemical oxidation impact category, the footprint of offshore pipelines was the lowest found, followed by offshore pipelines (three times higher). For LNG transport, values almost twice as high as those for pipeline transport were obtained. In addition, the comparison of photochemical oxidation to fugitive emissions suggested that LNG tanker transport is equivalent to about 0.85% fugitive methane.

Lastly, for the acidification and eutrophication categories (Figure 2F) transport by gas pipelines had less impact than the LNG options.

4 CONCLUSIONS

The study of the NG supply chain is of great importance, due to the implications it has on how modern societies cover their (energy) needs. The analysis of the environmental footprint of this supply chain can help make choices aligned with the current (global) sustainability goals.

Some relevant highlights encountered during this study are:

- The evaluation of NG transport methods suggests that the LNG option requires efforts to avoid human toxicity (of workers and the population in general) in addition to measures that mitigate the impact on key environmental matrices (water bodies and terrains);
- For onshore NG pipeline transport, the impact on the ozone layer continues to be a critical point, which is less marked for LNG, while for the LNG fewer resources depletion (chemicals and materials, non-fossil) should be targeted;
- In terms of global warming, the differences between onshore NG pipelines and LNG are low (c. 12%), amounting to 2.51 (onshore pipeline) and 2.83 (LNG) $gCO_{2eq}/MJ_{transported}$. These emissions can even be exceeded by the fugitive methane footprint (if they exceed 0.6% of the transported NG);
- In energy terms, LNG transport requires almost 9-10 times more energy than gas pipeline transport. Hence, in the contexts where this option is being applied, energy efficiency should be reviewed and attempts to exploit waste energy streams (cold and heat) should be made. The possibility to perform energy integration with other key operations of the supply chain should be also explored (storage, liquefaction, regenerations of chemicals, pre-cooling and pre-heating).

Although each NG supply chain is particular (due to the different distances, the involved technologies, the age of the facilities, the suppliers and required specifications), the presented approach could serve to rationalize the NG supply and evaluate key stages within it. Furthermore, although secondary data were used for the present study, these may serve to perform initial comparisons and forecast trade-offs in the future changes to the NG transport chain. These data also allow identifying possible criticalities of NG transport options. More research is required to monitor the impact of the growing LNG industry and to further mitigate the environmental risks of the new alternatives as much as possible.

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