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Analysis and assessment of the possibility of transporting liquefied natural gas on the Oder in the context of the island gasification of Poland

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ABSTRACT

The article examined the possibility of transporting liquefied natural gas (LNG) by the Oder River as an alternative solution for Poland's island gasification. With the growing importance of LNG in the green transition and the need for increased energy security, river transport can be an efficient and environmentally friendly method of gas distribution. The paper presented the legal regulations for the transport of LNG by inland waterways, including the European ADN Agreement, and discussed studies on river transport in Poland. The analysis focused on the potential of the Oder as a transport route, highlighting its economic, environmental, and logistical advantages. Various LNG vessel concepts were compared, including inland barges and ISO containers, as well as an analysis of potential locations for regasification stations along the Oder River was conducted. A proposed method for describing the energy efficiency design index (EEDI) for a theoretical pusher-barge set was also presented. On the basis of an energy and mass balance, an attempt was made to estimate potential opportunities, including the possible benefits of utilizing waste cold from the LNG regasification process at small island stations.

Keywords: liquefied natural gas, island gasification, Poland, EEDI, waste cold.

INTRODUCTION

Liquefied natural gas (LNG) is seen as a transition fuel on the way to zero emissions. The current global situation shows that liquefied natural gas is a key energy resource in the process of green transformation. With the aim of reducing or completely eliminating CO_2 production (related to emissions resulting from the use of fossil fuels, such as oil, hard coal, and lignite) in the maritime industry, the use of LNG as a transition fuel is associated with lower CO_2 emissions compared to traditional marine fuels and higher efficiency of LNG in retaining heat in the atmosphere compared to CO_2, which is a very strong greenhouse gas [1].

LNG as a raw material is not only important for ecological reasons, but also in terms of energy security, as evidenced by the rapid increase in the expansion of floating storage and regasification unit (FSRU) terminals in Europe after Russia's attack on Ukraine in February 2022. European countries, wanting to become energy independent from Russia, were building floating terminals in their countries at a very fast pace [2].

In recent years, there has been an increase in demand for LNG and this trend is expected to continue [1]. This raw material plays a huge role in ensuring Poland's energy security, as evidenced by the decision to expand the terminal in Świnoujście and to build a FSRU terminal in the Bay of Gdańsk. Despite large investments in gas infrastructure, the availability of this resource in many areas of Poland is insufficient. A concept that may allow for increased availability in the areas that are not covered by the pipeline network is the concept of "island gasification", in which the main role is played by small regasification stations to which LNG is delivered by road using tanker trucks. Such a solution generates problems in the field of safety as well as environmental protection. Alternatively, LNG could be transported by barge on an inland waterway such as the Oder River.

The transport of LNG by inland waterways in Poland is regulated by ADN (European Agreement concerning the International Carriage of Dangerous Goods by Inland Waterways). This is a European agreement that introduces regulations for the transport of dangerous goods on European rivers. This agreement unifies transport regulations, classifying dangerous goods according to their properties and degree of risk, and prescribes, among other things, the methods of packaging cargo or how to label and document shipments. It also indicates the qualifications of personnel involved in the transport of materials that may pose a serious threat to humans and the environment [3]. Poland has ratified the ADN agreement, so from a legal point of view, transport of dangerous goods by inland waterways is possible.

The use of the Oder for freight transport has already been discussed by many authors in numerous contexts: economic, ecological, political, or social. For example, the work by Budziewicz-Guźlecka et al. [4] discussed the issues related to sustainable inland waterway transport in the context of stimulating a transition towards a green economy. The authors' considerations focused on Poland's second largest river - the Oder. The clear economic needs and benefits of regulating the river and restoring its transport capacity are juxtaposed with the results of surveys on public perceptions of these changes. To clarify, these were residents of the Oder River basin, i.e. people in the area directly affected by the river.

On the other hand, the work of Wiśnicki et al. [5] presented a study of the location of river ports on the Oder Waterway (ODW), the Silesian Canal and the Polish section of the Danube-Oder-Elbe Canal (DOL). A multi-criteria analysis of the transport and economic potential of the ODW allowed the location of transport hubs and river ports to be identified as well as categorised. According to the authors, the designated river ports should be concentration points for transport and logistics services in the future.

Another paper by Filina-Dawidowicz [6] undertook an assessment of the usefulness of the qualitative method for estimating the demand for inland waterway cargo transport in the hinterland of seaports. The verification was carried out on the example of the Oder Waterway, analysing potential inland navigation operations to/from the seaports of Szczecin and Świnoujście, assuming that the waterway was upgraded to Class III navigability. The analysis carried out shows that such a study is possible and produces useful results for land use planning.

On the other hand, Durajczyk et al. investigated the potential of inland shipping in the assessment of a key element of Poland's sustainable transport strategy, with particular reference to the Opole-Szczecin route. Their work [7] presented inland waterways as an environmentally friendly and efficient alternative to road and rail transport, potentially revitalising the local economy and reducing reliance on more traditional modes of transport. A comparative analysis of freight transport on the Opole-Szczecin route using road, rail and inland waterway transport was made, showing the advantages of river transport in both economic and ecological terms.

Apart from the economic or social aspect, navigable rivers in Poland such as the Oder have an important impact on the national security. In [8], Jursza carried out an analysis in which he showed that inland navigation can be one of the key elements of the state economic, as well political security, and the lack of development of this branch may pose a threat to the country.

Inland navigation is one of the pillars of the EU's energy policy. According to many authors [1, 6, 8], this type of transport is one of the most effective in terms of CO_2 emissions per tonne of cargo transported. Studies show that inland navigation consumes only 17% of the energy that road transport needs when transporting the same amount of goods and 50% in the case of rail transport. Currently, the carriage of goods by rivers in EU countries represents on average around 6% of the transport market. The leaders are the Netherlands (43%), Bulgaria (31%) and Romania (28%) [9]. For comparison, in Poland, the share of inland waterway transport is less than 1%, and almost 76%

of inland waterway transport by Polish shipowners took place as part of international transport [10].

The greatest problem for the inland transport market in Poland is the condition of Polish rivers. Only 5.5% (206 km) meet the requirements that are imposed on international roads (classes IV and V) [11], therefore it is necessary to act at the national level in order to navigate the Oder and the Vistula. In October 2023, the Council of Ministers adopted a resolution on the adoption of a development program called "National Shipping Program until 2030" [12]. The National Shipping Program until 2030 is to cover two sections of inland waterways: the Oder Waterway (E30) from Gliwice to the ports of Szczecin and Świnoujście, and the Vistula from Toruń to Gdańsk (E40). The programme also aims to ensure stable transit depths of shipping lanes, the availability of locks and clearances under bridges and other infrastructure that crosses the waterway. It is also intended to develop a market for the inland waterway sector and a partnership for sustainable waterway development [13]. Despite the current government's unclear position on the continuation of the Program, in July 2024, Deputy Infrastructure Minister Arkadiusz Marchewka declared that the development of inland navigation was one of the ministry's policy priorities [14].

Given the potential of inland shipping from an economic and, above all, environmental point of view, as well as the role played by LNG in the green transition, the concept of transporting this raw material has already been explored in the past. Hongjun Fan et al., 2018 [15] proposed the concept of transporting LNG by special pontoons, which would solve the problem of refuelling LNG ships on inland waterways with large fluctuations in water level height and channel width according to seasonal changes. This solution provides for the operation of pontoons with type C tanks with a capacity of 250 m^3. Some of these units are currently in operation; they consist of two tanks with a total capacity of 500 m^3 and a draught of 1.6 m.

The concept of vessels that could transport LNG via the Oder River is also described in [16]. In their work [17], Kaup et al. investigated the possibility of transporting liquefied natural gas (LNG) via the Oder waterway. The work discussed existing LNG carriers and presented inland vessel concepts for operation on the Oder Waterway. Examples of inland LNG barges operating on waterways with high performance inland navigation infrastructure were presented. Possible inland LNG tanker options for operation on the Oder Waterway were considered. The authors presented two variants of barges meeting the requirements for navigation on the Oder (after its modernisation), which, with a draught of 1.6 m, could carry 622 m^3 and 1.060 m^3 of cargo, respectively. Another possible method of LNG transport is the use of ISO [18] containers. Containers that can hold approximately 21.5 m^3 (about 9.5 tonnes) of LNG are already available on the market. The total weight of such a 20-foot container is approximately 18 tonnes [19]. In Poland, this method of LNG transport has been used since 2018 [20]. The modernisation of the Oder to achieve Class V navigability standards would allow vessels with a draught of 2.8 metres [21].

LNG could be transported to the ports built along the Oder River and from there transported by rail or tankers to the final destination (over short distances). Another solution would be to build LNG storage tanks and a pipeline network, in the locations close to where there are the most regasification stations, e.g. the Wroclaw agglomeration. Such vessels are currently being operated on European inland waters. The most common solution is the barge, which consists of a pusher and a Europa barge. These vessels measure 32 × 11.4 × 1.85 m for the pusher and 76.5 × 11.4 × 2.5 m for the barge, and can carry up to 160 20 ft containers, with a maximum carrying capacity of around 2000 tonnes [22]. This type of solution is often used on the Danube, creating pusher-barge combinations (Figure 1).

An interesting solution is also to present [23] an innovative concept in which the authors created a model of an LNG-powered ship, which at maximum draught has a load capacity of 2.350 t and can load 208 20-foot containers (Figure 2). The proposed solution also makes it possible to form a ship-barge convoy or even a ship-3 barge convoy, which increases the payload capacity of the convoy without increasing its draught.

Inland transport requires relatively the least amount of energy. Using the same amount of energy that a truck will transport a load over a distance of 100 km, a train will transport it over a distance of 300 km, while a barge or ship will transport it over a distance of 370 km [24]. Other reports indicate that inland waterway transport consumes only 17% of the energy needed for road transport and 50% for rail transport [9]. The detailed analysis presented in [25] shows that river transport is by far the most advantageous in terms of the costs related to external factors such as noise, air pollution or accidents.

Figure 1. Pusher-barge set [22]

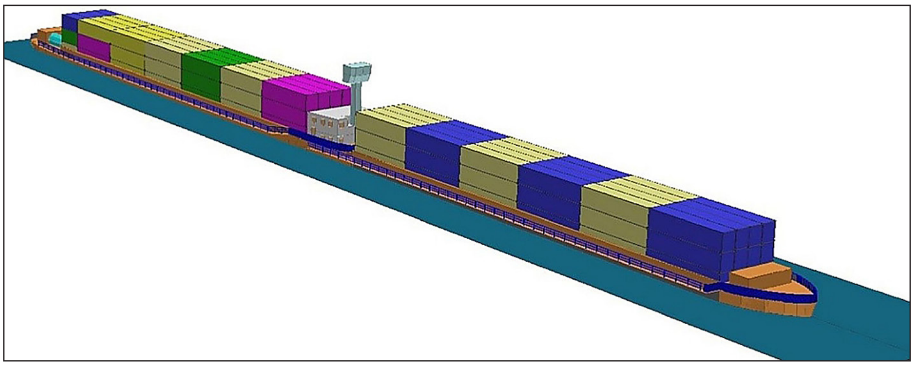

Figure 2. LNG-fuelled vessel with barges [23]

Therefore, it can be concluded that the main cost in the LNG supply chain, next to the gas itself, is transport [26]. As it was noted, the use of the Oder River transport may allow not only to improve the organisation of the LNG supply chain from the Świnoujście (Poland) terminal to the interior of the country, but also reduce costs and improve its efficiency. The liquefied natural gas from the offshore import terminal goes to the island station (SSLNG), where it is stored and then distributed to final recipients. At island stations, LNG is usually regasified. This process requires the supply of heat, the amount of which depends on the composition of the gas, in particular the content of methane (CH_4) and on the thermodynamic parameters of the gas.

LNG regasification at small island stations is mainly carried out in air evaporators called AAV. This type of exchanger uses widely available atmospheric air, which is a free source of heat, to vaporise LNG. A typical AAV evaporator consists of long, parallel or serial finned tubes, which allows for a large heat transfer area. One of the operational problems with AAV evaporators is the formation of frost on the heat transfer surface. The layer of frost that forms acts as additional thermal insulation, leading to a deterioration of heat transfer conditions and a consequent decrease in process efficiency. Hence, it is necessary to periodically remove frost from the exchanger surface, which undoubtedly affects the operating conditions of AAV evaporators. Another problem that occurs during their operation is the formation of ice fog. Despite these disadvantages and the low regasification efficiency per square metre of heat exchange surface area, this type of solution is widely used at small regasification stations, primarily due to low investment and maintenance costs. By using AAV vaporisers, there is also no possibility of using the physical energy accumulated in LNG. The NG liquefaction process requires lowering the gas temperature to -162 °C. As studies and simulations show, depending on the solution used and its efficiency, the specific electricity consumption during the liquefaction process can vary from 0.25 to as much as 1.4 kWh/kg LNG (900–5000 kJ/kg) [27–29]. At the same time, the smaller the condensing units, the higher the specific electricity consumption. The average electricity consumption at large liquefaction stations is in the range of 0.3–0.4 kWh/kg LNG (1080–1440 kJ/kg). Given the efficiency of the liquefaction process, some of this energy is stored in LNG in the form of so-called "cold". Essentially, this cold is treated as a waste product during regasification. Nevertheless, as the examples of large regasification terminals show, a significant part of this energy can be used efficiently. The implementation of appropriate solutions for the disposal of waste cold will allow the full potential of LNG to be realised and thus treat natural gas as an even more environmentally friendly energy source [30–32]. The subject of this study is an attempt to make efficient use of waste cold energy due to a closed-loop economy [33, 34]. With regard to environmental protection [35], it is also worth attempting to adapt the EEDI (energy efficiency design index) for inland conditions. The comparison of CO_2 emission factors for different types of vessels sailing on the Danube [23] is presented in Figure 3.

The proposed assessment method takes into account that inland vessels use considerably less engine power than the maximum available installed on the vessel, which is only needed in cases of extreme operating situations. On the Rhine, for example, a loaded motor vessel 110 m long, 11.45 m wide and with a draught of 2.8 m at medium and high water levels sailing against the current will use between approximately 600 kW and 1000 kW of power, and sailing downstream between approximately 100 kW and 300 kW. However, the installed drive power can be 2500 kW or more. Operating with a propulsion power of 75% of the total installed power, as is the case for seagoing vessels, is not representative of inland waterway vessels.

When comparing the ecological indicators for inland navigation with other modes of transport, it can be noticed that the tonne-kilometre of goods transported by waterways emits five times less CO_2 than road transport. and 10% less than rail transport [24].

The aim of the study was to indicate the possibility of transporting liquefied natural gas by the Oder River as an alternative solution for island gasification in Poland and to determine, based on an energy and substance balance, the potential possibilities of utilising waste cold from the LNG regasification process at small island stations, together with a description of the EEDI coefficient for a theoretical pusher-barge set-up.

MATERIALS AND METHODOLOGY

The subject of the study was regasification stations on the Oder River. On the basis of the data on the number of regasification stations in Poland, those located in the provinces through which the Oder River flows were selected. Out of 143 total stations in Poland, as many as 49 met this criterion [36]. These data were analysed using the geospatial analysis tool QGIS and are shown in Figure 5. The paper evaluates the EEDI index for the theoretical pusher-barge set, which is used to calculate the energy efficiency of a vessel. On the basis of the motor power for a given speed, the EEDI was calculated according to Equation 1 [37]:

$$EEDI = \frac{\mathrm{Cf} \cdot \mathrm{SFC} \cdot \mathrm{P}}{\mathrm{v} \cdot \mathrm{dw}} \tag{1}$$

where: Cf – conversion of grams of fuel (diesel) into grams of CO_2, 3.206 [-], SFC – fuel consumption = 220 g/kWh, V – speed over ground of the pushed vessel/convoy [km/h], dw – load capacity of the pushed vessel/convoy [t].

According to the data in [37], the lower the EEDI of a vessel, the more energy efficient it is and the lower its negative environmental impact. In addition, the study analyses the possibilities of managing waste cold from the LNG regasification process at small island stations.

Figure 4 shows the unit amount of heat necessary for the evaporation of LNG as a function of absolute compression for methane (CH_4) and selected gas compositions: GAZ1 (mass share of methane equal 88%), GAZ2 (mass share of methane equal 82%) and GAZ3 (mass share of methane equal 74%). For the calculations, the initial temperature of the LNG was assumed to be -161.5 °C and 5 °C after regasification. The unit heat quantity $q_{1\text{-}2}$ was calculated according to the relation (Eq. 2). The specific enthalpies of the gas, h, at the beginning and end of the process were determined using the Refprop software [38].

$$q_{1-2} = h_2 - h_1 \; [\frac{kJ}{kg} \tag{2}$$

As shown in Figure 4, under given temperature conditions, the amount of heat required to regasify LNG depends on pressure and methane content. Higher pressure and lower methane mass fraction reduce the amount of heat needed. According to data [36], it can be seen that the regasification capacity of stations along the Oder

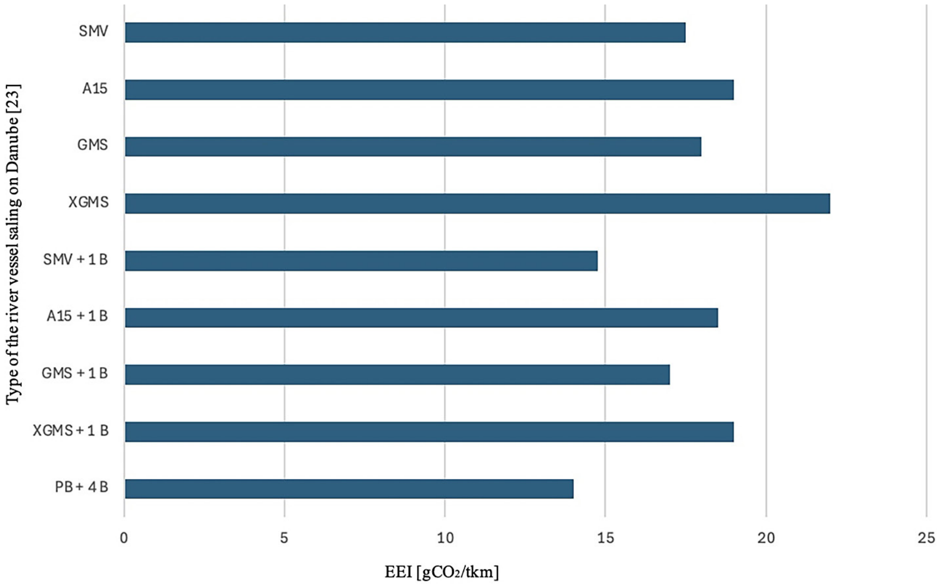

Figure 3. Comparison of CO_2 emission factors for different types of vessels operating on the Danube [23]

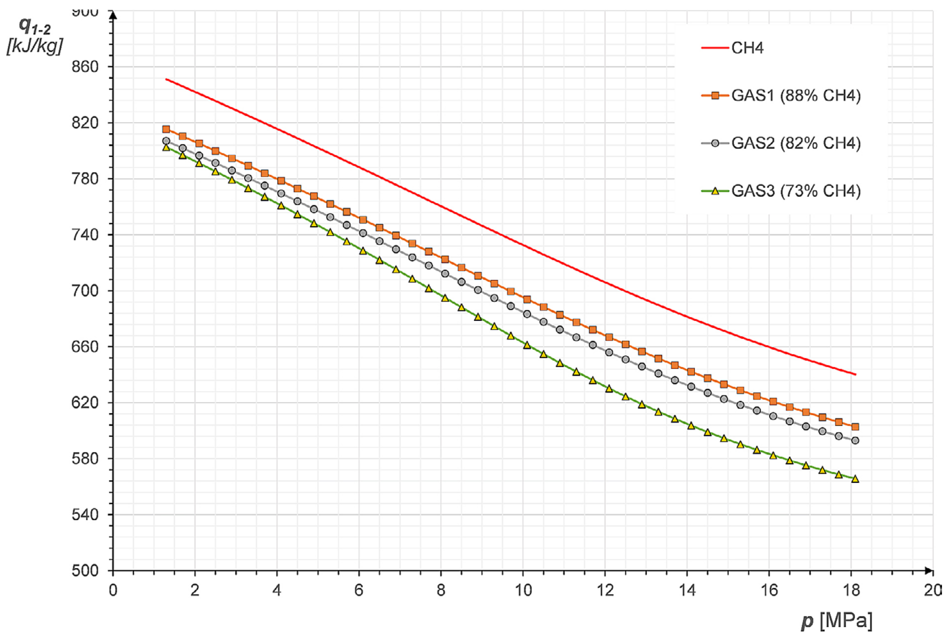

Figure 4. Specific heat delivered to LNG during regasification as a function of pressure

River ranges from 125 to 1600 m^3/h; therefore, the analysis focused on these two extremes.

RESULTS AND DISCUSSION

Analysis and evaluation of the distribution of stations along a selected section of the Oder River

The analysis shows that 44 stations out of 49 are located less than 100 km from the Oder River. The available data shows that the total capacity of the LNG tanks at these stations is more than 1700m^3 [36]. The average capacity of a tanker truck carrying LNG in Poland is 40 m^3. This means that around 43 such tankers are needed to load all the tanks in question at one time. In comparison, if the solutions proposed by [15] or [17] were applied, only 3 such vessels would be needed, while the use of a Europa 2 vessel (and one that is not fully loaded) or a vessel according to the concept presented in [23] would result in only 1 transport, which would significantly reduce both environmental costs and transport risks.

Description of the EEDI coefficient for the theoretical pusher-barge set

A fuel consumption of 220 g/kWh should be adopted for inland waterway vessels, instead of 215 g/kWh as for seagoing vessels. This value comes from inland ship engine test reports [35]. It should be noted that speed-power curves must be available prior to the calculation of the energy efficiency design index (EEDI) in order to estimate the speed of the vessel and the power required. Unfortunately, the results of river tests are not available in databases, so the ship power was calculated using the graph below built on the basis of the data obtained in the model tests presented in [23], which was presented in Figure 6.

Concept of the system for utilisation of waste

On the basis of the Equation 1 and using the data presented in Figure 6 as well as Table 1, EEDI was calculated for the theoretical set of pusher-barge.

The EEDI coefficient for the theoretical pusher-barge set is 17.31 gCO_2/tkm. These calculations, although based on theoretical assumptions, coincide with the actual data presented in [23, 35] for ships sailing on the Danube (Figure 3). From the analysis, the result was that none of the pushed sets exceeded the EEDI coefficient > 20 gCO_2/tkm and no type of ship exceeded the value of 25 gCO_2/tkm.

An attempt to estimate the potential opportunities from the management of waste cold from the LNG regasification process at small island stations

In order to identify the potential areas for the use of waste cold from the LNG regasification process at small island stations, the stock of available waste cold was divided into three temperature ranges (Table 2). Adopting such a division has made it possible to isolate application opportunities. On the basis of the division adopted, a proposal for an LNG regasification system with waste cold utilisation was developed for a small island station. A conceptual scheme of the system is shown in Figure 7. Performance simulations were carried out in the Aspen Plus® environment, using the NIST model and Peng Robinson.

The regasification system under consideration envisages the use of waste cold to produce electricity and cooling useful for production applications as well as storage of perishable products. Electricity generation was based on the organic Rankine cycle (ORC). Ethylene was chosen as the working medium. The circuit is fed with Q1 and Q2 heat from, among other sources, refrigeration processes, while the bottom source is regasified LNG. Thus, the realisation of this circuit allows the simultaneous production of electricity on turbines T1 and T2 as well as realisation of the cooling process. In another part of the system, the cold from the regasification process is used exclusively for cooling purposes; 60% ethylene glycol is used as a heat transfer

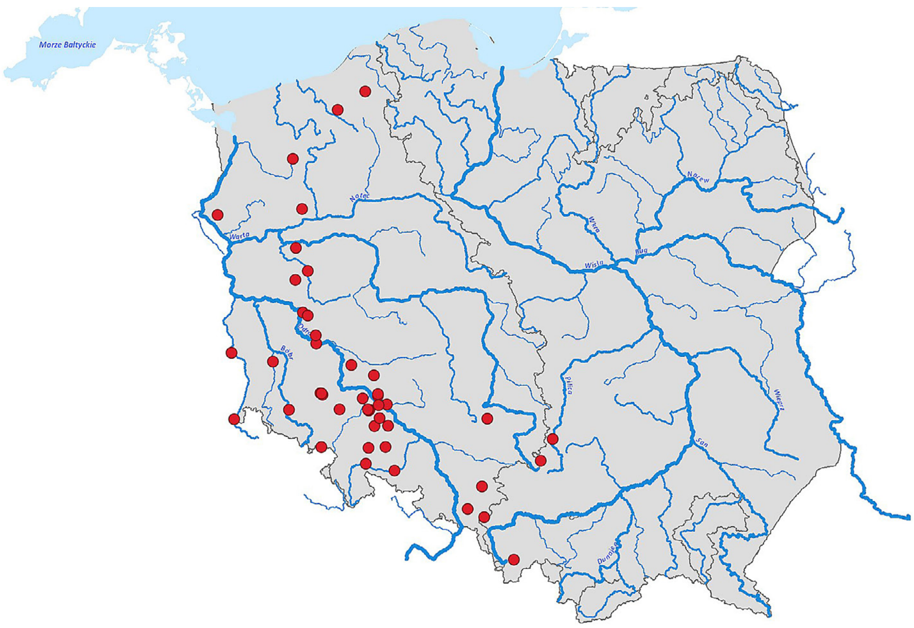

Figure 5. Location of regasification stations in the provinces through which the Oder River flows

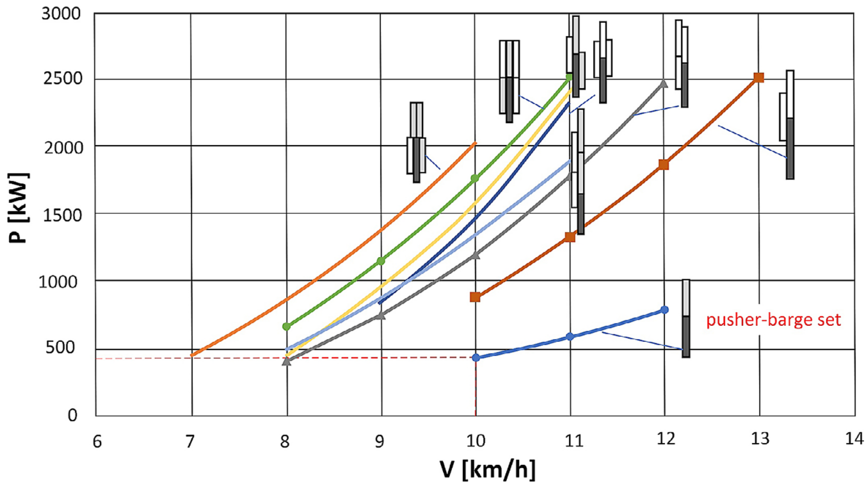

Figure 6. Power consumption depending on the speed for different configurations of pushed sets (Own study based on [23])

Table 1. Parameters of a theoretical pusher-barge for EEDI calculation

Parameter	Value
Width of pushed vessel/convoy, B	11.4 m
Depth of water, h	3.5 m
Load capacity of the pushed vessel/convoy, dw	2000 t
Speed above over ground of the pushed vessel/convoy, V	10.0 km/h
Power used to achieve speed, P	490.0 kW

medium between the regasified LNG and the cooled facility. Detailed process parameters are shown in Table 3.

The following simplifying assumptions were made for the calculations and analyses:

- LNG and NG gas fuel is treated as pure methane,
- no heat loss to the environment, no pressure drops in the pipelines,
- the heat exchange process is quasi-static,
- the expansion process on the turbine is isentropic with an internal efficiency of 0.88.

On the basis of the heat and mass balance, the following quantities were determined for the assumed conditions (Eq. 3–10).

The unit amount of heat transported in the HE1 exchanger (Eq. 3):

$$q_{HE1} = h_2 - h_1 = h_A - h_B \left[\frac{kJ}{kg}\right] \quad (3)$$

The unit amount of heat transported in the HE2 exchanger (formula 4):

$$q_{HE2} = h_3 - h_2 = h_{1-4} - h_{1-1} \left[\frac{kJ}{kg}\right] \quad (4)$$

The unit amount of heat transported in the HE1 exchanger (Eq. 5):

$$q_{HE3} = h_4 - h_3 = h_{2-4} - h_{2-1} \left[\frac{kJ}{kg}\right] \quad (5)$$

The unit amount of heat delivered to the EVA1 evaporator (Eq. 6):

$$q_{EVE1} = h_D - h_C \left[\frac{kJ}{kg}\right] \quad (6)$$

Table 2. Available waste cold resource and potential application areas (based on the Refprop programme [38])

No.	LNG temperature variation range [°C]	Amount of available heat *q* [kJ/kg$_{LNG}$]	Proposed areas for the use of cold waste	Circulation operation parameters
1.	od -161.0 do -96.0	633.88	Dry ice production (Q1), electricity (ORC circuit) (lower source), refrigeration (Q2)	Electricity production ORC cycle, working medium, e.g. ethylene
2.	od -96.0 do -51.0	98.08	Refrigeration, freeze-drying of foodstuffs, (Q3), electricity (ORC)	Use of a heat transfer medium. Working medium, e.g. ethylene glycol
3.	od -51.0 do +5.0	123.09	Air conditioning, refrigeration (Q4)	Use of a heat transfer medium, e.g. ethylene glycol 60%

The unit amount of heat delivered to the EVA1 evaporator (Eq. 7):

$$q_{EVE2} = h_F - h_E \left[\frac{kJ}{kg}\right] \quad (7)$$

Unit expansion work on turbine T1 (Eq. 8):

$$l_{T1} = h_D - h_E \left[\frac{kJ}{kg}\right] \quad (8)$$

Unit expansion work on turbine T1 (Eq. 9):

$$l_{T2} = h_F - h_A \left[\frac{kJ}{kg}\right] \quad (9)$$

The energy efficiency of the ORC cycle calculated according to the formula below (Eq. 10):

$$\eta_{EORC} = \frac{l_{ORC}}{q_d} = \frac{(l_{T1} + l_{T2}) - l_{pump}}{q_{EVA2} + q_{EVA1}} [-] \quad (10)$$

For the temperature range and operating medium adopted, the efficiency of the ORC cycle was 18%. As a result of this circuit, the work achieved was 126 kJ/kg. In addition, the total amount of cold for refrigeration and air conditioning purposes was 658 kJ/kg in the temperature range from -70 °C to +10 °C. Assuming the capacity of the regasification station at the level of 125 m_n^3/h, for the analysed system the waste cold stream would equal 19.5 kW. Mass flow rate of the working medium in the ORC circuit $\dot{m}_{ORC}$ = 0.0312 kg/s, hence the theoretical power generated on the turbines is 3.98 kW, and the heat fluxes Q1 = 15 kW, Q2 = 2.5 kW. Power required to power pump P1 0.7 kW. The fluxes Q3 and Q4 are 3 kW and 2.2kW, respectively, for glycol mass flow rates $\dot{m}_{1-1}$ = 0.0444 kg/s and $\dot{m}_{2-1}$= 0.098 kg/s.

As demonstrated, the utilisation of waste cold generated during the LNG regasification process at small-scale island regasification stations enables the comprehensive recovery of the energy potential accumulated in LNG. This approach contributes significantly to improving the overall quality and efficiency of the supply chain. Numerous studies address systems for utilizing waste cold from LNG regasification for electricity generation or cooling applications [30–32].

In the future studies expanding on this topic, the analysis will be refined by considering a broader range of working fluids, varying thermal parameters, and operating conditions.

Table 3. Thermodynamic parameters of operating media at characteristic points

Characteristic point		t [°C]	p [MPa]	ρ $\left[\frac{kg}{m^3}\right]$	h $\left[\frac{kJ}{kg}\right]$	s $\left[\frac{kJ}{kg \cdot K}\right]$
LNG	1	-161	0.6	421.45	-5551.76	-11.68
NG	2	-96	0.6	6.97	-4917.88	-7.10
	3	-51	0.6	5.39	-4819.79	-6.46
	4	5	0.6	4.23	-4696.70	-6.12
Ethylene	A	-91	0.2	4.06	1689.85	-2.89
	B	-100	0.2	562.69	1227.08	-5.44
	C	-91	4.0	550.05	1249.92	-5.34
	D	5	4.0	82.96	1735.25	-3.38
	E	-46	1.2	24.62	1694.50	-3.31
	F	-21	1.2	18.57	1776.74	-2.95
Ethylene-glycol	1–1	-60	0.5	1194.63	-7529.29	-7.13
	1–2	-60	0.5	1194.63	-7529.00	-7.13
	1–3	-30	0.3	1168.96	-7461.21	-7.40
	1–4	-30	0.3	1168.89	-746.24	-7.40
	2–1	0	0.3	1142.67	-7393.33	-7.13
	2–2	0	0.5	1142.64	-7393	-7.13
	2–3	10	0.5	1133.80	-7370.55	-7.06
	2–4	10	0.3	1133.77	-7370.38	-7.06

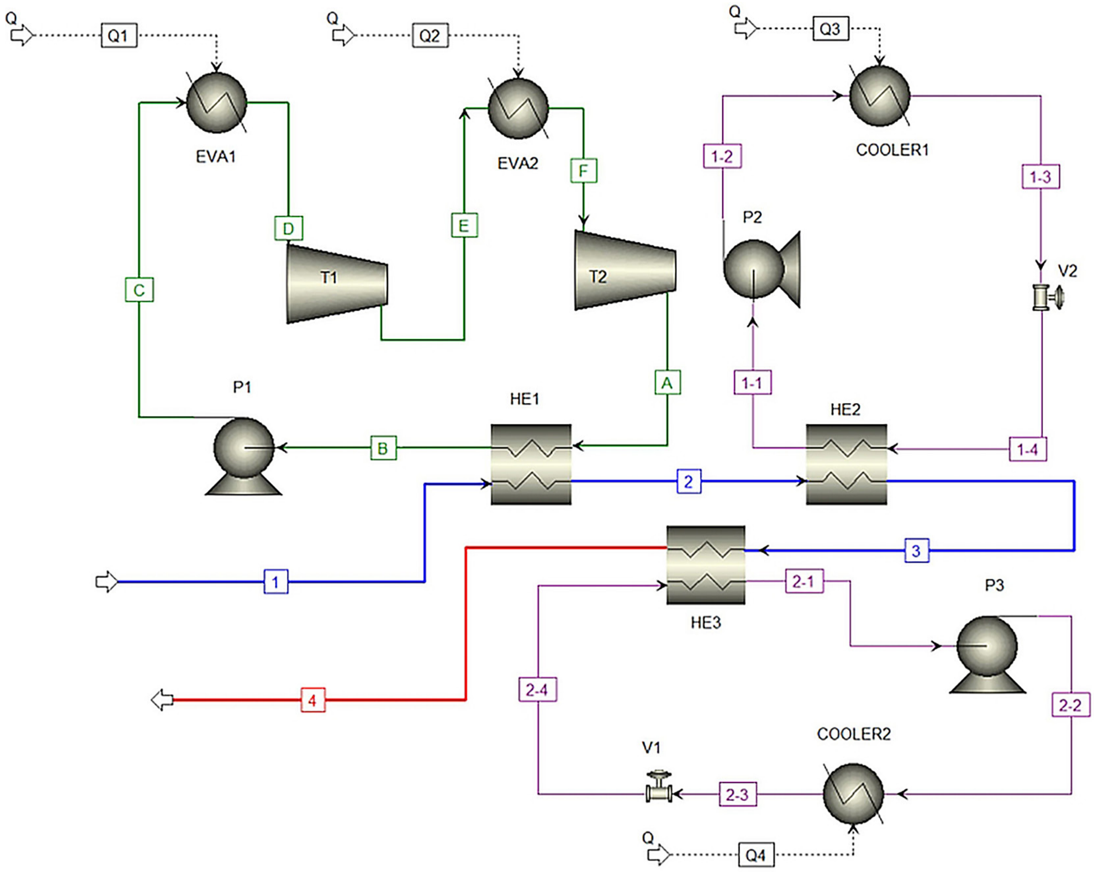

Figure 7. Concept of the system for utilisation of waste cold from the LNG regasification process (developed by Aspen plus): T1, T2 – turbine, P1, P2, P3 – pump, HE1, HE2, HE3 – LNG regasification heat exchanger, EVA 1, EVA 2 – ORC cycle evaporators, COOLER1, COOLER2 – heat exchangers fed with heat from cooling processes, Q1, Q2, Q3, Q4 – heat streams, V1, V2 – control valve.

CONCLUSIONS

The results has shown that LNG transport on the Oder River in Poland can be an efficient, ecological and economically viable alternative to road transport. In particular, it can play a key role in the process of island gasification in Poland, i.e. supplying natural gas to the regions without access to the national gas network. The increase in demand for LNG in these areas is linked to the need to optimise its transport, and inland waterways can be an important complement to current logistics methods, based mainly on tanker transport.

There were used an energy and mass balance approach to estimate the potential opportunities and benefits of managing waste cold from the LNG regasification process at small island stations. According to the data, the regasification capacity of stations along the Oder River ranges from 125 to 1.600 m³/h. The research indicated that this concept of estimating potential for waste cold utilisation is a viable method for harnessing the energy contained in LNG. Studies demonstrated the significant energy potential of LNG, showing that even simple heat recovery systems can effectively utilise waste cold from the regasification process.

Furthermore, it was pointed out that there are many areas where waste cold can be used effectively. The introduction of a specific solution depends on many factors, including the capacity of the regasification system, the continuity of the process, the location of the island station, the possibility of selling cold to external customers, etc. Studies have shown that it seems reasonable to introduce systems to manage waste cold in the case of island gasification. This will allow the efficient use of all the energy potential accumulated in LNG and will have a positive impact on environmental protection.

The analysis showed that inland waterway transport has a significantly lower carbon footprint compared to road transport, as the specific fuel consumption per tonne-kilometre is up to four times lower than for truck transport. This means that the use of LNG barges would allow a significant reduction in CO_2 and other pollutant emissions, in line with the European Union's policy of decarbonising the transport sector. The obtained results of the EEDI coefficient for inland conditions, although based on theoretical assumptions, coincide with the actual data presented for ships sailing on the Danube and none of the pushed sets exceeded the EEDI coefficient > 20 gCO_2/tkm and no type of ship exceeded the emission value of 25 gCO_2/tkm. The results of the research showed that it seems reasonable to indicate the CO_2 emission coefficient in the context of the island gasification of Poland.

In addition, river transport is characterised by greater safety than road transport, which involves the risk of accidents, traffic jams and changing weather conditions. LNG transported by barges could arrive at transhipment terminals. and from there be distributed to individual customers in a more efficient manner.

However, a key barrier to realising this solution is the state of the inland infrastructure. Currently, only 5.5% of Polish rivers meet European waterway standards (Classes IV and V). In order to enable the efficient transport of LNG, the Oder needs to be upgraded to Class V, which would allow the free navigation of modern vessels. However, this requires significant investment in dredging the river, building new locks and upgrading existing river ports. which could act as transhipment points for LNG.

The European Union is promoting inland waterway transport as a greener and more sustainable logistics solution. The inclusion of the Oder River in the TEN-T network (Trans-European Transport Network) and the implementation of projects under EU funds may accelerate the development of this form of transport. In addition, it has been shown that reducing CO_2 emissions by transporting LNG by water would allow Poland to facilitate achieving its climate goals under the European Green Deal.

The study showed that LNG transport via the Oder can make a significant contribution to the development of island gasification reducing emissions and improving the energy efficiency of gas supply.

The use of inland waterways for this purpose is part of both the national strategy and the EU policy. A key challenge, however, remains the modernisation of river infrastructure, without which it will be impossible to realise its full potential. Investment in the development of inland shipping as well as integration of river transport into the existing LNG logistics system can bring tangible economic benefits in the long term. environmental and energy benefits.

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