Lund University International Master's Program in Environmental Sciences

The feasibility of a transition to a hydrogen economy in Iceland – an overview

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Abstract

Hydrogen is for many reasons interesting candidate for replacing oil as an energy carrier. Rich renewable energy sources in Iceland makes the country optimal place for transition to hydrogen economy. In the thesis the magnitude and feasibility of the transition to hydrogen fuel is estimated with systematic approach. The transition includes all vehicles and fishing vessels. The possible transition is analyzed with computer model where pros and cons are analyzed. Three parameters are used to evaluate the feasibility, energy, CO_2 emission and cost and revenue. The energy use of the fishing vessels and vehicles is similar. The annual electricity needed to produce the hydrogen for all of the vehicles and vessels in the end of the case-study is about 6,3 million MWh. The transition to hydrogen economy can reduce the total annual CO_2 emission in Iceland by 55% or from 2,9 million tons to 1.3 million tons. The transition can exclude an annual oil invoice of almost 212 million USD$. Instead the annual revenue from electricity for the hydrogen production could reach up to 226 million USD$. The total cost of harnessing the energy needed to drive all the vehicles and vessels of the hydrogen economy is almost 13 billion USD$. The size of the hydro-electric power plants for hydrogen vehicles needs to be about 905 MWh. The prices of hydrogen fuel seem to be competitive in price to conventional fuel. The transition to hydrogen economy would be a great step towards sustainability and both environmental and economic factors recommend the transition.

Key words: Hydrogen, Conventional fuel, renewable energy, CO_2 emission, economy

"Water will one day be employed as fuel, that hydrogen and oxygen which constitute it, used singly or together, will furnish an inexhaustible source of heat and light, of an intensity of which coal is not capable…I believe that when the deposits of coal are exhausted, we shall heat and warm ourselves with water. Water will be the coal of the future."

Jules Verne, 1870 'The Mysterious Island'

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1. Introduction

One major obstacle towards sustainability is the use of the nonrenewable fossil fuel. Increasing content of greenhouse gases in the atmosphere is partly caused by the enormous burn of the fossil fuel and is presumably creating one of the largest global environmental threats to earth, known as the global warming [1]. Even if the global warming factor is left out of the picture the fact is, that ongoing depletion of the fossil fuel especially oil will sooner or later lead to energy scarcity unless new solutions are implemented. Therefore, one of the biggest sustainable challenges of mankind is to cut out the fossil fuel and shift to renewable energy.

Even though renewable energy is reaching the earth from sun in endless amounts, it has been a problem to utilize it as cheap and mobilized way as the fossil fuels. In the quest for new energy carrier that can reserve different renewable energy, more and more researchers are looking towards hydrogen as the candidate for future zero emission fuel.

Hydrogen has a great potential to be dominant energy carrier of the future. First, hydrogen is the simplest and the most abundant element in the universe. Second, hydrogen is equally distributed around the world, mostly bounded with oxygen in water and therefore essentially limitless. Third, the high energy content of hydrogen and the main advantage is that burning of hydrogen fuel is clean, as the oxidation of hydrogen yields only water [2].

Obviously there are some problems with hydrogen utilization. Hydrogen exists only as attached to other elements, which means that energy is needed to isolate hydrogen from water or other compounds. Unless the energy, used to make hydrogen fuel, is coming from renewable sources, the environmental advantages of hydrogen are smaller. Even though the energy content of hydrogen is high the density is low which causes storages problems, both in production- and use phase. Finally, the transition to hydrogen fuel needs an almost completely new infrastructure that calls for huge investments and restructuring [3].

The promising development of fuel cells, which have much better efficiency than current traditional engines, have made the future vision of the hydrogen economy a little bit clearer and more veritable. Most of the biggest car manufactures already have or are developing their first editions of the new generation of hydrogen vehicles [4,5,6].

In 1998, the Icelandic government made a clear policy statement towards a hydrogen economy. The document's vision envisages that hydrogen could replace fossil fuels in the transport sector and fishing fleet. The government supports the idea of making Iceland a pioneer community in the transition to hydrogen economy by using renewable energy sources [7]. Followed by that the company New Energy Ltd. was established to serve as an international platform for hydrogen research in Iceland. The main shareholders are the Icelandic government institutions and companies with 51% share. The other half is owned equally by Shell Hydrogen, Norsk Hydro and Daimler Chrysler.

New Energy Ltd has divided its work to three key projects:

1. Fuel cell bus demonstration
2. Fuel cell passenger vehicles
3. Fuel cell fishing vessel demonstration

The fuel cell bus demonstration project has already started with the opening of the world's first hydrogen fueling station using Norsk Hydro technology [8]. Three hydrogen busses, from Daimler Chrysler, were imported to the country and have been in use as an experiment with promising results. Steps two and three will most likely start for real in the year 2005 [9]. The first steps to the long term goal of make Iceland a hydrogen society has been taken and the year 2050 has been mentioned as a possible endpoint of that journey with establishment of total hydrogen economy [10].

1.1 Objectives and scope

The objective of this thesis is to look at the energy flow in the Icelandic transportation and fisheries with a systemic approach. The goal is to analyze the current energy system in Iceland which depends on oil as a main energy carrier and the transition over to a planned hydrogen economy. The specific aims are following:

- Analyze the difference between the hydrogen vehicles project and the hydrogen fishing vessels project
- Analyze the environmental effects of the current oil system and the hydrogen system
- Estimate the total energy need for the hydrogen projects
- Estimate the cost of the production of hydrogen for vehicles and fishing vessels
- Analyze the difference in cost and revenue of the current energy system and the hydrogen economy
- Compare the price of oil and hydrogen
- Analyze how changes in efficiency of engines will affect both systems

The scope is Iceland, where possible transition to total hydrogen economy is defined as the change of all current vehicles and fishing vessels to fuel cell engines running on hydrogen. The scope is limited to vehicles and fishing vessels leaving airplanes and cargo ships out of the pictures. The justification is that cargo ships mainly take fuel abroad and the system of airplanes is interconnected to other countries and cannot be shifted to hydrogen without transition in other countries as well.

The approach is as following: It is assumed that the hydrogen economy will be realized therefore the possible future scenarios are analyzed with the starting point of 2004. A back casting approach will be used, assuming that the official goal of the hydrogen project will be accomplished. The questions about technical hindrances e.g. if fuel cells will be commercially competitive to traditional engines, will be left out of the scope of this thesis.

The main research question is therefore to estimate **the magnitude and feasibility of the hydrogen project.** Using the concept of sustainability to approach the main research question, three main parameters will be used:

- **The energy factor.** What is the amount of energy used in the current system and how much energy is needed for the hydrogen economy?
- **The environmental factor.** How much greenhouse gas emission is coming from the current system and how will that change with the transition to hydrogen economy?
- **The economic factor.** What is the difference in cost and revenue between the current system and the hydrogen economy?

1.2 Methods and materials

A system thinking approach was used during the work with this thesis. [11,12]. System thinking is a common concept used to gain overview and understanding of different problems. With system analysis, causal relationships and feedbacks within a problem can be identified. The conceptual part of the work includes the mapping of the problem with systematic methodology through Causal Loop Diagrams (CLD) [13]. The conceptual work is then used to transfer the dynamics of the system to a computer model implemented with real data.

The data used in this research is a secondary data collected from various sources. Different stakeholders of the case study were visited to discuss the case and find proper data for every part of the model. Numbers used in the model come from official documents, scientifically approved articles and confident data from companies and institutions.

2. The case study

2.1 Introduction to the case study

Iceland is a 103.000 km^2 island in the North-Atlantic Ocean with about 290.000 inhabitants and gross domestic product (GDP) of ca 10,6 billion USD [14].

Settlement is primarily along the coast. About 62% of the nation lives in the capital, Reykjavik, and surrounding areas. The population density is three inhabitants per square kilometer. Given the large percentage of the population living in and around the capital, the rest of the country is even more sparsely populated, with less than one inhabitant per km^2 [15].

In the last decade Iceland has developed from community almost completely based on autarky, to one of the most advanced and richest nations in the world. The key factors in this transformation are increase in fishery with new technique and expansion of the fishing jurisdiction and the utilization of the renewable energy sources of the country. The extent of the renewable energy sources and fishing grounds can be seen in comparison to other countries. In Iceland there is more marine fish catch, geothermal power use and electricity production per capita than in any other country in the world [16].

Iceland depends heavily on its natural resources to generate foreign revenue. Fishing and fish processing accounted for 40% of total exports and aluminum and ferrosilicon production accounted for 15% of exports in 2001 [14].

2.1.1 Renewable energy

The energy sector is quite unique in many perspectives especially the harness of renewable energy. Figure 1 shows that of the total energy budget, 70% is coming from domestic renewable energy.

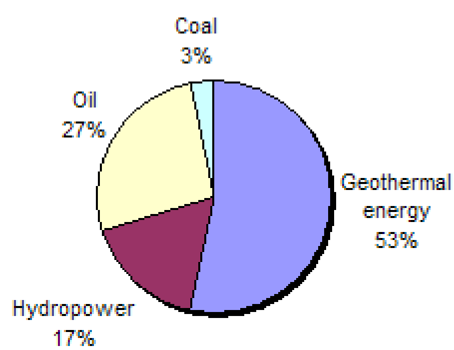


Figure 1. Breakdown of domestic energy use in Iceland by different sectors 2002 [17].

Volcanic activity and interior of the country consisting high plateaus with frequent rain, create an optimal environment for renewable energy potentials. In recent decades, Icelanders have been quite active in harnessing hydro- and geothermal power for electricity production due to increasing demand especially from energy intensive industry like aluminum smelters. Nevertheless only a small part of the energy potentials have been harnessed. The total annual potentials for hydropower and geothermal power for electricity production that are both profitable and environmentally acceptable have been estimated as 50TWh. In the year 2002 the electricity production was amounted to only 17% of this estimated applied energy (Table1).

Table 1. Potential for electricity production in Iceland [17].

	Hydropower (TWh/a)	**Geothermal** (TWh/a)	**Total** (TWh/a)
Potentials	30	20	50
Harnessed thereof	7,9	1,4	8,5
Proportion, %	23	7	17

A cool climate in Iceland calls for high energy use for space heating. In the year 2000, 87% of all houses in Iceland where heated with geothermal heat and another 11,5% with electricity. That leaves only 1,5% of houses using oil for space heating [17]. The expansion of energy-intensive industry in the last decades has been met with increased electricity production. That leaves the fishing- and transportation as the main oil consuming sectors.

2.1.2 Oil consumption

There are no fossil fuel resources in Iceland and they are therefore all imported. In other countries coals or oil are widely used for space heating and electricity production. The abundance of renewable energy in Iceland almost excludes the need for import of coals and oil for such purposes. Figure 2 shows around 90% of the oil consumption is bounded to two equally big sectors, fishing vessels and vehicles.

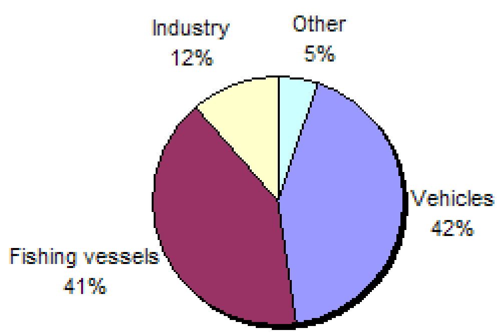


Figure 2. Breakdown of oil consumption in Iceland by different sectors 2002 [18].

The fish industry is big in Iceland with the most marine fish catch per capita in the world [16]. In 2003 the total catch was almost 7.000 kg per capita [19]. Such catch calls for a great deal of oil consumption. The other big inland oil consuming sector is the vehicles. Sparsely populated country with high standard of living calls for high number of vehicles and great use. On top of that the status of public transport is poor with no trains and poorly used buses [20]. The system approach is therefore pointed at these dominant oil consuming sectors.

2.2 Analyzing the case

Iceland is optimal as a full-scale case-study for several reasons:

- Iceland is an island and it is therefore easy to make definite clear boundaries for the system.
- The fuel use pattern is easier to track in an island than for a society on the continent where transport occurs back and forth over the boundaries and refueling often takes place outside the chosen area.
- Data registration is highly developed and accurate and being a small society, figures are smaller and more manageable than for many other societies.

The flow in the current oil system in Iceland is described in Figure 3.

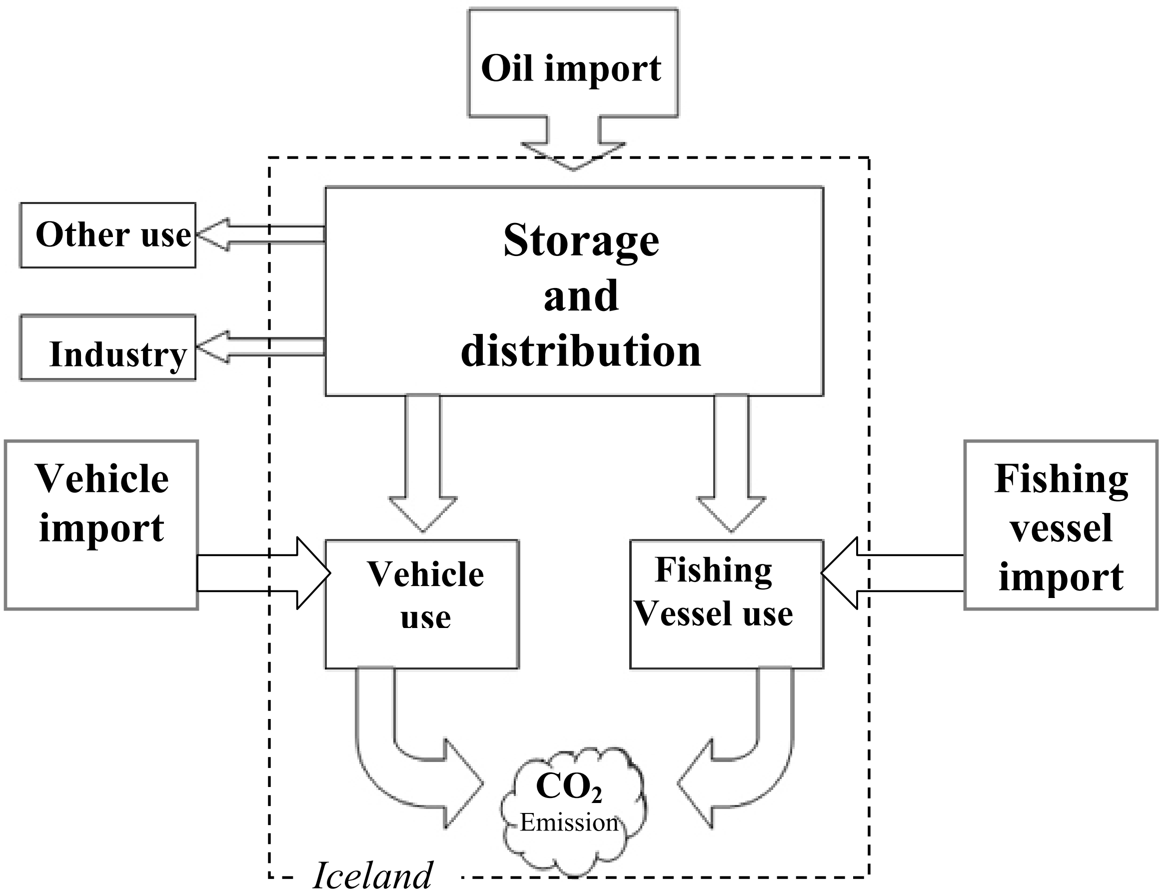


Figure 3. Overview of the flow of oil in current fuel system in Iceland.

As seen on the flow chart the current oil system consists of import of energy from abroad. The oil is then stored and distributed to different user sectors where it is burned with subsequent CO_2 emission. The broken line has been drawn around the system boundaries of the case-study. The fraction of oil that flows to industry and other use will not be included in the study because the hydrogen transition will not include these sectors.

The flow in the prospective hydrogen system in Iceland is described in Figure 4.

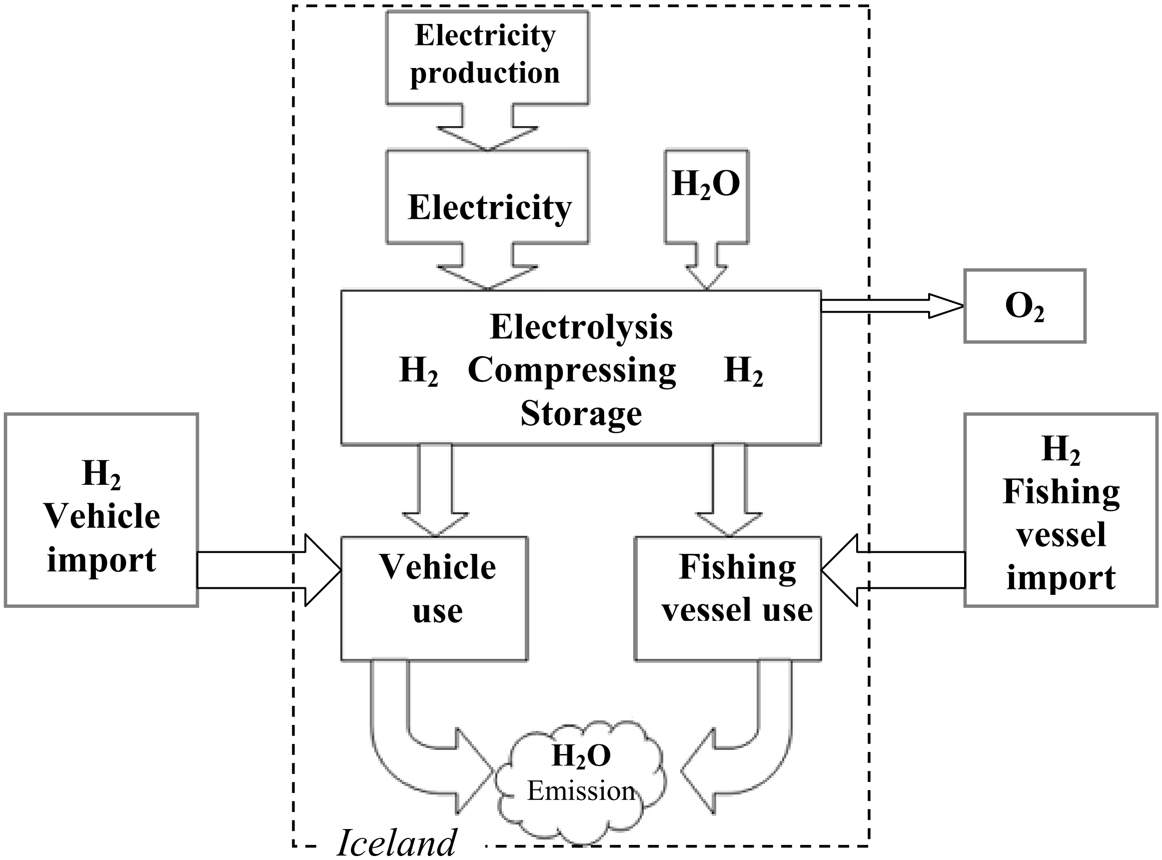


Figure 3. Overview of the flow in prospective hydrogen fuel system in Iceland.

The main difference between the two systems is that energy is produced within the hydrogen system unlike the energy import in the oil system. The energy flow in the hydrogen system covers the whole energy field from production to end use. Another main difference is the different type of emission with water vapor in the hydrogen system compared to CO_2 emission from the oil. In the thesis the two different systems will be analyzed in a model with a systemic approach.

3. The Model

The model is developed in two phases. First the case-study is analyzed in a conceptual model where the flow and the dynamics in the system are analyzed without the real data. This mental model is then used as a foundation and a map to steer the search for data needed. The data collected through the system dynamic approach is then synthesized in model using STELLA software. The whole STELLA model is presented in the Appendix.

3.1 Background Assumptions

Throughout the project following background assumptions were used:

- In the future hydrogen society in Iceland, when the transition has been completed, all imported vehicles and fishing vessels are equipped with fuel cell engines using pure hydrogen as fuel.
- The hydrogen will be produced on-site by electrolyses of water.
- The process of the transition will formally start from the year 2010 after developing period from 2002.
- Full transition to hydrogen society will be accomplished in the year 2050.
- The orbit of the transition will be even from the year 2002-2050.

The core of the model is divided to two similar categories.

- The system of vehicles, divided to two categories, currently driven on gasoline and diesel, and then the transition to hydrogen vehicles.
- The system of fishing vessels, currently driven on diesel and fuel oil, and the transition to hydrogen vessels.

The model can be divided in following parts:

- Life cycle of vehicles and vessel.
- Energy flow through the different systems.
- Cost and revenue of the different systems.
- CO_2 emission.
- Price of hydrogen and different types of oil.

3.2 Life cycle of vehicles and vessels

The life cycle part of the model includes the flow of vehicles and vessels through the system. All vehicles and vessels are manufactured outside the system and therefore imported. The life span of the vehicles and vessels controls how long they stay in the system. The need for import is controlled by the average life span and every decomposed vehicle or vessel must be replaced by new one through import. Another factor affecting the import is changes in population for vehicles.

The life cycle of vehicles with hydrocarbon (HCV) and hydrogen vehicles (H_2V) is demonstrated in Figure 4.

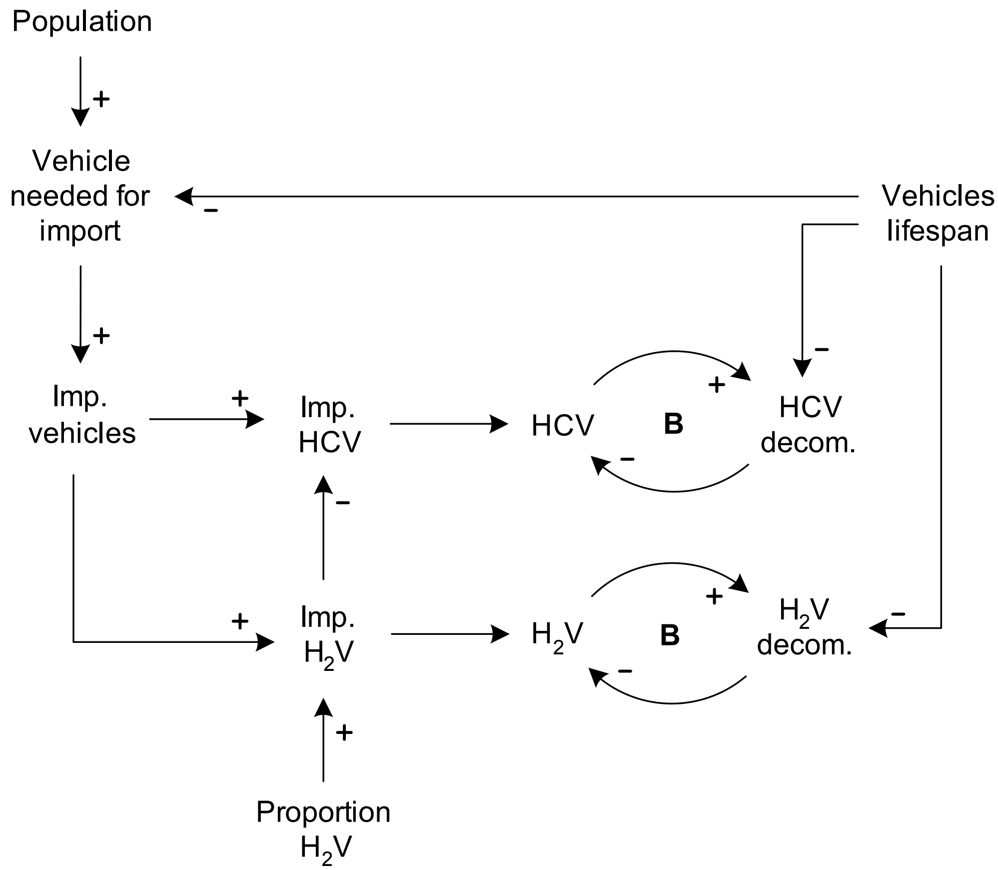


Figure 4. The conceptual model of the life-cycle for vehicles.

Changes in number of vehicles are affected by the change in population. The population projection in the model is made from data from Statistic Iceland [21]. The projected population size at 2050 is expected to be 375 thousand inhabitants. [21].

Another important figure is variation in the number of vehicle per person. In the year 2002 there were 637 vehicles per 1000 persons [22]. In transportation researches there is often talked about certain saturation stage in passenger car per person. This saturation stage differs between communities and is manly based on the status of public transport and standard of living. This saturation stage is considered to be very high for the Icelandic community or 0.6 passenger cars per person or total vehicles of 0.672. Experts believe that the saturation stage will be reached in the year 2010 and after that the increase in number of vehicles will only be driven by changes in the size of population [22]. These same assumptions are used in the model (figure 4).

In the model the vehicles are imported into the system and stay there for 10,8 years which is the average age of all vehicles in Iceland 2002 [23]. The life span of the vehicle controls the need for replacement in form of import. Full transition to hydrogen economy is assumed to be finished in the year 2050 when all imported vehicles are hydrogen driven. That means that in the model the last oil driven vehicle will be gone out of the system by the year 2061. The life cycle part of vehicles in the STELLA model can be seen in the Appendix (STELLA model 1)

The life cycle for fishing vessels is basically the same as for vehicles. The main difference is that the numbers of vessels are not relative to changes in population. There is not an open access to the Icelandic fishing grounds and they are carefully controlled with quotas. The goal of the quota system is to control the fishing in maximum economic way with transferable quotas [24]. The number of fishing vessels is therefore only determined by the life span of the fleet which has the average age of 19 years [25]. In the model the last oil driven vessels will then be gone out of the system by the year 2069. The life cycle part of fishing vessels, in the STELLA model, can be seen in the Appendix (STELLA model 2)

3.3 The energy flow in the system

The flow of energy in the conceptual model, both in current system, based on oil, and the hydrogen system can be seen in Figure 5 and Figure 6. The energy use of vehicles and fishing vessels, in the STELLA model, can be seen in the Appendix (STELLA model 1 and 2). The hydrogen production, in the STELLA model, can be seen in the Appendix (STELLA model 3)

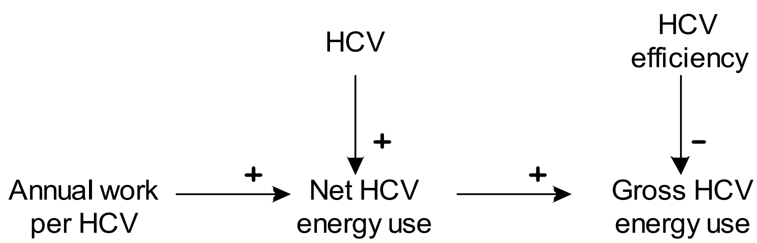


Figure 5. The conceptual model of the current oil energy system in Iceland.

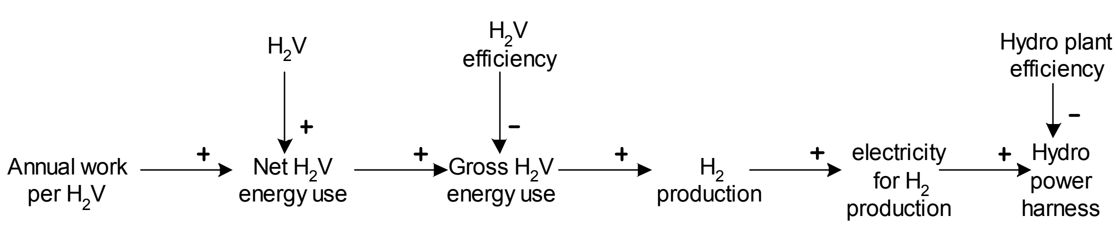


Figure 6. The conceptual model of the prospective hydrogen fuel system in Iceland.

The energy flow in the system is the same for vehicles and vessels. Assumptions used for energy content and density of different types of energy carriers used in the model can be seen in Table 2.

Table 2. Energy content and density of different types of fuel [26].

Type of energy carrier	**Energy content, kWh/kg**	**Density, Kg/L**
Gasoline	11,9	0,755
Diesel	11,7	0,848
Fuel oil	11,5	0,925
Hydrogen	33,3	0.0000899

Diesel- and the combustion engines have different efficiency. Efficiency of an engine is defined as the percentage of the total energy content of the fuel that is directly changed to work. Most of the energy is lost as a heat and the minority of the energy in current engines goes to the direct movement of the vehicle. The assumptions for energy efficiency of the different engines used in the model are shown in Table 3.

Table 3. The assumptions for the average efficiency of different type of engines.

Type of engine	**Average efficiency, %**
Combustion **[26]**	21
Diesel vehicles **[26]**	30
Diesel fishing vessel **[27]**	33
Fuel cell **[28, 31]**	42

The fuel cells and the conventional engines are in constant development towards increased efficiency. The effects of improvements in efficiency will be analyzed in this thesis

3.3.1 Vehicles

The most important assumption in the model is the definition on the energy need for an average vehicle in Iceland. The vehicles are using different energy carriers that are for comparison converted to kWh. The information and assumptions used to estimate the average annual work that hydrogen vehicle needs to perform is shown in Table 4.

Table 4. The number and energy use of conventional vehicles in Iceland in 2002.

Type of fuel	Number of cars [20]	Proportion of total vehicles, %	Total use in 2002 tons[18]	Total use per car kg	Total work per car kWh
Gasoline	152.142	82,8	144.973	952	11.340
Diesel	31.501	17,2	61.137	1.941	22.707

As seen in Table 4 the two types of vehicles, gasoline and diesel, have very different needs of energy. The reason is mainly that vehicles running on diesel are in average much bigger and more used than the gasoline cars. Most of the big jeeps, construction equipment and busses are in this category [23].

The transition to hydrogen economy is supposed to cover the whole spectrum of vehicles and the annual work that the average hydrogen vehicle must complete has to be weighed average of the annual work of all of the current vehicles in the country.

The annual work that the average hydrogen vehicle needs to perform is defined as:

$$(GV * EG * R) + (DV * ED * R)$$

GV = Annual work per gasoline vehicle in kWh
DV = Annual use per diesel vehicle in kWh
EG = Efficiency of combustion engine
ED = Efficiency of diesel engine
R = Ratio of total vehicles

The average hydrogen vehicle needs to complete work equal to **3.143 kWh** per year.

3.3.2 Fishing vessels

The energy flow of oil in current fishing vessels is different from that in the vehicles. Oil consumption is more related to the annual catch and the combination of catch rather than number of vessels. It is impossible to predict the total annual catch in long term perspective. The data from recent years are therefore used as basis for the estimation of the energy need for the hydrogen vessels. The simplest classification of the fishing fleet is decked ships and open boats [25]. The number and size of the different groups of vessels can be seen in Table 5.

Table 5. The number and size of the fishing fleet in Iceland 2000-2002 [25].

Number and size	2000	2001	2002	Average
Decked ships	1.067	1.136	1.135	1.113
Gross tons	220.874	230.748	235.776	229.133
Open boats	1.361	1.329	1.273	1.321
Gross tons	7.570	7.745	7.473	7.596
Total number	2.428	2.465	2.408	2.434
Total gross tons	228.444	238.439	243.249	236.711

Table 5 shows that the number of open boats are little more than the decked ships but only a fraction of the total size of the fishing fleet. If the size (gross tons) is used to compare these two groups of vessels, the open boats stand for only 3,2% of the total size. The ratio will be used in the model to estimate the oil use and need for the different groups. The ratio of total catch is supporting that e.g. the numbers for the total fish catch in Iceland 2003, where the small open boats caught 3,6% of the total catch [19].

All of the vessels are using diesel engine and the fuel oil use is assumed to be used equally through the whole fleet (Table 6).

Table 6. Total oil consumption of the Icelandic fishing fleet 2000-2002 [18].

	2000	2001	2002	Average
Diesel, tons	228.018	203.027	234.016	221.687
Fuel oil, tons	16.008	21.760	12.119	16.629

As seen in Tables 5 and 6 the number of vessels is not controlling the oil consumption. The oil consumption in the year 2002 was more than in 2001 even though there were fewer vessels. The assumptions used to estimate the energy need for the average decked hydrogen ship and the open hydrogen boat are seen in Table 7.

Table 7. The average annual oil consumption of the fishing fleet in Iceland [18].

Fuel type	Total average oil use, tons	Decked ships use, tons	Open boats use, tons	Oil use per decked ship, kg	Oil use per open boat, kg	Oil use per decked ship, kWh	Oil use per open boat, kWh
Diesel	221.687	214.593	7.094	199.180	5.370,2	2.330.402	62.831
Fuel oil	16.629	16.097	532	1.4463	402,7	166.321	4.631

The transition to hydrogen economy within the fisheries will be in two groups in the model, decked hydrogen vessels and open hydrogen boats. The annual work that the average hydrogen vessel needs to perform is defined as:

Annual work per vessel in kWh * efficiency

The average decked hydrogen ship needs to complete work equal to **726.645 kWh** per year.

The average open hydrogen boat needs to complete work equal to **20.239 kWh** per year.

As said before the total annual catch and the combination of the catch controls the oil consumption. The average numbers made with data from 2000-2003 will be used as constant number throughout the time scale of the case-study both for oil consumption and number of decked ships and open boats.

3.4 Greenhouse gas emission

The greenhouse gas emission part of the conceptual model the total amount of CO_2 equivalent emission is collected from four different sources (Figure 7). The CO_2 emissions, in the STELLA model, can be seen in the Appendix (STELLA model 4)

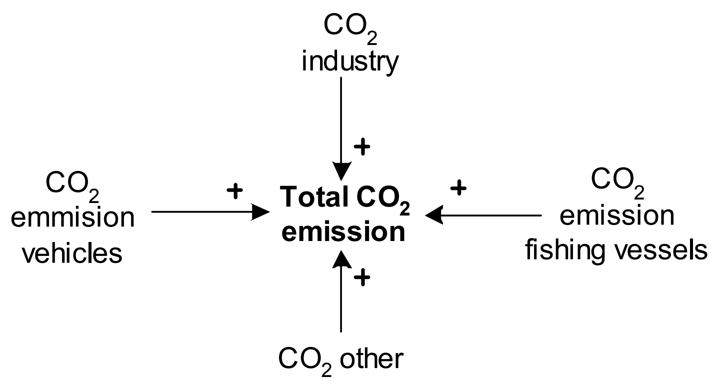


Figure 7. The conceptual model of total CO_2 equivalent emission in Iceland.

The CO_2 emission from vehicles and vessels is calculated from the total burn of different oil types. The assumption for the amount of CO_2 emission from every ton of fuel used in the model can be seen in Table 8.

Table 8. Ton of CO_2 emission from burned ton of different type of fuel [26].

Type of fuel	CO_2, ton/ton
Gasoline	3,07
Diesel	3,18
Fuel oil	3,08
Hydrogen	0

For the industry and other sources a projections to the year 2020 from, the ministry of environment, are used in the model [29]. There are two main factors that make significant changes in the emission from industry.

- Three additional energy-intensive industrial projects, new huge aluminum smelter and enlargement of two older smelters which have been authorized.
- A voluntary agreement between aluminum smelters and the government to lower emissions per production unit. The goal is to keep emissions from existing smelters at the level of 0.22 tons of CO_2 equivalents per ton of aluminum produced, but for new smelters the target level is 0.14 tons of CO_2 equivalents [29].

Many companies from energy intensive industry aspire to use the cheap renewable energy in Iceland for their production. It is likely that more energy intensive factories will rise in Iceland next 50 years but it is difficult to estimate the number or the amount of production. Therefore there is no extra emission added to the industry part of the model after the year 2020.

3.5 Cost and revenue of the different fuel systems

The cost of oil import for the Icelandic community is shown in Figure 8, where increase in oil use or higher oil price on world market calls for increased cost of oil import. The revenue of the sales of fuel from the Icelandic oil companies to the customers is not included in the case-study. The cost of oil import, in the STELLA model, can be seen in the Appendix (STELLA model 5)

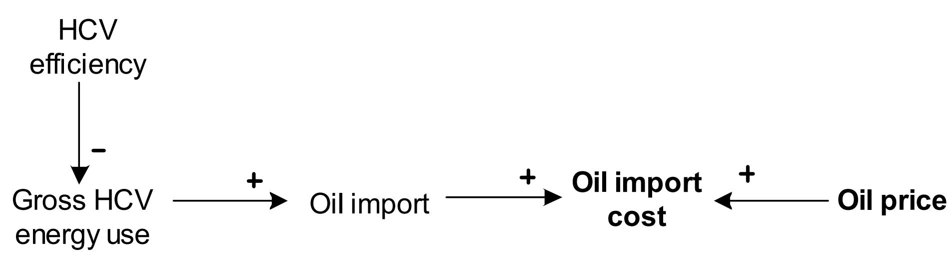


Figure 8. The conceptual model of the cost of oil import in Iceland.

There are two cost factors of the hydrogen economy analyzed in this case study:

- Initial capital expenditure of the equipments needed for hydrogen production.
- Initial capital expenditure of power plant to make electricity needed for hydrogen production by electrolysis.

The only revenue part of the hydrogen system analyzed in the model is the income of electricity sold for hydrogen production. The justification for defining the sale of electricity as revenue instead of cost is that the electricity is produced and sold within the system boundaries. The revenue from electricity sale will stay within the Icelandic economy. This will change the current fuel consumption paradigm where oil is imported and revenues are made by the supplying nations. Closing the system will reduce the outflow of money and keep profits local. The cost and revenue part of the prospective hydrogen society in the conceptual model can be seen in Figure 9. Increase in hydrogen use calls for more hydrogen production that needs more electricity. More electricity use increases hydropower harness cost but at the same time the income from electricity sale, which is internalized in Iceland. The cost and revenue part of the hydrogen production, in the STELLA model can be seen in the Appendix (STELLA model 3)

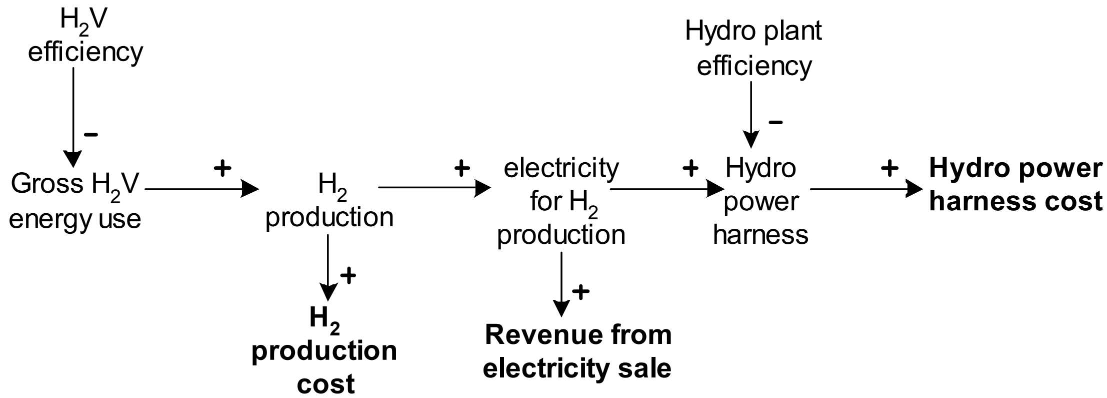


Figure 9. The conceptual model of the cost and revenue of the prospective hydrogen society.

As said before Iceland has vast resources of clean renewable electricity and additionally Iceland has the most water availability in the world [16]. The electricity and water infrastructures are already in place throughout most of the island. The focus has therefore been on hydrogen production by electrolysis.

Electrolysis is a simple process where water is separated into its components, hydrogen and oxygen, by passing an electrical current through the water. The process takes place in electrolysis cells, including 2 electrodes (Figure 10).

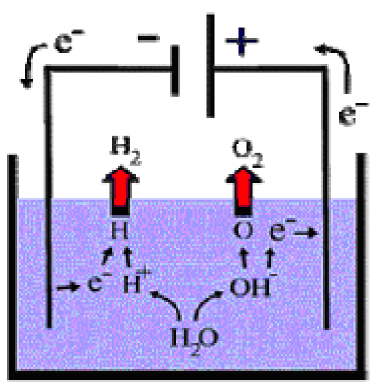


Figure 10. Schematic picture of electrolysis of water.

The electricity for the hydrogen production will be produced in hydropower- or/and geothermal power plants. In the model a hydropower plant is used as an example for the harness cost of the electricity production. The National power company of Iceland uses 14 thousand USD$ as a paradigmatic number of the capital cost of every harnessed MW [30]. The revenue from electricity sale is assumed to be estimated kWh use for hydrogen production times mean price of kWh from the pricelist of the National Power Company [30].

The information about the cost of the equipments for hydrogen production in an on-site fuelling station is coming from project done for New Energy Ldt. Electrolysis technique from Norsk Hydro is used as an example in the project [31]. Initial capital expenditure of the equipments can be divided to three units:

The production unit, where the electrolyser separates water to hydrogen and oxygen. The oxygen is then released to the atmosphere but the hydrogen gas is fed via gas purification and dryer system to the compressor and into the storage tanks.

The compressor unit, where compressor is compressing the hydrogen gas from 5-15 bars up to 440 bars as required for a hydrogen refueling station.

The storage unit, where hydrogen is stored until it is sold and acts as a buffer between the production and the demand.

Total electricity needed for hydrogen production using technique from Norsk Hydro is **51,11 kWh/kg** of hydrogen [31]. The average price of electricity used for hydrogen production is assumed to be 0,043 USD$ [30]. The exchange rate, between the Icelandic krona (ISK) and USD$, used in the model is from October 11, 2004, where 1 ISK is 70 USD$.

Figures used for the cost and revenue part of the model can be seen in Table 9.

Table 9. The cost of electricity and different units of hydrogen production.

	Price, USD$ / kg H_2
Electricity [30]	2,190
The production unit [31]	0.133
The compressor unit [31]	0.057
The storage unit [31]	0.004

The model does not cover the total cost of constructing a new infrastructure for hydrogen fuel. The focus is only on the capital cost of the equipments needed for the production of hydrogen fuel. Labor-, construction-, installation- and property cost are left outside the scope of the thesis.

3.6 The price of hydrogen and different conventional fuels

All of the oil imported to Iceland is bought in Rotterdam [32]. The price of the different types of oil used in the model is the average spot price of the years 2001-2004. The Icelandic oil companies buy the oil on average price of each month. The average price of different oil types from 2001 - 2004 from Rotterdam can be seen in Table 10. The average price for the year 2004 is the period from January to October.

Table 10. Average spot price of oil from Rotterdam 2001-2004.

Fuel type	2001	2002	2003	2004	Average
Gasoline, USD$/L	0,26	0.25	0,31	0,42	0,31
Diesel, USD$/L	0,26	0,25	0,31	0,39	0,30

As seen in Table 10 there price of oil have been increasing since 2001. The world market price of oil is formulated in USD$ per barrel of crude oil. The average price of Brent barrel of crude oil 2001-2004 is 26,8 USD$.

The electricity is a dominant factor in the prime cost of hydrogen fuel. The price of hydrogen is therefore totally controlled by the price of electricity. The prime cost of hydrogen can be seen in Table 9. Every other cost of hydrogen fuel falls under the operational costs of hydrogen fuelling station. The operational cost of conventional- and hydrogen fuel is included in the markup of the fuel companies and is therefore outside the scope of comparison between the fuel types.

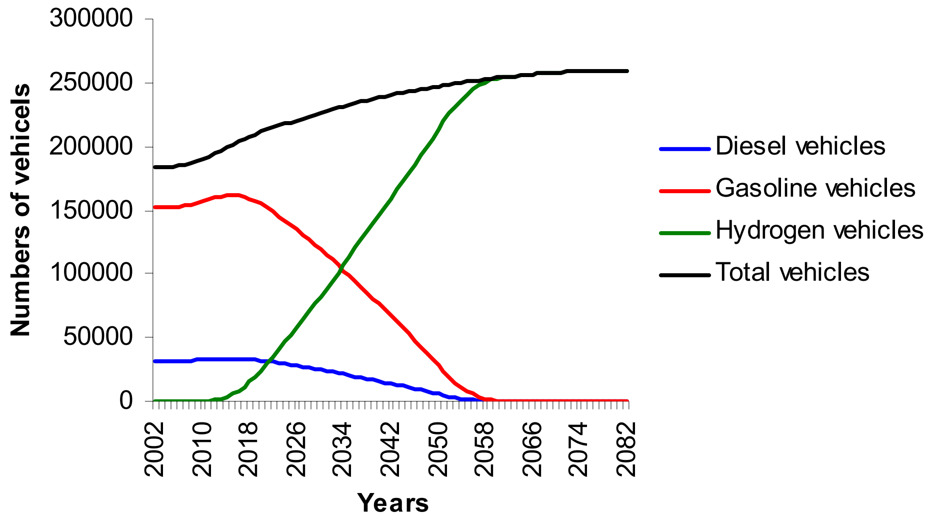
4. Results

The results will be divided to three main parts, the vehicles, the vessels and then the total amount. Finally, prices of the energy carriers are compared and the most critical variables in the system identified. The current oil system and the prospective hydrogen system will be analyzed through following parameters:

- **Energy use.**
- **CO_2 emission.**
- **Cost of revenue of oil import and hydrogen production.**

4.1 Vehicles

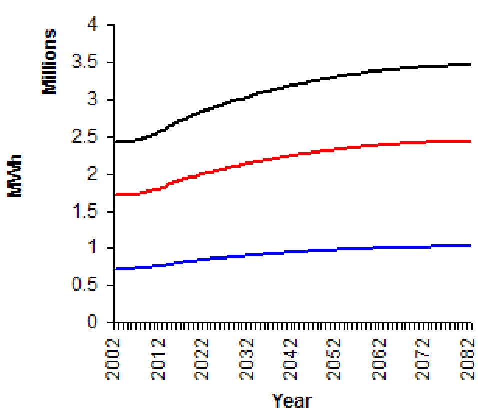
The transition to hydrogen economy for the vehicles is illustrated in Graph 1. The number of cars increases with increase in population. The population reaches certain stability around the year 2070 with 388 thousand inhabitants. The total number of cars will be around 260 thousand at the end of the case study.



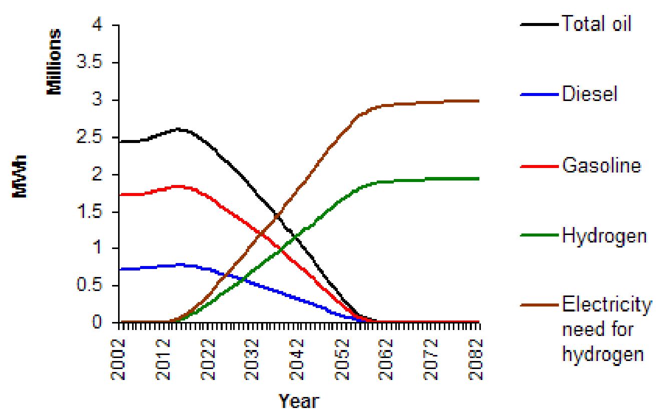
Graph 1. Numbers of cars from 2002-2082 in Iceland.

4.1.1 Energy use of vehicles

The energy use of the vehicles in Iceland can be seen in Graphs 2 with projection without hydrogen transition and Graph 3 with hydrogen fuel.



Graph 2. The energy use of vehicles

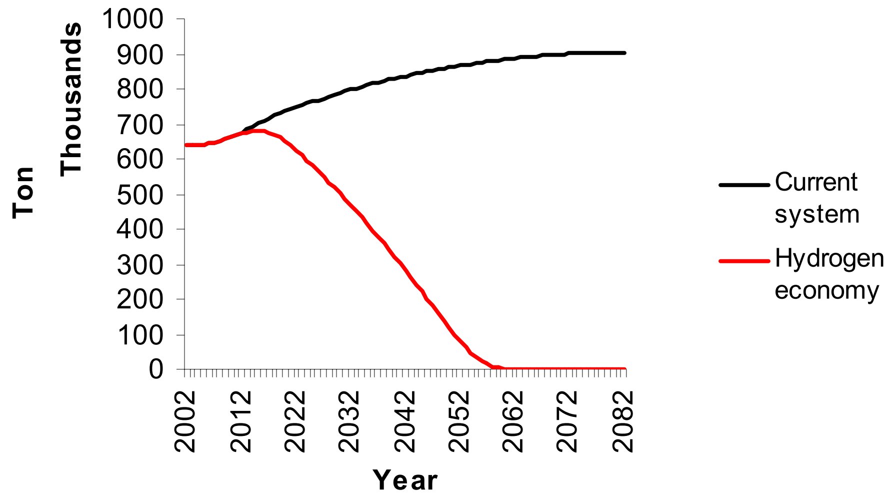


Graph 3. The energy use with transition to hydrogen fuel.

Graph 2 shows that total energy use from oil can reach up to 3,5 million MWh by year 2080. The oil use is increasing with increased number of cars. Graph 3 shows how the transition to hydrogen fuel phases out the energy use from oil. The hydrogen vehicles use less energy than the hydrocarbon vehicles or only about 1,9 million MWh. The electricity needed to produce the hydrogen is about 3 million MWh.

4.1.2 CO_2 emission from vehicles

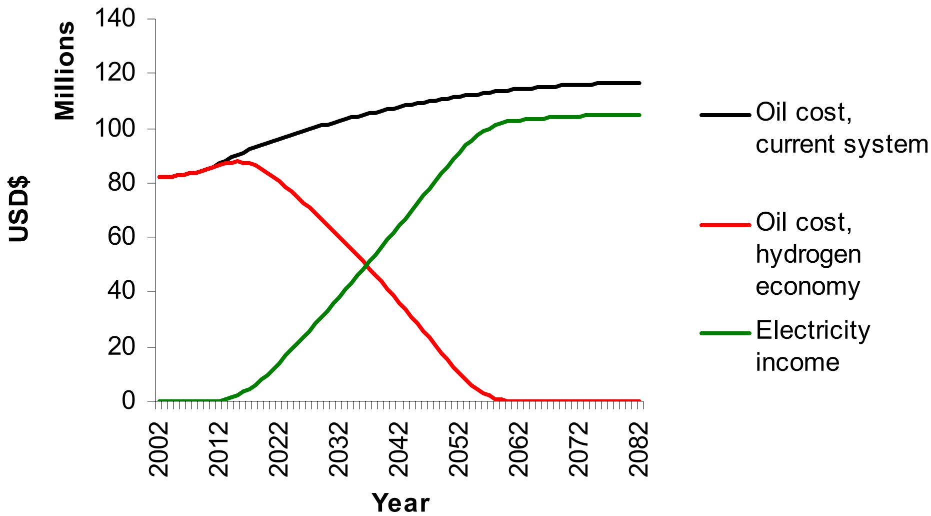
The possible future of CO_2 emission with and without the transition to hydrogen is illustrated in Graph 4. With current development in number of vehicles the CO_2 emission from transport could increase from about 640 thousand tons to 900 thousand tons in next 80 years. The hydrogen transition can on the other hand turn the emission down to zero emission in year 2060.



Graph 4. CO_2 emission from vehicles of the current system compared to hydrogen economy.

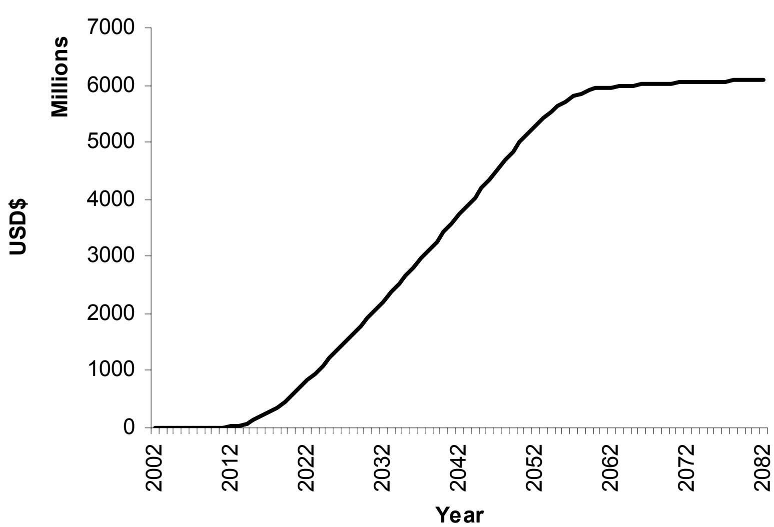
4.1.3 Cost and revenue of oil import and hydrogen production for vehicles

The cost of oil import for vehicles and the revenue from electricity sale for hydrogen production is illustrated in Graph 5. The current cost of oil for vehicles, with average price 2001-2004, is about 82 million USD$ per year and could go up to 116 million USD$ with increased number of vehicles and constant price of oil. The transition to hydrogen can cut that cost of oil import down to zero and the annual income from electricity sale, needed to produce the hydrogen, could go up to 104 million USD$.



Graph 5. The cost of oil import for vehicles and income from electricity sale in Iceland.

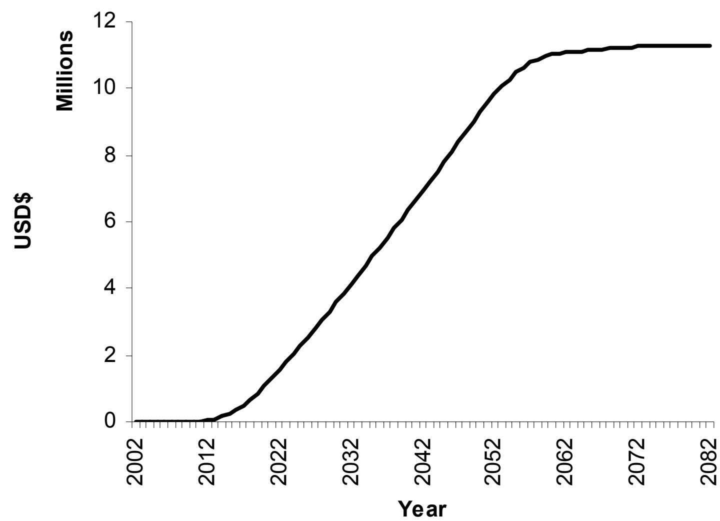
The accumulated harness cost needed to produce the electricity for hydrogen production for vehicles can be seen in Graph 6. The harnessing cost of the annual energy needed to drive all the vehicles of the hydrogen economy is about 6 billion USD$. The size of the hydro-electric power plants for hydrogen vehicles needs to be about 425 MWh.



Graph 6. Accumulated harnessing cost for vehicles in Iceland.

The main increase in electricity need is between the year 2012 and 2062. If the accumulated harnessing cost is divided equally on this 50 year period the average annual harnessing cost would be around 120 million USD$

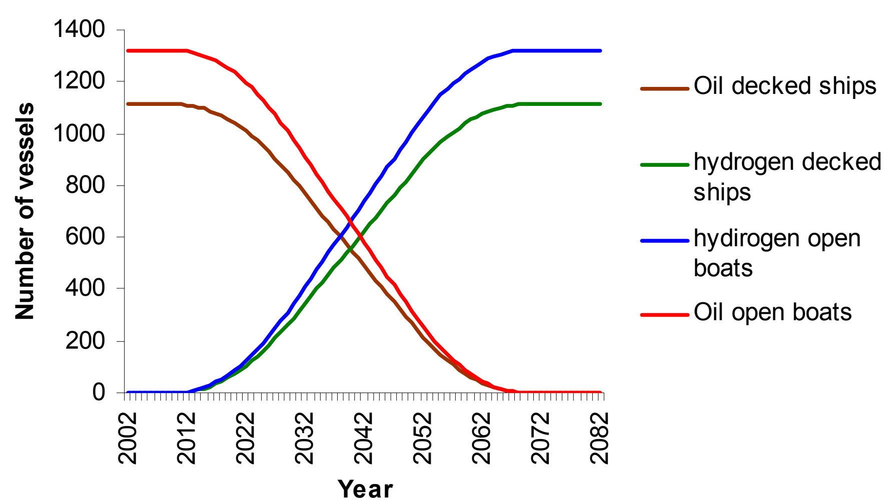
The accumulated capital cost of equipments for H_2 production is illustrated in Graph 7. The capital cost of equipments for H_2 production, needed to produce the annual hydrogen need at the end of the case-study, is about 11 million USD$



Graph 7. Accumulated capital cost of equipments for H_2 production for vehicles in Iceland.

4.2 Vessels

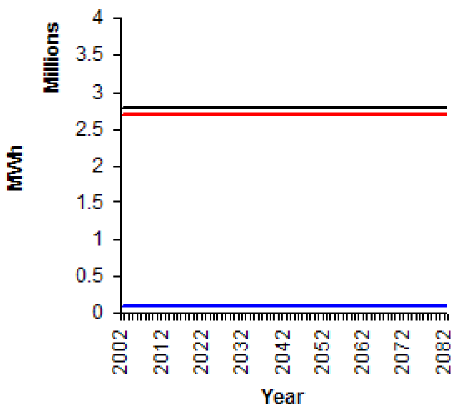
The transition to the hydrogen economy for the vessels is illustrated in Graph 8, which shows the transition of the total fishing fleet of 2434 vessels in Iceland. Unlike the vehicles there is no change in number of vessels through time and the model assumes that by the year 2069 there will be 2434 hydrogen vessels.



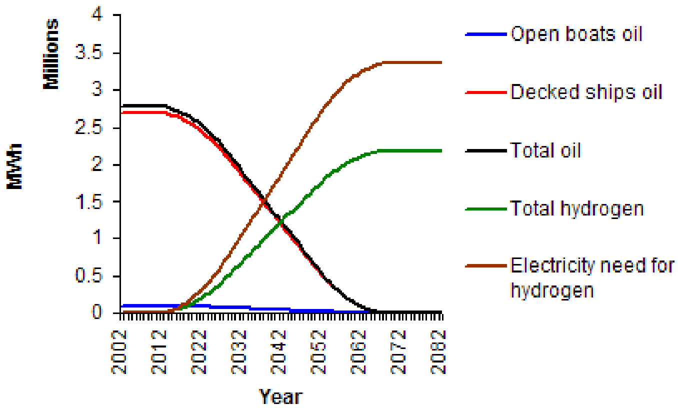
Graph 8. Number of vessels from 2002 to 2082 in Iceland.

4.2.1 Energy use of fishing vessels

The energy use of the vessels in Iceland without hydrogen transition can be seen in Graph 9 and with hydrogen fuel in Graph 10.



Graph 9. The energy use of vessels fuel.

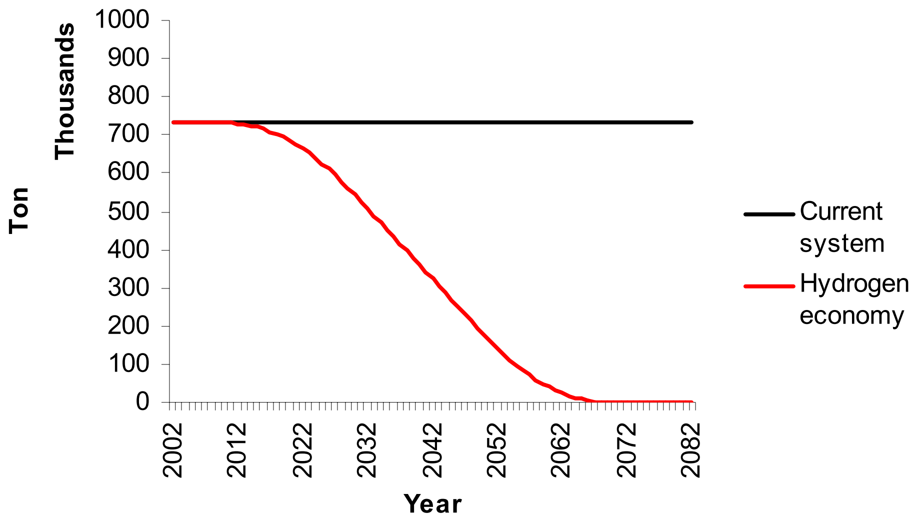


Graph 10. The energy use with transition to hydrogen

Graph 9 and 10 show how dominant the 1113 big vessels are in the energy use or about 2,8 million MW. Graph 11 shows how the transition to hydrogen phases out the energy use from oil. The graph shows that the hydrogen vessels use less energy than the oil vessels or about 2.2 million MWh. The electricity needed to produce the hydrogen is about 3.4 million MWh.

4.2.2 CO_2 emission from fishing vessels

The CO_2 emission from vessels is illustrated in Graph 11.

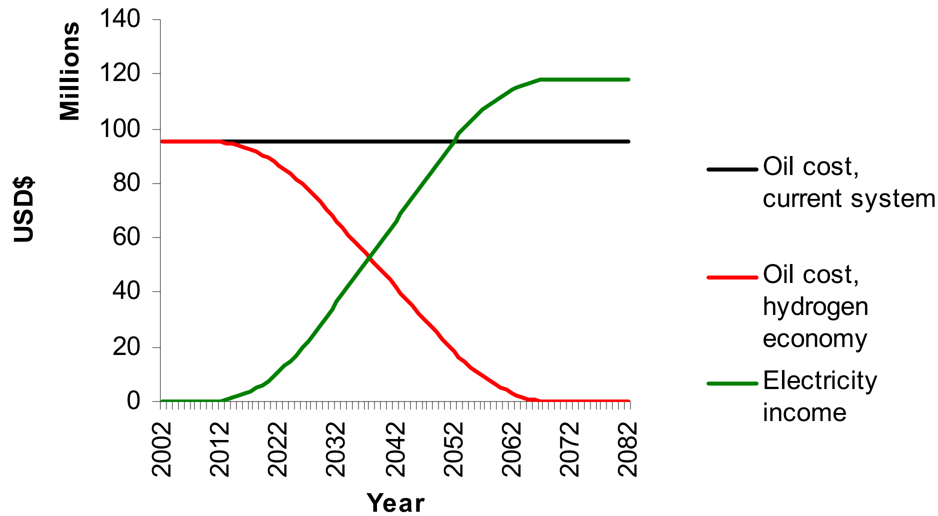


Graph 11. CO_2 emission from vessels of the current system compared to hydrogen economy.

Because of the constant number of vessels in the model, the CO_2 emission from vessels is not changing. The hydrogen transition can reduce the emission by 732 thousand ton of CO_2.

4.2.3 Cost and revenue, fishing vessels

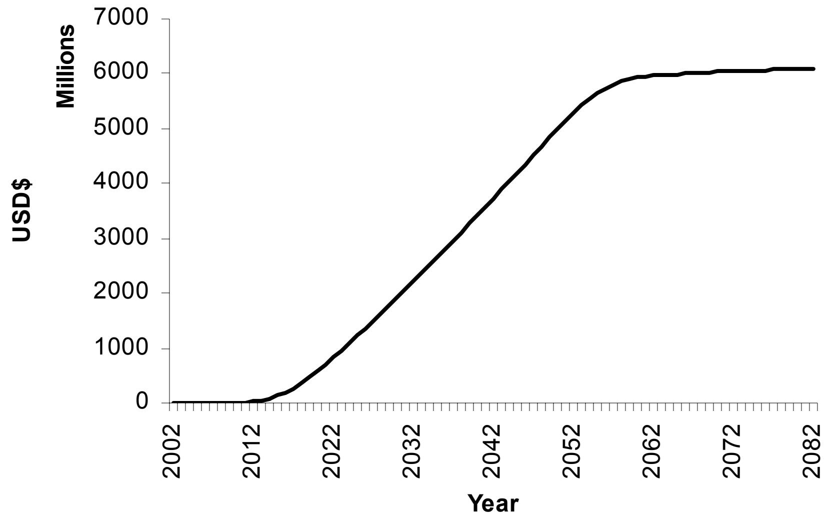
The cost of oil import for vessels and the revenue from electricity sale for hydrogen production can bee seen in Graph 12.



Graph 12. The cost of oil import for vessels and income from electricity sale in Iceland.

The graph shows that current cost of oil for vessels, with average price 2001-2004, is about 95 million USD$ per year. The transition to hydrogen cuts that cost down to zero and the annual income from electricity sale, needed to produce the hydrogen could go up to 118 million USD$. Unlike the vehicles the revenue from electricity production for hydrogen vessels is higher than the current cost of oil import. The higher efficiency of vessels explains the difference in electricity revenue.

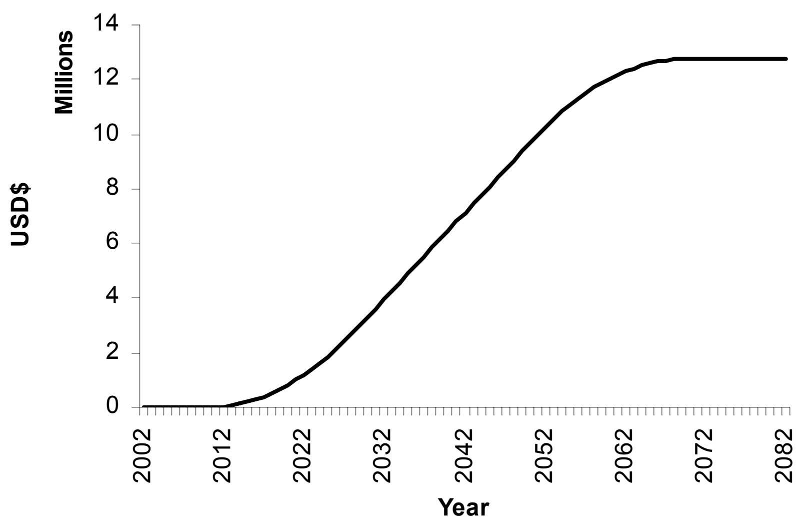
The accumulated harness cost needed to produce electricity for hydrogen production for vessels can be seen in Graph 13. The graph shows that the cost of harnessing the energy needed to drive all the hydrogen vessels is larger than for the vehicles or about 6,8 billion USD$. The size of the hydro-electric power plants for hydrogen vehicles needs to be about 479 MWh.



Graph 13. Accumulated harnessing cost for vessels in Iceland.

If the accumulated harnessing cost is divided equally on a 50 year period the average annual harnessing cost would be around 133 million USD$

The accumulated capital cost of equipments for H_2 production is illustrated in Graph 14. The capital cost of equipments for H_2 production, needed to produce the annual hydrogen need for vessels ,at the end of the case-study, is about 13 million USD$

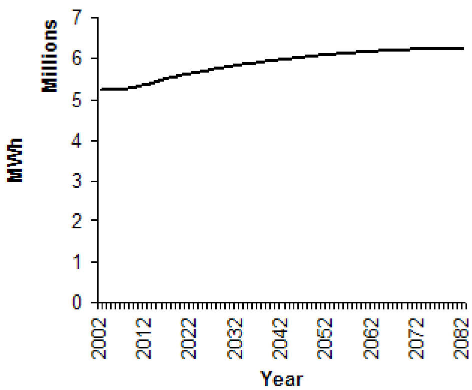


Graph 14. Accumulated capital cost of equipments for H_2 production for vessels in Iceland.

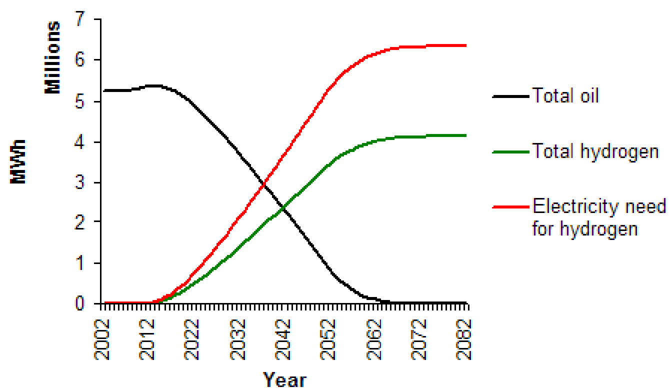
4.3 Total hydrogen economy

4.3.1 Total energy use

The total energy use of all vehicles and vessels in Iceland can be seen in Graph 15 without hydrogen transition and Graph 16 with the transition to hydrogen fuel.



Graph 15. The total energy use.

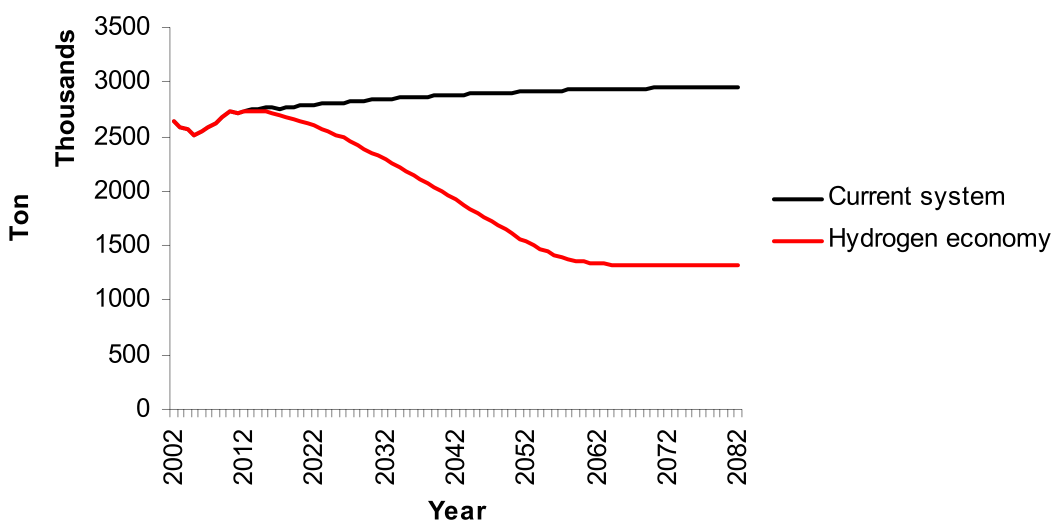


Graph 16. The total energy use with transition to hydrogen fuel.

Graph 16 shows that total energy use from oil can reach up to 6,2 million MWh by year 2080. Graph 17 shows how the transition to hydrogen fuel phases out the energy use from oil. The hydrogen vehicles and vessels use less energy than the hydrocarbon vehicles or only about 4,1 million MWh. The electricity needed to produce the hydrogen for all of the vehicles and vessels in the end of the case-study is about 6,3 million MWh.

4.3.2 Total CO_2 emission

The total aggregate CO_2 emission in Iceland, from vessels, vehicles, industry and other sectors is illustrated in Graph 17.

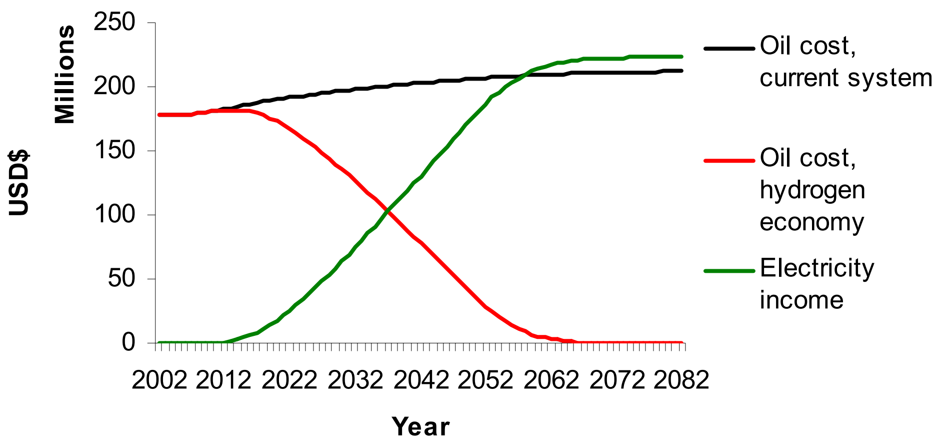


Graph 17. Total CO_2 emission in Iceland.

Graph 17 shows that the transport and fishing vessels are responsible for almost half of the total CO_2 emission. The transition to hydrogen economy can reduce the total CO_2 emission in Iceland by 55% or from 2,9 million tons to 1.3 million tons.

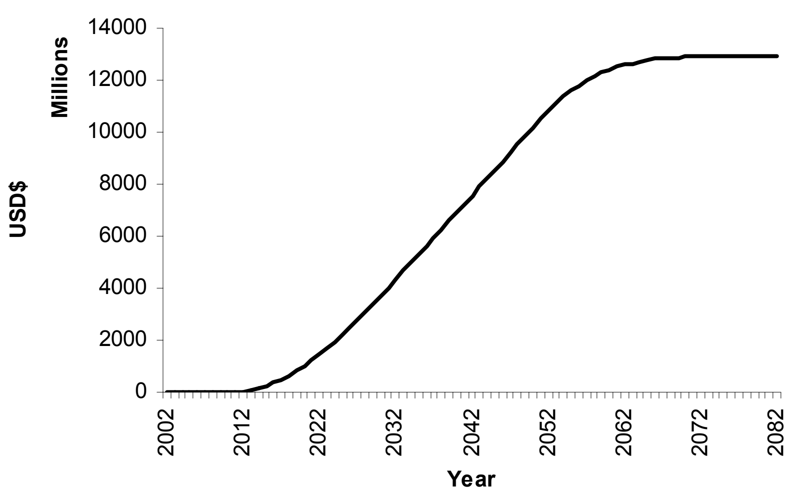
4.3.3 Total cost of revenue of oil import and hydrogen production

The total annual cost of oil import for vessels and the revenue from electricity sale for hydrogen production can bee seen in Graph 18.



Graph 18. The total cost of oil import and income from electricity sale in Iceland.

Graph 18 shows that with the transition to hydrogen economy, almost 212 million USD$ annual oil invoice can be avoided. Instead the annual revenue from electricity for the hydrogen production could reach up to 226 million USD$.

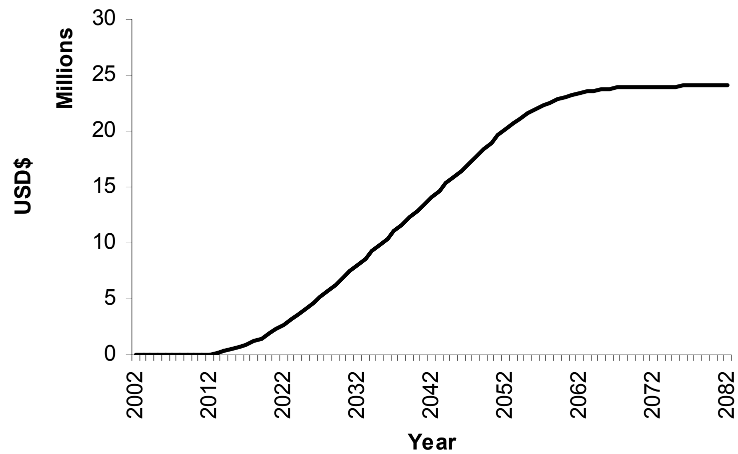


Graph 19. Accumulated harnessing cost for vehicles and vessels in Iceland.

Graph 19 shows that the accumulated cost of harnessing the energy needed to drive all the vehicles and vessels of the hydrogen economy is almost 13 billion USD$. The size of the hydro-electric power plants for hydrogen vehicles needs to be about 905 MWh.

If the accumulated harnessing cost is divided equally on a 50 year period the average annual harnessing cost would be around 258 million USD$.

The accumulated capital cost of equipments for H_2 production is illustrated in Graph 20. The total capital cost of equipments for H_2 production, needed to produce the annual hydrogen need at the end of the case-study, when every vessel and vehicle is driven on hydrogen fuel, is about 24 million USD$.



Graph 20. Accumulated capital cost of equipments for H_2 production in Iceland.

4.4 Price of hydrogen compared to oil

The comparison of price of imported oil and hydrogen can be seen in Table 11.

Table 11. The efficiency and price of different fuel.

Fuel type	Efficiency, %	USD$ /kg	USD$/kW	USD$/ used kW
Hydrogen	42	1,8	0,045	0,11
Gasoline	21	0,41	0,034	0,16
Diesel vehicle	30	0,42	0,036	0,12
Diesel vessel	33	0,42	0,036	0,11

Table 11 shows that hydrogen is at least four times more expensive per kg than the conventional fuel. Due to higher energy content of hydrogen than the other fuel types, it becomes more competitive in price per kWh. When the higher efficiency of the fuel cells is included in the comparison, the hydrogen is less or similarly expensive as the other fuel. Diesel used for engines in fishing vessels is at the same price for every used kW as the hydrogen.

For the vehicles the price of gasoline needs to stay under 0,2 USD$ /L and diesel 0,28 USD$ /L to be cheaper than hydrogen fuel. The price of hydrogen fuel should be competitive when the price of Brent barrel of crude oil is over 24 USD$.

4.5 Sensitivity analyses

By using sensitivity analysis the most critical variable of the system can be identified. By changing figures of different variables it is possible to pinpoint the numbers with the most significant effects through the system. The conclusion of the sensitivity analysis points to the efficiency as a key factor in the system. Small changes in efficiency of the fuel cells, combustion engines or diesel engines have critical effects on the outcome of the parameters used in the case study.

Fuel cells manufacturers believe it is possible to drive the efficiency of the fuel cell up to 60% [28]. The effects of change in efficiency of fuel cells, by 60%, in the end of the case-study with total hydrogen economy, are presented in Table 12.

Table 12. Overview of hydrogen economy with different efficiency of fuel cells.

Engine	Total annual hydrogen use, million MWh	Annual electricity for H_2 production, million MWh	Annual revenue from electricity, million USD$	Cost of harnessing , billion USD$	Cost of equipments for H_2 , million USD$
Fuel cell 42%	4,1	6,3	226	12,9	24
Fuel cell 60%	2,9	4,4	158	9,0	17

If same efficiency improvements, 43% increased efficiency, could be accomplished in the conventional oil engines following results would change (Table 13).

Table 13. Effects of increased efficiency in conventional engines.

Engines	Annual use, million Mwh	Annual oil cost, Million USD$	Annual CO_2 emission, million tons
Current oil engines	6,2	215	2,9
High efficient oil engines	4,4	150	2,5

The effects of increased efficiency (43%) on price can bee seen in Table 14.

Table 14. Effects of increased efficiency on price of fuel.

Engine	Fuel	Efficiency, %	USD$/ used kW
Fuel cell	Hydrogen	60	0,07
Combustion	Gasoline	30	0,11
Diesel vehicle	Diesel	43	0,08
Diesel vessel	Diesel	47	0,07

Discussion

The transition to a hydrogen economy would clearly be beneficial for the Icelandic society. The transport section and the fishing vessels seem to be equivalent in oil consumption and the transition to hydrogen vessels and vehicles would have similar environmental and economic effects. The fact that the current oil consumption of fishing vessels is the same or even more than that of all the vehicles is very interesting since the vessels are only about three thousand compared to 180 thousand vehicles. Considering that only 1113 of theses vessels are consuming 97% of the total vessel consumption makes the fishing industry a promising candidate for transitioning to hydrogen fuel

It is a tough task to transit a car pool with 200 thousand vehicles to hydrogen especially with the variability of size and types within the sector. Consumers do not only choose the type of vehicle by efficiency or environmental performance. Appearance and certain brands play important role in the consumer's decision making. The transition in the fishing fleet seems to be more manageable especially the bigger fishing vessels. The practicality of a vessel is a key the factor in decision making within the fishing industry. Certain appearance or brands play a minor role when new vessels are bought. It could even motivate the Icelandic shipbuilding industry and create new business opportunities [10].

The setback is that the development of fuel cells have until now been focused on the car industry and the cost reduction of mass production is essential for the future competitiveness of the fuel cell. Another dilemma is the problem of hydrogen storage which is even greater for vessels that need to store fuel for up to a month for every fishing trip [33].

The transition to hydrogen leads to more efficient energy use than the current energy system based on oil. The amount of electricity needed to produce all the hydrogen for the vehicles and vessels is large but manageable. The total annual energy needed for hydrogen production in the end of the case study is about 6 million MW. As mentioned before, the total annual potentials for electricity production in Iceland, that are both profitable and environmentally acceptable, have been estimated as 50 million MWh [17]. Totally 8.5 million MWh have already been utilized and although the hydrogen production would be added, only 30% of the total potentials are used.

The size of hydro power plants needed to serve the total hydrogen society in the end of the case study is about 905 MWh. The largest hydropower plant in use in Iceland today is 273 MW [34]. Construction of three to four similar power plants could cover the whole hydrogen production needed. To get full environmental gain of the hydrogen transition, the energy production needs to come from renewable energy. Very few countries are as fortunate as Iceland with renewable energy sources. Currently the utilization of renewable energy, like solar energy or wind power, often calls for huge subsidies. The story is different in Iceland where most of the renewable energy could be utilized in economical way without any subsidies. It is therefore very desirable to try to create demand for energy in Iceland and hydrogen production could be an attractive candidate.

Iceland is a party of the United Nations Framework Convention on Climate Change, UNFCCC, and Iceland ratified the Kyoto Protocol in 2002. The aim of the policy is to curb emissions of greenhouse gases so that they will not exceed the benchmark emission of the year 1990. In 1990, the total emissions of the six greenhouse gases covered by the Kyoto Protocol were 2,8 million tons of CO_2 equivalents [29]. There are huge potentials in the reduction of greenhouse gases involved in the hydrogen transition. This case study indicates that transition to hydrogen fuel could reduce the emission by 55% or from 2,9 million tons to 1.3 million. The shift to a hydrogen economy would put the total emission way under the benchmark for the year 1990. If a transferable emission quota system will be established, a significant amount of emission credits could be transferred to other countries with enhanced economic benefits of the hydrogen project.

The shift to hydrogen fuel will not be complimentary and the cost of the harnessing the energy needed and the equipments for hydrogen production is considerable. The total cost of harnessing all the energy needed for hydrogen fuel production is estimated as 13 billion USD$. Annual revenue from electricity sale is however estimated as 226 million USD$. The refund of the investments cost of the power plants would therefore take about 55 years. The main economical benefit is the reduction of oil import cost. The annual oil import cost in the case-study is between 180 and 211 million USD$. If the Total harnessing cost is divided on the 50 year period of the transition the average annual harnessing cost would be around 258 million USD$. The annual savings from the reduction of oil import are therefore almost enough to pay for the harnessing of the renewable energy needed for the hydrogen production.

The fact that hydrogen fuel needs completely new infrastructure to be a real alternative has caused a perfect example of the "chicken-and-egg" dilemma. Automakers are hesitating in the mass production of hydrogen vehicles because they fear that there will be a lack of hydrogen refueling stations in place to supply their customers. Energy companies, on the other hand, are not willing to invest in new infrastructure before there is a significant demand for the new fuel [35]. The capital cost of equipment for H_2 production that could produce all the hydrogen needed for both vehicles and vessels is about 24 million USD$. Initial capital expenditure of the equipment is only part of the total infrastructure cost but gives an insight in the magnitude of the transition cost. The aggregate profit of the three oil companies in Iceland for the year 2002 was about 68 million USD$ [36, 37, 38] that should give them some breathing space for investments in hydrogen infrastructure.

Hydrogen seems to be competitive in price with the conventional fuel when the efficiency of fuel cell is considered. The hydrogen fuel is less competitive for the fishing vessels due to a higher efficiency of the conventional vessels. Nevertheless, the price of hydrogen fuel should not be the main hurdle in the transition to alternative fuel. For hydrogen to be competitive the price of the oil barrel needs to stay over ca. 24 USD$ which has been the case for only 40 months of the last 46 [25].

Basic economics tells that price is controlled by supply and demand and the limits of the oil wells in the world will sooner or later lead to increased oil price. The Icelandic Energy Forecast Committee assumes an annual average markup of oil will be 3% [18]. If that will be the case the hydrogen will only be more and more competitive with time compared to conventional fuel. The price of imported oil is only 23% of the final price of fuel to customers. About 60% of the final prices are taxes used to pay for the expensive of the transport system [17]. The government can therefore control the final prices of fuel and stimulate the use of one fuel over another and enhance the transition to hydrogen fuel.

The sensitivity analysis shows that increase in efficiency, in fuel cells and conventional engines, leads to significant environmental and economic improvements. Enhancement of conventional engines can decrease the CO_2 emissions and the cost of oil import. However the, fuel cell will always be more feasible due to zero emissions and improved balance of trade.

Conclusions

The model used in the present study is made of many different elements and the aggregate uncertainty is significant. The results are nevertheless quite decisive and demonstrate clearly the feasibility of the possible transition to a hydrogen economy in Iceland. Everything within the boundaries of the studied system indicates that Iceland is an optimal place for the conversion to hydrogen fuel. There are more than enough potentials to harness all the energy needed to drive the total fleet of vessels and vehicles in the country.

The hydrogen fuel can be produced with economically feasible and renewable energy at competitive price. It must be desirable to minimize the foreign expenditures by lowering the oil bill and gain more national energy security at the same time.

The environmental gain is equally desirable and total hydrogen transition would make Iceland almost free of fossil fuels with following reduction of CO_2 emission. Hydrogen production is therefore very feasible and promising way to utilize the renewable energy resources in Iceland.

The cost of the transition will be considerable but the largest part is the harnessing of energy needed. Unlike many other countries, increased energy demand is feasible in Iceland and opens possibilities of utilizing the renewable energy resources in economical way. That makes Iceland an interesting place for pioneering researches for the development of hydrogen technology.

Although the transition to hydrogen fuel seems to be feasible within the studied system the obstacles outside the system boundaries are still many and unsolved. Fuel cells still have to go through further development to be able to compete with the conventional engines. Iceland is a small country but could nevertheless make an important contribution to the development of the hydrogen fuel technique. The country could serve as a test ground where new technology is tested in small society and the results could then be extrapolated and transferred to larger societies. Participation in the development of the hydrogen technique could create new business opportunities and jobs in Iceland.

It is especially important for Iceland to try to stimulate and support researches pointed at the development of hydrogen use within the fishing vessels. The fishing vessels are the single largest oil consuming sector in Iceland and transit of only few vessels to hydrogen would have a significant positive environmental and economic effects.

With a transition to hydrogen economy a considerable step towards sustainability would be taken in Iceland. The transition would benefit the development of both environmental and economical sustainability. Different stakeholders like the government, energy companies, fish industry etc. should take the hydrogen development seriously and make significant effort to stimulate and support further development towards the sustainable transition to hydrogen fuel use in Iceland.

The science-fiction writer, Jules Verne wrote in 1870, "**Water will be the coal of the future.**" The isolation of hydrogen fuel from water with electricity from renewable energy sources could make that prophecy a reality.

References:

[1] ACIA, *Impacts of a Warming Arctic: Arctic Climate Impact Assessment.* Cambridge Press, 2004, 140p.

[2] U.S. Department of Energy, *The hydrogen future*, *benefits of hydrogen economy.* Hydrogen, Fuel Cells and Infrastructure Technologies Program, Retrieved September 20, 2004, Web site: http://www.eere.energy.gov/hydrogenandfuelcells/future/benefits.html

[3] U.S. Department of energy, *The hydrogen future*, *benefits of hydrogen economy, Barriers to commercialization.,* Hydrogen, Fuel Cells and Infrastructure Technologies Program. Retrieved September 20, 2004, Web site: http://www.eere.energy.gov/hydrogenandfuelcells/future/barriers.html

[4] Daimler Chrysler, *DaimlerChrysler Delivers the First Fuel Cell Cars to Customers in Berlin*, Daimler Chrysler official website, Top stories June 18 2004, Retrieved August 15, 2004, Web site: http://www.daimlerchrysler.com

[5] Torrance CA, (2004), Toyota, *UC Irvine and Horiba Expand the Hydrogen Community,* Toyota, North American pressroom, news releases. Jan 3 2004. Retrieved September 28, 2004, Web page: http://pressroom.toyota.com/photo_library/display_release.html?id=20040301

[6] Ford Motor company, *Ford Focus FCV-Hybrid*, Retrieved September 20, 2004, Web site: http://www.ford.com/en/vehicles/specialtyVehicles/environmental/fuelCell/focusFCVHybrid.htm

[7] Pétursson B., Bjarnason H., (2002), *Towards a Hydrogen Economy*, Published by the Ministry of Industry and Commerce Iceland, Reykjavik, Iceland

[8] Hydro, *Hydro opens world's first hydrogen station on Iceland*, Hydro official web site, press releases, April 24 2003, Retrieved September 5, 2004, Web site: http://www.hydro.com/en/press_room/news/archive/2003_04/hydrogen_island_en.html

[9] Icelandic New Energy Ltd., (2004), *Hydrogen activities start Hydrogen activities start-up, The ECTOS project*, Retrieved August 5, 2004, Web site: http://www.newenergy.is/subjects/45/original/video_cover/doc004763.pdf

[10] Skúlason J. (2001), *Hydrogen – The fuel of the future*. Orkuþing 200, Samorka, Prentstofan Viðey, p224-228

[11] Weinberg, Gerald M. (1975), *An introduction to general system thinking*. New York, Dorset House Publishing, 43pp.

[12] Maani, K. E. and Cavana, R. Y. (2000), *System Thinking and Modelling, Understanding Change and Complexity*. Prentice Hall: Auckland, 262p

[13] Haraldsson, H. (2004), *Introduction to systems thinking and causal loop diagrams.* Lund: Lunds University

[14] Statistic Iceland (2004). *Key figures*, Retrieved October 5, 2004,
Web site: http://hagstofan.is/template44.asp?pageid=338

[15] National Land Survey of Iceland, (2004), *Geographical information about Iceland,* Retrieved October 17, 2004,
Web site: http://www.lmi.is/landmaelingar.nsf/pages/Landfraedilegarupplysingar.html

[16] Nationmaster.com, Retrieved October 3, 2004, Web sites:
http://www.nationmaster.com/graph-T/env_mar_fis_cat_cap,
http://www.nationmaster.com/graph-T/ene_ele_pro_cap
http://www.nationmaster.com/graph-T/ene_geo_pow_use_cap
http://www.nationmaster.com/graph-T/env_wat_ava

[17] Ragnarsson Á., Helgason H., (2003), *Energy in Iceland,* Published by National Energy Authority and Ministries of Industry and Commerce. Reykjavik Iceland

[18] Energy Forecast Committee, (2002), *Oil consumption in Iceland,* The National Energy Authority, Published by National Energy Authority, Reykjavik, Iceland

[19] Statistical series (2004), *Catch, value and processing of catch 2003*, Statistics Iceland's publication, Reykjavik, Iceland.

[20] NMS - Nordiske Storbyers Miljöindaikatorer (2004). *Transport, Inandningsbara partiklar och Vägtrafikbuller: Nordiskt Storstadssamarbete 2004 – ett project mellan 7 städer i Norden*. Retrieved October 1, 2004, Web site: http://umhverfisstofa.is/Files/Skra_0006198.pdf

[21] Statistical series (2004), *Population in Iceland 2004,* Statistics Iceland's publication, Reykjavik, Iceland.

[22] Haraldsson H., Guðmundsson J., Guðjónsson R., (2001), *Emission of green house gasses from transport*, Published by The Icelandic Ministry of Communications, The Public Roads Administration, Reykjavik, Iceland.

[23] The Road Traffic Directorate, (2003), *Vehicle statistics*, Retrieved October 1, 2004.
Web site: http://www.us.is/

[24] The Ministry Of Fisheries (2003), *Close to the Sea,* Retrieved October 20, 2004, Web site: http://brunnur.stjr.is/interpro/sjavarutv/sjavarutv.nsf/Files/close2001.pdf/$file/close2001.pdf

[25] The Icelandic Maritime Administration, (2004), *Register of Icelandic Decked Ships and Open Boats,* Published by The Icelandic Maritime Administration, Kopavogur, Iceland

[26] Energy Forecast Committee, (2002), *Expected oil consumptions 2001-2003,* Published by The National Energy Authority, Reykjavik, Iceland.

[27] Rúnarsson G., (1999), *What happens to the krona*, Ægir, tímarit um sjávarútveg, Volume 2. Published by Athygli, Reykjavik, Iceland

[28] U.S. Department of Energy, *Multi-Year Research, Development and Demonstration Plan,* Hydrogen, Fuel Cells and Infrastructure Technologies Program. Retrieved September 29, 2004, Web site: http://www.eere.energy.gov/hydrogenandfuelcells/mypp/pdfs/3.4_fuelcells.pdf

[29] Ministry of the environment in Iceland ,(2003), *Iceland´s Third National Communication under the United Nations Framework Convention on Climate Change,* Published by the Ministry for the Environment in Iceland

[30] Sigurðsson, E. Landsvirkjun (The National Power Company of Iceland) Reykjavík, Iceland, Personal communications

[31] Fanney F., (2004), *Hydrogen Infrastructure in a Modern Society*, Technical University of Denmark, Final Thesis – May 2004.

[32] Official Energy Statistics from the U.S. Government, *Spot Prices of Crude Oil, Motor Gasoline, and Heating Oils,* Retrieved November 14, 2004,
Web site: http://www.eia.doe.gov/emeu/international/prices.html

[33] Altmann M., Schmidt P., Wurster R., Zerta M., Zittel W., (2004), *Potential for Hydrogen as a Fuel for Transport in the Long Term (2020 - 2030),* Institute for Prospective Technological Studies, European Commission.

[34] Landsvirkjun, National Power Company, (2003), *Annual report 2003*, Published by Landsvirkjun, Reykjavik, Iceland.

[35] Dunn. S., (2002), *Hydrogen futures: toward a sustainable energy system,* International Journal of Hydrogen Energy Volume 27, Pages 235-264

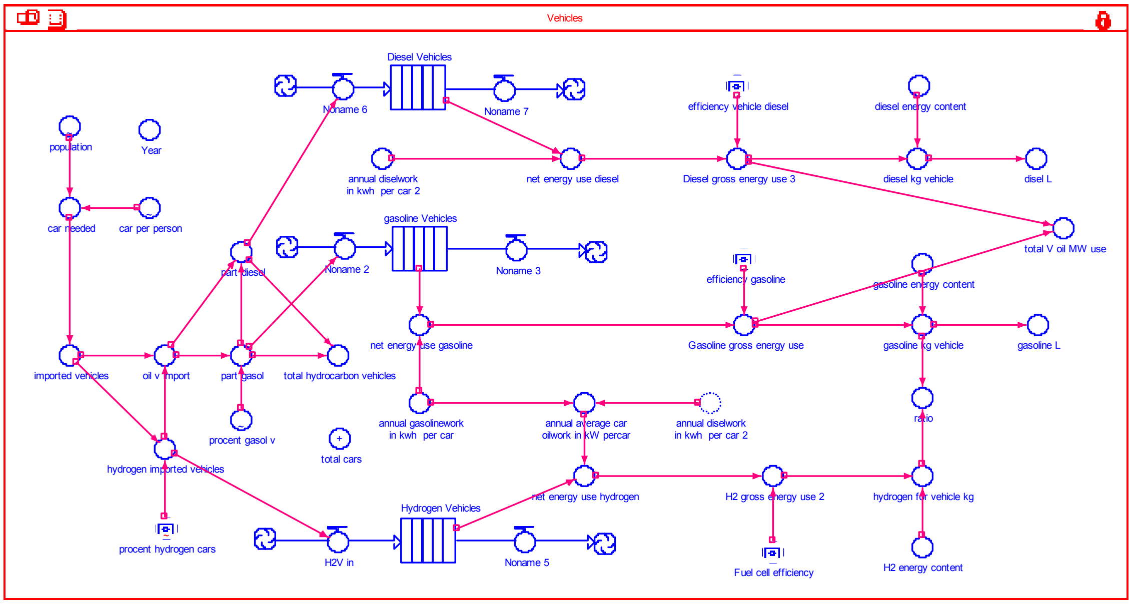
[36] Skeljungur Iceland, (2002), *Annual report*, Reykjavik, Iceland. Published by Skeljungur, Reykjavik, Iceland.

[37] Oliufelagid, (2002), *Annual report*, Reykjavik, Iceland. Published by Oliufelagid, Reykjavik, Iceland.

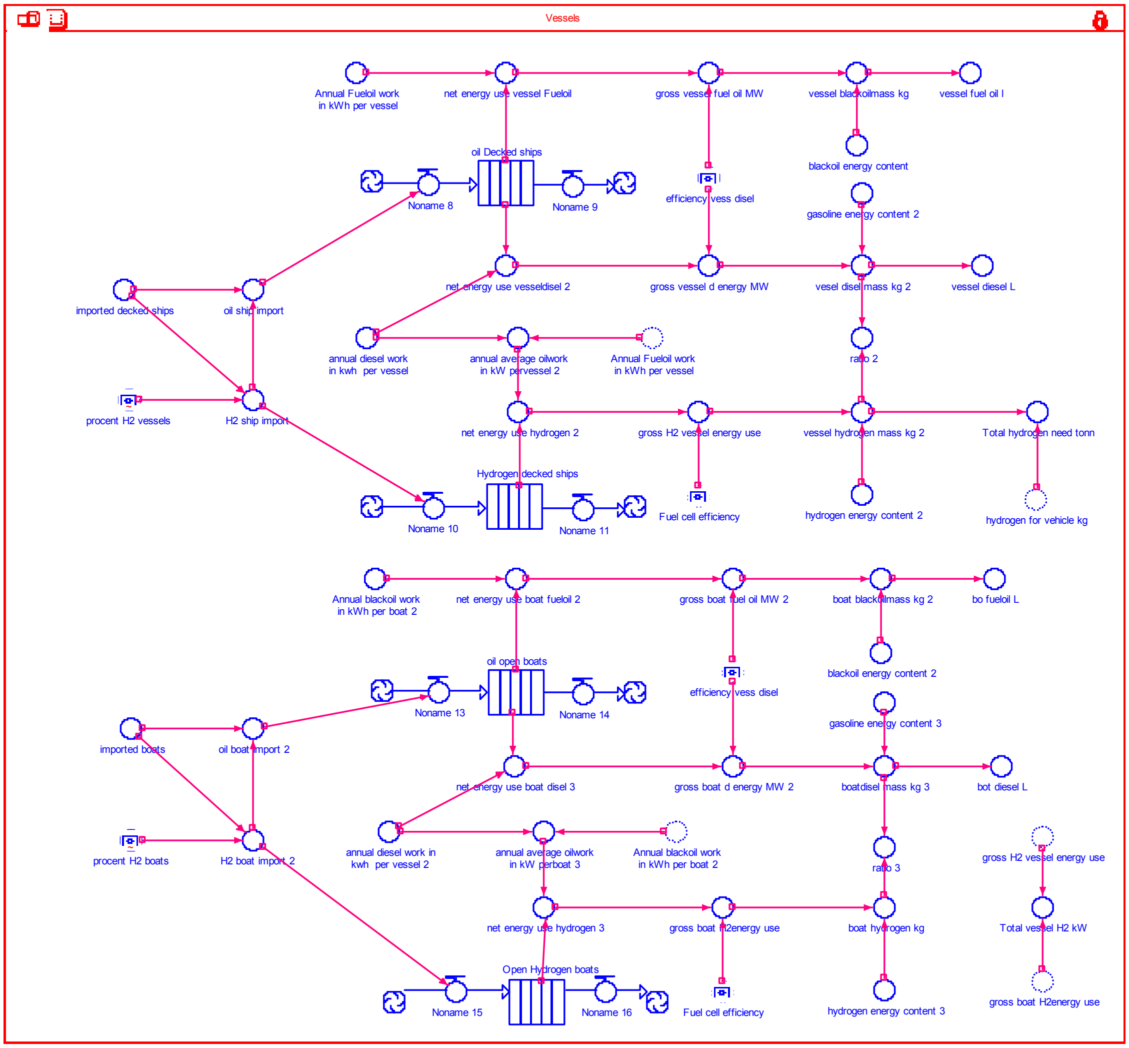
[38] Iceland oil Ldt., (2002), *Annual report*, Reykjavik, Iceland. Published by Iceland Oil, Reykjavik, Iceland.

Appendix

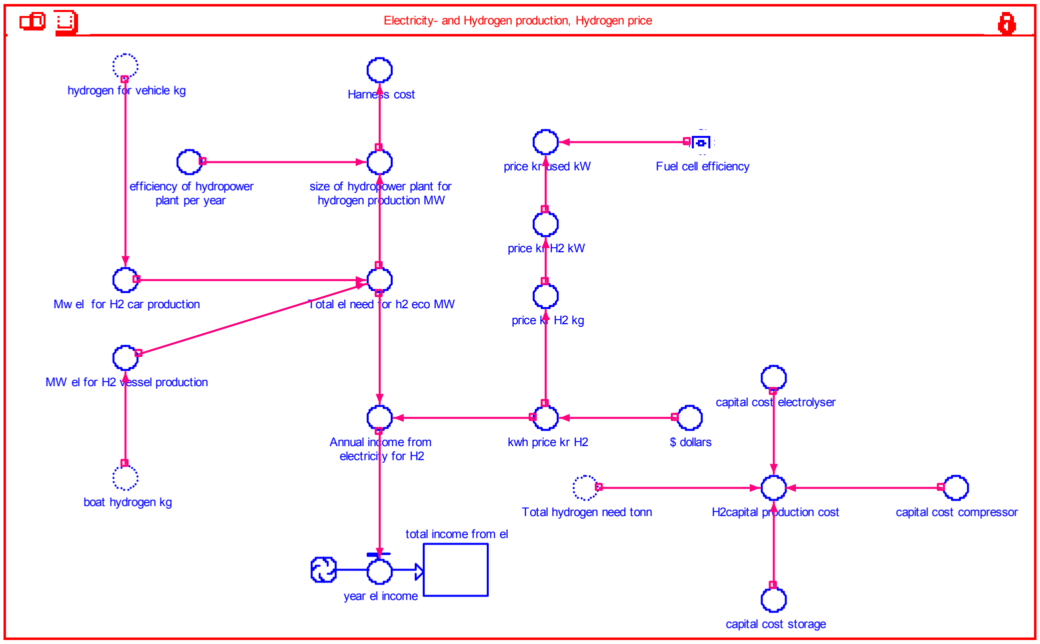
Stella model 1: According to figure 4 and 5.



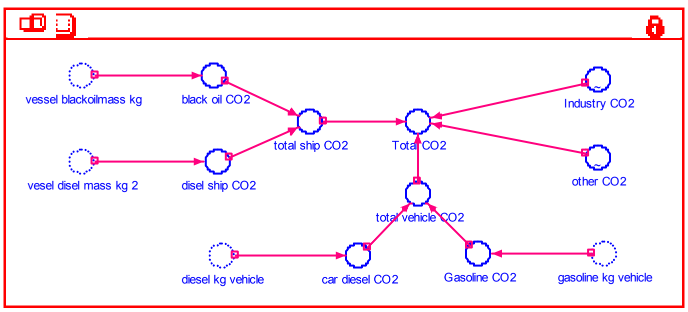
Stella model 2: According to figure 4 and 5.



Stella model 3: According to figure 6 and 9.



Stella model 4: According to figure 7.



Stella model 5: According to figure 8.