clean technologies

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# Applicability of Hydrogen Fuel for a Cruise Ship

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**Abstract:** Cruise ships function as a means of transport while simultaneously accommodating thousands of guests, providing a holiday experience with various entertainment options. This translates to high energy requirements for propulsion and hotel operations, typically covered by the combustion of fossil fuels. The operation of cruise vessels with fossil fuels contributes to carbon dioxide and also local harmful emissions in ports when shore power connections are not available. To enable cleaner and sustainable cruising, alternative technologies and fuels must be adopted. The present study evaluated the applicability of hydrogen fuel in combustion engines in a Meraviglia-class cruise ship. The fuel consumption of the ship was based on a real operation in Europe. This study examined how fuel energy in the form of $LH_2$ could be stored on the ship for a European cruise route and concludes that 3700 $m^3$ of storage space would be needed to accommodate the liquid hydrogen. The mass of the $LH_2$ would only be one-third of that of fossil fuels, but the weight of the $LH_2$ tanks would most likely increase the total weight of the hydrogen storage. Additional new technologies and combined power production could significantly reduce the amount of $LH_2$ to be stored.

**Keywords:** marine engines; cruise ships; renewable fuels; hydrogen; fuel consumption; fuel storage; safety

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Academic Editors: Leonid Tartakovsky and Damien Guilbert

Received: 16 October 2024
Revised: 19 December 2024
Accepted: 25 December 2024
Published: 10 January 2025

**Citation:** Mäkelä, M.; Niemi, S.; Nuortila, C.; Nyystilä, L. Applicability of Hydrogen Fuel for a Cruise Ship. *Clean Technol.* **2025**, *7*, 6. https://doi.org/10.3390/cleantechnol7010006

## 1. Introduction

Cruise vessels have a high-energy demand for propulsion and considerable hotel load [1]. Today, cruise ships are mostly operating with a diesel–electric configuration and hybridized power trains. Diesel engines usually operate with fossil fuels like heavy fuel oil (HFO) and marine gas oil (MGO) in conjunction with technologies to reduce emissions to meet MARPOL regulations as well as regional (e.g., on an EU level) and local (e.g., port) requirements. The market for marine fuels is still dominated by conventional fossil fuels [2].

Hellström et al. [3] say that, in 2018, the cruise shipping segment caused an annual amount of greenhouse gas (GHG) emissions of approx. 30 million tonnes of $CO_2$ equivalents. The data were taken from the Fourth IMO GHG Study 2020 Executive Summary [4]. This reference also reports that shipping caused 1076 million tons of greenhouse gas emissions (GHG) in 2018, of which 1056 million tons were $CO_2$ emissions [4]. Thus, only approx. 3% of $CO_2$eq emissions from shipping originate from cruise ships. The emissions per a cruise ship are, however, higher compared to other ship types, because of which the GHG emissions from the cruise shipping segment are important to study [3] and reduce. Lately, significant steps have been taken to reduce the greenhouse gas intensity of shipping, most prominently driven by amendments to MARPOL's Annex VI (EEDI, EEXI and CII). The uptake of zero or near-zero GHG emission technologies, fuels and/or energy sources is to be increased.

In addition to GHG emissions, the operation of ships with fossil fuels contributes to harmful emissions, including particulate matter (PM), sulphur oxides ($SO_x$) and nitrogen oxides ($NO_x$). These emissions are a great concern locally. Harmful emissions can have negative health effects on the coastal human population [5]. These include, e.g., an increased number of asthma diagnoses and heart attacks. In fact, a linkage between PM and $SO_x$ pollution and lung cancer and cardiopulmonary mortality has been shown [6,7]. Again, recent amendments to MARPOL Annex VI have considerably cut the allowable limits of local emissions, which can be met by adopting very low sulphur blends or exhaust gas treatment units (scrubbers) for $SO_x$ reduction and Tier II or Tier III engine technologies for $NO_x$ reduction.

In their revised GHG strategy, the International Maritime Organization [8] adopted the goal to reach net-zero GHG emissions in international shipping by or close to 2050. Ambitious regulations are also being introduced at an EU level (EU ETS and FuelEU Maritime), involving remarkable financial penalties to ships that do not significantly reduce their environmental footprint. The cruise shipping industry has a clear interest to further improve energy efficiency and to reduce emissions by adopting alternative technologies and fuels, ultimately enabling sustainable net-zero cruising.

The uptake of low-carbon or carbon-free fuels is one of the most important measures to achieve reductions in both global and local emissions. Although of fossil origin, liquefied natural gas brings about significant improvements to $CO_2$ and $NO_x$ emissions as compared to HFO or diesel oil [9]. Since 2018 when the first fully LNG-powered cruise ship was commissioned, there are tens of cruise ships on order and operating on LNG. Fuels such as biomethane, methanol or hydrogen are at present some of the most discussed alternative fuels in shipping. Research has shown that the use of biomethane can provide huge GHG benefits compared with the use of marine diesel oil [10].

By applying hydrogen fuel for propulsion, in theory, it is possible to eliminate all $CO_2$, CO and PM emissions. The combustion of hydrogen in an internal combustion engine can still produce $NO_x$ emissions. However, $NO_x$ emissions can be reduced by controlling the combustion temperature or by adding after-treatment devices [11], as is being done today on vessels, powered by conventional fuel oil. One concern is the volumetric energy density of hydrogen—to store an equivalent amount of energy, liquid hydrogen requires four times more space than MGO and about two times more space than LNG [12]. However, cruise routes are usually relatively short; thus, frequent bunkering is possible, and hydrogen can be considered as a potential future fuel for cruise ships. In addition to combustion engine machinery powered by hydrogen, liquid hydrogen is already used with fuel cells [13,14].

This study evaluates the applicability of hydrogen fuel in combustion engines in a Meraviglia-class cruise ship [15]. The fuel consumption of the ship is based on real historical operations in Europe.

It is assumed that the conventional engines of the cruise ship are replaced with novel hydrogen engines, achieving similar efficiency to today's efficient dual-fuel (LNG/fuel oil) engines. Based on these assumptions, the future operational profile of the cruise ship was defined. This study explores the demand of the cruise ship for liquid hydrogen at full engine load for various fuel conversion efficiencies of the engine. This study presents the volume and mass of liquid hydrogen relative to the consumed fuel energy during a ten-day itinerary of the cruise ship and calculates the fuel storage mass and volume of required fossil fuels versus liquefied hydrogen.

## 2. Materials and Methods

Currently, the examined vessel is equipped with four-stroke diesel engines, two Wärtsilä 12V46 and two Wärtsilä 16V46 engines. The future hydrogen engines are assumed to have properties like the existing Wärtsilä 46TS-DF engines [16]. With a cylinder power of 1300 kW/cylinder, the rated power for a 12-cylinder engine would be 15.6 MW and for a 16-cylinder engine 20.8 MW. Concerning hydrogen fuel consumption, it is assumed that the fuel conversion efficiency with hydrogen is the same as it is with LNG. No pilot fuel is expected to be needed. Hydrogen is less energy dense than conventional marine fuels, which affects the volumetric fuel consumption [2]. As per the engine's manufacturer, Table 1 shows the fuel conversion efficiency at various engine loads.

**Table 1.** Fuel conversion efficiencies for specific engine loads (based on [17]).

| Engine Load (%) | Fuel Conversion Efficiency (%) |
|---|---|
| 50 | 46 |
| 75 | 48 |
| 85 | 49 |
| 100 | 49 |

The historical operational profile of the Meraviglia cruise ship is based on a seven-day itinerary, which well represents a typical voyage in the Mediterranean Sea. The cruise starts at Genova, visiting Civitavecchia, Napoli, Messina, La Valletta and Palermo, and then returns to Genova. The cruise ship is equipped with exhaust gas treatment systems (scrubbers), and the machinery can operate on high-sulphur HFO (3.5% sulphur) as the primary fuel and MGO (0.1% sulphur) as the secondary fuel. Some key parameters defined for baselining are collected in Table 2. The total fuel energy consumption of the cruise ship is baselined to be 6049 MWh for the seven-day itinerary. This figure also includes the boiler energy consumption that is assumed at 1.8% of the total fuel consumption based on the baseline ship machinery arrangements and energy consumption specification.

**Table 2.** Baseline parameters for a 7-day itinerary.

| Parameter | Value |
|---|---|
| Maximum number of people onboard | 8034 |
| Voyage distance | 1472 nm |
| Main engine fuel (HFO) | 530 t |
| Boiler fuel | 9 t |
| Propulsion transformer energy consumption | 1082 MWh |
| Hotel transformer energy consumption | 1396 MWh |
| Total fuel energy consumption | 6049 MWh |
| Powerplant efficiency (average) | 41.7% |

It is assumed that the limited availability of hydrogen fuel in ports will affect the amount of hydrogen stored onboard in the coming years. To ensure the safe return of the vessel to port, hydrogen tank capacities are sized based on a minimum of a 10-day itinerary with a granted survivability of seven (7) continuous days at sea. For 10 days, the total energy consumption would be 8641 MWh without any improvements to the technical efficiency or power generation.

## 3. Results

The above values were used as a reference to evaluate the inventory of hydrogen. It was decided to store hydrogen as liquid ($LH_2$). The density of $LH_2$ is 70.8 kg/m$^3$ or much higher than the density of compressed gaseous hydrogen. Here, the effect of boil-off was not evaluated.

Figure 1 shows the volume flow rate of $LH_2$ required by engines having various fuel conversion efficiencies (41, 45 and 49%). The lower heating value of hydrogen is assumed at 120 MJ/kg and the density of liquid hydrogen at 70.8 kg/$m^3$. At full load of all the engines (72.8 MW), the consumption of hydrogen would be 63 $m^3$/h, if the fuel conversion efficiency is 49%, or that given by the engine manufacturer (Table 1).

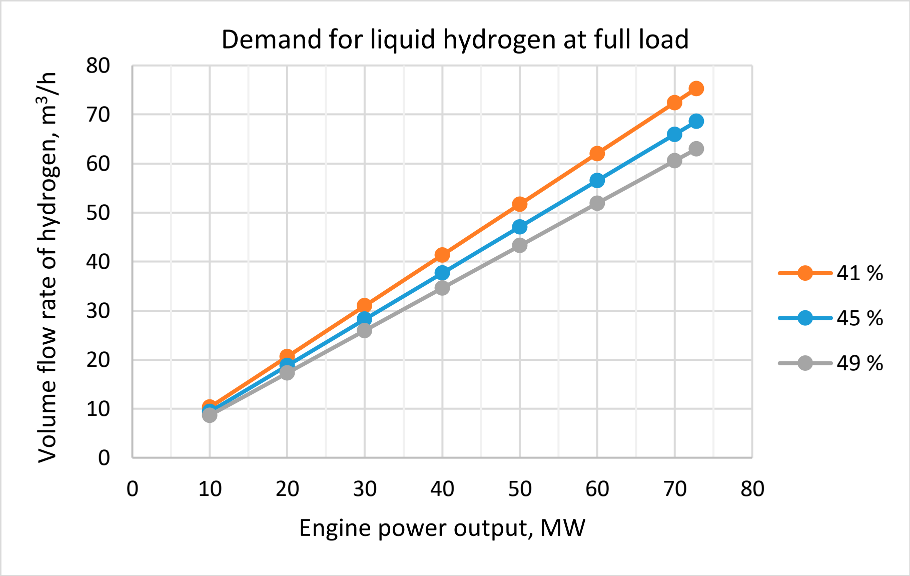

**Figure 1.** Volume flow rate of liquid hydrogen against engine brake power at various fuel conversion efficiencies of the engine.

Figure 2 depicts the total volume and mass of liquid hydrogen needed for a ten (10)-day itinerary. The values of the figure are based on the total fuel energy consumption of the cruise ship, thus also including the energy consumption of the boilers (approx. 1.8% of the total). If the ten-day consumption is 8641 MWh, the total volume of liquid hydrogen is, approximately, 3700 $m^3$ and the mass is 260 t (Figure 2). Hydrogen's lower heating value was again assumed at 120 MJ/kg and the density at 70.8 kg/$m^3$ when computing the values for Figure 2.

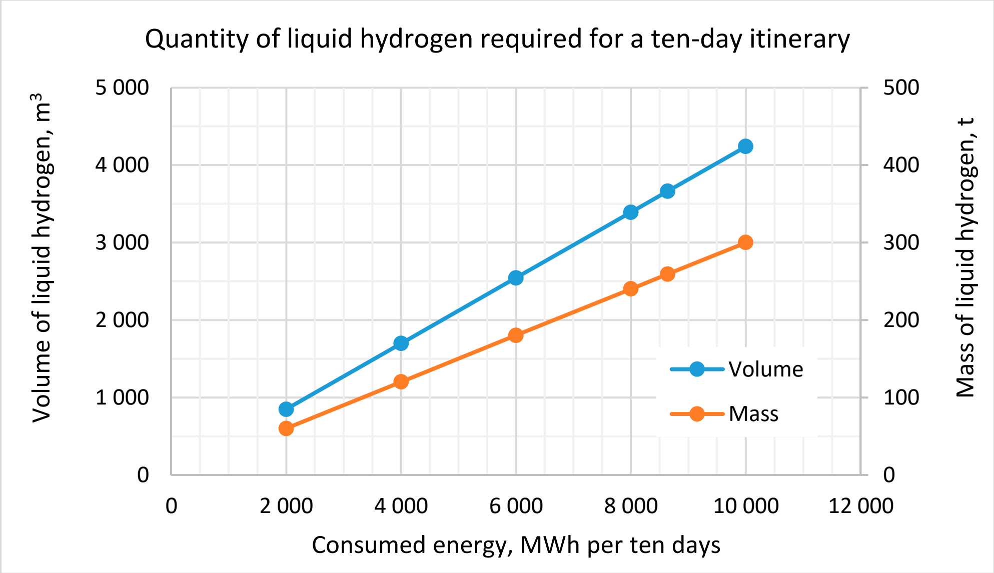

**Figure 2.** Volume and mass of liquid hydrogen versus the consumed fuel energy during a ten-day itinerary.

Based on the 10-day itinerary energy consumption, the fuel mass and total volume of the HFO and MGO fuel storage were calculated as a weighted average reflecting the vessel’s existing fuel tank volume. The fuels’ lower heating value was considered to be 40 MJ/kg. Approximately 780 tons or 806 to 830 $m^3$ of fuel oils, HFO and MGO, contain the energy needed for the 10-day itinerary (Table 3).

**Table 3.** Comparison of fuel storage mass and volume for a 10-day itinerary operated on fossil fuels versus liquefied hydrogen.

| 10-Day Itinerary | Energy [MWh] | Fuel Mass [tons] | Total Volume of Fuel Storage Needed [$m^3$] |
|---|---|---|---|
| HFO and MGO | 8641 | 780 | 806 to 830 |
| $LH_2$ | 8641 | 260 | 3700 |

To be able to store 8641 MWh in the form of liquefied hydrogen, 260 tons or 3700 $m^3$ of $LH_2$ need to be accommodated. While the weight of the HFO and MGO for a 10-day voyage adds up to 780 tons, only 260 tons of liquid hydrogen would be needed to produce the same amount of energy. Here, the additional weight of the $LH_2$ tanks due to effective insulation has not been considered and will naturally increase the total weight of the hydrogen storage. Still, the reduction in the fuel mass is substantial.

## 4. Discussion

To mitigate the effects of the greenhouse effect on the planet, it is necessary to also reduce GHG emissions of maritime transport and cruise ships. Crucial measures toward this goal have been implemented over the past few years; however, reaching the ultimate goal of net-zero shipping requires the adoption of carbon-neutral fuels. For the time being, the use of alternative fuels is very limited in marine applications. DNV [2] discussed the uptake of alternative fuels in the world ship fleet. In June 2024, almost 1240 LNG-capable ships operated and approximately 830 LNG ships were on order, while only three (3) ships of the world fleet operated on hydrogen and another ten (10) were on order. Approximately 73% of ships on order, representing about 50.5% of gross tonnage, are still going to be built to operate on conventional fuel [2]. The whitepaper by ABS [12] on hydrogen as a marine fuel projected that by 2050, there will be 35% ammonia/hydrogen in use in a mix of fuels.

In general, it has been stated that the usage of LNG can lower the barrier for the use of liquid hydrogen in shipping [18,19]. It is seen as a benefit that the marine industry has learned from the usage of LNG. There is knowledge and good practices of storing cryogenic liquid, which boils off, and the bunkering of cryogenic liquid. Of course, it must be noted that liquid hydrogen is in many ways different to LNG.

Many projects during the past decade or so have envisioned hydrogen to power ships, typically combined with fuel cells as an energy conversion mechanism. Klebanoff et al. [20] reported on the feasibility of a research vessel, powered by a zero-emission hydrogen fuel cell. The vessel was designed for coastal voyages, equipped with two on-deck fuel tanks for liquefied hydrogen with a capacity of 10.9 t, which is a small fraction of the projected amount for the present cruise ship’s 260 t. The research vessel’s operational range was given to be 2400 nautical miles. The vessel design received a conditional Approval in Principle (AiP) from DNV GL.

However, there also are some examples of vessels powered by hydrogen-driven combustion engines. Volvo Penta and CMB.TECH have developed a dual-fuel marine engine for hydrogen and diesel. Small ferries in Belgium and off the coast of Japan have been operating with this engine technology for some time [21]. The DF solution helps to overcome situations when hydrogen is not available.

In 2023, the Japanese classification society ClassNK issued the concept AiP for the world's first hydrogen-powered vessel with a two-stroke engine operating on liquefied hydrogen [22]. The engine will be supplied by the Japan Engine Corporation (J-ENG) and the fuel supply system by Kawasaki [23]. The ship shall be built in 2027–2028.

The present study also looked at an engine-driven marine solution, a cruise ship powered by hydrogen-driven engines. Liquid hydrogen was selected as the fuel for the ship. This study sized the hydrogen tank capacities based on a minimum of a 10-day itinerary with a granted survivability of seven (7) continuous days at sea. For 10 days, the total historical energy consumption was 8641 MWh. Cruise ships typically operate relatively short routes where it is basically possible to bunker hydrogen fuel regularly in ports. If only there were more bunkering possibilities, less space could thus be required. However, here it was assumed that bunkering limits the range of a cruise ship still today, since hydrogen infrastructure in ports is missing for now.

Nevertheless, based on the cruise ship's existing tank volumes, enough liquefied hydrogen could be stored onboard to cover the energy demand of a 10-day itinerary. In addition to the cryogenic storage, the fuel supply system would require space, however, and safety measures specific to the use of hydrogen will also affect the overall arrangement and layout. This has not been included in the present considerations. The IMO is working on developing interim guidelines for the safety of ships using hydrogen as fuel [24].

The result of this study can be compared to a study by Mao et al. [25] who evaluated the energy demand and the need of refueling for container ships if operated with hydrogen fuel cells instead of slow-speed diesel engines operating on HFO. The focus of the paper was on container ships on transpacific routes between China and the United States. Mao et al. [25] concluded that more than 40% of the voyages could be completed without losing cargo space to hydrogen storage and even without additional refueling. Almost all or 99% of the voyages could be made with liquid hydrogen, with the ship's fuel capacity or operations somewhat adapted. One such change was to replace 5% of the cargo space with hydrogen storage. If the ship called at one or two additional ports and refueled, the voyage attainment rate increased.

Practice has shown that although liquid hydrogen is stored in highly insulated vessels, hydrogen always boils off because of heat leakage into the tank, ortho- to para-hydrogen conversion, sloshing and flashing [26]. The boil-off phenomenon is more pronounced with small tanks because of the higher surface area-to-volume ratio [27]. Boil-off is also dependent on the initial pressure of the tank and on how much hydrogen is consumed [28]. In 2020, Kawasaki Heavy Industries [29] announced completion of its basic design for a large spherical liquefied hydrogen storage tank. The tank was described as a double-shell tank with a vacuum-insulation structure. The storage capacity for liquefied hydrogen was given with 10,000 $m^3$ having a boil-off rate of 0.1 wt% per day or less.

Boil-off hydrogen can be used for additional power generation, e.g., in fuel cells. Only recently, DNV awarded an AiP to Korean shipbuilders for a new hydrogen system, in which hydrogen dual-fuel (DF) engines and fuel cells utilize boil-off gas from hydrogen transport [30]. This type of hydrogen carrier is expected to be ready by around 2030. Another publication by Alkhaledi et al. [31] discusses the design of a hydrogen-fueled tanker ship where the boil-off hydrogen was planned to be utilized in a hydrogen-fueled combined-cycle gas turbine. This design ship was equipped with four liquid hydrogen type-C tanks with a volume of 70,600 $m^3$ per tank. One tank can fit 5000 tons of liquid hydrogen. The total weight of the tank was estimated to be 21,955 tons, which shows that the tank itself has a remarkable weight (almost 80% of the total weight). The boil-off loss was expected to be 0.1% per day, which resulted in 20 tons per day. However, this reported tank design has been under criticism [32]. In fact, cryogenic tanks are currently the focus of research and the aim is to develop large enough tanks with minimal boil-off while at the same time optimizing, e.g., the weight of the tank for different applications [26,33,34].

In the present study, the assumption was that the engines do not use any pilot fuel for ignition. The goal was to eliminate any GHG emissions caused by the pilot. It should be noted, however, that the pilot fuel can also be renewable diesel or high-quality biodiesel with very small GHG emissions. The amount of pilot fuel is small, ranging from approx. 3 to 10% of the energy input depending on the engine load [35]. Some companies and researchers report on even smaller pilot fuel quantities, like 1% of the total input of fuel energy at full load [36,37].

It seems that the availability of renewable diesel or biodiesel does not pose any problems for the future. A separate tank is, of course, still needed onboard. Compared with spark- or glow-plug ignition, the use of pilot fuel is a very robust ignition source. With high-pressure direct injection of $H_2$ and pilot ignition, there is no premixed fuel that could lead to a knocking condition. The combustion process allows the engine to reach high power outputs and a high thermal efficiency with a favorable transient response [38]. As said, Volvo Penta and CMB.TECH have decided on the DF technology, and small ferries have already been operating with it [21]. In addition to the effective ignition, the DF solution helps to overcome situations when hydrogen is not available.

Finally, expressed as estimated HFO-equivalent fuel consumption in 2018, most of the fuel in international shipping is being consumed by container ships, bulk carriers and oil tankers and only roughly 3% by cruise vessels [4]. It is to be expected that other vessel types will shape the development of the marine fuel market more strongly than the cruise ship industry.

## 5. Conclusions

As part of the global effort to drastically reduce greenhouse gas emissions from human activity, it also is important to reduce emissions from cruise shipping. Largely driven by the introduction of relevant regulations, significant progress is being made by improving ship technology, striving for operational energy efficiency and investing in transitional fuels, such as LNG. A transition to renewable fuels is the next step toward green and sustainable cruising. Among the new fuel options, hydrogen is envisioned to be of importance in near-coastal areas and, thus, even cruise shipping.

The present study evaluated the applicability of hydrogen fuel in a Meraviglia-class cruise ship. The fuel consumption of the ship was based on real historical data. It was assumed that the current ship engines are replaced by novel hydrogen engines and liquid hydrogen ($LH_2$) is used as the fuel. This study examined how the fuel energy could be stored in the ship for a common European cruise route.

Theoretically, the existing fuel storage capacity of a Meraviglia-class cruise ship would be enough to enable hydrogen storage for a 10-day itinerary in the Mediterranean. While the tank volume would be almost filled to the brim, the weight of $LH_2$ was only one-third of that of the current fossil fuels.

Further research is, however, needed to find out how the special requirements set for the fuel supply system, $LH_2$ tanks and safety would affect the storage arrangements and total space. Also, optimization of storage is needed to minimize the boil-off losses. Engines with pilot fuel ignition should also be further examined because, on one hand, the ignition system is very robust and, on the other hand, pilot fuel can be a renewable diesel or other easily ignitable low-carbon fuel.

Moreover, it is evident that additional new technologies such as air lubrication, ultrasound hull-cleaning systems, waste-heat recovery and the use of boil-off hydrogen in fuel cells could reduce the $LH_2$ mass to be stored quite a lot.

**Author Contributions:** Conceptualization, M.M., S.N., C.N. and L.N.; methodology, M.M., S.N., C.N. and L.N.; validation, S.N.; formal analysis, C.N. and S.N; investigation, M.M., S.N., C.N. and L.N.; writing—original draft preparation, M.M., S.N., C.N. and L.N.; writing—review and editing, C.N., S.N. and L.N.; visualization, S.N., M.M. and C.N.; supervision, S.N.; project administration, M.M. and S.N.; funding acquisition, S.N. All authors have read and agreed to the published version of the manuscript.

**Funding:** The CHEK project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 955286. The content of this report reflects only the authors' view, and the European Commission is not responsible for any use that may be made of the information it contains.

**Institutional Review Board Statement:** Not applicable.

**Informed Consent Statement:** Not applicable.

**Data Availability Statement:** The data are contained within this article.

**Acknowledgments:** The authors gratefully acknowledge the provision of the baseline parameters and comments on this manuscript by the project partners.

**Conflicts of Interest:** The authors declare no conflicts of interest. The funders had no role in the design of the study; in the collection, analyses or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

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