Evaluation of Policies on Green Hydrogen Role in the Global Energy System

by

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I wish a better world and a better future for my daughter and all children. A world without war. A world without inequality. And a greener world with less carbon emissions. We all need to take action on them.

ABSTRACT

Background:
In some industries, the use of hydrogen as an energy carrier is necessary to decarbonize the global energy system. Green hydrogen is currently too expensive. The problem is that our knowledge of how to invest in green hydrogen technologies to ensure their future is limited. The choice made by investors today could either guarantee or demolish the future of green hydrogen by making it less competitive than other energy sources.

Method:
Share of hydrogen was obtained from a competition between energy technologies based on their energy costs. Capital costs, operating costs, and efficiency of them were found from concepts of "learning by doing" and "economy of scale". Each technology's exponents were roughly calculated using data. A factor was also introduced to demonstrate the resistance to using a technology. The effects of various subsidizing levels and the carbon tax were then studied.

Results:
Subsidizing green hydrogen is not enough. Even with high subsidises, market share of hydrogen will be negligible in 2050. Governments shall invest to reduce the resistance against hydrogen as an energy carrier.

Conclusion:
Expanding infrastructures and reducing social resistance is crucial for not only green hydrogen market, but also to be closer to a fossil fuel free global energy system.

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CHAPTER 1 . **INTRODUCTION**

Global warming has been detected as a serious problem for our planet that requires immediate action. All nations are required by the Paris Agreement to keep global warming to well below 2 °C (or ideally 1.5 °C) above pre-industrial levels (from 1850 to1900). In order to slow or stop global warming, we need an energy transition from fossil fuels to renewable energies. However, there are some technical obstacles to this transition, such as: (1) necessity for extremely large storage capacities for renewable energies because the majority of them are not available at the same time that we need energy, (2) the high cost of energy storage, (3) impossible use of incredibly heavy batteries in the aviation and maritime industries which makes electrification of those sectors unrealistic under current battery technology, and (4) high tendency among industries to not change their fossil based technologies very much (e.g. by replacing with synthetic fuels).

Green Hydrogen, which is produced from renewable energies, is critical to achieve a deep decarbonization that has the potential to overcome nearly all of the above-mentioned obstacles. Hydrogen is a long-term energy storage technology, it can be used in all forms of transportation, and has the ability of being used in industries with a minor modification. The main issue right now is the high cost of green hydrogen. Thus, the main problem that this study will concentrate on is: "how could we accelerate the share of green hydrogen in the global energy system?". This question is crucial because making the wrong investment choices could cause the energy transition to be postponed for several years or even decades.

Forecasting the future of hydrogen production has been the subject of numerous studies. It is predicted that hydrogen will make up 5% of global energy mix in 2050, or a little more than 310 million tons of hydrogen per year compared to the current value of about 90 Mt/year (DNV, 2022). Others found different approximations for hydrogen production in 2050: 528 Mt/year to achieve a net zero emission (Bouckaert et al., 2021), 660 Mt/year (Hydrogen Council, 2021), and 250 Mt/year (IEA, 2021b). There is a lot of uncertainty in the prediction of the production of hydrogen in 2050, which ranges from 250 to 660 Mt/year. The difference is also dependent on the assumptions. For instance, if current hydrogen production growth continues, the global demand will be 130 Mt/year, whereas the best case scenario gives 568 Mt/year (Yusaf et al., 2022).

The current study seeks to provide an answer to the research question by taking into account cost reduction over time, technical details, and uncertainties. According to the hypothesis, encouraging investment in green hydrogen production sub-technologies through subsidies and carbon taxes could accelerate the rise of hydrogen's share in the global energy mix. More investment leads to lower hydrogen cost due to "learning by doing" and "economy of scale". Green hydrogen will thus be able to compete with other energy sources like fossil fuels. Additionally, since different hydrogen production technologies have different sub-technologies and requirements, it is important to differentiate between them. Three different electrolysis technology types are examined in this study, along with the currently in use steam reforming process (both with and without carbon capture). Based on learning rates of their sub-technologies, which were derived from available data, the cost of hydrogen was determined. The market share of each of the other major energy sources (fossil fuel, solar PV, solar thermal, wind power, nuclear power, and hydropower) was then compared to it.

The system dynamic approach was used to investigate how different energy carriers interact with the entire energy system. Two different learning rates were utilized by the model: (1) learning rate for cost reduction, and (2) learning rate for technical efficiency improvement. The model relies on the relation between market share and energy costs of various technologies. To improve the performance of the developed model for the period of 2010-2020, a factor was added to the model to represent the barriers to each technology's development.

CHAPTER 2 . **MODEL DESCRIPTION**

The model's primary task is to determine the share of hydrogen in the future global energy market as well as how much different electrolysis technologies will contribute to making up the future green hydrogen market. Beginning with the hydrogen market, these shares depend on competition between all technologies that will be based on their future cost of hydrogen production. Because future costs are unknown, the concept of "learning by doing" was used to estimate the cost of green hydrogen in the coming decades. The phrase "learning by doing" is a widely used concept which refers to the phenomenon of cost reduction tied to a company's accumulation of production experience (Thompson, 2010). Accordingly, the cost of an electrolysis-based green hydrogen technology will depend on the accumulated production or accumulated capacity.

While using learning models, "learning by doing" is more frequently used, though "learning by searching" is also occasionally added as a second factor (Malerba, 1992). Here, another two-factor learning model was used which is based on (Schumacher & Kohlhaas, 2007) which showed there is a difference between equipment cost reduction due to gaining experience, and operational efficiency improvement came from achieving more experience by time. The second one reduces capital expenditures (CapEx) through having a more efficient operation. For instance, enhanced electrolysis efficiency reduces the need for solar photovoltaic (PV) cells in solar-based green hydrogen production.

Having an estimation of hydrogen production cost for various electrolysis technologies, the market will invest more on the technologies with lower hydrogen cost. For hydrogen market, current model considered five different technologies: (1) grey hydrogen (made from fossil fuels), (2) blue hydrogen (made from fossil fuels but equipped with carbon capture), (3) alkaline electrolysis, (4) PEM (polymer electrolyte membrane[1]) electrolysis, and (5) solid oxide electrolysis cell (SOEC). A simple causal loop diagram (CLD) of competition between two technologies is shown in Figure 2-1. It is applicable for all five technologies, too.

As illustrated in Figure 2-1, increasing the capacity of a technology that is normally identical to higher production per year will lead to an exponential growth of accumulated experience (here it means accumulated production). Higher experience means they have gained more opportunities in reduction of CapEx, then that technology results in less hydrogen cost. Lower cost of technology #1 leads to higher market share for its new built hydrogen production units. That means the investors prefer to invest more on the

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[1] Also called "Proton Exchange Membrane"

technology #1 because of its lower hydrogen cost. Obviously, the effect of new built market share on expansion of capacity is delayed for the construction time. This reinforcing loop is shown in Figure 2-1 by "R1#1".

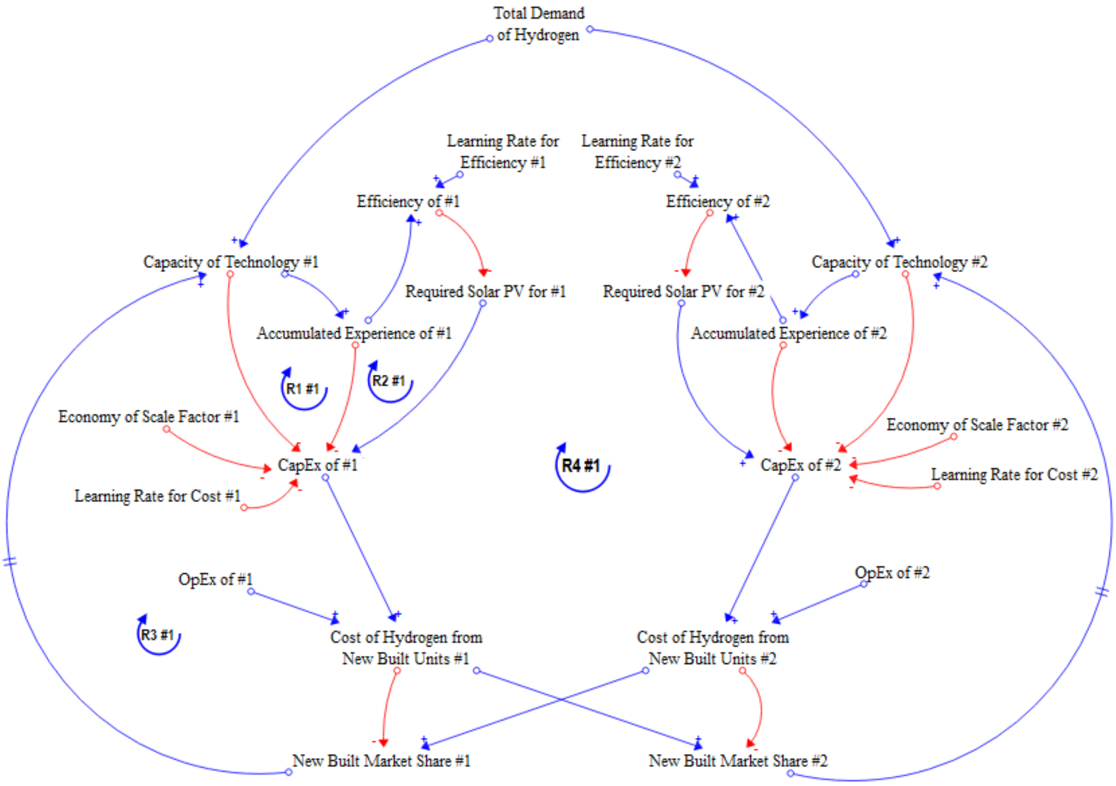

Figure 2-1. CLD of market competition between two technologies of hydrogen production

The other reinforcing loop (R1#2: capacity- accumulated experience-efficiency-required solar PV-CapEx-cost of hydrogen- new built market share- capacity) represents the second effect of learning by doing. As mentioned earlier, gaining experience will also result in improving the efficiency of electrolysis and its sub-components which means they need less solar PV cells to power them.

Third loop (R3#1) that is also reinforcing, is not about learning by doing. It refers to economy of scale (Ostwald, 1989), in which equipment production costs decrease as a result of mass production. The direct influence of capacity (and not accumulated experience) on CapEx means that if capacity of a technology declines because of falling market share while the old units are scraping, the effect of economy of scale on cost reduction will diminish. These three loops also exist for the second technology, however, are not shown in Figure 2-1.

There are still more loops in this CLD (Figure 2-1) for the interaction of different technologies. Reduction of cost of hydrogen for technology #1 via each of three discussed loops (learning of doing for cost/learning of doing for efficiency/economy of scale) will follow by a reduction of "new built market share" for technology #2. At least, it will diminish the effects of three reinforcing loops of technology #2. Therefore, there will be less desire to invest in capacity expansion of technology #2 that means its CapEx and cost of hydrogen will decline more slowly compared to what was before. This helps the new built market share of technology #1 to grow faster. Considering three ways in which CapEx of technology #1 and #2 can be influenced by capacity #1 and #2, there will be 9 reinforcing loops for technology #1. All of them are shown in the CLD as "R4#1" for simplicity. Because there are 5 different technologies of hydrogen production in this model, the number of these loops will be 243 but all of them are doing the same thing.

The last point on this CLD is that although there is no balancing loop, opposition of different technologies restricts these reinforcing loops (success to the successful). In addition, the competition is all about reaching a higher fraction of new built market share. So, in the best case for a technology, all loops could make its new built market share close to 1. Even in this case its capacity is restricted by "total demand of hydrogen".

Total global demand for hydrogen is now mostly from industries such as oil refining, metals refining, ammonia, and biofuels where hydrogen is used as feedstock. But hydrogen could also play a role in transportation, power sector, building heating/cooling, and industry (as fuel) in the future (Reigstad et al., 2019). There are various barriers in front of intensive hydrogen usage that most of them could be overcome by investing more on research and gaining further experience. One of the most important motivators to accelerate scaling up the green hydrogen market is price. Hydrogen cost for electrolysis is 3-8 $/kg (IEA, 2021c). Considering the average price of natural gas (Henry Hub) in 2020 that was 2 $/MBtu (IEA, 2021a) and heating value of natural gas, the price of natural gas per weight unit was almost 0.09 $/kg. Keeping in mind the fact that the heating value of hydrogen is almost 2.5 times of natural gas, natural gas has a cost of 0.225 $ for the same energy of one kilogram of hydrogen. This is 13-35 times more expensive. Even grey hydrogen with product cost of 0.5-1.7 $/kg (IEA, 2021c) is not cheap enough. It is one of the reasons why hydrogen is not widely used as an energy carrier. But this situation may change later if the cost of green hydrogen production declines significantly.

Global Energy Demand

Total hydrogen demand depends on two parameters: (1) global energy demand, and (2) average cost of hydrogen production in relation to other energy technologies. In this model, global energy demand is defined as a stock with two flows. The first inflow is a fixed annual growth that is usually correlated with the population, economic growth and GDP (Keho, 2016). Referring to the data on global energy demand from 2010-2019 (Ritchie & Roser, 2020), the average annual growth is almost 1.5%. The second inflow, that can also be an outflow, is the change in energy demand because of the average energy cost in the world. Obviously, it depends on both fossil fuel and renewable energies costs. The cost elasticity of energy demand in the long term was assumed to be -0.524 (Labandeira, Labeaga, & López-Otero, 2017). This is shown in Figure 2-2 by a simple CLD where increasing the average energy cost results in lower energy demand. Through learning by doing and economy of scale mechanisms, increasing global energy demand could also lower the average energy cost of renewable energies. As the share of renewable energies is not significant yet, the link is currently weak. Influence of fossil fuel prices on average energy prices will also lessen in the future when we get closer to the net zero emission energy system.

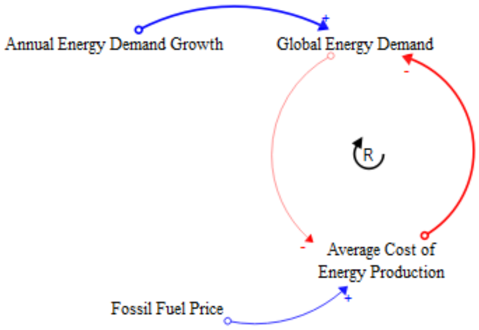

Figure 2-2. Global energy demand affected by average energy price

Competition of Hydrogen with Other Options

Having an approximation of global energy demand, as was mentioned, calculation of relative cost of hydrogen to other energy carriers can determine the global hydrogen demand. So, we need to compare the cost of hydrogen production with fossil fuel and renewable energies. In this model, renewable energies consist of solar thermal, solar PV, wind power, and hydropower. Nuclear power was also included as a fossil fuel free technology. All renewable energies were not included in the model such as geothermal and biofuels. The main reason was to make it simpler and more concentrated on technologies with higher globally potential and/or higher potential of cost reduction due to learning by doing.

These seven energy technologies (i.e. hydrogen, fossil fuel based, solar thermal, solar PV, wind, nuclear, and hydropower) have a competition with each other according to cost of production of one unit of energy. A similar structure to Figure 2-1 was applied for competition of these technologies. The outcomes are market share of newly built energy production units in each year. The CLD is illustrated in Figure 2-3 where there are some differences with the CLD of Figure 2-1. The CLD is shown only for solar PV and wind power. Solar thermal is very similar to solar PV, only with different values. For nuclear, fossil fuel and hydropower, no efficiency improvement from gaining experience was considered. There are rational reasons for these decisions, but they will also discuss later according to data analysis.

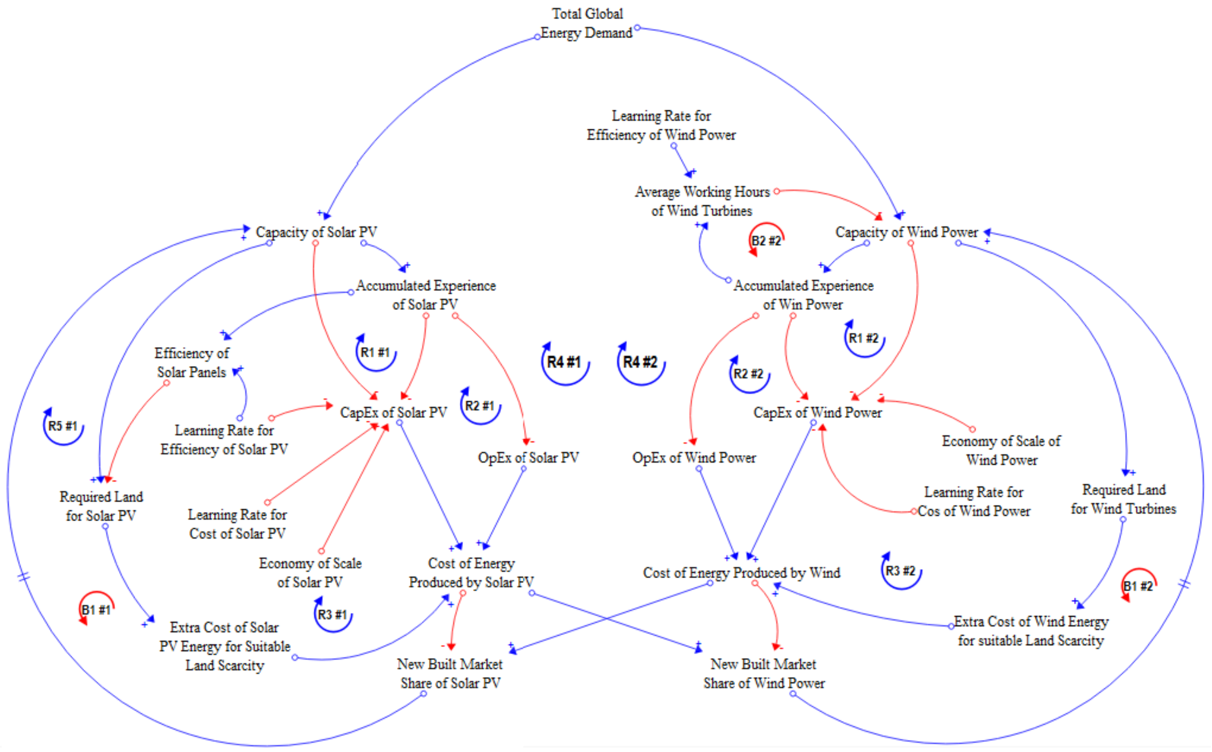

Figure 2-3. CLD of market competition between solar PV and wind power (other technologies are not included)

Same as CLD for hydrogen (Figure 2-1), there are two reinforcing loops in Figure 2-3 for solar PV and wind power because of economy of scale and cost reduction for learning by doing (R3#1, R1#1, R3#2, R1#2). Two reinforcing loops are added (R2#1, R2#2) showing the effect of gaining more experience on operating expenditures (OpeX). There is a balancing loop for wind power (B2#2) that is related to capacity factor. Over time, the capacity factor of wind turbines has been improved while their efficiency is almost constant. In other words, the ratio of produced energy to available wind energy is almost unchanged. But according to available data, the technical developments of wind turbines (e.g. aerodynamics design of rotors, gearbox efficiency) have concentrated more on increasing the operating hours of windmills during one year. Thus, increasing the accumulated experience results in a higher capacity factor. Then, the requirement for installation of new wind turbines for a specific global wind power energy demand will be reduced, as one new wind turbine can produce more energy over one year.

Competition for Land

Regardless of R4#1 and R4#1 which have the same description as explained for CLD of Figure 2-1, there are three more loops in Figure 2-3 that are relevant to land use. Now, there are plenty of unused lands which are completely suitable for solar energy. But in the future, as we get closer to a 100% renewable energy system, there may be scarcity of suitable lands and an increase in land price. In fact, land is a natural resource with restrictions, and we don't want to make the situation worse by adding to suitable lands, for example by deforestation. Therefore, increasing the capacity of solar PV could add an extra cost because of higher land cost (due to more competition). This leads to an increase in cost of energy produced by solar PV (or a decrease in reducing the effect of learning rates). Then there will be less desire to add new built solar PVs. The balancing loop (B1#1 in Figure 2-3) will be stronger when the operating capacity of solar PV becomes very large compared with current values. This could be important as in the future, the cost reduction of solar PVs for accumulated experience would be very slow. The same loop (B1#2) exists for wind power as the appropriate lands for wind farms should have special characteristics.

While the learning rate for efficiency of solar PV reduces the CapeX of it directly, higher efficiency of PV cells means there is less need for the area of solar panels. Then, the land requirement will be lowered to diminish the negative effect of B1#1 loop. This reinforcing loop is marked as R5#1 (Figure 2-3). Because no references were found on this topic, it was assumed that the land cost for solar (PV and thermal) and wind power will increase by a cost factor which is an exponential decay function of ratio of available suitable lands (Figure 2-4). As it could be seen, the more land is used, the more will be the land cost. However, this is not sensible until more than half of suitable lands for solar systems or wind farms are used.

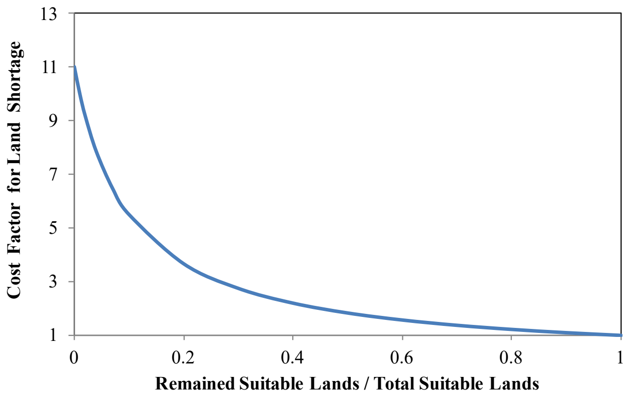

Figure 2-4. Assumed graphical function for cost increase due to shortage in required land for solar and wind units

Estimation of Fossil Fuel Price

In this model, the price of fossil fuel is estimated using the same idea. Crude oil was assumed to be the fuel representing all other fossil fuels such as natural gas and coal. Hence, natural gas and coal resources were considered as "oil equivalent". The fossil fuels are not unlimited resources, and they are depleting over time. The awareness of depletion of oil resources (all fossil fuels) will increase by time. Then, the oil producers will tend to sell their depleting resource with a higher price. This causes a reduction in fossil fuel demand that slows down the depletion of fuel resources (Figure 2-5). In contrast with this balancing loop, there is a reinforcing loop with the same elements except that higher oil extraction leads to less production cost for fuel because of learning rate. Obviously, the learning rate in the oil industry is not too much.

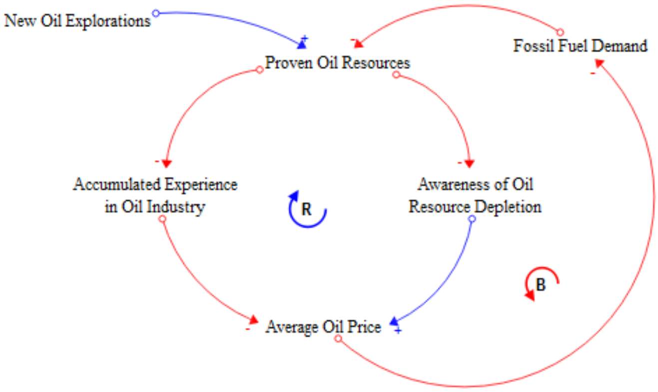

Figure 2-5. CLD of oil resource depletion

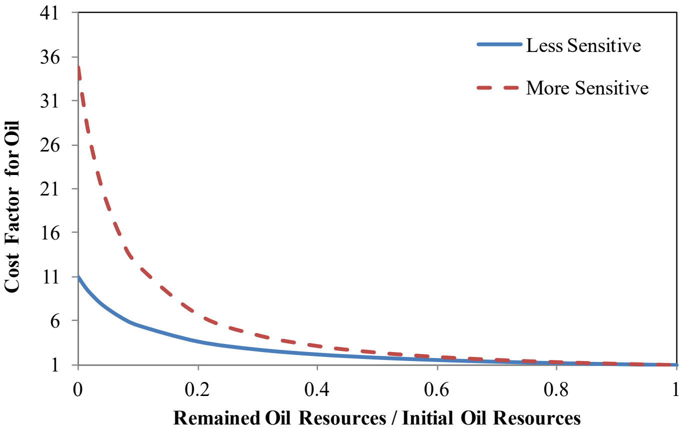

Figure 2-6. Assumed graphical function for cost increase due to oil resource depletion

The influence of fossil fuel resource depletion on the cost of fossil fuel was also assumed to be in exponential form, like what was done for land cost. This function involved both the increase in price from oil producers because of their growing concern, and the increase in oil extraction cost due to decline of oil reservoirs' pressure. Here, two scenarios were considered (Figure 2-6). The first one (less sensitive) means that summation of the concern and production cost has not a huge influence on the oil price. For example, if only 10% of current proven resources of oil remains, the oil price will be 5.5 times more than current value. While based on the more sensitive scenario, oil price will be more than 12 times compared to current price. The less sensitive scenario for oil price has exactly the same shape of what was assumed for land cost factor.

Sub-Technologies of Electrolysis

In this model, integration of electrolysis with off-grid solar PV was considered as the main method of producing green hydrogen. It means that the hydrogen will be produced by stand-alone units, in contrast with those ideas which suggest a grid connected electrolysis that only consumes the surplus of electricity of the power grid. One advantage of off-grid electrolysis is avoiding the expense of grid connections (Yates et al., 2020). It was assumed that these units will be located close to sea for providing the needed water using desalination units. Then the only essential transportation will be for hydrogen (by pipelines) and not electricity or water.

Thus, the considered stand-alone green hydrogen units have to be the integration of these sub-technologies: (1) electrolysis, (2) solar PV, (3) sea water desalination, and (4) hydrogen compressor. As the learning rates of these sub-technologies are not the same, seeing all of them together may end in a very wrong cost estimation for the future. When sub-technologies of an equipment have different learning rates, as capacity increases the components with higher learning rates will represent a smaller share of the overall cost (Böhm, Goers, & Zauner, 2019).

The CLD of Figure 2-1 is used for each of these components while three electrolysis technologies (alkaline, PEM, and SOEC) were considered separately. In other words, experience gaining and cost reduction for solar PV, hydrogen compressors or desalination units of three electrolysis technologies took into account together. Of course, accumulated experience of solar PV for electricity generation (Figure 2-3) and solar PV for electrolysis (Figure 2-1) were added together. It is worth mentioning that solar PV in electrolysis was assumed to have the duty of supplying the required electricity for electrolysis, desalination unit, and compressors.

SFD of the model

Stock flow diagram (SFD) may help to better understand the presented model. A simple SFD, by omitting some exogenous converters, is shown in Figure 2-7. This SFD is equivalent to the CLD of Figure 2-1.

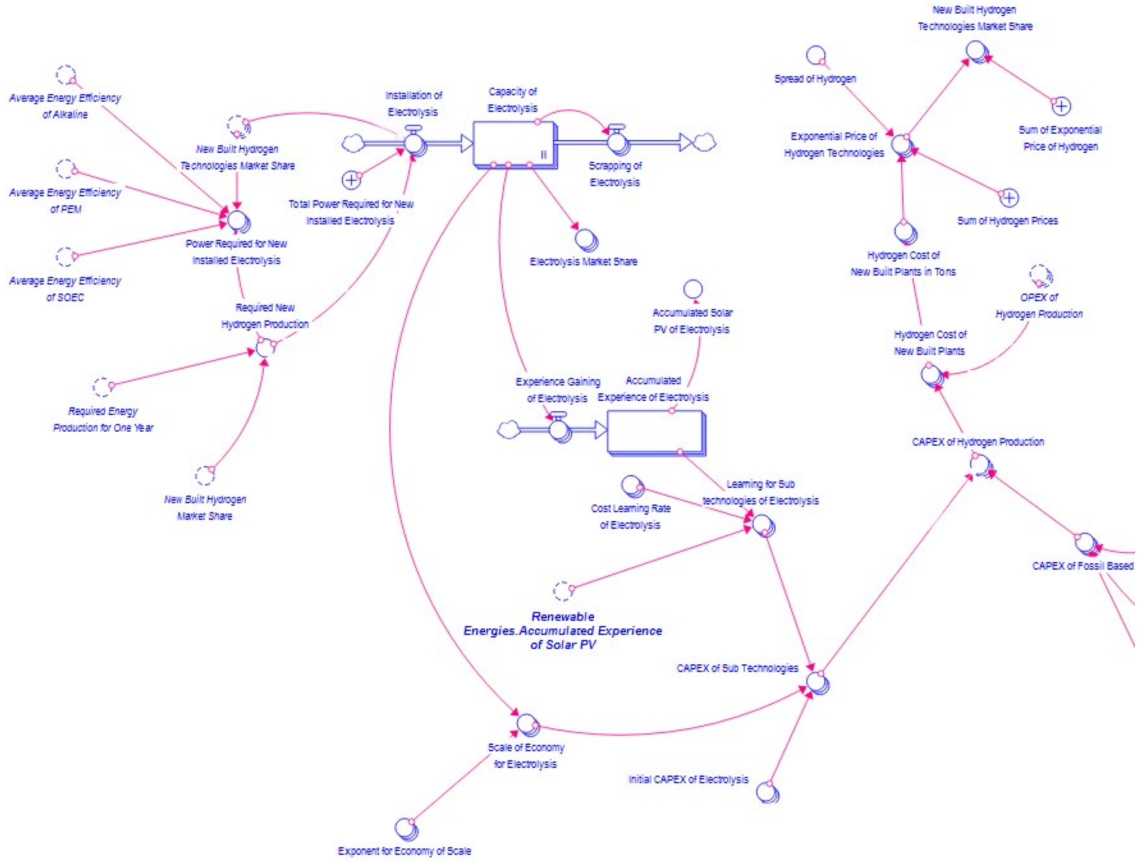

Figure 2-7. Stock flow diagram of electrolysis sub-technologies cost reduction and competition

In Figure 2-7, the capacities and accumulated productions of all sub-technologies are stock. As all sub-technologies of electrolysis have the same model structure but with different values, they have been considered as elements of an array. After adding all CapEx of solar PV, compressor, and desalination to each of electrolysis types (alkaline, PEM, and SOEC), the CapEx and then the hydrogen cost of new plants will be obtained. According to hydrogen price ($/ton or $/kWh) of five considered hydrogen production types (i.e. alkaline, PEM, SOEC, fossil based, and fossil based with carbon capture), newly built market share of each of them could be find from below equation:

$$(New\ Built\ Market\ Share)_i = \frac{e^{\frac{\left(\frac{-Cost_i}{\sum_{i=1}^{n} Cost_i}\right)}{spread}}}{\sum_{i=1}^{n} e^{\frac{\left(\frac{-Cost_i}{\sum_{i=1}^{n} Cost_i}\right)}{spread}}} \tag{1}$$

Where *i* denotes the hydrogen production type, *n* is number of technologies (here it is five), $Cost_i$ is hydrogen production cost for technology *i*, and *spread* is a parameter showing the sensitivity of investors to the differences between hydrogen costs of various technologies. Higher *spread* means that investors pay less attention to comparison of the cost of hydrogen production by various technologies when they want to choose one of them to invest on.

The same equation was used for finding the desire to invest in different energy technologies (solar PV, solar thermal, wind, hydropower, nuclear, fossil fuel, and hydrogen). Obviously, for that case *n* is equal to 7.

Data Analysis and Learning Rates

The essential part of this model was gathering learning rates for various technologies: electrolysis (alkaline, PEM, SOEC), solar PV, compressors, desalination, solar thermal, wind power, hydropower, nuclear power, and fossil fuel-based systems. The values in various references were very different and scattered. For example, for alkaline electrolysis the learning rate of 9, 18±6 (Taibi, Blanco, Miranda, & Carmo, 2020), 16±8 (Patonia & Poudineh, 2022) is mentioned in only two references. Additionally, it seems many calculations gave the credit of economy of scale in cost reduction to learning rate. As mentioned before, in this model the learning rates were divided into two parts: cost reduction, and efficiency improvement. So, in this section, these values were derived from raw data. Depending on the availability of data, in some cases the effect of gaining experience on cost was divided into CapEx and OpEx.

It is important to note that there are two methods for figuring out learning rates. One suggests that learning takes place by accumulating capacity while the other believes that accumulation of production leads to cost reduction. Both ideas seem rational. The former place a greater emphasis on equipment production and supply chain advancements, regardless of whether those who purchase the equipment ultimately use it. The second approach believes that more usage by consumers results in more experience of suppliers by getting feedback. So, it is important to choose between these two approaches. In this thesis, this was done by comparing the goodness of fit of the equation regarding the available data. R-square and root mean square error (RSME) were chosen to compare the goodness of curve fittings.

The equation used in curve fitting of cost is:

$$\text{Cost}= C_0.\left(\left(\frac{Exp.}{Exp._{initial}}\right)+B\right)^{\log_2(1-LR)}.\left(\frac{Cap.}{Cap._{initial}}\right)^{ESE} \qquad (2)$$

Where C_0 and B are constant, *Exp.* is once the accumulated capacity and another time the accumulated production, *LR* is the learning rate (form 1 not in percentage), *Cap.* is the current capacity, *ESE* is the economy of scale exponent, and "*init*" refers to the value of a parameter at the beginning of the simulation. Two parentheses usually have a value less than 1 to show a reduction in cost due to experience and mass production of equipment. Using a logarithm function with base of 2 is related to the definition of learning rate which is the fractional reduction in cost for each doubling of accumulative capacity or production.

The learning curve formulation used is a bit different from the classical model (Wright, 1936). This is a model developed by Stanford Research Institute named "Stanford-B" model (Daugaard, Mutti, Wright, Brown, & Componation, 2015). The concept behind this formulation is that sometimes there is prior knowledge on a matter that results in a non-zero slope of cost reduction at the beginning. During curve fitting, it was observed that B is sometimes zero.

Before proceeding with the curve fitting, cost values of solar thermal and solar PV were modified by their efficiency. In other words, while the cost data is per capacity of electricity generation (MW), the cost per input solar energy was calculated as an indicator of cost per unit of area of solar panels. The same modification was done for electrolysis to separate the effect of cost reduction in manufacturing from efficiency improvement.

Almost in all cases, the accumulated production had a little better fit with data. Thus, the accumulated production was used in the model to approximate the cost reduction over time. The results of data analysis are shown in Table 2-1.

Table 2-1. Learning rates for CapEx and economy of scale exponents from data analysis

Technology	ESE	Learning Rate	Range of learning rate		Studied Period
			Low	High	
Solar PV	0.916	*0.207*	*0.05*	*0.33*	1989-2020
Solar thermal	-	-	-	-	2000-2020
Wind Power	1	0.247	-	-	2000-2020
Hydropower	1	-0.186	-0.10	-0.33	2007-2020
Nuclear Power	1	-0.11	-0.09	-0.13	1980-2020
Desalination	0.79	0.014	-	-	1980-2020
Alkaline elec.	1	0.09	-	-	2000-2020
PEM elec.	1	0.033	-	-	2000-2020
SOEC elec.	1	0.107	-	-	2000-2020

In the case of solar thermal, data on CapEx was so scattered that no meaningful fit was not found, so the learning rate for its capital cost was assumed to be zero. Because solar thermal systems use tubes to absorb heat of sunlight, there was a little improvement in their manufacturing. Hence, their capital cost didn't decrease significantly. Instead, their CapEx is more dependent on raw material prices of collectors' pipes.

For hydrogen production by electrolysis, a limited amount of data was found. In addition, because they have not experienced a mass production of equipment, economy of scale was not easy to find. For these cases, an economy of scale exponent equal to 0.95, something between solar PV and wind power. For nuclear power, a negative learning curve was obtained that is consistent with other resources (Grubler, 2010). The main reason behind this is the necessity of increasing the safety of nuclear power plants. But the negative learning rate of hydropower was only mentioned in a few references (Child & Breyer, 2016). The reason for increased capital cost of hydropower could be changes in scale of hydropower units across the world over time (small ones are more expensive than large scales).

For efficiency improvement through learning by doing, the same was done but the data was fitted against equation (3). Where E_0 and $B_{eff.}$ are constants, *Exp.* is either accumulated capacity or accumulated production, and $LR_{eff.}$ is the learning rate for efficiency improvement. Economy of scale had to influence the efficiency increase, that is rational. On the other hand, accumulated production again showed a better correlation with efficiency compared to accumulated capacity.

$$\text{Efficiency}= E_0.\left(\left(\frac{Exp.}{Exp._{initial}}\right)+B_{eff.}\right)^{\log_2(1+LR_{eff.})} \tag{3}$$

Table 2-2. Learning rates for efficiency improvement from data analysis

Technology	Learning Rate	Range of learning rate		Studied Period
		Low	High	
Solar PV	*0.036*	*0.023*	*0.047*	1989-2020
Solar thermal	0.36	0.14	0.62	2000-2020
Wind Power	0.117	0.094	0.14	2000-2020
Hydropower	-	-	-	2007-2020
Nuclear Power	-	-	-	1980-2020
Desalination	0.36	0.3	0.42	1980-2020
Alkaline elec.	0.053	-	-	2000-2020
PEM elec.	0.11	-	-	2000-2020
SOEC elec.	0.078	-	-	2000-2020

As could be seen from Table 2-2, hydropower and nuclear power stations have no efficiency improvement because they are mature technologies from this aspect. While solar thermal had no learning effect on CapeX, the effect of gaining experience on the efficiency is considerable, but with a high uncertainty. For electrolysis, while the learning rate for cost was low in PEM, the learning rate for efficiency is the highest compared with alkaline and SOEC technologies.

The last part of the data analysis section is dedicated to finding learning rate for OpEx. Because of lack of data, this could not be done for electrolysis. So, it was not also derived for sub-technologies of electrolysis, such as desalination. In fact, the operating cost of electrolysis sub-technologies are assumed to be constant over time. The same was done for solar thermal and hydropower. Based on results (Table 2-3), even though the CapEx of nuclear power has a negative learning rate, its learning rate for OpEx is a large positive number.

Table 2-3. Learning rates for OpEx from data analysis

Technology	Learning Rate	Studied Period
Solar PV	*0.25*	2005-2018
Wind Power	0.08	2005-2020
Nuclear Power	0.65	2011-2020

Assumptions and Model Boundaries

Modeling the global energy system is impossible at least in a limited time. But as was told, a rough estimation of the energy system was required to find the place of hydrogen in it. The only way is simplification in a way that doesn't make the model far from reality. In fact, a trade-off between accuracy and spend time is needed, as well as all other modeling techniques. So, these assumptions were applied to the model:

- Some renewable energies were not included in the model.
- Oil is representing all the fossil fuels with adding them as oil equivalent.
- It was assumed that the overhead costs (e.g. electrical, structural, soft cost) for renewable energies will remain constant after 2020. In some cases, this is very close to the real world. For example, this additional cost remained almost constant from 2018 to 2020 for solar PVs.
- The barriers to investing in different kinds of energies will remain unchanged after 2020. This is far from reality, but they depend on various social and political systems that make them difficult to model.
- All kinds of systems based on fossil fuels were gathered in one sub-model with one stock. In other words, all vehicles, factories, residential and commercial heating equipment, and so on, were put together.
- Possible negative indirect influence of land usage by green energies on the energy system was not considered.
- No difference between values of thermal energy and electricity was assumed.
- Other types of green hydrogen production, such as thermal techniques, were ignored.
- A rough increase in global energy demand due to growth in population and industrial activities was assumed.
- Obviously, no revolutionary invention in fossil free energy technologies was considered. While something like practical fusion, for example, could change the whole system.
- No energy storage was included in the model.

Some exogenous parameters were used in the model which are mentioned in Table 2-4. More complete list of these parameters is available at Appendix A. In addition to the lifetime of each technology, the construction time is also considered to project the different delay time for them. Capacity factor which is the ratio of full-load operation of an energy unit over a year obtained from references. Obviously, solar systems have very low-capacity factors because of clouds and varying solar angle. The other series of parameters are subsidies. Among different types of subsidizing energy technologies, in this model the feed-in-tariff is used. Their values mean the percentage of electricity cost paid by the government. For example, based on available data, roughly 41% of the cost of electricity produced by wind was paid by the government in 2012 on a global scale. This average value reduced to 34% in 2017. Current model used a linear interpolation to calculate subsidies values over each 5 years period. This was done to have a smoother behavior. In the period of 2010-2020, the subsidies for hydrogen were not found in any references, so the average feed-in-tariff for renewable energies was 36% for 2012 and 40% for 2017.

Despite the fact that fossil fuels attract the highest amount of subsidies each year (Gould, Adam, & Walton, 2020), the allocated subsidies fraction to them varied in the range of 6-8.5% in the past decade according to calculations.

Table 2-4. Some exogenous parameters used in the model

Parameter	Value	Unit	Reference
Solar PV Plants Lifetime	15	years	multiple ref.
Solar Thermal Lifetime	20	years	(Linus, 2016)
Wind Turbine Lifetime	20	years	(Cooperman, Eberle, & Lantz, 2021)
Nuclear Plant Lifetime	40	years	(Krivanek, 2020)
Hydropower Lifetime	50	years	(Gallagher, Styles, McNabola, & Williams, 2015)
Desalination Lifetime	30	years	(Caldera, Bogdanov, & Breyer, 2016)
H_2 Compressor Lifetime	35000	hours	(Jeff, 2019)
Alkaline Electrolysis Lifetime	60000	hours	(Taibi, Miranda, Carmo, & Blanco, 2020)
PEM Electrolysis Lifetime	65000	hours	(Taibi, Miranda, et al., 2020)
SOEC Electrolysis Lifetime	20000	hours	(Taibi, Miranda, et al., 2020)
Photovoltaic Panel Lifetime	25	years	(Glenk, Meier, & Reichelstein, 2021)
Fossil Based Hydrogen Plant Lifetime	20	years	(Bhandari, Trudewind, & Zapp, 2014)
Average Lifetime of Fossil Based	30	years	Multi
Capacity Factor for Solar Systems	0.18	-	(Christensen, 2020)
Capacity Factor for Nuclear	0.825	-	(Association, 2021) - (Statista, 2022)
Capacity Factor for Hydropower	0.44	-	(Edenhofer et al., 2011)
Capacity Factor for Fossil Hydrogen	0.85	-	(Wales, 2020)
Construction Time for Solar PV	1	year	(Linus, 2016)
Construction Time for Solar Thermal	2	years	(Linus, 2016)
Construction Time for Wind	1.5	years	(D'Angelo, 2020)
Construction Time for Nuclear	7	years	(Association, 2021)
Construction Time for Hydropower	5.5	years	(AQPER)-(Kabanda et al., 2021)
Subsidies for Solar PV	72 / 55 *	%	(Stefanides, 2021)-(Taylor, 2020)-(IEA, 2022)
Subsidies for Solar Thermal	10.6 / 9.8 *	%	(Stefanides, 2021)-(Taylor, 2020)-(IEA, 2022)
Subsidies for Wind Power	41 / 34 *	%	(Stefanides, 2021)-(Taylor, 2020)-(IEA, 2022)
Subsidies for Hydropower	0.4 / 0.44 *	%	(Stefanides, 2021)-(Taylor, 2020)-(IEA, 2022)
Learning Rate of Oil Industry	0.04	-	(Kim & Lee, 2018)
Average Energy Cost Elasticity	-0.524	-	(Labandeira et al., 2017)

* The first number is for 2012 and the second for 2017

Calibration

The operating capacities of six clean energy technologies (solar PV, solar thermal, wind power, hydropower, nuclear, and hydrogen) were compared to historical data from 2010 to 2020 to calibrate the model. In fact, it was tried to minimize the mismatch between the output of the model and the historical data. First of all, calibrating the model was done by adjusting two parameters: "carbon tax" and "spread". The latter is the constant value in equation (1) which determines the sensitivity of the market to costs. Smaller "spread" means the market pays more attention to cost differences when wanting to decide about investment on a technology. After performing this calibration, results were not satisfactory. In fact, the difference between historical trends and simulation, especially for solar PV, was huge.

Investigating the reasons behind the poor calibration led to adding more parameters (e.g. subsidies for each technology) to the calibration. Even the learning rates were chosen to be calibrated by suspecting the resulting values from data analysis (Table 2-1,Table 2-2, and Table 2-3). None of these ended with a good result. Therefore, the model was changed so that the historical average energy costs were used to calculate the new technology market share. In other words, the market share from equation (1) was obtained not from calculated costs from simulation but from real values. This temporary disconnecting of the main loop of the model was done to test if equation (1) is valid at all, for finding the market share. This test demonstrated that decisions taken by investors for determining the newly installed technologies have not been completely on energy costs.

Barrier Factor

Thereafter, a parameter was introduced for each technology, named "barrier factor". This factor was multiplied with the calculated energy costs to give an apparent energy cost. This means that equation (1) will be reformulated to:

$$(New\ Built\ Market\ Share)_i = \frac{e^{\frac{\left(\frac{-B.F._i \times Cost_i}{\sum_{i=1}^{n} B.F._i \times Cost_i}\right)}{spread}}}{\sum_{i=1}^{n} e^{\frac{\left(\frac{-B.F._i \times Cost_i}{\sum_{i=1}^{n} B.F._i \times Cost_i}\right)}{spread}}} \tag{4}$$

where $B.F._i$ is the barrier factor for technology i.

The intention to do this, was considering the resistance against a specific technology that can highlight or fade its high/low energy cost. Barrier factor can represent all social, technical, infrastructural, and political obstacles. Values smaller than one means the technology is welcomed more than normal.

For newer energy technologies like solar PV, solar thermal, wind power, and hydrogen, the barrier factor was assumed to be changed linearly from 2010 to 2020. There were two reasons behind this. First, these technologies are not mature enough. So, different mechanisms against or in favor of them are not fully developed, especially compared to hydro, nuclear, and fossil energies. Secondly, it was interesting to see how much the effect of obstacles against these technologies have been changed during only one decade.

Table 2-5. Barrier factors for energy technologies obtained from calibration

Technology	Barrier Factor	Barrier Factor	
		2010	2020
Fossil Based	0.59	-	-
Nuclear	49.4	-	-
Hydro	43.3	-	-
Solar PV	-	14.8	49.4
Solar Thermal	-	11±10#	50±10#
Wind	-	14.5	28.6
Hydrogen	-	24.8	100

\# The barrier factors for solar thermal were not trustable as the historical data was not reproduced

Barrier factors from calibration are illustrated in Table 2-5. These factors are meaningful. Low barrier factor (less than one) for fossil-based fuels shows that even if the price of fossil fuels is very high, the response of the market will not be very quick. The possible reasons could be a very good available infrastructure, difficulty for rapid switching to alternatives in many industrial and residential applications, and society's inertia against changes. The nuclear power is on the other band with a very high barrier factor. The main issues for nuclear energy could be the technical difficulties, environmental considerations, and the safety concerns especially after the Fukushima accident in 2011. There are a lot of social resistances against nuclear power as well. The high factor for hydropower is probably due to limitations in suitable topographical locations. So, even though the energy cost for hydropower is very low, in many countries it is not possible to generate all the required energy from hydropower, because of those limitations.

For renewable energies the barrier factors were much less compared with nuclear and hydro but were not comparable with fossil fuels. In 2010, solar technologies and especially solar thermal faced less obstacles. But they became less welcomed 10 years later. For wind power, although the barrier factor has increased, the value was least among renewable energies in 2020. It means that the wind power was selected in many cases even if the cost of energy produced by solar PV was less. Of course, preferring offshore wind farms over onshore, might be one reason for the less increase in barrier factor for wind power compared to solar technologies. The situation for hydrogen was more severe. This could be due to poor infrastructure, an undeveloped demand market, and negative opinions at the society about dangers of using hydrogen for example in cars.

In Table 2-6, the barrier factors for hydrogen technologies are stated. These factors should not be compared with the factors mentioned above, as their scales are not the same. Calibration argues that fossil-based hydrogen has less resistance compared to green and blue options. Interestingly, alkaline has a barrier factor very close to one that could be due to its known scientific fundamentals for decades.

Table 2-6. Barrier factors for hydrogen technologies obtained from calibration

Technology	Barrier Factor
Alkaline	1.18
PEM	66.6
SOEC	99
Fossil Based	0.67
Fossil + CCS	41.3

It is worth mentioning that the spread values, equation (4), both for the energy sub-system and the hydrogen sub-system, were also obtained during the calibration, 0.0165 and 1.98, respectively. This shows that the internal competition between electrolysis technologies is less sensitive and dependent on their production cost. Because they are in primary stages of development, investing in them may be more decided based on other factors such as having more knowledge or production facilities for a specific technology in that region. The globally average carbon tax was also zero.

Independency to Time Step

There are many rough estimations for choosing the right time step for the simulation. One of the best approaches is to use a time step smaller (for example, one order smaller) than the smallest time constant of the model. As the smallest time constant in this model is the construction time for solar PV, it seems that using DT=0.1 be good enough. However, I preferred to use the usual approach in discrete numerical modeling, that is studying the independency of the results to the size or degree of discrimination. The aim is to see how far using an Euler method for solving the governing equations can influence the results. Here, nothing will be compared with real data, but the main purpose is to find out when the model is close to its best.

For this reason, the time step was assumed to be 1/1000 as the finest meshing in the time domain. Both Euler and Runge-kuta4 (RK4) had the same results. Then the time step was increased to 1/200, 1/100, 1/50, 1/20, and 1/10. The results for solar PV market share in 2010-2050 are shown in Figure 2-8. It is obvious that getting DT equal to 0.1 or 0.05 could result in a behavior too far from what the model should represent. Based on this figure, using a time step equal to 1/200 (=0.005) can save computation time by 5 times while the outcome is as good as DT=0.001. However, using DT=0.01 is also acceptable. Its difference with DT=0.001 is only 7%, compared to the 2% difference for DT=0.005.

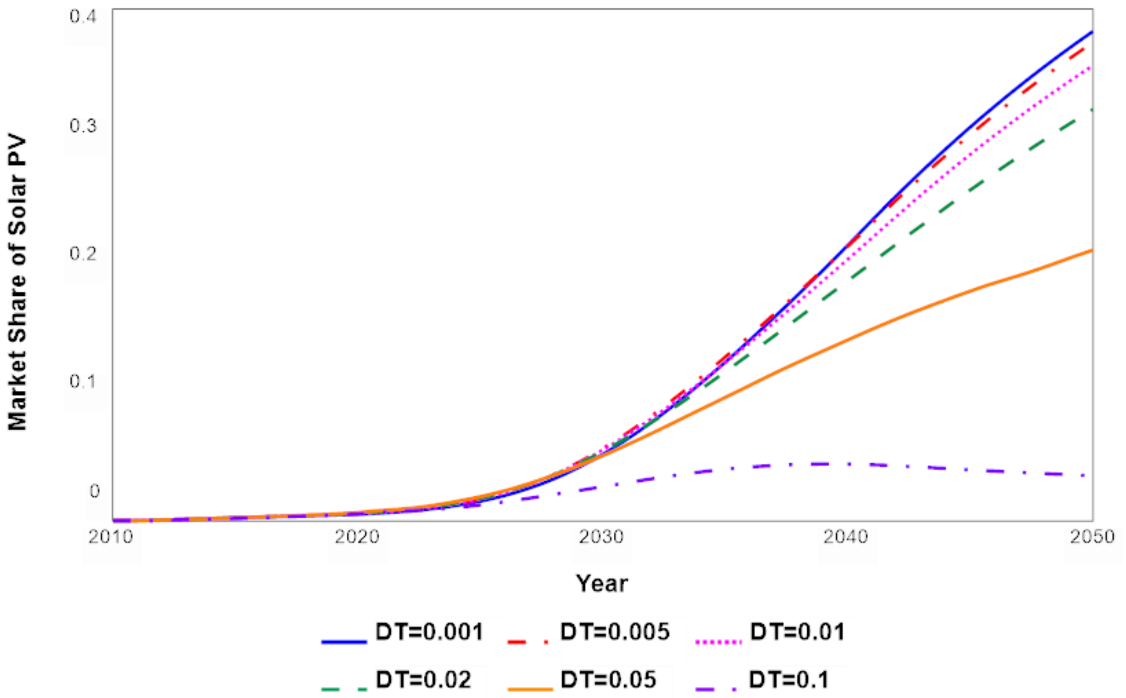

Figure 2-8. Independency to time step by comparing results for solar PV market share

CHAPTER 3 . **TESTING THE HYPOTHESIS**

In this chapter the developed model will be validated and compared to the reference mode. This is essential for confidence building in the model both for modeler and the audience who was not involved in the modeling process. The validation took place by conducting various tests mainly according (Forrester & Senge, 1980) and (Barlas, 1996).

Model Structure Validity

Direct Structure Tests

Direct structure tests examine the validity of a model by comparing its structure with theoretical and empirical knowledge about the real system, without any simulation. The main purpose is to ensure the validity of the model by comparing each relationship with qualitative and quantitative information as well as the generalized knowledge about the system. Six tests have been considered here:

1- STRUCTURE CONFIRMATION TEST

This test aims to check whether the structure of the model contradicts knowledge about the real system's structure. As explained in Chapter 2, the model was developed by integrating sub-models of different energy supply technologies while all of them have almost the same structure. The structures of all parts (learning by doing, market competition, etc.) are simple presentations of the complex global energy system in the real world. All relations and equations are also based on what is happening in the real system. For example, when the energy cost of a technology increases, the desire to invest in new units based on that technology drops.

2- PARAMETER CONFIRMATION TEST

In this test, it was double checked to see if all values are in the accepted range compared to real the system. All the values, as presented in Chapter 2, are in the usual range. Although there is high uncertainty on some parameters with a diverse range of suggested values in the literature, the average values were considered in these cases. For example, the lifespan of hydropower varies from 20 to 100 years in the literature (Gallagher et al., 2015), while 50 years was assumed here. Some uncertainties will be seen later in the next chapter.

3- DIRECT EXTREME CONDITION TEST

The model has to be tested by using extremely low and high values for every single equation. Avoiding the division by zero and using rational extreme values (e.g. annual working hours not more than 8760), the model passed this test.

4- DIMENSIONAL CONSISTENCY TEST

All the units in the model are consistent. In some cases, a multiplier was used to change the unit of a parameter to be the same as the real one. For instance, all sub-technologies of electrolysis which are included in one array have units of "MW" while one of them, water desalination, should have a unit of "m^3/year". For avoiding the separation of water desalination from other sub-technologies, a multiplier was used to correct its unit from "MW" to "m^3/year".

Structure Oriented Behavior Tests

This series of tests assess the validity of the model's structure by indirect comparison of model behavior with the model structure.

1- INDIRECT EXTREME CONDITION TEST

This test is similar to direct extreme condition test with one difference that here the simulation is used to test the model for extreme values. The model behavior was rational when the extreme values were selected in the meaningful range.

2- BEHAVIOR SENSITIVITY TEST

The model behavior was studied by analyzing its sensitivity to various exogenous parameters. Market share of hydrogen in the future energy mix was more sensitive to some parameters such as annual growth in global energy demand, new exploration of fossil fuel resources, and in some cases to fraction of equipping the fossil-based hydrogen units with CCS. Distance from production to demand region and sensitivity of oil price to resource depletion (Figure 2-6) had less influence on results. Compared with a real energy system, the model passes this test. More detailed presentation of sensitivity analysis could be found in Appendix B. Nevertheless, for this model with many affecting parameters, using a Monte-Carlo method is a better choice. This will be discussed later.

1- BOUNDARY ADEQUACY TEST

The global energy system is too massive and complex, so that even big national and international projects focus on some aspects and ignore some others. Various top-down, bottom-up, and hybrid models exist, such as TIMES, NEMS, MARKAL, POLES, LEAP, etc. (Spataru, 2017). Many of these huge models couldn't include all levels, sectors, and technologies in supply, demand, and distribution sides. For the same reason, in this study there should be boundaries in a way that the simplicity doesn't hurt the performance of the model too much. The modeling started by considering a core part for green hydrogen production. Then the boundaries extended as much as was really necessary and feasible. In fact, boundary adequacy test was conducted many times during the modeling phase. For example, the demand of hydrogen was planned to be found as a function of hydrogen cost, but such a function or curve was not found in the literature. Hence, the boundary was extended to include major energy production technologies to have a reference for compassion of their energy cost to hydrogen cost. The current model doesn't require additional structure to study the hypothesis, so it could be concluded that it passes the boundary adequacy test.

Model Behavior Validity

These kinds of tests try to evaluate the validity of a model by observing its behavior.

Behavior Reproduction Tests

Among different behavior reproduction tests, the symptom generation was used here. This test examines how well the behavior of the model matches the historical data of the real system. As historical data for capacities of energy technologies were used for calibration purposes, another kind of data is needed to show the behavior of systems in the real world. The best option could be the cost of energy. In Figure 3-1 and Figure 3-2, the historical costs (red dash-dot line) of solar PV, solar thermal, wind, and nuclear powers were compared with the simulation outcomes (blue solid line). Although there are big differences in some technologies and especially in solar thermal, the trend is the same. For nuclear power, because of rising costs to improve the safety of power plants after the Fukushima accident, the electricity cost started to increase. But the model shows an almost constant value that is close to the average of the historical data.

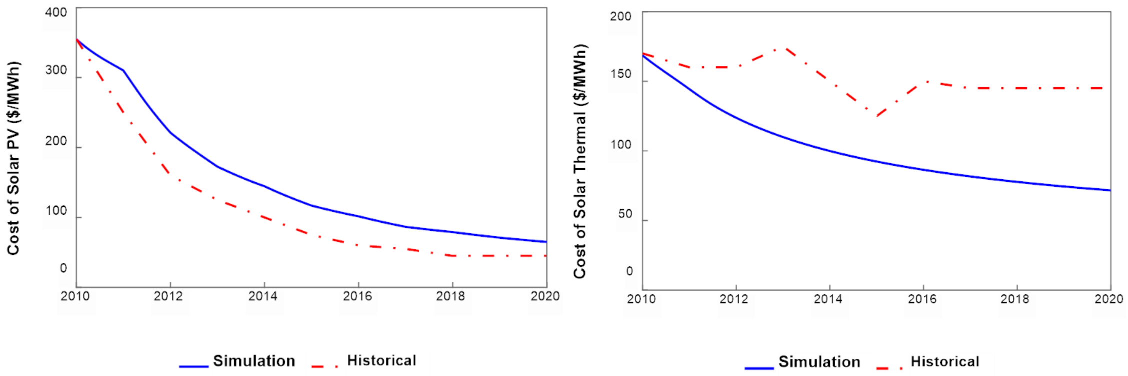

Figure 3-1. Comparing historical electricity cost ($/MWh) with simulation for solar PV (left) and solar thermal (right)

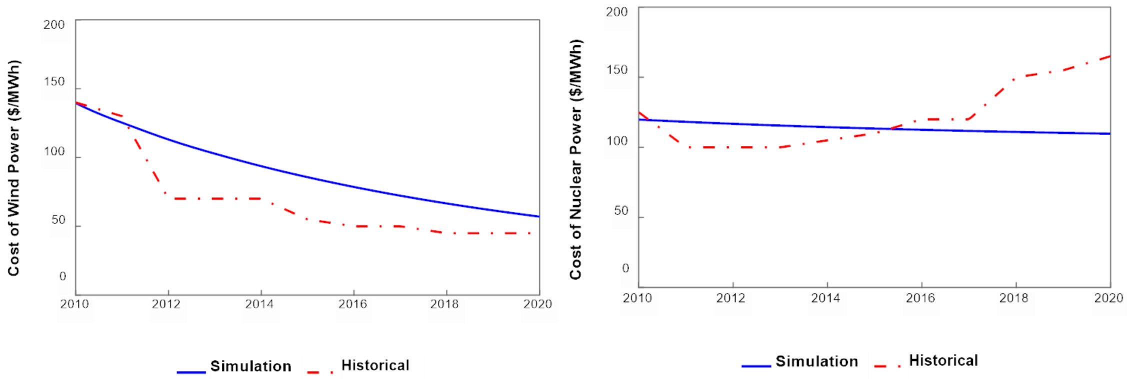

Figure 3-2. Comparing historical electricity cost ($/MWh) with simulation for wind (left) and nuclear (right)

Behavior Prediction Tests

These tests are like Behavior Reproduction Tests except that they focus on the future behavior. As we don't have future data, this should be done qualitatively. The future behavior of the model strongly depends on parameters like carbon tax, subsidies on different technologies and the way they change over time. Assuming that exactly the same feed-in tariffs as 2020 for each technology will apply until 2050, Figure 3-3 was obtained representing the market share of all considered energy technologies. Looking at this behavior qualitatively, this is what is expected to happen in the future based on all implemented studies. Solar and wind energies are promising, and we expect them to provide a significant portion of the global energy demand.

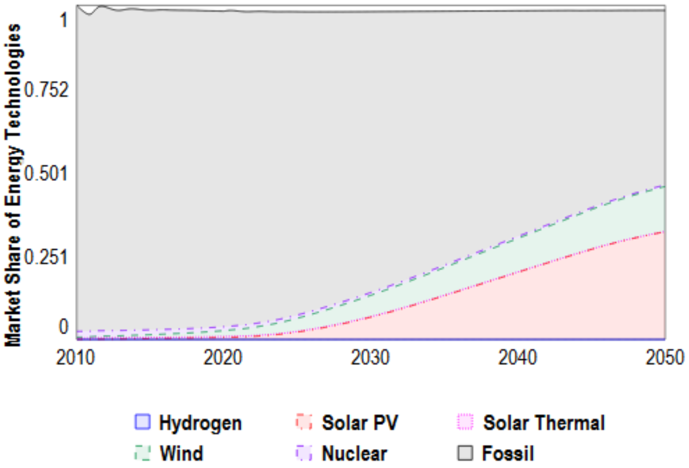

Figure 3-3. A typical market share for energy technologies as the model output

1- PATTERN PREDICTION TEST

This test assesses how much the model can generate correct behavior for the future qualitatively. For example, it is expected that the share of renewable energies like solar PV and wind power will increase in the future because of their continuous cost reduction. As shown in Figure 3-3, the model (in a specific set of parameters) reproduced the same behavior. This is comparable to the roadmap presented by IRENA (International Renewable Energy Agency) illustrated in Figure 3-4. Though the assumed parameters are not the same, the drop in fossil fuel consumption and rise in solar PV and wind power is very similar.

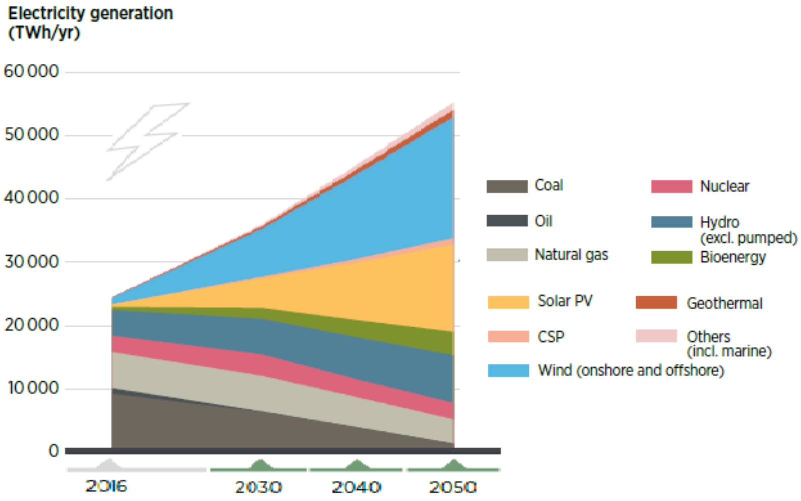

Figure 3-4. A sample of estimated energy market share until 2050 by IRENA (Gielen et al., 2019)

2- EVENT PREDICTION TEST

The model then has to be examined by a particular change in the circumstances, for example a shock in fossil fuel price. However, fossil fuel price is an endogenous variable in this model, a sudden fuel price increase for a period of 10 years was induced by the step function to make it double from 2025 to 2035. The behavior could be compared with the behavior without shock in Figure 3-4. As it was expected, the willingness to install new solar PV accelerated during those 10 years. And after the fossil price goes back to the ordinary levels, the share of Solar PV from the newly built market will decline again because the cheaper alternative with a low barrier factor has come back.

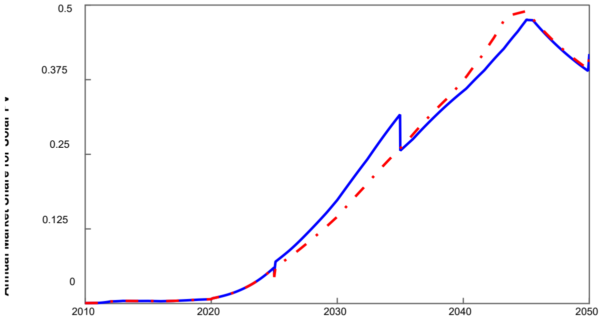

Figure 3-5. Effect of increase in fossil fuel price over a period of 10 years on share of solar PV of newly built market

More Evaluation of the Model

The model passed the above-mentioned tests. But it is worth looking at the results deeper. The reason why the model behaved like Figure 3-3, which is similar to other studies (Figure 3-4), is based on the simple explanation given in Figure 2-3. The success to the successful archetype is obvious here, by competing with a few technologies seeking for a higher share of the market. Because the cost reduction occurred for Solar PV and wind power due to high investment on them during the past decade, they are the successful one. The one who will gain more and more because of its good initial situation. Of course, this success strongly depends on the amount of subsidies they attract.

In fact, three reinforcing loops for solar PV and wind power dominated the same reinforcing loops for hydrogen, hydropower, solar thermal, and nuclear in the case of Figure 3-3. Loops R1 and R2 especially had a larger effect so that each of them resulted in 30 and 40 times less cost (capital and operational costs) from 2010 to 2050. Reinforcing loop R3 had a less important influence (almost halving).

Reviewing the scores for the loops of the model, showed that among 41 non-identical loops of the model, 23 of them are describing 80% of model behavior. Here is a brief explanation of a few loops with higher impact on the system behavior (most dominating loops) that was obtained only for a specific set of parameters and subsidies:

- A reinforcing loop: Less cost for renewable energy (for example wind power) leads to a lower average cost on a global scale. Therefore, the global energy demand will increase a bit as the energy prices become less. As a result, more demand for all kinds of energies and that renewable energy will be required. Higher installation rate for new units of renewable energy will be identical to gaining more experience and reaching a lower cost for that renewable energy.
- A reinforcing loop: When the cost of solar PV falls, the share of solar PVs in the newly installed energy market will be increased. More new installed solar PVs leads to gaining more experience and further reduction in energy generation cost of them. This could happen for all renewable energies.
- A balancing loop: The lower cost for wind energy that is followed by higher global energy demand (as mentioned for the first loop), will result in higher fossil fuel demand as well. This means the price of fossil fuel will increase. So, the market share of fossil fuel will decline. Solar PVs fill the gap. While wind power partially loses the competition with solar PV, the installation of new wind turbines will be reduced, resulting in higher wind energy cost (or it is better to say less decrease in production cost). These could occur between any two renewable energies and fossil fuel.
- A series of balancing loops saying that when installation of any energy technology increases, it will produce more energy, so, there will be less gap with the global energy demand to be filled for the next year. Therefore, less new installation will be needed.

CHAPTER 4 . **POLICY TESTING**

In this chapter, the selected policy to help fossil-free hydrogen production will be discussed. As explained in the model description, two leverages to help renewable energies were selected. First is a carbon tax that will work the same for all renewable energies. The second is subsidizing each renewable energy technology by a specific amount. Here, all kinds of subsidizing were presented in the form of feed-in-tariff.

Subsidizing Green and Blue Hydrogen

The hypothesis argued that green hydrogen could have a more promising future if the government helped it by subsidizing as well as applying carbon tax. Assuming that the subsidizing of all green energy technologies until 2050 will remain the same as 2020, the subsidies to all green and blue hydrogen productions was set to 40% and 90%. The results showed that supporting the hydrogen technologies, even by paying 90% of their costs, still results in a negligible hydrogen share in 2050. The reason behind this is the fact that not only the amount of subsidies to green hydrogen is important, but the amount of subsidies to other green technologies like wind power is deterministic.

This is why it is a better idea to use Monte-Carlo to see all the possibilities regarding the uncertainties. In fact, a random combination of different scenarios could be evaluated by this method. It was assumed that the subsidies for all renewable energies may be a value between 0 to 70% and carbon tax in the range of 0-300 \$/ton CO_2. To be more realistic, the probability of allocating any of these values to each subsidy was assumed to not be incremental, but with log-normal distribution. The mean of these log-normal distributions was chosen to be the amount of subsidies of 2020. For example, for solar thermal, the subsidies until 2050 could be any value between 0 and 70% but the probability of values close to 9.8% (amount for 2020) are much higher. For wind power it is the same while the probability of any subsidies close to 34% (amount for 2020) is higher.

Referring to the outcome (Figure 4-1), market share for hydrogen will be almost nothing in 2050 for all combinations of energy subsidies and carbon tax. Even the hydrogen market may start declining in some scenarios from a year around 2022-2035. This happens because of other renewable energies gaining more market due to less energy cost.

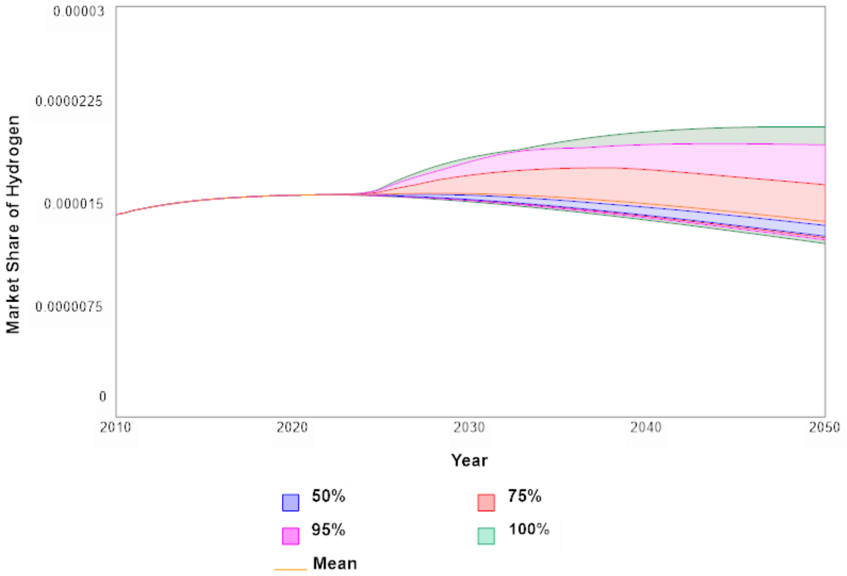

Figure 4-1. Market share for Hydrogen assuming various amount of subsidies for hydrogen and other renewable energies

The disappointing point is that although other renewable energies are successful in this policy analysis, still 59% of the global energy demand will be fulfilled by fossil fuels in the mean scenario (in 2050). At the best combination of subsidies and carbon tax this may be 42% which is far from net-zero scenario for 2050.

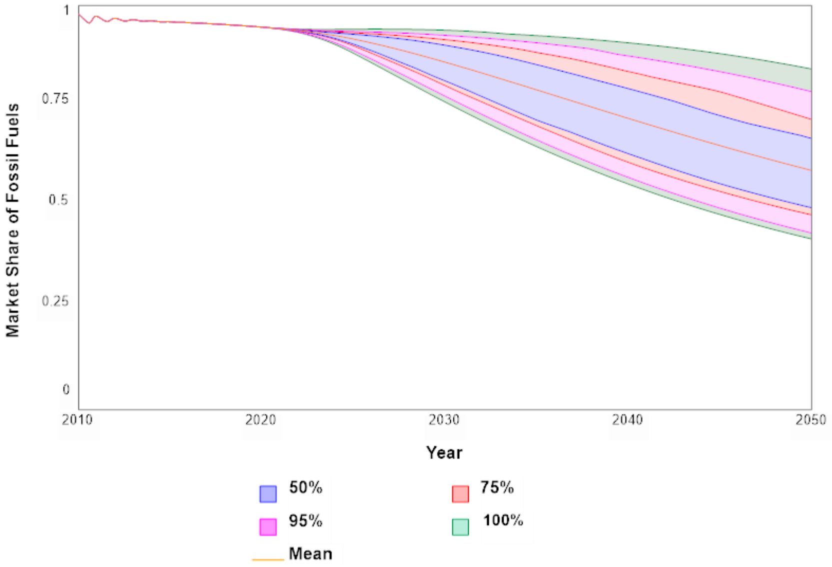

Figure 4-2. Share of fossil fuels from the global energy market for a combination of various amounts for subsidies and carbon tax

But what is the reason behind not satisfying renewable energy development and a very disappointing future for hydrogen, even with high fractions of subsidies? The answer is the barrier factors which were included in this model to make it more realistic. Both Figure 4-1 and Figure 4-2 were obtained based on an assumption that barrier factors will not change after 2020. As it was mentioned in Table 2-5, for not fully developed technologies, the barrier factors changed over 10 years. So, it could be expected that they change after 2020 as well.

Taking three fully developed energy technologies (fossil, hydropower, and nuclear) in addition to solar PV and wind power in 2020 which were more mature compared to 2010, it could be seen that the barrier factors are less for technologies with higher capacities. The logic behind this relationship is that when capacity of an energy technology is considerably higher, it means there are more infrastructures and less social and political resistance against using that. If it was not, investors never invest that much on it. By curve fitting, an exponential function seems to be the best option for estimation of these barrier factors. The barrier factor for technology *i* with (*capacity)ᵢ* was estimated by:

$$Barrier\ Factor_i \approx 53\ e^{-2E-7(Capacity_i)} \tag{5}$$

This formula can give a rough estimation for how a barrier factor may be related to the accumulated capacity of an energy technology. But there are more items influencing the barrier factor. For example, this formulation gives a barrier factor 80% higher than what was proposed in Table 2-5 for wind power in 2020. This shows that for wind power other things more than just expanded infrastructure played the role.

For this reason, using the above formulation to take into account the infrastructure expansion, results in a 2050 market with 48% (not more than 65%) renewable energy while in the best case less than 0.05% of it is from hydrogen (Figure 4-3). While on average, 35% of the market will be for wind power and 10% for solar photovoltaic.

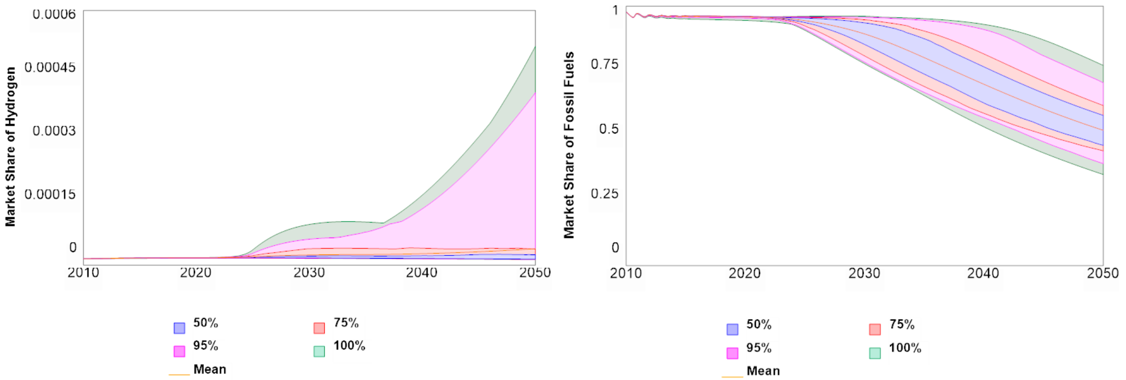

Figure 4-3. Market share for hydrogen (left) and fossil fuel (right) assuming dependency of barrier factor to capacity

What could be concluded is that green hydrogen production needs more support rather than only allocating subsidies and expecting the system to give positive feedback to our investment.

Although the share of hydrogen in the energy market will be very low in this BAU scenario (business as usual), it is still interesting to see how the share of each hydrogen production technologies would be. According to Figure 4-4, fossil-based hydrogen production will decline from near 100% to 32% by 2050 and be replaced by blue hydrogen with a share of 38%. Alkaline and PEM will be very similar to each other with shares close to 25% of the market. SOEC will have the lowest share (Figure 4-5).

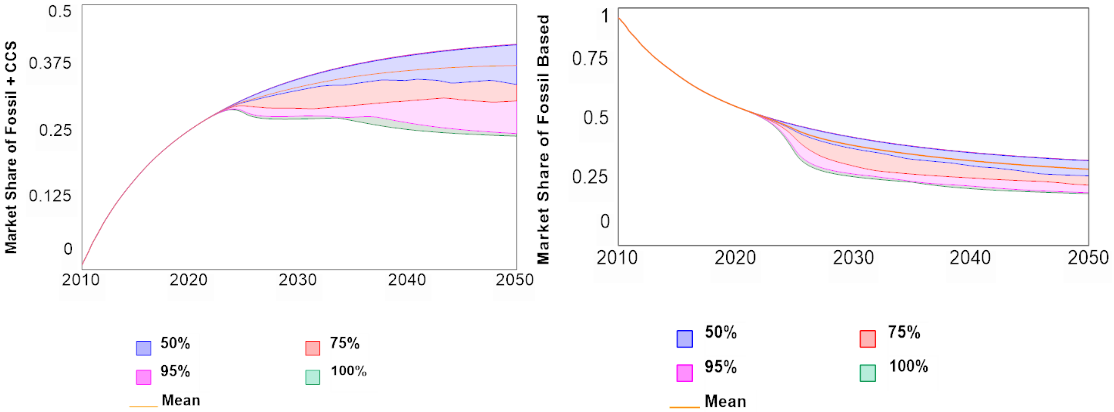

Figure 4-4. Share of fossil-based hydrogen production from hydrogen market: grey (left) and blue (right)

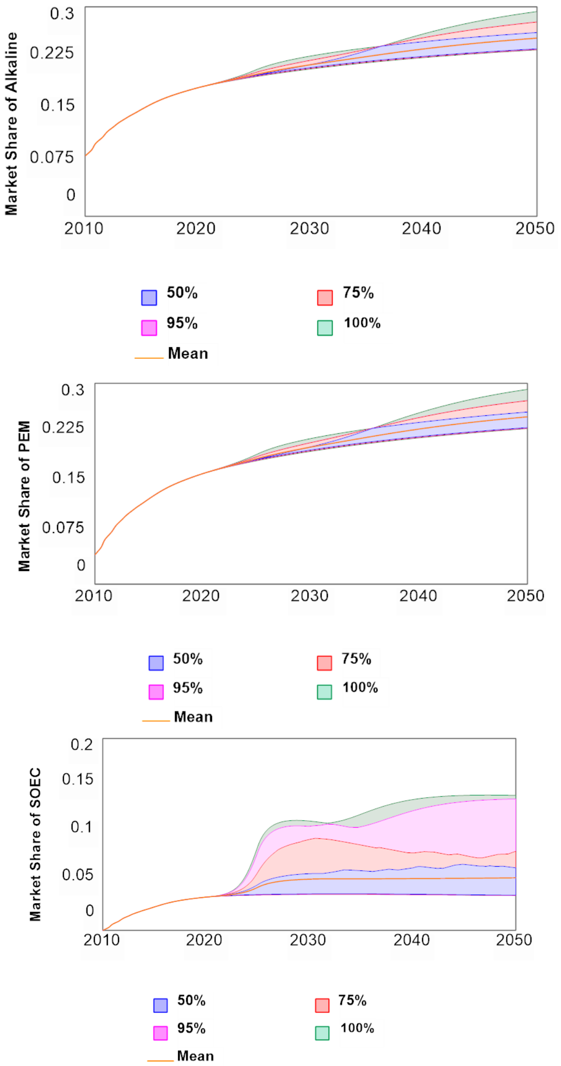

Figure 4-5. Share of Alkaline (top), PEM (middle), and SOEC (bottom) electrolysis from hydrogen market

Effect of Reducing Barrier Factor for Hydrogen

According to Table 2-5, the barrier factor for hydrogen as an energy carrier was the highest and close to 100 in 2020. As discussed in the previous section, subsidizing the hydrogen technologies is not enough and we need to reduce the resistance against using hydrogen in the global energy basket. Here, the ways to decrease the barrier factor will not be evaluated, but in brief they could be strengthening the infrastructures (transportation and distribution pipelines, charging stations for vehicles, etc.), providing the sufficient knowledge for switching to hydrogen in industries and marine transportation, increasing the safety of hydrogen storage tanks, and ensuring the society about benefits and safety of hydrogen as a fuel.

In this section, two scenarios are considered for the future of the hydrogen barrier factor to compare them with the BAU case which were shown in Figure 4-3. First, it was assumed that the barrier factor for using hydrogen will decline linearly from 100 to 25 in the period of 2020-2050. It means that hydrogen is in the same situation as wind power is now. Simulation showed that in this case, the share of hydrogen could increase from 0.01% to 0.05%. Secondly, the target for the barrier factor of hydrogen is set to 10 in 2050. In this case, the hydrogen will provide close to 0.6% of the global energy demand (1.9% at the best case). But another side effect is that developing solar PV powered electrolysis increases the experience gained of the solar photovoltaic panels. This helps the solar PV industry to offer lower electricity prices. In other words, the share of hydrogen increases a lot but still not too significant, while this leads to a higher share of solar PVs. In this case, renewable energies will have 55% of the global market on average.

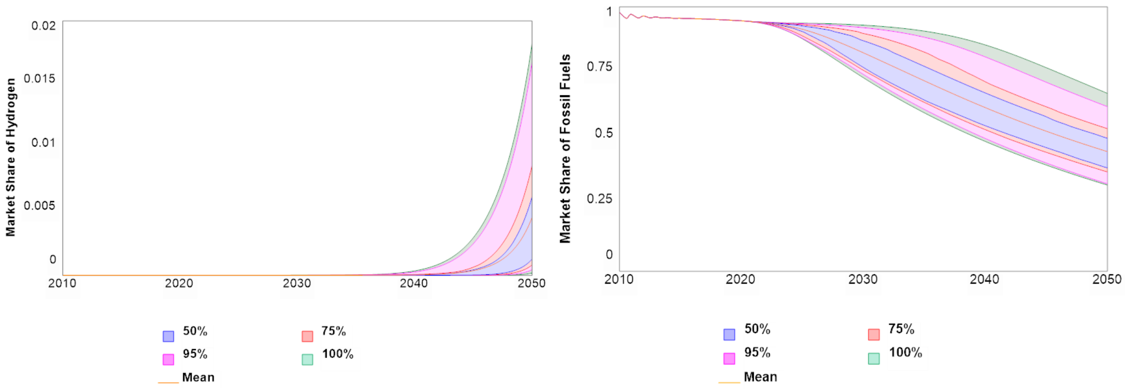

Figure 4-6. Market share of hydrogen (left) and fossil fuels (right) assuming a linear drop of barrier factor for hydrogen to 10% of current value

Optimized Policy

Any outcomes of optimization depend on the selected objective function (parameter or parameters we intended to minimize or maximize). In the current studying system, some objective functions will have an obvious outcome. For example, if we decide to minimize the emission to the atmosphere, the best solution will be cutting the fossil fuel subsidies and giving the highest possible subsidies to all kinds of renewable energies accompanied with an enormous carbon tax. Though this will not be feasible.

#1) Minimizing Global Warming & Specific Investment on CO_2 Emission Reduction

The emitted carbon dioxide to the atmosphere was estimated by model. According to data from 1940 to 2020, a simple linear interpolation was performed and based on that every 95 ppm increase at CO_2 concentration of the atmosphere will lead to 1°C global temperature rise. No, it was decided to minimize the global temperature rise above pre-industrial value. At the same time, a parameter was defined representing the investment needed to avoid emission of one ton of CO_2. The intention is to have a cheaper energy basket to achieve the lowest global temperature.

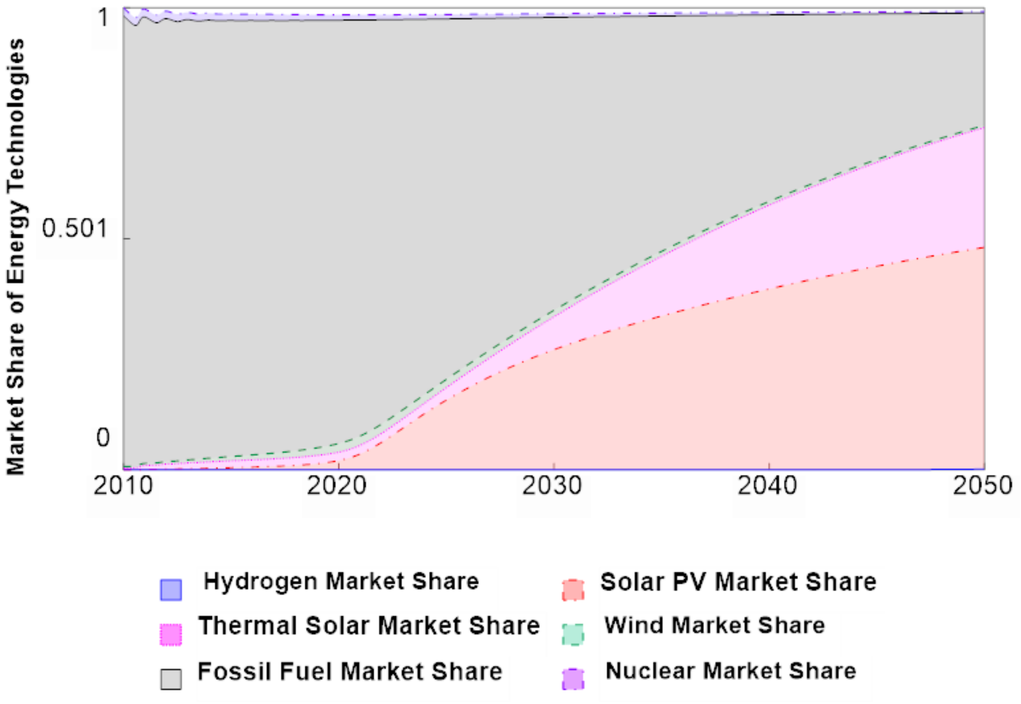

Figure 4-7. Share of technologies for optimization #1

The market shares for various technologies are illustrated in Figure 4-7. In this case, fossil fuels will have only 24% of the energy market in 2050. Most of the global energy demand is fulfilled by solar PV and solar thermal. Hydrogen will serve 0.2% of the market. Surprisingly, wind power will be less than 0.5% because the optimization resulted in almost no subsidizing the wind power. The range for subsidies was assumed to be from 1 to 70%, while some technologies were found to have in the highest value of this range (Table 4-1). The same for carbon tax that the highest value was chosen.

Table 4-1. Optimized parameters for optimization #1

Parameter	Value
Subsidies for Wind	0
Subsidies for Solar PV	70%
Subsidies for Hydro	15%
Subsidies for Solar Thermal	70%
Subsidies for Hydrogen	70%
Subsidies for Fossil Fuels	0
Carbon Tax	300 USD/ton
Barrier Factor for Hydrogen at 2050	15

This case will end up in a global temperature roughly 2 degrees higher than pre-industrial value. While the requirement for avoiding CO_2 by using renewable energies will decline from 350 $ in 2020 to 62 $ in 2050.

#2) Minimizing Global Warming

As it was said earlier, it is expectable how we can minimize global warming. But it could be interesting to look at it quantitatively. Subsidies for all energies will be maximum that here was assumed 70% while for fossil fuels will be zero. To exaggerate the case, carbon tax was selected 500 $/ton. The results show that the global temperature rise (Figure 4-8) will be 1.87 °C that is still less than the desired decided goal (1.5 °C). In this case, fossil fuels will still have a share of 19% in 2050. And hydrogen's share will not exceed 1.4% of the global energy demand. The market shares have been illustrated in Figure 4-9.

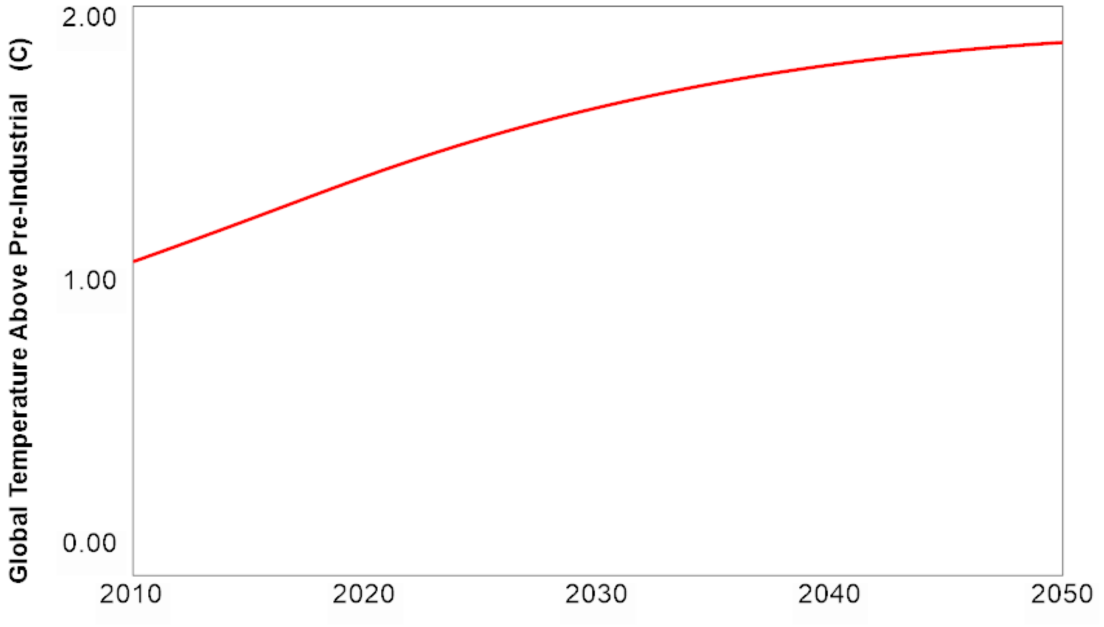

Figure 4-8. Global Temperature Above Pre-Industrial Period for optimization #1

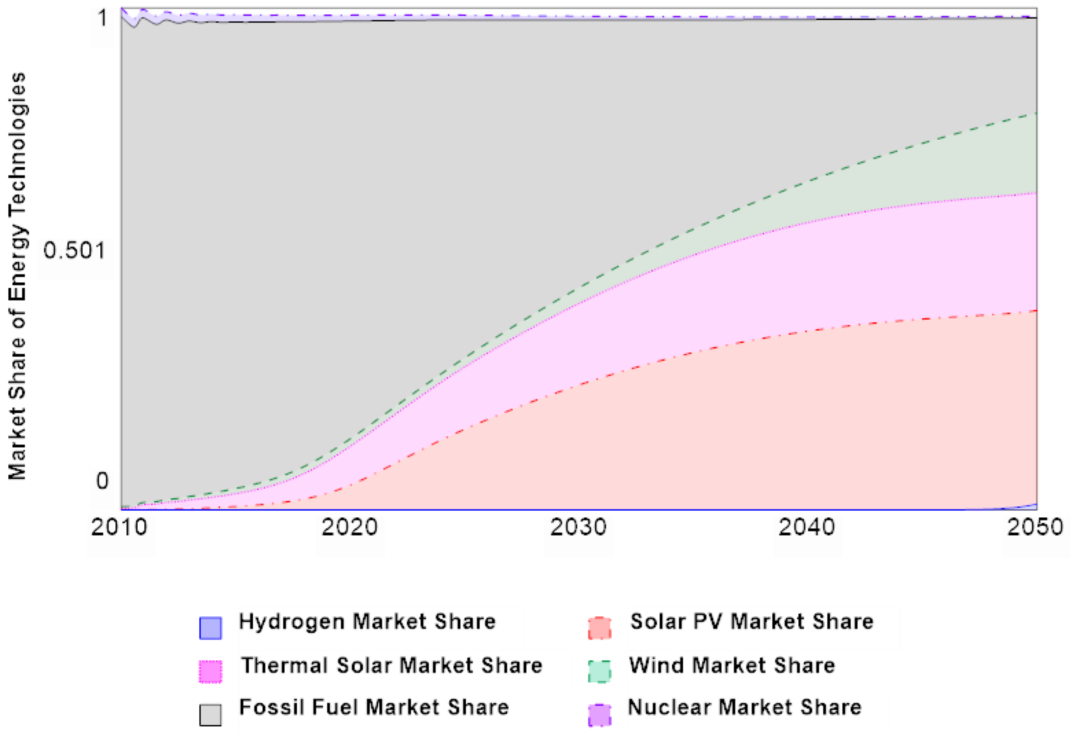

Figure 4-9. Share of technologies for optimization #2

In this extreme case, share of each hydrogen producing technology is shown in Figure 4-10. Share of electrolysis technologies increases mainly after 2040 but will take longer time to overcome the fossil-based technologies (blue and grey).

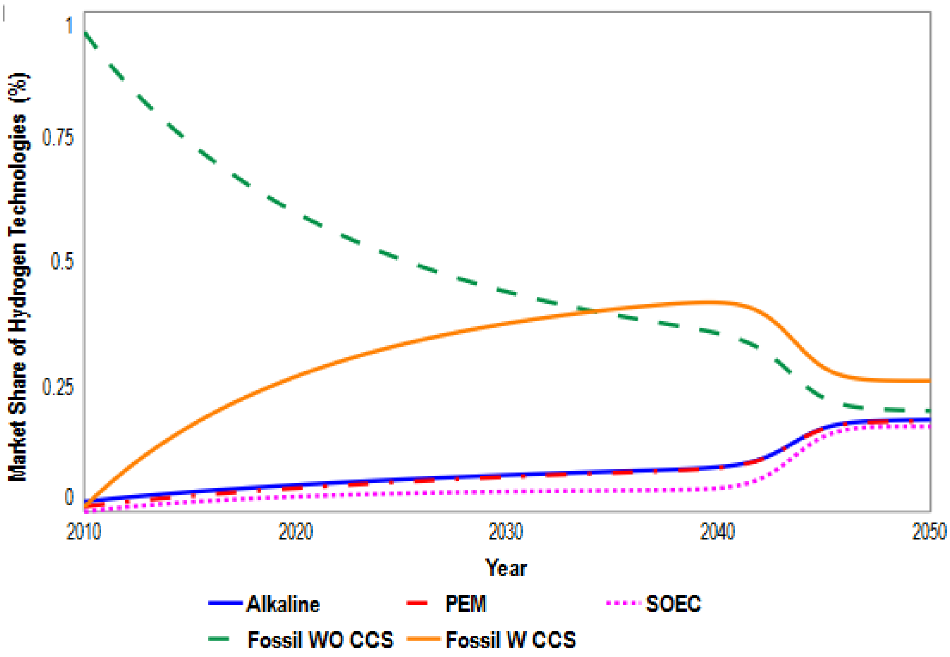

Figure 4-10. Share of hydrogen technologies for optimization #2

CHAPTER 5 . CONCLUSIONS

A simple form of global energy system was modeled to evaluate the role of green hydrogen powered by solar PVs. The main purpose was to find policies which can help the green hydrogen industry to take more share from the future market. The necessity of having hydrogen in the energy basket was that hydrogen seems very appropriate for some applications such as ship engines. The model calibration showed that a pure competition based on energy cost could not be a realistic option. Therefore, a barrier factor was used representing all types of resistances against using a technology. Hydrogen has a high barrier factor.

Studies using the developed model demonstrated that the hydrogen would not get more than 1.9% of the global energy market by 2050. Of course, this number is the highest optimistic level. This result is far from other studies, mentioned in the introduction, saying that at least 4% of the energy market in 2050 will be dedicated to hydrogen.

On the other hand, achieving a fossil free energy system until 2050 seems unrealistic. It depends on the actions that government take on energy transition, but the share of fossil fuels in 2050 may be in range of 20-50%. This means that the global temperature in 2050 will be 2-2.8 °C above the pre-industrial period. This study showed that allocating subsidies to renewable energies and particularly green hydrogen technologies is not sufficient. The barrier factor of hydrogen should be reduced. That means, governments must provide needed infrastructure and try to decrease social resistances.

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CHAPTER 7 APPENDIX

Appendix A: (Model Documentation)

	Equation	Properties	Units	Documentation	Annotation
Top-Level Model:					
Accumulated_Experience_of_Electrolysis[SubTech_Elect](t)	Accumulated_Experience_of_Electrolysis[SubTech_Elect](t - dt) + (Experience_Gaining_of_Electrolysis[SubTech_Elect]) * dt	INIT Accumulated_Experience_of_Electrolysis[SubTech_Elect] = INIT(Capacity_of_Electrolysis)*(1+TIME-STARTTIME)	MW*year		NON-NEGATIVE
Accumulated_Experience_of_Fossil_Based_Plants[Fossil_Hydrogen](t)	Accumulated_Experience_of_Fossil_Based_Plants[Fossil_Hydrogen](t - dt) + (Experience_Gaining_of_Fossil_Based_Hydrogen_Plants[Fossil_Hydrogen]) * dt	INIT Accumulated_Experience_of_Fossil_Based_Plants[Fossil_Hydrogen] = (INIT("Capacity_of_Fossil_Based_(Blue)")+INIT("Capacity_of_Fossil_Based_(Grey)"))*(1+TIME-STARTTIME)	MW*year		NON-NEGATIVE
Accumulated_Investment_on_Hydrogen[H2_Market](t)	Accumulated_Investment_on_Hydrogen[H2_Market](t - dt) + (Investing_Rate_on_Hydrogen[H2_Market]) * dt	INIT Accumulated_Investment_on_Hydrogen[H2_Market] = 0	USD		NON-NEGATIVE
Accumulated_Oil_Production(t)	Accumulated_Oil_Production(t - dt) + (Oil_Production_Rate) * dt	INIT Accumulated_Oil_Production = 213e9	ton	Based on data from 1900 from these references: ref. (IEA, 2020)	NON-NEGATIVE
Accumulated_Spent_Money_on_All_Hydrogen_Technologies(t)	Accumulated_Spent_Money_on_All_Hydrogen_Technologies(t - dt) + (Rate_of_Spending_Money_on_All_Hydrogen) * dt	INIT Accumulated_Spent_Money_on_All_Hydrogen_Technologies = 0	USD		NON-NEGATIVE

Available_Land_for_Hydrogen_Production(t)	Available_Land_for_Hydrogen_Production(t - dt) + (- Rate_of_Land_Usage_for_Hydrogen_Production) * dt	INIT Available_Land_for_Hydrogen_Production = 13e6*1e6	square meter	This value is now for Africa. Ref. (Trieb, 2009)	NON-NEGATIVE
Available_Land_for_Solar_Energy(t)	Available_Land_for_Solar_Energy(t - dt) + (- Rate_of_Land_Usage_for_Solar_Energy) * dt	INIT Available_Land_for_Solar_Energy = 20.4e11	square meter	From "globally average tilted irradiation at optimum angle" and the below reference that estimated a potential for solar PV as high as 613e12 kwh/year in the global scale, the usable land could be calculated. In the below reference, many factors for the land requirements are considered. As the 613e12 is calculated for PV with efficiency of 20%, the potential for solar energy will be 5 times more. Ref. (Korfiati et al., 2016) However, a sum from below reference results in a value equal to 8e11 for all countries. https://www.finder.com/uk/solar-power-potential	NON-NEGATIVE
Available_Land_for_Wind_Energy(t)	Available_Land_for_Wind_Energy(t - dt) + (- Rate_of_Land_Usage_for_Wind_Energy) * dt	INIT Available_Land_for_Wind_Energy = 1.656e14	square meter	From the reference below, the total energy generation from wind is mentioned to be 3024 EJ globally. It is stated that all the suitable lands are considered (unforested, ice-free, nonmountainous areas away from any towns and that the turbines had to be spaced by several hundred meters) where there is enough wind speed based on Global Wind Atlas. While they assumed 20% for capacity factor, it could be found that the maximum capacity potential is around 4.8e5 GW.	NON-NEGATIVE

				As it is stated in "Specific Land Requirement for Wind Farm", each MW of wind energy needs 34.5 ha in average. So, it could be estimated roughly that the maximum area of lands suitable for wind energy is 1.656e14 m^2 (1.656e8 km^2). https://www.e-education.psu.edu/earth104/node/925	
Avoided_CO2_for_Hydrogen(t)	Avoided_CO2_for_Hydrogen(t - dt) + (Rate_of_Avoiding_CO2_for_Green_Blue_Hydrogen) * dt	INIT Avoided_CO2_for_Hydrogen = 0	ton		
Avoided_CO2_for_Renewable_Energies(t)	Avoided_CO2_for_Renewable_Energies(t - dt) + (Rate_of_Avoiding_CO2_for_Renewable_Energies) * dt	INIT Avoided_CO2_for_Renewable_Energies = 0	ton		
Capacity_of_Electrolysis[Solar_PV](t)	Capacity_of_Electrolysis[Solar_PV](t - dt) + (Installation_of_Electrolysis[Solar_PV] - Scrapping_of_Electrolysis[Solar_PV]) * dt	INIT Capacity_of_Electrolysis[Solar_PV] = LOOKUP(History_of_Solar_PV_Capacity, Simulation_Start_Year)	MW	For water purification the unit is "cubic meter per year" 100e6 USD https://southeast.newschannelnebraska.com/story/45910970/alkaline-water-electrolysis-market-statistics-and-research-analysis-detailed-in-latest-research-report-2022-to-2028 Alkaline, PEM, SOEC for 2020 https://www.iea.org/data-and-statistics/charts/global-installed-electrolysis-capacity-by-technology-2015-2020 NOTE:	NON-NEGATIVE

				the initial value for hydrogen compressors was derived from the initial value of "total required power for compression" as an estimation	
Capacity_of_Electrolysis[Water_Purification](t)	Capacity_of_Electrolysis[Water_Purification](t - dt) + (Installation_of_Electrolysis[Water_Purification] - Scrapping_of_Electrolysis[Water_Purification]) * dt	INIT Capacity_of_Electrolysis[Water_Purification] = LOOKUP(History_of_Desalination, Simulation_Start_Year)*Multiplier_for_Unit_Difference_of_Water_Desalination			
Capacity_of_Electrolysis[Compression](t)	Capacity_of_Electrolysis[Compression](t - dt) + (Installation_of_Electrolysis[Compression] - Scrapping_of_Electrolysis[Compression]) * dt	INIT Capacity_of_Electrolysis[Compression] = LOOKUP(History_of_Compressor, STARTTIME)			
Capacity_of_Electrolysis[H2_Module_Alkaline](t)	Capacity_of_Electrolysis[H2_Module_Alkaline](t - dt) + (Installation_of_Electrolysis[H2_Module_Alkaline] - Scrapping_of_Electrolysis[H2_Module_Alkaline]) * dt	INIT Capacity_of_Electrolysis[H2_Module_Alkaline] = LOOKUP(History_of_Alkaline, Simulation_Start_Year)			
Capacity_of_Electrolysis[H2_Module_PEM](t)	Capacity_of_Electrolysis[H2_Module_PEM](t - dt) + (Installation_of_Electrolysis[H2_Module_PEM] - Scrapping_of_Electrolysis[H2_Module_PEM]) * dt	INIT Capacity_of_Electrolysis[H2_Module_PEM] = LOOKUP(History_of_PEM, Simulation_Start_Year)			
Capacity_of_Electrolysis[H2_Module_SOEC](t)	Capacity_of_Electrolysis[H2_Module_SOEC](t - dt) + (Installation_of_Electrolysis[H2_Module_SOEC] - Scrapping_of_Electrolysis[H2_Module_SOEC]) * dt	INIT Capacity_of_Electrolysis[H2_Module_SOEC] = LOOKUP(History_of_SOEC, Simulation_Start_Year)			
"Capacity_of_Fossil_Based_(Blue)"(t)	"Capacity_of_Fossil_Based_(Blue)"(t - dt) + (Adding_CCS + Installation_of_New_Blue_Hydrogen_Plants - Scrapping_of_Blue_Hydrogen_Plants) * dt	INIT "Capacity_of_Fossil_Based_(Blue)" = 0.01*LOOKUP(History_of_Fossil_	MW	1% of fossil based hydrogen is with CCS	NON-NEGATIVE

		Based_Hydrogen, Simulation_Start_Year)		Reference: (IEA, 2016)	
"Capacity_of_Fossil_Based_(Grey)"(t)	"Capacity_of_Fossil_Based_(Grey)"(t - dt) + (Installation_of_New_Grey_Hydrogen_Plants - Scrapping_of_Grey_Hydrogen_Plants - Adding_CCS) * dt	INIT "Capacity_of_Fossil_Based_(Grey)" = LOOKUP(History_of_Fossil_Based_Hydrogen, STARTTIME)	MW	BLUE HYDROGEN - Global CCS Institute & https://www.iea.org/fuels-and-technologies/hydrogen It came from 75 Mt of H2 production	NON-NEGATIVE
Capacity_of_Fossil_Fuel_Based_Energy(t)	Capacity_of_Fossil_Fuel_Based_Energy(t - dt) + (New_Fossil_Based_Installation - Scrapping_of_Fossil_Based_Plants) * dt	INIT Capacity_of_Fossil_Fuel_Based_Energy = 21.26e6	MW	Solar Heat Worldwide, Detailed Market Data 2019, AEE - Institute for Sustainable Technologies page 9	NON-NEGATIVE
CO2_Emitted_to_Atmosphere(t)	CO2_Emitted_to_Atmosphere(t - dt) + (CO2_Emission_Rate - CO2_Removal_by_Forrest) * dt	INIT CO2_Emitted_to_Atmosphere = 3.21e12+ LOOKUP(History_of_Annual_CO2_Emission, STARTTIME)	ton	This is a roughly estimation by assuming that the only sink is forest and it is constant. The initial value of 3.21e12 is the current total amount of carbon dioxide in the atmosphere. The value was obtained from currently CO2 concentration of ~410 ppm. https://en.wikipedia.org/wiki/Carbon_dioxide_in_Earth%27s_atmosphere	
Global_Energy_Demand(t)	Global_Energy_Demand(t - dt) + (Change_in_Global_Average_Energy_Demand + Change_in_Global_Energy_Demand_in_Response_to_Cost_Change) * dt	INIT Global_Energy_Demand = LOOKUP(History_of_Global_Energy_Demand, STARTTIME)	MW*hour/year		NON-NEGATIVE
Government_Expenditure(t)	Government_Expenditure(t - dt) + (Subsidizing_Rate - Earning_Rate_by_Taxing) * dt	INIT Government_Expenditure = 0	USD		
Land_Used_for_Electrolysis(t)	Land_Used_for_Electrolysis(t - dt) + (Rate_of_Change_in_Required_Land_for_Electrolysis) * dt	INIT Land_Used_for_Electrolysis = (Capacity_of_Electrolysis[Solar_PV])*Annual_Working_Hours_of_Elec	square meter	The electrolysis working with solar PV is almost nothing by now. So an initial value of zero is acceptable.	NON-NEGATIVE

		trolysis*Required_Land_per_MWh_of_new_Solar_PV_for_Electrolysis			
Land_Used_for_Solar_PV(t)	Land_Used_for_Solar_PV(t - dt) + (Rate_of_Change_in_Required_Land_for_Solar_PV) * dt	INIT Land_Used_for_Solar_PV = Required_Land_per_MWh_of_new_Solar_PV*(Renewable_Energies.Capacity_of_Solar_PV*Renewable_Energies.Average_Working_Hours_of_Solar_Systems_in_Global_Scale)	square meter	The initial value for land used was estimated by using the efficiency of solar PV at the year our simulation starts. Obviously, the efficiency of the previously installed PVs are lower, but as the installed PVs are not too much (compared to what will be later), this approximation could be accepted.	NON-NEGATIVE
Land_Used_for_Solar_Thermal(t)	Land_Used_for_Solar_Thermal(t - dt) + (Rate_of_Change_in_Required_Land_for_Solar_Thermal) * dt	INIT Land_Used_for_Solar_Thermal = Required_Land_per_MWh_of_new_Solar_Thermal*(Renewable_Energies.Capacity_of_Solar_Thermal*Renewable_Energies.Average_Working_Hours_of_Solar_Systems_in_Global_Scale)	square meter	The initial value for land used was estimated by using the efficiency of solar thermal at the year our simulation starts. Obviously, the efficiency of the previously installed solar panels are lower, but as the installed panels are not too much (compared to what will be later), this approximation could be accepted.	NON-NEGATIVE
Land_Used_for_Wind_Power(t)	Land_Used_for_Wind_Power(t - dt) + (Rate_of_Land_Usage_for_Wind_Energy) * dt	INIT Land_Used_for_Wind_Power = Renewable_Energies.Capacity_of_Wind*Specific_Land_Requirement_for_Wind_Farm	square meter		NON-NEGATIVE
Proven_Oil_Reservoirs(t)	Proven_Oil_Reservoirs(t - dt) + (New_Oil_Exploration - Oil_Production_Rate) * dt	INIT Proven_Oil_Reservoirs = 230.666E9 +155.7E9 +737E9	ton	I estimated the amount of resources that are based on oil equivalent: - OIL: Referring to Statistical Review of World Energy - BP (2021)), the proven reserves of oil raised from 121 to 230 billion tones from 1987 to 2020. - Natural gas: Data for 2017 (https://www.worldometers.info/gas/) shows it was equal to 1154e9 oil barrel	NON-NEGATIVE

				that will be 155e9 tons. -Coal: Based on data for 2016 (https://www.worldometers.info/coal/) it was equivalent to 5458E9 of oil barrel that will be 737E9 tons	
Total_Accumulated_Investment_on_Non_Fossil(t)	Total_Accumulated_Investment_on_Non_Fossil(t - dt) + (Rate_of_Investing_on_non_Fossil_Based) * dt	INIT Total_Accumulated_Investment_on_Non_Fossil = 0	USD		NON-NEGATIVE
Adding_CCS	"Capacity_of_Fossil_Based_(Grey)"*Fraction_of_Grey_Hydrogen_Plants_to_Blue_Ones	OUTFLOW PRIORITY: 2	MW/Year		UNIFLOW
Change_in_Global_Average_Energy_Demand	Average_Rate_of_Global_Energy_Demand_Increase*Global_Energy_Demand		MW*hour/year/year		UNIFLOW
Change_in_Global_Energy_Demand_in_Response_to_Cost_Change	(Global_Energy_Demand/Per_year)*(Effect_of_Energy_Cost_on_Demand-1)*DT/Per_year		MW*hour/year/year		
CO2_Emission_Rate	(Total_Annual_Energy_of_Fossil_Based/Oil_Fuel_LHV)*Specific_Emission_of_Fossil_Fuels +(Produced_Hydrogen[Fossil_WO_CCS]/Hydrogen_Lower_Heating_Value)*(Specific_Emission_of_Fossil_Based_Hydrogen-Specific_Emission_of_Fossil_Fuels*Hydrogen_Lower_Heating_Value/Natural_Gas_LHV)		ton/Year		UNIFLOW
CO2_Removal_by_Forrest	7.6e9		ton/Year	https://www.nasa.gov/feature/goddard/2021/nasa-satellites-help-quantify-forests-impacts-on-the-global-carbon-budget	UNIFLOW
Earning_Rate_by_Taxing	CO2_Emission_Rate*Carbon_Tax		USD/year		UNIFLOW

Experience_Gaining_of_Electrolysis[Solar_PV]	Capacity_of_Electrolysis[Solar_PV]		MW		UNIFLOW
Experience_Gaining_of_Electrolysis[Water_Purification]	(Capacity_of_Electrolysis[Water_Purification]+Multiplier_for_Unit_Difference_of_Water_Desalination*Water_Desalination_Capacity_for_Fossil_Based)				
Experience_Gaining_of_Electrolysis[Compression]	Capacity_of_Electrolysis[Compression]				
Experience_Gaining_of_Electrolysis[H2_Module_Alkaline]	Capacity_of_Electrolysis[H2_Module_Alkaline]				
Experience_Gaining_of_Electrolysis[H2_Module_PEM]	Capacity_of_Electrolysis[H2_Module_PEM]				
Experience_Gaining_of_Electrolysis[H2_Module_SOEC]	Capacity_of_Electrolysis[H2_Module_SOEC]				
Experience_Gaining_of_Fossil_Based_Hydrogen_Plants[Fossil_Hydrogen]	"Capacity_of_Fossil_Based_(Grey)"+"Capacity_of_Fossil_Based_(Blue)"		MW		UNIFLOW

Installation_of_Electrolysis[Solar_PV]	(Total_Power_Required_for_New_Installed_Electrolysis+Total_Power_Required_for_New_Installed_Compression+Total_Power_Required_for_New_Installed_Desalination)/Construction_Time_of_Electrolysis		MW/year		UNIFLOW
Installation_of_Electrolysis[Water_Purification]	Multiplier_for_Unit_Difference_of_Water_Desalination*((New_Built_Hydrogen_Technologies_Market_Share[Alkaline]+New_Built_Hydrogen_Technologies_Market_Share[PEM]+New_Built_Hydrogen_Technologies_Market_Share[SOEC])*Total_Required_New_Hydrogen_Production*Water_Requirement_of_Electrolysis)/Construction_Time_of_Electrolysis { +Scrapping_of_Electrolysis[Water_Purification]				
Installation_of_Electrolysis[Compression]	(Total_Power_Required_for_New_Installed_Compression)/Construction_Time_of_Electrolysis				
Installation_of_Electrolysis[H2_Module_Alkaline]	Total_Required_New_Hydrogen_Production*(New_Built_Hydrogen_Technologies_Market_Share[Alkaline]/Annual_Working_Hours_of_Electrolysis)/Construction_Time_of_Electrolysis				
Installation_of_Electrolysis[H2_Module_PEM]	Total_Required_New_Hydrogen_Production*(New_Built_Hydrogen_Technologies_Market_Share[PEM]/Annual_Working_Hours_of_Electrolysis)/Construction_Time_of_Electrolysis				
Installation_of_Electrolysis[H2_Module_SOEC]	Total_Required_New_Hydrogen_Production*(New_Built_Hydrogen_Technologies_Market_Share[SOEC]/Annual_Working_Hours_of_Electrolysis)/Construction_Time_of_Electrolysis				
Installation_of_New_Blue_Hydrogen_Plants	MAX((Total_Required_New_Hydrogen_Production_1*New_Built_Hydrogen_Technologies_Market_Share[Fossil_W_CCS]/Annual_Working_Hours_of_Fossil_Based_Hydrogen_Plants) /Construction_Time_for_Fossil_Based_Plants - Adding_CCS, 0)		MW/Year		UNIFLOW
Installation_of_New_Grey_Hydrogen_Plants	(Total_Required_New_Hydrogen_Production_1*New_Built_Hydrogen_Technologies_Market_Share[Fossil_WO_CCS]/Annual_Working_Hours_of_Fossil_Based_Hydrogen_Plants)/Construction_Time_for_Fossil_Based_Plants		MW/Year		UNIFLOW
Investing_Rate_on_Hydrogen[Alkaline]	CAPEX_of_Hydrogen_Production[Alkaline]*Installation_of_Electrolysis[H2_Module_Alkaline]		USD/year		UNIFLOW

Investing_Rate_on_Hydrogen[PEM]	CAPEX_of_Hydrogen_Production[PEM]*Installation_of_Electrolysis[H2_Module_PEM]				
Investing_Rate_on_Hydrogen[SOEC]	CAPEX_of_Hydrogen_Production[SOEC]*Installation_of_Electrolysis[H2_Module_SOEC]				
Investing_Rate_on_Hydrogen[Fossil_WO_CCS]	CAPEX_of_Hydrogen_Production[Fossil_WO_CCS]*Installation_of_New_Grey_Hydrogen_Plants				
Investing_Rate_on_Hydrogen[Fossil_W_CCS]	CAPEX_of_Hydrogen_Production[Fossil_W_CCS]*Installation_of_New_Blue_Hydrogen_Plants +(CAPEX_of_Hydrogen_Production[Fossil_W_CCS]-CAPEX_of_Hydrogen_Production[Fossil_WO_CCS])*Adding_CCS				
New_Fossil_Based_Installation	(Required_Energy_Production_for_One_Year*New_Built_Fossil_Fuel_Based_Market_Share/Average_Working_Hours_of_Fossil_Based_Plants)/Construction_Time_of_Fossil_Based_Energy		MW/Year		UNIFLOW
New_Oil_Exploration	7.15E9 +4.4E9		ton/year	This is the average value in the period of 1987-2020 for Oil. For natural gas, the average from 2016 to 2018 (https://www.statista.com/statistics/1088776/global-natural-gas-discovery-volume/) And for coal, because of older history, no new exploration was considered.	UNIFLOW
Oil_Production_Rate	(Fossil_Fuel_Market_Share*Estimated_Global_Energy_Demand)/Oil_Fuel_LHV		ton/year		UNIFLOW
Rate_of_Avoiding_CO2_for_Green_Blue_Hydrogen	((Produced_Hydrogen[Alkaline]+Produced_Hydrogen[PEM]+Produced_Hydrogen[SOEC]+Produced_Hydrogen[Fossil_W_CCS]+Produced_Hydrogen[Fossil_WO_CCS])/Hydrogen_Lower_Heating_Value)*(Hydrogen_Lower_Heating_Value/Natural_Gas_LHV)*Specific_Emission_of_Fossil_Fuels -(Produced_Hydrogen[Fossil_WO_CCS]/Hydrogen_Lower_Heating_Value)*(Speci		ton/year		

	fic_Emission_of_Fossil_Based_Hydrogen-Specific_Emission_of_Fossil_Fuels*Hydrogen_Lower_Heating_Value/Natural_Gas_LHV)				
Rate_of_Avoiding_CO2_for_Renewable_Energies	Total_Produced_Energy_from_Non_Fossil*Specific_Emission_of_Fossil_Fuels/Natural_Gas_LHV		ton/year		
Rate_of_Change_in_Required_Land_for_Electrolysis	IF Land_Used_for_Electrolysis=0 AND Installation_of_Electrolysis[Solar_PV]<Scrapping_of_Electrolysis[Solar_PV] THEN 0 ELSE (Installation_of_Electrolysis[Solar_PV]-Scrapping_of_Electrolysis[Solar_PV])*Annual_Working_Hours_of_Electrolysis*Required_Land_per_MWh_of_new_Solar_PV_for_Electrolysis		square meter/Year		
Rate_of_Change_in_Required_Land_for_Solar_PV	(Renewable_Energies.Installation_of_Solar_PV-Renewable_Energies.Scrapping_of_Solar_PV)*Renewable_Energies.Average_Working_Hours_of_Solar_Systems_in_Global_Scale*Required_Land_per_MWh_of_new_Solar_PV		square meter/Year		
Rate_of_Change_in_Required_Land_for_Solar_Thermal	(Renewable_Energies.Installation_of_Solar_Thermal-Renewable_Energies.Scrapping_of_Solar_Thermal)*Renewable_Energies.Average_Working_Hours_of_Solar_Systems_in_Global_Scale*Required_Land_per_MWh_of_new_Solar_Thermal		square meter/Year		
Rate_of_Investing_on_non_Fossil_Based	SUM(Investing_Rate_on_Hydrogen)-Investing_Rate_on_Hydrogen[Fossil_WO_CCS] +Total_Annual_Expenditure_on_Non_Fossil		USD/year		UNIFLOW
Rate_of_Land_Usage_for_Hydrogen_Production	Rate_of_Change_in_Required_Land_for_Electrolysis		square meter/Year		
Rate_of_Land_Usage_for_Solar_Energy	Rate_of_Change_in_Required_Land_for_Solar_Thermal+Rate_of_Change_in_Required_Land_for_Solar_PV		square meter/Year		
Rate_of_Land_Usage_for_Wind_Energy	Specific_Land_Requirement_for_Wind_Farm*(Renewable_Energies.Installation_of_Wind-Renewable_Energies.Scrapping_of_Wind)		square meter/Year		

Rate_of_Spending_Money_on_All_Hydrogen	Total_Investment_Rate+ Capacity_of_Electrolysis[H2_Module_Alkaline]*OPEX_of_Hydrogen_Production[Alkaline]+"Capacity_of_Fossil_Based_(Blue)"*OPEX_of_Hydrogen_Production[Fossil_W_CCS]+Capacity_of_Electrolysis[H2_Module_PEM]*OPEX_of_Hydrogen_Production[PEM]+Capacity_of_Electrolysis[H2_Module_SOEC]*OPEX_of_Hydrogen_Production[SOEC] +"Capacity_of_Fossil_Based_(Grey)"*OPEX_of_Hydrogen_Production[Fossil_WO_CCS]		USD/year		UNIFLOW
Scrapping_of_Blue_Hydrogen_Plants	"Capacity_of_Fossil_Based_(Blue)"/Average_Lifetime_of_Fossil_Based_Hydrogen_Plants		MW/Year		UNIFLOW
Scrapping_of_Electrolysis[SubTech_Elect]	Capacity_of_Electrolysis/Average_Lifetime_of_Electrolysis_Sub_Systems		MW/year		UNIFLOW
Scrapping_of_Fossil_Based_Plants	Capacity_of_Fossil_Fuel_Based_Energy/Lifetime_of_Fossil_Based_Energy_Production_Plants		MW/Years		UNIFLOW
Scrapping_of_Grey_Hydrogen_Plants	"Capacity_of_Fossil_Based_(Grey)"/Average_Lifetime_of_Fossil_Based_Hydrogen_Plants	OUTFLOW PRIORITY: 1	MW/Year		UNIFLOW
Subsidizing_Rate	Government's_Total_Expenditures_on_Subsidy		USD/year		UNIFLOW
Accumulated_Solar_PV_of_Electrolysis	Accumulated_Experience_of_Electrolysis[Solar_PV]		MW*year		
Additional_Land_Cost_for_Hydrogen_Production	Average_Land_Cost*(Cost_Factor_of_Land_Cost_for_Hydrogen_Production-1)*Land_Used_for_Electrolysis		USD/year		
Additional_Land_Cost_for_Solar_PV	Average_Land_Cost*(Cost_Factor_of_Land_Cost_for_Solar_Energy-1)*Land_Used_for_Solar_PV		USD/year		

Additional_Land_Cost_for_Solar_Thermal	Average_Land_Cost*(Cost_Factor_of_Land_Cost_for_Solar_Energy-1)*Land_Used_for_Solar_Thermal		USD/year		
Additional_Land_Cost_for_Wind_Farms	Average_Land_Cost*(Cost_Factor_of_Land_Cost_for_Wind_Farms-1)*Land_Used_for_Wind_Power		USD/year		
Annual_Working_Hours_of_Electrolysis	Renewable_Energies.Average_Working_Hours_of_Solar_Systems_in_Global_Scale		hour/year		
Annual_Working_Hours_of_Fossil_Based_Hydrogen_Plants	0.85*8760.0		hour/year	(Wales, 2020)	
Apparent_Cost_of_Fossil_Based	Fossil_Based_Energy_Cost_for_Consumer*Barrier_Factor_for_Fossil_Fuel		USD/MW/Hour		
Apparent_Cost_of_Hydro_Power	Hydro_Energy_Cost_for_Consumer*Barrier_Factor_for_Hydro_Power		USD/MW/Hour		
Apparent_Cost_of_Hydrogen	((1-Subsidy_Fraction_for_Hydrogen_Technologies[Alkaline])*New_Built_Hydrogen_Technologies_Market_Share[Alkaline]*Hydrogen_Cost_of_New_Built_Plants[Alkaline]+(1-Subsidy_Fraction_for_Hydrogen_Technologies[PEM])*New_Built_Hydrogen_Technologies_Market_Share[PEM]*Hydrogen_Cost_of_New_Built_Plants[PEM]+(1-Subsidy_Fraction_for_Hydrogen_Technologies[SOEC])*New_Built_Hydrogen_Technologies_Market_Share[SOEC]*Hydrogen_Cost_of_New_Built_Plants[SOEC]+(1-Subsidy_Fraction_for_Hydrogen_Technologies[Fossil_WO_CCS])*New_Built_Hydrogen_Technologies_Market_Share[Fossil_WO_CCS]*Hydrogen_Cost_of_New_Built_Plants[Fossil_WO_CCS]+(1-Subsidy_Fraction_for_Hydrogen_Technologies[Fossil_W_CCS])*New_Built_Hydrogen_Technologies_Market_Share[Fossil_W_CCS]*Hydrogen_Cost_of_New_Bu		USD/MW/Hour		

	ilt_Plants[Fossil_W_CCS])* (IF TIME<=2020 THEN (((TIME-2010)/10/Per_year)*(Barrier_Factor_for_Hydrogen_1-Barrier_Factor_for_Hydrogen)+Barrier_Factor_for_Hydrogen) ELSE Barrier_Factor_for_Hydrogen_1)				
Apparent_Cost_of_New_Built_Hydrogen_Production[H2_Market]	Hydrogen_Cost_of_New_Built_Plants_in_Tons*(1+MIN(5, EXP(-Barrier_Factor_for_Hydrogen_Production*(TIME-Time_00))))*0+Hydrogen_Cost_of_New_Built_Plants_in_Tons		usd/ton		
Apparent_Cost_of_Nuclear_Power	Barrier_Factor_for_Nuclear_Power*Renewable_Energies.Nuclear_Power_Electricity_Cost		USD/MW/Hour		
Apparent_Cost_of_Solar_PV	IF TIME<=2020 THEN Solar_PV_Energy_Cost_for_Consumer*(((TIME-2010)/10/Per_year)*(Barrier_Factor_for_Solar_PV_1-Barrier_Factor_for_Solar_PV)+Barrier_Factor_for_Solar_PV) ELSE Solar_PV_Energy_Cost_for_Consumer*Barrier_Factor_for_Solar_PV_1		USD/MW/Hour		
Apparent_Cost_of_Solar_Thermal	IF TIME<=2020 THEN Solar_Thermal_Energy_Cost_for_Consumer*(((TIME-2010)/10/Per_year)*(Barrier_Factor_for_Solar_Thermal_1-Barrier_Factor_for_Solar_Thermal)+Barrier_Factor_for_Solar_Thermal) ELSE Solar_Thermal_Energy_Cost_for_Consumer*Barrier_Factor_for_Solar_Thermal_1		USD/MW/Hour		
Apparent_Cost_of_Wind_Power	IF TIME<=2020 THEN Wind_Energy_Cost_for_Consumer*(((TIME-2010)/10/Per_year)*(Barrier_Factor_for_Wind_Power_1-Barrier_Factor_for_Wind_Power)+Barrier_Factor_for_Wind_Power) ELSE Wind_Energy_Cost_for_Consumer*Barrier_Factor_for_Wind_Power_1		USD/MW/Hour		
Average_Capacity_Factor_of_Fossil_Based_Plants	0.8		dmnl		
Average_Cost_of_All_Hydrogen_Production_over_Year	(Average_Cost_of_Hydrogen_over_Year[Alkaline]*Capacity_of_Electrolysis[H2_Module_Alkaline]+Average_Cost_of_Hydrogen_over_Year[PEM]*Capacity_of_Electrolysis[H2_Module_PEM]+Average_Cost_of_Hydrogen_over_Year[SOEC]*Capacity_of_Electrolysis[H2_Module_SOEC]+Average_Cost_of_Hydrogen_over_Year[Fossil_WO_CCS]*"Capacity_of_Fossil_Based_(Grey)"+Average_Cost_of_Hydrogen_over_Year[Fossil_W_CCS]*"Capacity_of_Fossil_Based_(Blue)")/ Current_Total_Hydrogen_Production_Capacity		USD/year		

Average_Cost_of_Energy	((1-Subsidy_Fraction_for_Solar_PV)*Renewable_Energies.Average_Cost_of_Solar_PV_over_Year*Renewable_Energies.Energy_From_Solar_PV +(1-Subsidy_Fraction_for_Solar_Thermal)*Renewable_Energies.Average_Cost_of_Solar_Thermal_over_Year*Renewable_Energies.Energy_From_Solar_Thermal +(1-Subsidy_Fraction_for_Wind_Power)*Renewable_Energies.Average_Cost_of_Wind_Power_over_Year*Renewable_Energies.Energy_from_Wind +Renewable_Energies.Average_Cost_of_Nuclear_over_Year*Renewable_Energies.Energy_from_Nuclear +(1-Subsidy_Fraction_for_Hydro_Power)*Renewable_Energies.Energy_from_Hydro*Renewable_Energies.Average_Cost_of_Hydro_over_Year +(1-Average_Subsidies_Fraction_for_Hydrogen)*Average_Cost_of_All_Hydrogen_Production_over_Year +(1-Subsidy_Fraction_for_Fossil_Based_Energy)*Total_Annual_Energy_of_Fossil_Based*Fossil_Fuel_Base_Energy_Cost) / (Renewable_Energies.Energy_From_Solar_PV+Renewable_Energies.Energy_From_Solar_Thermal+Renewable_Energies.Energy_from_Wind+Renewable_Energies.Energy_from_Nuclear+Renewable_Energies.Energy_from_Hydro+Total_Hydrogen_Produced+Total_Annual_Energy_of_Fossil_Based)		USD/MW/hour		
Average_Cost_of_Fossil_Based_Energy_over_Year	Spent_Money_for_Fossil_over_Year/Capacity_of_Fossil_Fuel_Based_Energy		USD/MW/year		
Average_Cost_of_Hydrogen_in_ton	Average_Hydrogen_Production_Cost*Hydrogen_Lower_Heating_Value		USD/ton		
Average_Cost_of_Hydrogen_over_Year[Alkaline]	Installation_of_Electrolysis[H2_Module_Alkaline]*Hydrogen_Cost_of_New_Built_Plants[Alkaline]*Annual_Working_Hours_of_Electrolysis*DT+ (Capacity_of_Electrolysis[H2_Module_Alkaline]-Installation_of_Electrolysis[H2_Module_Alkaline]*DT)*(Annual_Working_Hours_of_Electrolysis)* PREVIOUS(SELF, INIT(Hydrogen_Cost_of_New_Built_Plants[Alkaline])*INIT(Capacity_of_Electrolysis[H2_Module_Alkaline])*INIT(Annual_Working_Hours_of_Electrolysis))/ (PREVIOUS(Annual_Working_Hours_of_Electrolysis, INIT(Annual_Working_Hours_of_Electrolysis))*PREVIOUS(Capacity_of_Electrolysis[H2_Module_Alkaline], INIT(Capacity_of_Electrolysis[H2_Module_Alkaline])))		USD/year		

Average_Cost_of_Hydrogen_over_Year[PEM]	Installation_of_Electrolysis[H2_Module_PEM]*Hydrogen_Cost_of_New_Built_Plants[PEM]*Annual_Working_Hours_of_Electrolysis*DT+ (Capacity_of_Electrolysis[H2_Module_PEM]-Installation_of_Electrolysis[H2_Module_PEM]*DT)*(Annual_Working_Hours_of_Electrolysis)* PREVIOUS(SELF, INIT(Hydrogen_Cost_of_New_Built_Plants[PEM])*INIT(Capacity_of_Electrolysis[H2_Module_PEM])*INIT(Annual_Working_Hours_of_Electrolysis))/ (PREVIOUS(Annual_Working_Hours_of_Electrolysis, INIT(Annual_Working_Hours_of_Electrolysis))*PREVIOUS(Capacity_of_Electrolysis[H2_Module_PEM], INIT(Capacity_of_Electrolysis[H2_Module_PEM])))				
Average_Cost_of_Hydrogen_over_Year[SOEC]	Installation_of_Electrolysis[H2_Module_SOEC]*Hydrogen_Cost_of_New_Built_Plants[SOEC]*Annual_Working_Hours_of_Electrolysis*DT+ (Capacity_of_Electrolysis[H2_Module_SOEC]-Installation_of_Electrolysis[H2_Module_SOEC]*DT)*(Annual_Working_Hours_of_Electrolysis)* PREVIOUS(SELF, INIT(Hydrogen_Cost_of_New_Built_Plants[SOEC])*INIT(Capacity_of_Electrolysis[H2_Module_SOEC])*INIT(Annual_Working_Hours_of_Electrolysis))/ (PREVIOUS(Annual_Working_Hours_of_Electrolysis, INIT(Annual_Working_Hours_of_Electrolysis))*PREVIOUS(Capacity_of_Electrolysis[H2_Module_SOEC], INIT(Capacity_of_Electrolysis[H2_Module_SOEC])))				
Average_Cost_of_Hydrogen_over_Year[Fossil_WO_CCS]	Installation_of_New_Grey_Hydrogen_Plants*Hydrogen_Cost_of_New_Built_Plants[Fossil_WO_CCS]*Annual_Working_Hours_of_Fossil_Based_Hydrogen_Plants*DT+ ("Capacity_of_Fossil_Based_(Grey)"-Installation_of_New_Grey_Hydrogen_Plants*DT)*(Annual_Working_Hours_of_Fossil_Based_Hydrogen_Plants)* PREVIOUS(SELF, INIT(Hydrogen_Cost_of_New_Built_Plants[Fossil_WO_CCS])*INIT("Capacity_of_Fossil_Based_(Grey)")*INIT(Annual_Working_Hours_of_Fossil_Based_Hydrogen_Plants))/ (PREVIOUS(Annual_Working_Hours_of_Fossil_Based_Hydrogen_Plants, INIT(Annual_Working_Hours_of_Fossil_Based_Hydrogen_Plants))*PREVIOUS("Capacity_of_Fossil_Based_(Grey)", INIT("Capacity_of_Fossil_Based_(Grey)")))				
Average_Cost_of_Hydrogen_over_Year[Fossil_W_CCS]	(Installation_of_New_Blue_Hydrogen_Plants+Adding_CCS)*Hydrogen_Cost_of_New_Built_Plants[Fossil_W_CCS]*Annual_Working_Hours_of_Fossil_Based_Hydrogen_Plants*DT+ ("Capacity_of_Fossil_Based_(Blue)"-(Installation_of_New_Blue_Hydrogen_Plants+Adding_CCS)*DT)*(Annual_Working_Hours_of_Fossil_Based_Hydrogen_Plants)* PREVIOUS(SELF, INIT(Hydrogen_Cost_of_New_Built_Plants[Fossil_W_CCS])*INIT("Capacity_of_				

	Fossil_Based_(Blue)")*INIT(Annual_Working_Hours_of_Fossil_Based_Hydrogen_Plants))/(PREVIOUS(Annual_Working_Hours_of_Fossil_Based_Hydrogen_Plants, INIT(Annual_Working_Hours_of_Fossil_Based_Hydrogen_Plants))*PREVIOUS("Capacity_of_Fossil_Based_(Blue)", INIT("Capacity_of_Fossil_Based_(Grey)")))				
Average_Cost_of_New_Hydrogen	New_Built_Hydrogen_Technologies_Market_Share[Alkaline]*Hydrogen_Cost_of_New_Built_Plants[Alkaline]+ New_Built_Hydrogen_Technologies_Market_Share[PEM]*Hydrogen_Cost_of_New_Built_Plants[PEM]+ New_Built_Hydrogen_Technologies_Market_Share[SOEC]*Hydrogen_Cost_of_New_Built_Plants[SOEC]+ New_Built_Hydrogen_Technologies_Market_Share[Fossil_WO_CCS]*Hydrogen_Cost_of_New_Built_Plants[Fossil_WO_CCS]+ New_Built_Hydrogen_Technologies_Market_Share[Fossil_W_CCS]*Hydrogen_Cost_of_New_Built_Plants[Fossil_W_CCS]		USD/MW/Hour		
Average_Cost_of_New_Hydrogen_for_Consumers	((1-Subsidy_Fraction_for_Hydrogen_Technologies[Alkaline])*New_Built_Hydrogen_Technologies_Market_Share[Alkaline]*Hydrogen_Cost_of_New_Built_Plants[Alkaline]+(1-Subsidy_Fraction_for_Hydrogen_Technologies[PEM])*New_Built_Hydrogen_Technologies_Market_Share[PEM]*Hydrogen_Cost_of_New_Built_Plants[PEM]+(1-Subsidy_Fraction_for_Hydrogen_Technologies[SOEC])*New_Built_Hydrogen_Technologies_Market_Share[SOEC]*Hydrogen_Cost_of_New_Built_Plants[SOEC]+(1-Subsidy_Fraction_for_Hydrogen_Technologies[Fossil_WO_CCS])*New_Built_Hydrogen_Technologies_Market_Share[Fossil_WO_CCS]*Hydrogen_Cost_of_New_Built_Plants[Fossil_WO_CCS]+(1-Subsidy_Fraction_for_Hydrogen_Technologies[Fossil_W_CCS])*New_Built_Hydrogen_Technologies_Market_Share[Fossil_W_CCS]*Hydrogen_Cost_of_New_Built_Plants[Fossil_W_CCS])		USD/MW/Hour		
Average_Efficiency_of_Hydrogen_Compressor	0.51		dmnl	(Gardiner, 2009) by multiplying isotropic and motor efficiencies. 0.56*0.92	

Average_Energy_Cost_Elasticity	-0.524		dmnl	The value varies extensively in different areas. It is in range of -0.01 to -1.12 but the global value is -0.19 (Atalla, Bigerna, & Bollino, 2016) ------------ Here it is -0.524 for long term from various resources. (Labandeira et al., 2017)	
Average_Energy_Efficiency_of_Alkaline	0.01*(LOOKUP(History_of_Energy_Efficiency_of_Alkaline, STARTTIME)*(Accumulated_Experience_of_Electrolysis[H2_Module_Alkaline]/INIT(Accumulated_Experience_of_Electrolysis[H2_Module_Alkaline]))^(LOG10(1-Efficiency_Learning_Rate_of_Electrolysis[H2_Module_Alkaline])/LOG10(2)))		dmnl	For three types of electrolysis there are various efficiency estimations, as below: AE=70-80% PEM=80-90% SOEC=90-100% (Kumar & Himabindu, 2019) AE=70 PEM=60 SOEC=81 (Christensen, 2020) AE=43-67% PEM=40-67% SOEC=60-74% (Reduction, 2020). here values from table ES1 were converted to efficiency knowing that 100% efficiency can produces 0.03 kg of hydrogen by 1 kWh AEL=67 PEM=61	

				SOEC=83% (When energy for steam generation is considered the eff. will be ~67%) Jens, J. (2020, December 14). Assessing the potential of Green Hydrogen using learning curves from expert elicitation and the implications for the Port of Rotterdam. Business Economics. Retrieved from http://hdl.handle.net/2105/55598	
Average_Energy_Efficiency_of_PEM	0.01*(LOOKUP(History_of_Energy_Efficiency_of_PEM, STARTTIME)*(Accumulated_Experience_of_Electrolysis[H2_Module_PEM]/INIT(Accumulated_Experience_of_Electrolysis[H2_Module_PEM]))^(LOG10(1-Efficiency_Learning_Rate_of_Electrolysis[H2_Module_PEM])/LOG10(2)))		dmnl	Same as Alkaline	
Average_Energy_Efficiency_of_SOEC	0.01*(LOOKUP(History_of_Energy_Efficiency_of_SOEC, STARTTIME)*(Accumulated_Experience_of_Electrolysis[H2_Module_PEM]/INIT(Accumulated_Experience_of_Electrolysis[H2_Module_PEM]))^(LOG10(1-Efficiency_Learning_Rate_of_Electrolysis[H2_Module_PEM])/LOG10(2)))		dmnl	Same as Alkaline	
Average_Hydrogen_Production_Cost	PREVIOUS(Average_Cost_of_All_Hydrogen_Production_over_Year, INIT(Average_Cost_of_All_Hydrogen_Production_over_Year))/Total_Hydrogen_Produced		USD/MW/hour	This is the average hydrogen cost for producers after considering the subsidy	
Average_Land_Cost	0.1		USD/square meter/year	It is not easy to consider the same value for land rental cost all over the world. In US, it is stated that the rent is 300-2000 USD per acre per year [1]. In India, for example, 650 USD/acre per year is stated [2]. Keeping the fact that most of the sun rich countries are in less expensive countries, maybe 1000 usd/acre/year is a better choice. [1]. https://www.ysgsolar.com/blog/solar-farm-land-lease-rates-ysg-	

				solar#:~:text=Solar%20Farm%20Land%20Lease%20Rates%20Around%20the%20United%20States&text=Taking%20location%20into%20account%2C%20as,to%20%242%2C000%20per%20acre%20annually. [2]. https://www.solarmango.com/ask/2015/09/20/what-are-the-initial-investment-and-om-costs-required-for-a-mw-solar-plant-in-india-what-kind-of-financial-returns-can-we-expect-from-it/	
Average_Lifetime_in_Hour[Solar_PV]	0		hour	...........For Solar PV and PEM: (Glenk et al., 2021) For electrolysis: (Taibi, Miranda, et al., 2020) for screw compressor: https://www.rapidairproducts.com/blog/questions-you-should-ask-yourself-before-buying-a-new-air-compressor#:~:text=On%20the%20other%20hand%2C%20rotary,compressor%20room%20when%20in%20use.	
Average_Lifetime_in_Hour[Water_Purification]	0				
Average_Lifetime_in_Hour[Compression]	35000				
Average_Lifetime_in_Hour[	60000				

H2_Module_Alkaline]					
Average_Lifetime_in_Hour[H2_Module_PEM]	65000				
Average_Lifetime_in_Hour[H2_Module_SOEC]	20000				
Average_Lifetime_of_Electrolysis_Sub_Systems[Solar_PV]	25		year	for desalination: (Caldera et al., 2016) for solar PV: (Caldera et al., 2016)	
Average_Lifetime_of_Electrolysis_Sub_Systems[Water_Purification]	30				
Average_Lifetime_of_Electrolysis_Sub_Systems[Compression]	Average_Lifetime_in_Hour[Compression]/Annual_Working_Hours_of_Electrolysis				
Average_Lifetime_of_Electrolysis_Sub_Systems[H2_Module_Alkaline]	Average_Lifetime_in_Hour[H2_Module_Alkaline]/Annual_Working_Hours_of_Electrolysis				
Average_Lifetime_of_Electrolysis_Sub_Sy	Average_Lifetime_in_Hour[H2_Module_PEM]/Annual_Working_Hours_of_Electrolysis				

stems[H2_Module_PEM]					
Average_Lifetime_of_Electrolysis_Sub_Systems[H2_Module_SOEC]	Average_Lifetime_in_Hour[H2_Module_SOEC]/Annual_Working_Hours_of_Electrolysis				
Average_Lifetime_of_Fossil_Based_Hydrogen_Plants	20		years	this reference used 20 years for steam reforming plants: (Bhandari et al., 2014) This one is 25 years for post combustion carbon capture plants: (Yakub, Mohamed, & Danladi, 2014) For plants with carbon capture, for simplicity, it is assumed that aged plants without CC had a rehabilitation while CC was constructed. So that the life expectancy is equal to a new plant.	
Average_Lifetime_of_Hydrogen_Plants[Alkaline]	Average_Lifetime_of_Electrolysis_Sub_Systems[H2_Module_Alkaline]		years		
Average_Lifetime_of_Hydrogen_Plants[PEM]	Average_Lifetime_of_Electrolysis_Sub_Systems[H2_Module_PEM]				
Average_Lifetime_of_Hydrogen_Plants[SOEC]	Average_Lifetime_of_Electrolysis_Sub_Systems[H2_Module_SOEC]				
Average_Lifetime_of_Hydro	Average_Lifetime_of_Fossil_Based_Hydrogen_Plants				

gen_Plants[Fossil_WO_CCS]					
Average_Lifetime_of_Hydrogen_Plants[Fossil_W_CCS]	Average_Lifetime_of_Fossil_Based_Hydrogen_Plants				
Average_Rate_of_Global_Energy_Demand_Increase	0.015		dmnl/year		
Average_Subsidies_Fraction_for_Hydrogen	Governments_Expenditure_on_Hydrogen_Technologies/(Average_Cost_of_Hydrogen_over_Year[Alkaline]+Average_Cost_of_Hydrogen_over_Year[PEM]+Average_Cost_of_Hydrogen_over_Year[SOEC]+Average_Cost_of_Hydrogen_over_Year[Fossil_W_CCS])		dmnl		
Average_Working_Hours_of_Fossil_Based_Plants	Hour_Per_Year*Average_Capacity_Factor_of_Fossil_Based_Plants		hour/year		
Avoided_CO2_by_Investment_on_Hydrogen	IF Total_Accumulated_Investment_on_All_Hydrogen=0 THEN 0 ELSE Avoided_CO2_for_Hydrogen/Total_Accumulated_Investment_on_All_Hydrogen		Ton/USD		
Avoided_CO2_by_Investment_on_Non_Fossil	IF Total_Accumulated_Investment_on_Non_Fossil=0 THEN 0 ELSE Avoided_CO2_for_Renewable_Energies/Total_Accumulated_Investment_on_Non_Fossil		Ton/USD		
Barrier_Factor_for_Fossil_Fuel	5.35E+01*EXP(-2E-07*Capacity_of_Fossil_Fuel_Based_Energy)		dmnl		
Barrier_Factor_for_Hydro_Power	5.35E+01*EXP(-2E-07*Renewable_Energies.Capacity_of_Hydro)		dmnl		

Barrier_Factor_for_Hydrogen	24.7940674348		dmnl		
Barrier_Factor_for_Hydrogen_1	(IF TIME<=2020 THEN 100 ELSE (Goal_for_barrier_factor_of_Hydrogen-100)*(TIME-2020)/30/Per_year+100)		dmnl		
Barrier_Factor_for_Hydrogen_Production[Alkaline]	1.18685645295		dmnl		
Barrier_Factor_for_Hydrogen_Production[PEM]	66.6521304795				
Barrier_Factor_for_Hydrogen_Production[SOEC]	35.4358811733				
Barrier_Factor_for_Hydrogen_Production[Fossil_WO_CCS]	0.674186677429				
Barrier_Factor_for_Hydrogen_Production[Fossil_W_CCS]	41.3193837995				
Barrier_Factor_for_Nuclear_Power	5.35E+01*EXP(-2E-07*Renewable_Energies.Capacity_of_Nuclear_Energy)		dmnl		
Barrier_Factor_for_Solar_PV	14.8189528318		dmnl		

Barrier_Factor_for_Solar_PV_1	0.95*(5.35E+01*EXP(-2E-07*Renewable_Energies.Capacity_of_Solar_PV))		dmnl		
Barrier_Factor_for_Solar_Thermal	1.77055480143		dmnl	Barrier factor for 2010	
Barrier_Factor_for_Solar_Thermal_1	5.35E+01*EXP(-2E-07*Renewable_Energies.Capacity_of_Solar_Thermal)		dmnl	Barrier factor for 2020	
Barrier_Factor_for_Wind_Power	14.5161072815		dmnl		
Barrier_Factor_for_Wind_Power_1	0.55*(5.35E+01*EXP(-2E-07*Renewable_Energies.Capacity_of_Wind))		dmnl		
Baseline_for_Atmosphere_CO2_Concentration	310		dmnl	Unit is "ppm" (parts per million) This is the value for 1940. The reason why the value for preindustrial period (280ppm) was not chosen is that we experienced a decrease in global temperature before 1940 that increases the accuracy of the linear relationship between CO2 concentration and global temperature. The data were obtained from a figure of: (Yakub et al., 2014)	
CAPEX_History_Desalination	GRAPH(TIME) Points: (2010.00, 5.562425151), (2011.00, 5.345995123), (2012.00, 4.012891918), (2013.00, 5.375008301), (2014.00, 6.133305644), (2015.00, 4.720743041), (2016.00, 4.913477397), (2017.00, 4.890410959), (2018.00, 4.890410959), (2019.00, 4.890410959), (2020.00, 4.890410959)		USD*year/cubic meter		

CAPEX_History_for_Alkaline	GRAPH(TIME) Points: (2010.00, 955000.0), (2011.00, 928000.0), (2012.00, 899000.0), (2013.00, 871000.0), (2014.00, 842000.0), (2015.00, 814000.0), (2016.00, 786000.0), (2017.00, 758000.0), (2018.00, 731000.0), (2019.00, 705000.0), (2020.00, 679000.0)		USD/MW		
CAPEX_History_for_PEM	GRAPH(TIME) Points: (2010.00, 842000.0), (2011.00, 838000.0), (2012.00, 832000.0), (2013.00, 826000.0), (2014.00, 818000.0), (2015.00, 810000.0), (2016.00, 801000.0), (2017.00, 792000.0), (2018.00, 782000.0), (2019.00, 771000.0), (2020.00, 761000.0)		USD/MW		
CAPEX_History_for_SOEC	GRAPH(TIME) Points: (2010.00, 1450000.0), (2011.00, 1400000.0), (2012.00, 1350000.0), (2013.00, 1300000.0), (2014.00, 1250000.0), (2015.00, 1200000.0), (2016.00, 1150000.0), (2017.00, 1100000.0), (2018.00, 1050000.0), (2019.00, 1000000.0), (2020.00, 959000.0)		USD/MW		
CAPEX_History_for_Solar_PV	GRAPH(TIME) Points: (2010.00, 336308.6), (2011.00, 220981.15), (2012.00, 171718.6), (2013.00, 154546.74), (2014.00, 154546.74), (2015.00, 138874.72), (2016.00, 122759.07), (2017.00, 105222.06), (2018.00, 70148.04), (2019.00, 52611.03), (2020.00, 35074.02)		USD/MW	https://www.statista.com/statistics/971982/solar-pv-capex-worldwide-utility-scale/#:~:text=Global%20benchmark%20capital%20expenditure%20(CAPEX,0.61%20U.S.%20dollars%20per%20watt.	
CAPEX_of_Fossil_Based[Fossil_Hydrogen]	Scale_of_Economy_for_Fossil_Based_Hydrogen* Learning_for_Fossil_Based*Initial_CAPEX_of_Fossil_Based_H2		USD/MW		
CAPEX_of_Hydrogen_Production[Alkaline]	CAPEX_of_Sub_Technologies[H2_Module_Alkaline]+CAPEX_of_Sub_Technologies[Solar_PV]/Average_Energy_Efficiency_of_Alkaline+CAPEX_of_Sub_Technologies[Compression]*Required_Energy_to_Transmit_Hydrogen[Alkaline]+(CAPEX_of_Sub_Technologies[Water_Purification]*Total_Water_requirement_for_Electrolysis*Annual_Working_Hours_of_Electrolysis*Multiplier_for_Unit_Difference_of_Water_Desalination)		USD/MW		
CAPEX_of_Hydrogen_Production[PEM]	CAPEX_of_Sub_Technologies[H2_Module_PEM]+CAPEX_of_Sub_Technologies[Solar_PV]/Average_Energy_Efficiency_of_PEM+CAPEX_of_Sub_Technologies[Compression]*Required_Energy_to_Transmit_Hydrogen[PEM]+CAPEX_of_Sub_Technologies[Water_Purification]*Total_Water_requirement_for_Electrolysis*Annual_Working_Hours_of_Electrolysis*Multiplier_for_Unit_Difference_of_Water_Desalination				

CAPEX_of_Hydrogen_Production[SOEC]	CAPEX_of_Sub_Technologies[H2_Module_SOEC]+CAPEX_of_Sub_Technologies[Solar_PV]/Average_Energy_Efficiency_of_SOEC+CAPEX_of_Sub_Technologies[Compression]*Required_Energy_to_Transmit_Hydrogen[SOEC] +CAPEX_of_Sub_Technologies[Water_Purification]*Total_Water_requirement_for_Electrolysis*Annual_Working_Hours_of_Electrolysis*Multiplier_for_Unit_Difference_of_Water_Desalination				
CAPEX_of_Hydrogen_Production[Fossil_WO_CCS]	CAPEX_of_Fossil_Based[Without_CC]+CAPEX_of_Sub_Technologies[Compression]*Required_Energy_to_Transmit_Hydrogen[Fossil_WO_CCS]+CAPEX_of_Sub_Technologies[Water_Purification]*Total_Water_requirement_for_Fossil_Based*Annual_Working_Hours_of_Fossil_Based_Hydrogen_Plants*Multiplier_for_Unit_Difference_of_Water_Desalination				
CAPEX_of_Hydrogen_Production[Fossil_W_CCS]	CAPEX_of_Fossil_Based[With_CC]+CAPEX_of_Sub_Technologies[Compression]*Required_Energy_to_Transmit_Hydrogen[Fossil_W_CCS]+CAPEX_of_Sub_Technologies[Water_Purification]*Total_Water_requirement_for_Fossil_Based*Annual_Working_Hours_of_Fossil_Based_Hydrogen_Plants*Multiplier_for_Unit_Difference_of_Water_Desalination				
CAPEX_of_Sub_Technologies[SubTech_Elect]	Economy_of_Scale_for_Electrolysis* Learning_for_Sub_technologies_of_Electrolysis*Initial_CAPEX_of_Electrolysis		USD/MW	Unit for water desalination is USD per m3/year	
Carbon_Tax	0		usd/ton		
CO2_Concentration_of_the_Atmosphere	CO2_Emitted_to_Atmosphere/Weight_of_Each_ppm_of_CO2_in_the_Atmosphere		dmnl	The unit is "ppm" (parts per million)	
Construction_Time_for_Fossil_Based_Plants	2		years	(Bhandari et al., 2014)	
Construction_Time_of_Electrolysis	3		year	based on what expected from green hydrogen plants in Abu-Dhabi: https://www.pv-magazine.com/2022/01/21/the-hydrogen-stream-worlds-first-full-scale-pilot-plant-for-extracting-	

				hydrogen-from-natural-gas-pipeline/ Note: this value was used for all elements of the array (i.e. solar, desalination, ...) because the plant cannot be operated until all parts are installed. For example, even if solar panels could be installed in 3 months, the hydrogen cannot produced until the other parts are installed and commissioned.	
Construction_Time_of_Fossil_Based_Energy	4		year		
Cost_Factor_of_Land_Cost_for_Hydrogen_Production	GRAPH(Available_Land_for_Hydrogen_Production/INIT(Available_Land_for_Hydrogen_Production)) Points: (0.000, 11.00), (0.100, 5.50), (0.200, 3.666666667), (0.300, 2.75), (0.400, 2.20), (0.500, 1.833333333), (0.600, 1.571428571), (0.700, 1.375), (0.800, 1.222222222), (0.900, 1.10), (1.000, 1.00)		dmnl		
Cost_Factor_of_Land_Cost_for_Solar_Energy	GRAPH(Available_Land_for_Solar_Energy/INIT(Available_Land_for_Solar_Energy)) Points: (0.000, 11.00), (0.100, 5.50), (0.200, 3.666666667), (0.300, 2.75), (0.400, 2.20), (0.500, 1.833333333), (0.600, 1.571428571), (0.700, 1.375), (0.800, 1.222222222), (0.900, 1.10), (1.000, 1.00)		dmnl		
Cost_Factor_of_Land_Cost_for_Wind_Farms	GRAPH(Available_Land_for_Wind_Energy/INIT(Available_Land_for_Wind_Energy)) Points: (0.000, 11.00), (0.100, 5.50), (0.200, 3.666666667), (0.300, 2.75), (0.400, 2.20), (0.500, 1.833333333), (0.600, 1.571428571), (0.700, 1.375), (0.800, 1.222222222), (0.900, 1.10), (1.000, 1.00)		dmnl		
Cost_Factor_of_Oil_for_Resource_Depletion	IF Scenario_for_Future_Oil_Price=1 THEN Cost_Factor_of_Oil_for_Resource_Depletion_Less_sensitive ELSE Cost_Factor_of_Oil_for_Resource_Depletion_More_Sensitive		dmnl		
Cost_Factor_of_Oil_for_Resource_Depleti	GRAPH(Proven_Oil_Reservoirs/INIT(Proven_Oil_Reservoirs)) Points: (0.000, 11.00), (0.010, 10.00), (0.020, 9.166666667), (0.040, 7.857142857), (0.070, 6.470588235), (0.100, 5.50), (0.200, 3.666666667), (0.300, 2.75), (0.400, 2.20),		dmnl	The curve steepness and values are just an assumption which should be	

on_Less_sensitive	(0.500, 1.833333333), (0.600, 1.571428571), (0.700, 1.375), (0.800, 1.222222222), (0.900, 1.10), (1.000, 1.00)			modified by referring to references, if there is any.	
Cost_Factor_of_Oil_for_Resource_Depletion_More_Sensitive	GRAPH(Proven_Oil_Reservoirs/INIT(Proven_Oil_Reservoirs)) Points: (0.000, 34.78505426), (0.010, 30.15113446), (0.020, 26.46188734), (0.040, 20.99909758), (0.070, 15.69348162), (0.100, 12.29837388), (0.200, 6.694386814), (0.300, 4.348131783), (0.400, 3.111269837), (0.500, 2.366823156), (0.600, 1.878216386), (0.700, 1.537296735), (0.800, 1.288335343), (0.900, 1.10), (1.000, 0.953462589)		dmnl	The curve steepness and values are just an assumption which should be modified by referring to references, if there is any.	
Cost_Learning_Rate_of_Electrolysis[Solar_PV]	0		dmnl	All based on data analysis. (The learning curve for solar PV will be get from Renewable Module)	
Cost_Learning_Rate_of_Electrolysis[Water_Purification]	0.014				
Cost_Learning_Rate_of_Electrolysis[Compression]	0				
Cost_Learning_Rate_of_Electrolysis[H2_Module_Alkaline]	0.09				
Cost_Learning_Rate_of_Electrolysis[H2_Module_PEM]	0.0335				
Cost_Learning_Rate_of_Electrolysis[H2_Module_SOEC]	0.1075				
Cost_Learning_Rate_of_Fos	0.12		dmnl	For CCS: (Rochedo & Szklo, 2013)	

sil_Based_H2[With_CC]				and also: Carbon Capture and Storage (CCS) in 2100 For steam reforming: (Schoots, Ferioli, Kramer, & Van der Zwaan, 2008)	
Cost_Learning_Rate_of_Fossil_Based_H2[Without_CC]	0.11				
Cost_of_Hydrogen_Transportation_by_Ships[Alkaline]	Specific_Cost_of_Transportation_by_Ship*Distance_to_Market_Demand_Region/Hydrogen_Lower_Heating_Value		USD/MW/hour		
Cost_of_Hydrogen_Transportation_by_Ships[PEM]	Specific_Cost_of_Transportation_by_Ship*Distance_to_Market_Demand_Region/Hydrogen_Lower_Heating_Value				
Cost_of_Hydrogen_Transportation_by_Ships[SOEC]	Specific_Cost_of_Transportation_by_Ship*Distance_to_Market_Demand_Region/Hydrogen_Lower_Heating_Value				
Cost_of_Hydrogen_Transportation_by_Ships[Fossil_WO_CCS]	Specific_Cost_of_Transportation_by_Ship*Distance_to_Market_Demand_Region/Hydrogen_Lower_Heating_Value				
Cost_of_Hydrogen_Transportation_by_Shi	Specific_Cost_of_Transportation_by_Ship*Distance_to_Market_Demand_Region/Hydrogen_Lower_Heating_Value				

ps[Fossil_W_CCS]					
Current_Hydrogen_Capacity_Share[Alkaline]	Capacity_of_Electrolysis[H2_Module_Alkaline]/Current_Total_Hydrogen_Production_Capacity		dmnl		
Current_Hydrogen_Capacity_Share[PEM]	Capacity_of_Electrolysis[H2_Module_PEM]/Current_Total_Hydrogen_Production_Capacity				
Current_Hydrogen_Capacity_Share[SOEC]	Capacity_of_Electrolysis[H2_Module_SOEC]/Current_Total_Hydrogen_Production_Capacity				
Current_Hydrogen_Capacity_Share[Fossil_WO_CCS]	"Capacity_of_Fossil_Based_(Grey)"/Current_Total_Hydrogen_Production_Capacity				
Current_Hydrogen_Capacity_Share[Fossil_W_CCS]	"Capacity_of_Fossil_Based_(Blue)"/Current_Total_Hydrogen_Production_Capacity				
Current_Hydrogen_Market_Share[H2_Market]	Produced_Hydrogen/Total_Hydrogen_Produced		dmnl		
Current_Total_Hydrogen_Production_Capacity	"Capacity_of_Fossil_Based_(Blue)" + "Capacity_of_Fossil_Based_(Grey)" + Capacity_of_Electrolysis[H2_Module_Alkaline] + Capacity_of_Electrolysis[H2_Module_PEM] + Capacity_of_Electrolysis[H2_Module_SOEC]		MW		SUMMING CONVERTER
Delivery_Pressure_of_Hydrogen_at_Plants[Alkaline]	15		bar	I used average values of a range for pressure because higher pressures need more investment which may not be included in available data for capital	

				costs. For Green Hydrogen: ------------------------- (Taibi, Blanco, et al., 2020) For Steam reforming: (Speight, 2019) Target pressure to inject into pipelines (compare with current pipelines of natural gas in west Africa)= 150 bar https://www.wagpa.org/the-wagp/ for trucks different values is stated, from 170 to 500 bar https://www.sciencedirect.com/topics/engineering/compressed-hydrogen	
Delivery_Pressure_of_Hydrogen_at_Plants[PEM]	35				
Delivery_Pressure_of_Hydrogen_at_Plants[SOEC]	5				
Delivery_Pressure_of_Hydrogen_at_Plants[Fossil_WO_CCS]	15				

Delivery_Pressure_of_Hydrogen_at_Plants[Fossil_W_CCS]	15				
Diff_Hydro	ABS(Renewable_Energies.Capacity_of_Hydro-History_of_Hydro)		MW		
Diff_Hydrogen	ABS(Current_Total_Hydrogen_Production_Capacity-History_of_Hydrogen_Production)		MW		
Diff_Hydrogen_Alkaline	ABS(History_of_Alkaline-Capacity_of_Electrolysis[H2_Module_Alkaline])		MW		
Diff_Hydrogen_from_Fossil	ABS("Capacity_of_Fossil_Based_(Blue)"+"Capacity_of_Fossil_Based_(Grey)"-History_of_Fossil_Based_Hydrogen)		MW		
Diff_Hydrogen_PEM	ABS(History_of_PEM-Capacity_of_Electrolysis[H2_Module_PEM])		MW		
Diff_Hydrogen_SOEC	ABS(History_of_SOEC-Capacity_of_Electrolysis[H2_Module_SOEC])		MW		
Diff_Nuclear	ABS(Renewable_Energies.Capacity_of_Nuclear_Energy-History_of_Nuclear)		MW		
Diff_Solar_PV	ABS(Renewable_Energies.Capacity_of_Solar_PV-History_of_Solar_PV_Capacity)		MW		
Diff_Solar_Thermal	ABS(Renewable_Energies.Capacity_of_Solar_Thermal-History_of_Solar_Thermal)		MW		
Diff_Wind	ABS(Renewable_Energies.Capacity_of_Wind-History_of_Wind)		MW		
Distance_to_Market_Demand_Region	1000		km		
Economy_of_Scale_for_Electrolysis[Solar_PV]	Renewable_Energies.Economy_of_Scale_for_Solar_PV		dmnl	Subtracting "1" from the equation's power is for this reason: The standard equation that is "capacity Ratio^scale exponent" is expressing the total cost ratio. Here we need to	

				compare "cost/MW" not "cost". So the equation was changed.	
Economy_of_Scale_for_Electrolysis[Water_Purification]	(Capacity_of_Electrolysis[Water_Purification]/INIT(Capacity_of_Electrolysis[Water_Purification]))^(Exponent_for_Economy_of_Scale[Water_Purification]-1)				
Economy_of_Scale_for_Electrolysis[Compression]	(Capacity_of_Electrolysis[Compression]/INIT(Capacity_of_Electrolysis[Compression]))^(Exponent_for_Economy_of_Scale[Compression]-1)				
Economy_of_Scale_for_Electrolysis[H2_Module_Alkaline]	(Capacity_of_Electrolysis[H2_Module_Alkaline]/INIT(Capacity_of_Electrolysis[H2_Module_Alkaline]))^(Exponent_for_Economy_of_Scale[H2_Module_Alkaline]-1)				
Economy_of_Scale_for_Electrolysis[H2_Module_PEM]	(Capacity_of_Electrolysis[H2_Module_PEM]/INIT(Capacity_of_Electrolysis[H2_Module_PEM]))^(Exponent_for_Economy_of_Scale[H2_Module_PEM]-1)				
Economy_of_Scale_for_Electrolysis[H2_Module_SOEC]	(Capacity_of_Electrolysis[H2_Module_SOEC]/INIT(Capacity_of_Electrolysis[H2_Module_SOEC]))^(Exponent_for_Economy_of_Scale[H2_Module_SOEC]-1)				
Effect_of_Energy_Cost_on_Demand	(Average_Cost_of_Energy/INIT(Average_Cost_of_Energy))^Average_Energy_Cost_Elasticity		dmnl		
Efficiency_Learning_Rate_for_Desalination	0.36		dmnl	The formulation for efficiency learning rate is different than the one for cost in a negative sign. The formula is: 2^r-1 Where r is a positive number. In fact, if the accumulated capacity or	

				production doubles, the efficiency would increase to 2^r.	
Efficiency_Learning_Rate_of_Electrolysis[Solar_PV]	0		dmnl		
Efficiency_Learning_Rate_of_Electrolysis[Water_Purification]	0				
Efficiency_Learning_Rate_of_Electrolysis[Compression]	0				
Efficiency_Learning_Rate_of_Electrolysis[H2_Module_Alkaline]	0.053				
Efficiency_Learning_Rate_of_Electrolysis[H2_Module_PEM]	0.11				
Efficiency_Learning_Rate_of_Electrolysis[H2_Module_SOEC]	0.078				
Electrolysis_Market_Share[Alkaline]	Capacity_of_Electrolysis[H2_Module_Alkaline]/(Capacity_of_Electrolysis[H2_Module_Alkaline]+Capacity_of_Electrolysis[H2_Module_PEM]+Capacity_of_Electrolysis[H2_Module_SOEC])		dmnl		

Electrolysis_Market_Share[PEM]	Capacity_of_Electrolysis[H2_Module_PEM]/(Capacity_of_Electrolysis[H2_Module_Alkaline]+Capacity_of_Electrolysis[H2_Module_PEM]+Capacity_of_Electrolysis[H2_Module_SOEC])				
Electrolysis_Market_Share[SOEC]	Capacity_of_Electrolysis[H2_Module_SOEC]/(Capacity_of_Electrolysis[H2_Module_Alkaline]+Capacity_of_Electrolysis[H2_Module_PEM]+Capacity_of_Electrolysis[H2_Module_SOEC])				
Electrolysis_Market_Share[Fossil_WO_CCS]	0				
Electrolysis_Market_Share[Fossil_W_CCS]	0				
Energy_Lost_from_Scrapped_Electrolysis_in_one_year	Scrapped_Electrolysis_Power*Annual_Working_Hours_of_Electrolysis*Per_year		MW*hour/Years		
Energy_Lost_from_Scrapped_Fossil_Based_Units_in_one_year	Scrapping_of_Fossil_Based_Plants*Average_Working_Hours_of_Fossil_Based_Plants*Per_year		MW*hour/Years		
Estimated_Global_Energy_Demand	Global_Energy_Demand		MW*hour/year		
Exponent_for_Economy_of_Scale[Solar_PV]	Renewable_Energies.Exponent_for_Economy_of_Scale_of_Solar_PV		dmnl	While in some references, a 0.85 is used for unknown applications, I used it for "compressors". Others were achieved by data analysis. However, I used a roughly 0.95 for electrolysis while my data analysis gave 1. But because these technologies are not so developed so that we can see the effect of scaling up, I assumed something	

				close to what I found for solar PV so that I don't ignore future effects of large scaling up on cost. (Strømholm & Rolfsen, 2021)	
Exponent_for_Economy_of_Scale[Water_Purification]	0.794				
Exponent_for_Economy_of_Scale[Compression]	0.85				
Exponent_for_Economy_of_Scale[H2_Module_Alkaline]	0.95				
Exponent_for_Economy_of_Scale[H2_Module_PEM]	0.95				
Exponent_for_Economy_of_Scale[H2_Module_SOEC]	0.95				
Exponent_for_Scale_Economy_for_Fossil_Plants	0.85		dmnl		
Exponential_Cost_of_Fossil_Fuel	EXP(-(Apparent_Cost_of_Fossil_Based/Sum_of_Apparent_Energy_Costs)/Spread_of_All_Energies)		dmnl		

Exponential_Cost_of_Hydro_Power	EXP(-(Apparent_Cost_of_Hydro_Power/Sum_of_Apparent_Energy_Costs)/Spread_of_All_Energies)		dmnl		
Exponential_Cost_of_Nuclear_Power	EXP(-(Apparent_Cost_of_Nuclear_Power/Sum_of_Apparent_Energy_Costs)/Spread_of_All_Energies)		dmnl		
Exponential_Price_of_Hydrogen	EXP(-(Apparent_Cost_of_Hydrogen/Sum_of_Apparent_Energy_Costs)/Spread_of_All_Energies)		dmnl		
Exponential_Price_of_Hydrogen_Technologies[H2_Market]	EXP(-(Apparent_Cost_of_New_Built_Hydrogen_Production/Sum_of_Hydrogen_Prices)/Spread_of_Hydrogen)		dmnl		
Exponential_Price_of_Solar_PV	EXP(-(Apparent_Cost_of_Solar_PV/Sum_of_Apparent_Energy_Costs)/Spread_of_All_Energies)		dmnl		
Exponential_Price_of_Solar_Thermal	EXP(-(Apparent_Cost_of_Solar_Thermal/Sum_of_Apparent_Energy_Costs)/Spread_of_All_Energies)		dmnl		
Exponential_Price_of_Wind	EXP(-(Apparent_Cost_of_Wind_Power/Sum_of_Apparent_Energy_Costs)/Spread_of_All_Energies)		dmnl		
Fixed_Costs[H2_Market]	Fraction_of_Annual_Fixed_Cost*CAPEX_of_Hydrogen_Production		USD/MW/year	(Strømholm & Rolfsen, 2021) page 39	
Fossil_Based_Energy_Cost_for_Consumer	(1-Subsidy_Fraction_for_Fossil_Based_Energy)*Fossil_Fuel_Base_Energy_Cost		USD/MW/hour		
Fossil_Fuel_Base_Energy_Cost	((Fossil_Fuel_Price/Oil_Fuel_LHV)* (1-(IF TIME<=2015 THEN Fossil_Fuel_Subsidies_before_2020[1] ELSE (IF TIME<=2020 THEN Fossil_Fuel_Subsidies_before_2020[2] ELSE		USD/MW/hour		

	Matrix_of_Subsidies_for_Fossil_Fuels[INT((TIME-2020)/5)+1]))) + Carbon_Tax*Specific_Emission_of_Fossil_Fuels/Oil_Fuel_LHV)				
Fossil_Fuel_ Market_Share	Total_Annual_Energy_of_Fossil_Based/Estimated_Global_Energy_Demand		dmnl		
Fossil_Fuel_P rice	Oil_Price/Weight_of_One_Oil_Barrel		USD/ton		
Fossil_Fuel_S ubsidies_befor e_2020[1]	0.06		dmnl	The annual consumption of fossil fuels in 2012 and 2017 were 126e9 and 132.8e9 MWh [1]. Knowing the oil price (as representative to fossil fuel price) in these years, 72.5 and 35.3 $/MWh mean that total expenditure on fossil fuels were 9135 and 4687 billion $ in these two years. Subsidies on fossil fuels were 543 and 520 billion $ in 2015 and 2017. So the fossil fuel subsidies went roughly from 6% to 11%. [1]. https://ourworldindata.org/grapher/global-fossil-fuel-consumption [2]. https://ourworldindata.org/grapher/fossil-fuel-subsidies?tab=chart&country=~OWID_WRL	
Fossil_Fuel_S ubsidies_befor e_2020[2]	0.11				
Fossil_Fuel_S ubsidies_befor e_2020[3]	0				

Fossil_Fuel_Subsidies_before_2020[4]	0				
Fossil_Fuel_Subsidies_before_2020[5]	0				
Fossil_Fuel_Subsidies_before_2020[6]	0				
Fraction_of_Annual_Fixed_Cost	0.03		1/year		
Fraction_of_Grey_Hydrogen_Plants_to_Blue_Ones	0.02		1/year		
Global_Average_Tilted_Irradiation_at_Optimum_Angle	1.5		MW*hour/square meter/year	It is stated that the average horizontal surface irradiance is 170 W/m2. However, here I used tilted at optimum angle, but this lower value can keep the safe distance to be optimistic. 170 W/m2 is equal to 1500 Kwh/m2 per year. (Council, 2013)	
"Global_Temperature_Above_the_Pre-Industrial_Period"	(CO2_Concentration_of_the_Atmosphere-Baseline_for_Atmosphere_CO2_Concentration)/Global_Temperature_Rise_for_Each_CO2_ppm		degree C		
Global_Temperature_Rise_for_Each_CO2_ppm	95		1/degree C	Based on a simple linear correlation between 1940 to 2020 according to a figure of: (Moore, Heilweck, & Petros, 2021)	

Globally_Average_Optimum_Panel_Tilt_Angle	35		deg	This is a rough estimation from (https://globalsolaratlas.info). Because most of the potential area for solar panels have optimum angles of 30 (southern hemisphere) to near 40 (northern hemisphere), the average could be considered that is (30+40)/2= 35	
Goal_for_barrier_factor_of_Hydrogen	10		dmnl		
Government_Net_Expenditure_for_Avoiding_CO2	IF Avoided_CO2_for_Hydrogen<1 THEN 0 ELSE Government_Expenditure/Avoided_CO2_for_Hydrogen		USD/ton		
Government's_Total_Expenditures_on_Subsidy	Governments_Expenditure_on_Hydro_Power + Governments_Expenditure_on_Hydrogen_Technologies + Governments_Expenditure_on_Solar_PV + Governments_Expenditure_on_Solar_Thermal + Governments_Expenditure_on_Wind_Power		USD/year		SUMMING CONVERTER
Governments_Expenditure_on_Hydro_Power	Subsidy_Fraction_for_Hydro_Power*Total_Expenditure_on_Hydro_Power		USD/year		
Governments_Expenditure_on_Hydrogen_Technologies	Subsidy_Fraction_for_Hydrogen_Technologies[Alkaline]*Average_Cost_of_Hydrogen_over_Year[Alkaline]+Subsidy_Fraction_for_Hydrogen_Technologies[PEM]*Average_Cost_of_Hydrogen_over_Year[PEM]+Subsidy_Fraction_for_Hydrogen_Technologies[SOEC]*Average_Cost_of_Hydrogen_over_Year[SOEC]+Subsidy_Fraction_for_Hydrogen_Technologies[Fossil_W_CCS]*Average_Cost_of_Hydrogen_over_Year[Fossil_W_CCS]		USD/year		
Governments_Expenditure_on_Solar_PV	Subsidy_Fraction_for_Solar_PV*Total_Expenditure_on_Solar_PV		USD/year		
Governments_Expenditure_o	Subsidy_Fraction_for_Solar_Thermal*Total_Expenditure_on_Solar_Thermal		USD/year		

n_Solar_Thermal					
Governments_Expenditure_on_Wind_Power	Subsidy_Fraction_for_Wind_Power*Total_Expenditure_on_Wind_Power		USD/year		
Growth_in_Hydrogen_Demand_for_Usual_Industrial_Application	120.821786112		MW	In average the industrial demand for hydrogen increased by 33 MW every year based on historical data. But this is the net growth in capacity required for usual demand. Regarding the scrapping of units in this model, this number were adjusted to project a capacity close to historical one. The result was roughly 175 MW.	
Historical_Efficiency_of_Solar_PV	GRAPH(TIME) Points: (2010.00, 0.15427), (2011.00, 0.15595), (2012.00, 0.15754), (2013.00, 0.15754), (2014.00, 0.15754), (2015.00, 0.15926), (2016.00, 0.16089), (2017.00, 0.16089), (2018.00, 0.16089), (2019.00, 0.16089), (2020.00, 0.16089)		dmnl		
Historical_Efficiency_of_Solar_Thermal	GRAPH(TIME) Points: (2010.00, 0.300), (2011.00, 0.355), (2012.00, 0.274), (2013.00, 0.310), (2014.00, 0.285), (2015.00, 0.404), (2016.00, 0.362), (2017.00, 0.386), (2018.00, 0.451), (2019.00, 0.452), (2020.00, 0.453)		dmnl		
Historical_Price_of_Natural_Gas	GRAPH(TIME) Points: (2010.00, 174.8), (2011.00, 160.0), (2012.00, 110.0), (2013.00, 149.2), (2014.00, 174.8), (2015.00, 104.8), (2016.00, 100.8), (2017.00, 119.6), (2018.00, 126.0), (2019.00, 102.4), (2020.00, 81.2)		usd/ton	Yearly average Henry Hub Natural Gas Spot Price https://www.eia.gov/dnav/ng/hist/rngwhhdA.htm	
Historical_Price_of_Nuclear	GRAPH(TIME) Points: (2010.00, 125.0), (2011.00, 100.0), (2012.00, 100.0), (2013.00, 100.0), (2014.00, 105.0), (2015.00, 110.0), (2016.00, 120.0), (2017.00, 120.0), (2018.00, 150.0), (2019.00, 155.0), (2020.00, 165.0)		USD/MW/hour		
Historical_Price_of_PV	GRAPH(TIME) Points: (2010.00, 355.0), (2011.00, 250.0), (2012.00, 160.0), (2013.00, 125.0), (2014.00, 100.0), (2015.00, 75.0), (2016.00, 60.0), (2017.00, 55.0), (2018.00, 45.0), (2019.00, 45.0), (2020.00, 45.0)		USD/MW/hour		

Historical_Price_of_Solar_Thermal	GRAPH(TIME) Points: (2010.00, 170.0), (2011.00, 160.0), (2012.00, 160.0), (2013.00, 175.0), (2014.00, 150.0), (2015.00, 125.0), (2016.00, 150.0), (2017.00, 145.0), (2018.00, 145.0), (2019.00, 145.0), (2020.00, 145.0)		USD/MW/hour		
Historical_Price_of_Wind	GRAPH(TIME) Points: (2010.00, 140.0), (2011.00, 130.0), (2012.00, 70.0), (2013.00, 70.0), (2014.00, 70.0), (2015.00, 55.0), (2016.00, 50.0), (2017.00, 50.0), (2018.00, 45.0), (2019.00, 45.0), (2020.00, 45.0)		USD/MW/hour		
History_of_Alkaline	GRAPH(TIME) Points: (2010.00, 29.09260342), (2011.00, 34.83016995), (2012.00, 41.69928422), (2013.00, 49.9231071), (2014.00, 59.76881064), (2015.00, 71.55625787), (2016.00, 85.66839436), (2017.00, 102.5636892), (2018.00, 122.7910295), (2019.00, 147.0075526), (2020.00, 175.9999945)		MW	Reference: https://ourworldindata.org/grapher/installed-solar-pv-capacity	
History_of_Annual_CO2_Emission	GRAPH(TIME) Points: (2010.00, 33340000000), (2011.00, 34470000000), (2012.00, 34970000000), (2013.00, 35280000000), (2014.00, 35530000000), (2015.00, 3.55e+10), (2016.00, 35450000000), (2017.00, 35930000000), (2018.00, 36650000000), (2019.00, 3.67e+10), (2020.00, 34810000000)		ton	Hannah Ritchie and Max Roser, CO2 emissions, Our World in Data https://ourworldindata.org/grapher/annual-co2-emissions-per-country?facet=none&country=~OWID_WRL	
History_of_CAPEX_of_Blue_Hydrogen	GRAPH(TIME) Points: (2010.00, 2900000), (2011.00, 2523831.619), (2012.00, 2316827.45), (2013.00, 2174134.374), (2014.00, 2075865.729), (2015.00, 2000208.225), (2016.00, 1937922.057), (2017.00, 1885091.281), (2018.00, 1840889.38), (2019.00, 1803806.962), (2020.00, 1680349.886)		USD/MW		
History_of_CAPEX_of_Grey_Hydrogen	GRAPH(TIME) Points: (2010.00, 1510340), (2011.00, 1329719.159), (2012.00, 1229072.54), (2013.00, 1159094.359), (2014.00, 1110951.261), (2015.00, 1073806.191), (2016.00, 1043113.337), (2017.00, 1016995.943), (2018.00, 995147.4379), (2019.00, 976848.2158), (2020.00, 911758.4749)		USD/MW		
History_of_Compressor	GRAPH(TIME) Points: (2010.00, 301.6), (2020.00, 301.6)		MW	An estimation from 4000 MW capacity in 2020 (BLUE HYDROGEN - Global CCS Institute. It came from 75 Mt of H2 production where 1% is with CCS) by variation of carbon capture variation from 2010 to 2020. Reference: (IEA, 2016)	

History_of_Desalination	GRAPH(TIME) Points: (2010.00, 18863930000), (2011.00, 20419925000), (2012.00, 22354060000), (2013.00, 24588590000), (2014.00, 26526375000), (2015.00, 27943305000), (2016.00, 29954090000), (2017.00, 31394015000), (2018.00, 32854015000), (2019.00, 34209625000), (2020.00, 35256810000)		cubic meter/year	Reference: https://www.statista.com/statistics/275419/hydropower-and-renewable-energy-worldwide/	
History_of_Energy_Efficiency_of_Alkaline	GRAPH(TIME) Points: (2010.00, 61.47941653), (2011.00, 62.45437901), (2012.00, 63.35125755), (2013.00, 64.18163738), (2014.00, 64.9547025), (2015.00, 65.67785663), (2016.00, 66.35715552), (2017.00, 66.99761555), (2018.00, 67.60343876), (2019.00, 68.17818013), (2020.00, 68.72487391)		dmnl		
History_of_Energy_Efficiency_of_PEM	GRAPH(TIME) Points: (2010.00, 54.73805425), (2011.00, 56.0256486), (2012.00, 57.21012059), (2013.00, 58.30677036), (2014.00, 59.32772688), (2015.00, 60.28276791), (2016.00, 61.17989107), (2017.00, 62.02572127), (2018.00, 62.82580801), (2019.00, 63.58484618), (2020.00, 64.30684303)		dmnl		
History_of_Energy_Efficiency_of_SOEC	GRAPH(TIME) Points: (2010.00, 60.24441132), (2011.00, 61.74048494), (2012.00, 63.11673925), (2013.00, 64.39095173), (2014.00, 65.57721516), (2015.00, 66.68689049), (2016.00, 67.72927024), (2017.00, 68.71205201), (2018.00, 69.64168381), (2019.00, 70.52362071), (2020.00, 71.36251879)		dmnl		
History_of_Fossil_Based_Hydrogen	GRAPH(TIME) Points: (2010.00, 290.2744883), (2011.00, 299.8222844), (2012.00, 309.3745568), (2013.00, 318.9223529), (2014.00, 322.6734327), (2015.00, 325.045834), (2016.00, 327.4227115), (2017.00, 329.799589), (2018.00, 331.1066479), (2019.00, 331.2409347), (2020.00, 402.8605963)		MW	Reference: https://ourworldindata.org/grapher/installed-solar-pv-capacity	
History_of_Global_Energy_Demand	GRAPH(TIME) Points: (2010.00, 152249000000), (2011.00, 155559000000), (2012.00, 157293000000), (2013.00, 159957000000), (2014.00, 161069000000), (2015.00, 162024000000), (2016.00, 164081000000), (2017.00, 166824000000), (2018.00, 171240000000), (2019.00, 173340000000), (2020.00, 1.759e+11)		MW*hour/year		
History_of_Hydro	GRAPH(TIME) Points: (2010.00, 935000), (2011.00, 960000), (2012.00, 960000), (2013.00, 1018000), (2014.00, 1036000), (2015.00, 1064000), (2016.00, 1096000), (2017.00, 1116000), (2018.00, 1126000), (2019.00, 1151000), (2020.00, 1168000)		MW	Reference: https://www.statista.com/statistics/275419/hydropower-and-renewable-energy-worldwide/	
History_of_Hydrogen_Production	History_of_Alkaline + History_of_Fossil_Based_Hydrogen + History_of_PEM + History_of_SOEC		MW		SUMMING CONVERTER
History_of_Nuclear	GRAPH(TIME) Points: (2010.00, 370329), (2011.00, 337140), (2012.00, 332515), (2013.00, 333880), (2014.00, 337324), (2015.00, 346141), (2016.00, 352113), (2017.00, 356636), (2018.00, 370507), (2019.00, 371800), (2020.00, 392600)		MW	Reference: https://www.worldnuclearreport.org/T	

				he-World-Nuclear-Industry-Status-Report-2019-HTML.html	
History_of_Oil_Price	GRAPH(TIME) Points: (2010.00, 79.47), (2011.00, 111.26), (2012.00, 111.63), (2013.00, 108.56), (2014.00, 98.97), (2015.00, 52.32), (2016.00, 43.67), (2017.00, 54.25), (2018.00, 71.34), (2019.00, 64.3), (2020.00, 41.96)		USD/barrel	https://www.statista.com/statistics/262860/uk-brent-crude-oil-price-changes-since-1976/	
History_of_PEM	GRAPH(TIME) Points: (2010.00, 14.71159925), (2011.00, 17.61298206), (2012.00, 21.08656794), (2013.00, 25.24520527), (2014.00, 30.22399808), (2015.00, 36.18469529), (2016.00, 43.32094548), (2017.00, 51.86458811), (2018.00, 62.09318542), (2019.00, 74.33903971), (2020.00, 88.9999891)		MW	Reference: https://ourworldindata.org/grapher/installed-solar-pv-capacity	
History_of_SOEC	GRAPH(TIME) Points: (2010.00, 0.082650284), (2011.00, 0.098950355), (2012.00, 0.118465083), (2013.00, 0.141828454), (2014.00, 0.169799488), (2015.00, 0.203286895), (2016.00, 0.2433786), (2017.00, 0.291377086), (2018.00, 0.348841707), (2019.00, 0.417639348), (2020.00, 0.500005079)		MW	Reference: https://ourworldindata.org/grapher/installed-solar-pv-capacity	
History_of_Solar_PV_Capacity	GRAPH(TIME) Points: (2010.00, 40130), (2011.00, 72040), (2012.00, 101450), (2013.00, 135680), (2014.00, 171590), (2015.00, 217460), (2016.00, 291300), (2017.00, 384450), (2018.00, 482920), (2019.00, 580760), (2020.00, 707500)		MW	Reference: https://ourworldindata.org/grapher/installed-solar-pv-capacity	
History_of_Solar_Thermal	GRAPH(TIME) Points: (2010.00, 237536.6569), (2011.00, 279765.3959), (2012.00, 325513.1965), (2013.00, 373020.5279), (2014.00, 408211.1437), (2015.00, 434604.1056), (2016.00, 453958.9443), (2017.00, 469794.7214), (2018.00, 478592.3754), (2019.00, 483870.9677), (2020.00, 496187.6833)		MW	Reference: Solar Heat Worldwide. Global Market Development and Trends (2021)	
History_of_Specific_Energy_for_Desalination	GRAPH(TIME) Points: (2010.00, 0.002134088), (2011.00, 0.00209633), (2012.00, 0.002060578), (2013.00, 0.002026658), (2014.00, 0.001994419), (2015.00, 0.001963725), (2016.00, 0.001934456), (2017.00, 0.001906504), (2018.00, 0.001879772), (2019.00, 0.001854174), (2020.00, 0.001829632)		MW*hour/cubic meter		
History_of_Wind	GRAPH(TIME) Points: (2010.00, 198000), (2011.00, 238100), (2012.00, 282900), (2013.00, 318700), (2014.00, 369900), (2015.00, 432700), (2016.00, 487300), (2017.00, 539100), (2018.00, 591000), (2019.00, 650000), (2020.00, 745000)		MW	Reference: GWEC | GLOBAL WIND REPORT 2022	
Hour_Per_Year	8760		hour/year		
Hydro_Energy_Cost_for_Consumer	(1-Subsidy_Fraction_for_Hydro_Power)*Renewable_Energies.Hydro_Power_Electricity_Cost		USD/MW/hour		

Hydro_Market_Share	Renewable_Energies.Energy_from_Hydro/Estimated_Global_Energy_Demand		dmnl		
Hydrogen_Cost_of_New_Built_Plants[Alkaline]	(CAPEX_of_Hydrogen_Production[Alkaline]/Average_Lifetime_of_Electrolysis_Sub_Systems[H2_Module_Alkaline]+OPEX_of_Hydrogen_Production[Alkaline])/Annual_Working_Hours_of_Electrolysis		USD/MW/hour		
Hydrogen_Cost_of_New_Built_Plants[PEM]	(CAPEX_of_Hydrogen_Production[PEM]/Average_Lifetime_of_Electrolysis_Sub_Systems[H2_Module_PEM]+OPEX_of_Hydrogen_Production[PEM])/Annual_Working_Hours_of_Electrolysis				
Hydrogen_Cost_of_New_Built_Plants[SOEC]	(CAPEX_of_Hydrogen_Production[SOEC]/Average_Lifetime_of_Electrolysis_Sub_Systems[H2_Module_SOEC]+OPEX_of_Hydrogen_Production[SOEC])/Annual_Working_Hours_of_Electrolysis				
Hydrogen_Cost_of_New_Built_Plants[Fossil_WO_CCS]	(CAPEX_of_Hydrogen_Production[Fossil_WO_CCS]/Average_Lifetime_of_Fossil_Based_Hydrogen_Plants+OPEX_of_Hydrogen_Production[Fossil_WO_CCS])/Annual_Working_Hours_of_Fossil_Based_Hydrogen_Plants				
Hydrogen_Cost_of_New_Built_Plants[Fossil_W_CCS]	(CAPEX_of_Hydrogen_Production[Fossil_W_CCS]/Average_Lifetime_of_Fossil_Based_Hydrogen_Plants+OPEX_of_Hydrogen_Production[Fossil_W_CCS])/Annual_Working_Hours_of_Fossil_Based_Hydrogen_Plants				
Hydrogen_Cost_of_New_Built_Plants_in_Tons[H2_Market]	Hydrogen_Cost_of_New_Built_Plants*Hydrogen_Lower_Heating_Value		USD/ton		
Hydrogen_Density	Multiplier_for_Density_Formula*(Required_Final_Pressure_of_Hydrogen_at_Demand_side-1)/1000		ton/m^3	Based on a rough estimation (error<7%) from "www.engineeringtoolbox.com" Dividing by 1000 is for changing the units to "ton"	

Hydrogen_Lower_Heating_Value	33.33		MW*hour/ton		
Hydrogen_Market_Share	Total_Hydrogen_Produced/Estimated_Global_Energy_Demand		dmnl		
Hydrogen_Transmission_Pressure_Drop	Specific_Pressure_Drop_of_Hydrogen*Distance_to_Market_Demand_Region		bar		
Initial_Average_Oil_Price	LOOKUP(History_of_Oil_Price, STARTTIME)		USD/barrel		
Initial_CAPEX_of_Electrolysis[Solar_PV]	LOOKUP(Renewable_Energies.CAPEX_History_for_Solar_PV, Simulation_Start_Year)		USD/MW	For RO: (Caldera & Breyer, 2017) for H2 Compression! (it is for making liquid H2) (CleanTech, 2019) for H2 compression (for high pressure ratio of pipeline compressors) (Khan, Young, Mackinnon, & Layzell, 2021) For electrolysis: (Christensen, 2020)	
Initial_CAPEX_of_Electrolysis[Water_Purification]	LOOKUP(CAPEX_History_Desalination, Simulation_Start_Year)/Multiplier_for_Unit_Difference_of_Water_Desalination				
Initial_CAPEX_of_Electrolysis[Compression]	3e6				
Initial_CAPEX_of_Electrol	LOOKUP(CAPEX_History_for_Alkaline, Simulation_Start_Year)				

ysis[H2_Module_Alkaline]					
Initial_CAPEX_of_Electrolysis[H2_Module_PEM]	LOOKUP(CAPEX_History_for_PEM, Simulation_Start_Year)				
Initial_CAPEX_of_Electrolysis[H2_Module_SOEC]	LOOKUP(CAPEX_History_for_SOEC, Simulation_Start_Year)				
Initial_CAPEX_of_Fossil_Based_H2[With_CC]	LOOKUP(History_of_CAPEX_of_Blue_Hydrogen, STARTTIME)		USD/MW	Methodology and Specifications Guide Global Hydrogen & Ammonia, 2022	
Initial_CAPEX_of_Fossil_Based_H2[Without_CC]	LOOKUP(History_of_CAPEX_of_Grey_Hydrogen, STARTTIME)				
Invested_on_Hydrogen_for_Avoiding_CO2	IF Avoided_CO2_for_Hydrogen<1 THEN 0 ELSE Total_Accumulated_Investment_on_All_Hydrogen/Avoided_CO2_for_Hydrogen		usd/ton		
Invested_on_Non_Fossil_for_Avoiding_CO2	IF Avoided_CO2_for_Renewable_Energies<1 THEN 0 ELSE Total_Accumulated_Investment_on_Non_Fossil/Avoided_CO2_for_Renewable_Energies		usd/ton		
Learning_for_Fossil_Based[Fossil_Hydrogen]	(Accumulated_Experience_of_Fossil_Based_Plants/INIT(Accumulated_Experience_of_Fossil_Based_Plants))^ (LOG10(1-Cost_Learning_Rate_of_Fossil_Based_H2/100)/LOG10(2))		dmnl		
Learning_for_Sub_technologies_of_Electr	Renewable_Energies.Learning_for_Solar_PV		dmnl		

olysis[Solar_PV]					
Learning_for_Sub_technologies_of_Electrolysis[Water_Purification]	(Accumulated_Experience_of_Electrolysis[Water_Purification]/INIT(Accumulated_Experience_of_Electrolysis[Water_Purification]))^ (LOG10(1-Cost_Learning_Rate_of_Electrolysis[Water_Purification])/LOG10(2))				
Learning_for_Sub_technologies_of_Electrolysis[Compression]	(Accumulated_Experience_of_Electrolysis[Compression]/INIT(Accumulated_Experience_of_Electrolysis[Compression]))^ (LOG10(1-Cost_Learning_Rate_of_Electrolysis[Compression])/LOG10(2))				
Learning_for_Sub_technologies_of_Electrolysis[H2_Module_Alkaline]	(Accumulated_Experience_of_Electrolysis[H2_Module_Alkaline]/INIT(Accumulated_Experience_of_Electrolysis[H2_Module_Alkaline]))^ (LOG10(1-Cost_Learning_Rate_of_Electrolysis[H2_Module_Alkaline])/LOG10(2))				
Learning_for_Sub_technologies_of_Electrolysis[H2_Module_PEM]	(Accumulated_Experience_of_Electrolysis[H2_Module_PEM]/INIT(Accumulated_Experience_of_Electrolysis[H2_Module_PEM]))^ (LOG10(1-Cost_Learning_Rate_of_Electrolysis[H2_Module_PEM])/LOG10(2))				
Learning_for_Sub_technologies_of_Electrolysis[H2_Module_SOEC]	(Accumulated_Experience_of_Electrolysis[H2_Module_SOEC]/INIT(Accumulated_Experience_of_Electrolysis[H2_Module_SOEC]))^ (LOG10(1-Cost_Learning_Rate_of_Electrolysis[H2_Module_SOEC])/LOG10(2))				
Learning_rate_of_Oil_Industry	0.04		dmnl	(Kim & Lee, 2018)	
Lifetime_of_Fossil_Based_Energy_Production_Plants	30		year		

Matrix_of_Subsidies_for_Fossil_Fuels[1]	0.1		dmnl		
Matrix_of_Subsidies_for_Fossil_Fuels[2]	0.1				
Matrix_of_Subsidies_for_Fossil_Fuels[3]	0.1				
Matrix_of_Subsidies_for_Fossil_Fuels[4]	0.1				
Matrix_of_Subsidies_for_Fossil_Fuels[5]	0.1				
Matrix_of_Subsidies_for_Fossil_Fuels[6]	0.1				
Matrix_of_Subsidy_Fraction_for_Fossil_Based_Energy[1]	S_fossil		dmnl	This is the fraction of subsidy by governments to the production cost of hydrogen. It is a two dimensional array. One dimension is the type of technology and the other is the time. Here, I assumed that the subsidy could be changed every 5 years and will last for 15 years. The matrix starts from 2020	
Matrix_of_Subsidy_Fraction_for_Fossil_Based_Energy[2]	S_fossil				
Matrix_of_Subsidy_Fractio	S_fossil				

n_for_Fossil_Based_Energy[3]					
Matrix_of_Subsidy_Fraction_for_Fossil_Based_Energy[4]	S_fossil				
Matrix_of_Subsidy_Fraction_for_Fossil_Based_Energy[5]	S_fossil				
Matrix_of_Subsidy_Fraction_for_Fossil_Based_Energy[6]	S_fossil				
Matrix_of_Subsidy_Fraction_for_Hydro_Power[1]	MIN(S_Hy, 0.7)		dmnl	Same as "Matrix of Subsidy Fraction for Solar Thermal"	
Matrix_of_Subsidy_Fraction_for_Hydro_Power[2]	MIN(S_Hy, 0.7)				
Matrix_of_Subsidy_Fraction_for_Hydro_Power[3]	MIN(S_Hy, 0.7)				
Matrix_of_Subsidy_Fraction_for_Hydro_Power[4]	MIN(S_Hy, 0.7)				

Matrix_of_Subsidy_Fraction_for_Hydro_Power[5]	MIN(S_Hy, 0.7)				
Matrix_of_Subsidy_Fraction_for_Hydro_Power[6]	MIN(S_Hy, 0.7)				
Matrix_of_Subsidy_Fraction_for_Hydrogen_Technologies[Alkaline, 1]	S_H2[Alkaline]		dmnl	This is the fraction of subsidy by governments to the production cost of hydrogen. It is a two dimensional array. One dimension is the type of technology and the other is the time. Here, I assumed that the subsidy could be changed every 5 years and will last for 15 years. The matrix starts from 2020	
Matrix_of_Subsidy_Fraction_for_Hydrogen_Technologies[Alkaline, 2]	S_H2[Alkaline]				
Matrix_of_Subsidy_Fraction_for_Hydrogen_Technologies[Alkaline, 3]	S_H2[Alkaline]				
Matrix_of_Subsidy_Fraction_for_Hydrogen_Technologies[Alkaline, 4]	S_H2[Alkaline]				

Matrix_of_Subsidy_Fraction_for_Hydrogen_Technologies[Alkaline, 5]	S_H2[Alkaline]				
Matrix_of_Subsidy_Fraction_for_Hydrogen_Technologies[Alkaline, 6]	S_H2[Alkaline]				
Matrix_of_Subsidy_Fraction_for_Hydrogen_Technologies[PEM, 1]	S_H2[PEM]				
Matrix_of_Subsidy_Fraction_for_Hydrogen_Technologies[PEM, 2]	S_H2[PEM]				
Matrix_of_Subsidy_Fraction_for_Hydrogen_Technologies[PEM, 3]	S_H2[PEM]				
Matrix_of_Subsidy_Fraction_for_Hydrogen_Technologies[PEM, 4]	S_H2[PEM]				
Matrix_of_Subsidy_Fraction_for_Hydrog	S_H2[PEM]				

en_Technologies[PEM, 5]					
Matrix_of_Subsidy_Fraction_for_Hydrogen_Technologies[PEM, 6]	S_H2[PEM]				
Matrix_of_Subsidy_Fraction_for_Hydrogen_Technologies[SOEC, 1]	S_H2[SOEC]				
Matrix_of_Subsidy_Fraction_for_Hydrogen_Technologies[SOEC, 2]	S_H2[SOEC]				
Matrix_of_Subsidy_Fraction_for_Hydrogen_Technologies[SOEC, 3]	S_H2[SOEC]				
Matrix_of_Subsidy_Fraction_for_Hydrogen_Technologies[SOEC, 4]	S_H2[SOEC]				
Matrix_of_Subsidy_Fraction_for_Hydrogen_Technologies[SOEC, 5]	S_H2[SOEC]				
Matrix_of_Subsidy_Fraction_for_Hydrog	S_H2[SOEC]				

en_Technologies[SOEC, 6]					
Matrix_of_Subsidy_Fraction_for_Hydrogen_Technologies[Fossil_WO_CCS, 1]	0				
Matrix_of_Subsidy_Fraction_for_Hydrogen_Technologies[Fossil_WO_CCS, 2]	0				
Matrix_of_Subsidy_Fraction_for_Hydrogen_Technologies[Fossil_WO_CCS, 3]	0				
Matrix_of_Subsidy_Fraction_for_Hydrogen_Technologies[Fossil_WO_CCS, 4]	0				
Matrix_of_Subsidy_Fraction_for_Hydrogen_Technologies[Fossil_WO_CCS, 5]	0				
Matrix_of_Subsidy_Fraction_for_Hydrog	0				

en_Technologies[Fossil_WO_CCS, 6]					
Matrix_of_Subsidy_Fraction_for_Hydrogen_Technologies[Fossil_W_CCS, 1]	S_H2[Fossil_W_CCS]				
Matrix_of_Subsidy_Fraction_for_Hydrogen_Technologies[Fossil_W_CCS, 2]	S_H2[Fossil_W_CCS]				
Matrix_of_Subsidy_Fraction_for_Hydrogen_Technologies[Fossil_W_CCS, 3]	S_H2[Fossil_W_CCS]				
Matrix_of_Subsidy_Fraction_for_Hydrogen_Technologies[Fossil_W_CCS, 4]	S_H2[Fossil_W_CCS]				
Matrix_of_Subsidy_Fraction_for_Hydrogen_Technologies[Fossil_W_CCS, 5]	S_H2[Fossil_W_CCS]				
Matrix_of_Subsidy_Fractio	S_H2[Fossil_W_CCS]				

n_for_Hydrogen_Technologies[Fossil_W_CCS, 6]					
Matrix_of_Subsidy_Fraction_for_Solar_PV[1]	MIN(S_PV, 0.7)		dmnl	Same as "Matrix of Subsidy Fraction for Solar Thermal"	
Matrix_of_Subsidy_Fraction_for_Solar_PV[2]	MIN(S_PV, 0.7)				
Matrix_of_Subsidy_Fraction_for_Solar_PV[3]	MIN(S_PV, 0.7)				
Matrix_of_Subsidy_Fraction_for_Solar_PV[4]	MIN(S_PV, 0.7)				
Matrix_of_Subsidy_Fraction_for_Solar_PV[5]	MIN(S_PV, 0.7)				
Matrix_of_Subsidy_Fraction_for_Solar_PV[6]	MIN(S_PV, 0.7)				
Matrix_of_Subsidy_Fraction_for_Solar_Thermal[1]	MIN(S_therm, 0.7)		dmnl	The array elements start from 2020 and each array element pave 5 years in time. For example, Matrix[1] is the subsidies fraction allocated from 2020 to 2025. Matrix[2] is the fraction for 2025-2030, and so on. If the model starts running before	

				2020, to compare with real data and calibration purpose, it will use another array with only two elements (i.e. Subsidies before 2020)	
Matrix_of_Subsidy_Fraction_for_Solar_Thermal[2]	MIN(S_therm, 0.7)				
Matrix_of_Subsidy_Fraction_for_Solar_Thermal[3]	MIN(S_therm, 0.7)				
Matrix_of_Subsidy_Fraction_for_Solar_Thermal[4]	MIN(S_therm, 0.7)				
Matrix_of_Subsidy_Fraction_for_Solar_Thermal[5]	MIN(S_therm, 0.7)				
Matrix_of_Subsidy_Fraction_for_Solar_Thermal[6]	MIN(S_therm, 0.7)				
Matrix_of_Subsidy_Fraction_for_Wind_Power[1]	MIN(S_Wind, 0.7)		dmnl	Same as "Matrix of Subsidy Fraction for Solar Thermal"	
Matrix_of_Subsidy_Fraction_for_Wind_Power[2]	MIN(S_Wind, 0.7)				
Matrix_of_Subsidy_Fractio	MIN(S_Wind, 0.7)				

n_for_Wind_Power[3]					
Matrix_of_Subsidy_Fraction_for_Wind_Power[4]	MIN(S_Wind, 0.7)				
Matrix_of_Subsidy_Fraction_for_Wind_Power[5]	MIN(S_Wind, 0.7)				
Matrix_of_Subsidy_Fraction_for_Wind_Power[6]	MIN(S_Wind, 0.7)				
Minimum_Sun_Angle_in_Winter_Solstice	22		deg	https://keisan.casio.com/	
Multiplier_for_Density_Formula	0.08		ton/m^3/bar		
Multiplier_for_Unit_Difference_of_Water_Desalination	1		MW*year/m^3		
Multiplier_to_Change_Unit	1e5*1e-6*1e3/3600		MW*hour/bar/m^3	It is needed to change the units of available formula to the units used in this model: 1e+5 to change bar to pascal 1/3600 to change kg/s into kg/h (of hydrogen) 1e-6 to change W into MW (of electricity)	

				1e+3 to change kg into ton (of hydrogen)	
Natural_Gas_LHV	13.1		MW*hour/ton	https://www.engineeringtoolbox.com/fuels-higher-calorific-values-d_169.html	
Natural_Gas_Price	IF TIME<=2020 THEN Historical_Price_of_Natural_Gas ELSE LOOKUP(Historical_Price_of_Natural_Gas, 2020)*(Oil_Price/LOOKUP(History_of_Oil_Price, 2020))^0.37524		usd/ton	The equation to calculate gas price from oil price was obtained from figure 2 of the below reference by curve fitting. (Ramberg & Parsons, 2012)	
Natural_Gas_Required_for_Producing_Hydrogen	3.04		ton/ton	(Budsberg, Crawford, Gustafson, Bura, & Puettmann, 2015) The unit is ton (natural gas)/ton (H2)	
New_Built_Fossil_Fuel_Based_Market_Share	IF Sum_of_Exponential_Price_of_Energies=0 THEN 0 ELSE Exponential_Cost_of_Fossil_Fuel/Sum_of_Exponential_Price_of_Energies		dmnl		
New_Built_Hydro_Power_Market_Share	IF Sum_of_Exponential_Price_of_Energies=0 THEN 0 ELSE Exponential_Cost_of_Hydro_Power/Sum_of_Exponential_Price_of_Energies		dmnl		
New_Built_Hydrogen_Market_Share	IF Sum_of_Exponential_Price_of_Energies=0 THEN 0 ELSE Exponential_Price_of_Hydrogen/Sum_of_Exponential_Price_of_Energies		dmnl		
New_Built_Hydrogen_Technologies_Market_Share[H2_Market]	IF Sum_of_Exponential_Price_of_Hydrogen=0 THEN 0 ELSE Exponential_Price_of_Hydrogen_Technologies/Sum_of_Exponential_Price_of_Hydrogen		dmnl		
New_Built_Nuclear_Power_Market_Share	IF Sum_of_Exponential_Price_of_Energies=0 THEN 0 ELSE Exponential_Cost_of_Nuclear_Power/Sum_of_Exponential_Price_of_Energies		dmnl		

New_Built_Solar_PV_Market_Share	IF Sum_of_Exponential_Price_of_Energies=0 THEN 0 ELSE Exponential_Price_of_Solar_PV/Sum_of_Exponential_Price_of_Energies		dmnl		
New_Built_Solar_Thermal_Market_Share	IF Sum_of_Exponential_Price_of_Energies=0 THEN 0 ELSE Exponential_Price_of_Solar_Thermal/Sum_of_Exponential_Price_of_Energies		dmnl		
New_Built_Wind_Market_Share	IF Sum_of_Exponential_Price_of_Energies=0 THEN 0 ELSE Exponential_Price_of_Wind/Sum_of_Exponential_Price_of_Energies		dmnl		
Nuclear_Market_Share	Renewable_Energies.Energy_from_Nuclear/Estimated_Global_Energy_Demand		dmnl		
Oil_Fuel_LHV	11.4		MW*hour/ton	The heating value of fuel oil is almost 41 GJ/ton that will be equal to 11.4 MWh/ton. Fuel oil was assumed as a fuel presenting the all fossil fuels. Natural gas has higher heating value while coal has lower.	
Oil_Price	IF TIME<=2020 THEN History_of_Oil_Price ELSE Initial_Average_Oil_Price*(Cost_Factor_of_Oil_for_Resource_Depletion/INIT(Cost_Factor_of_Oil_for_Resource_Depletion))*Oil_Price_Change_for_Learning_Rate		USD/barrel		
Oil_Price_Change_for_Learning_Rate	(Accumulated_Oil_Production/INIT(Accumulated_Oil_Production))^ (LOG10(1-Learning_rate_of_Oil_Industry)/LOG10(2))		dmnl		
OPEX_of_Hydrogen_Production[Alkaline]	Fixed_Costs[Alkaline]+Variable_Costs[Alkaline]*Annual_Working_Hours_of_Electrolysis +(Additional_Land_Cost_for_Hydrogen_Production/Capacity_of_Electrolysis[H2_Module_Alkaline]) *(Capacity_of_Electrolysis[H2_Module_Alkaline]/(Capacity_of_Electrolysis[H2_Module_Alkaline]+Capacity_of_Electrolysis[H2_Module_PEM]+Capacity_of_Electrolysis[H2_Module_SOEC]))		USD/MW/year		

OPEX_of_Hydrogen_Production[PEM]	Fixed_Costs[PEM]+Variable_Costs[PEM]*Annual_Working_Hours_of_Electrolysis +(Additional_Land_Cost_for_Hydrogen_Production/Capacity_of_Electrolysis[H2_Module_PEM]) *(Capacity_of_Electrolysis[H2_Module_PEM]/(Capacity_of_Electrolysis[H2_Module_Alkaline]+Capacity_of_Electrolysis[H2_Module_PEM]+Capacity_of_Electrolysis[H2_Module_SOEC]))				
OPEX_of_Hydrogen_Production[SOEC]	Fixed_Costs[SOEC]+Variable_Costs[SOEC]*Annual_Working_Hours_of_Electrolysis +(Additional_Land_Cost_for_Hydrogen_Production/Capacity_of_Electrolysis[H2_Module_SOEC]) *(Capacity_of_Electrolysis[H2_Module_SOEC]/(Capacity_of_Electrolysis[H2_Module_Alkaline]+Capacity_of_Electrolysis[H2_Module_PEM]+Capacity_of_Electrolysis[H2_Module_SOEC]))				
OPEX_of_Hydrogen_Production[Fossil_WO_CCS]	Fixed_Costs[Fossil_WO_CCS]+Variable_Costs[Fossil_WO_CCS]*Annual_Working_Hours_of_Fossil_Based_Hydrogen_Plants +(Produced_Hydrogen[Fossil_WO_CCS]/Hydrogen_Lower_Heating_Value)*Specific_Emission_of_Fossil_Based_Hydrogen*Carbon_Tax/"Capacity_of_Fossil_Based_(Grey)"				
OPEX_of_Hydrogen_Production[Fossil_W_CCS]	Fixed_Costs[Fossil_W_CCS]+Variable_Costs[Fossil_W_CCS]*Annual_Working_Hours_of_Fossil_Based_Hydrogen_Plants				
Per_year	1		year		
Planning_Multiplier_to_Account_Delays_in_Constructions	(1+10*LOG10(Estimated_Global_Energy_Demand/Total_Produced_Energy))*PREVIOUS(SELF, 1)	INIT Planning_Multiplier_to_Account_Delays_in_Constructions = 2.6	dmnl		
Power_Required_for_New_Installed_Desalination[H2_Market]	MAX(0, Total_Power_Required_for_Desalination-PREVIOUS(Total_Power_Required_for_Desalination, INIT(Total_Power_Required_for_Desalination)))		MW		

Power_Required_for_New_Installed_Electrolysis[Alkaline]	(New_Built_Hydrogen_Technologies_Market_Share[Alkaline]/Average_Energy_Efficiency_of_Alkaline)*(Total_Required_New_Hydrogen_Production/Annual_Working_Hours_of_Electrolysis)		MW		
Power_Required_for_New_Installed_Electrolysis[PEM]	(New_Built_Hydrogen_Technologies_Market_Share[PEM]/Average_Energy_Efficiency_of_PEM)*(Total_Required_New_Hydrogen_Production/Annual_Working_Hours_of_Electrolysis)				
Power_Required_for_New_Installed_Electrolysis[SOEC]	(New_Built_Hydrogen_Technologies_Market_Share[SOEC]/Average_Energy_Efficiency_of_SOEC)*(Total_Required_New_Hydrogen_Production/Annual_Working_Hours_of_Electrolysis)				
Power_Required_for_New_Installed_Electrolysis[Fossil_WO_CCS]	0				
Power_Required_for_New_Installed_Electrolysis[Fossil_W_CCS]	0				
Produced_Hydrogen[Alkaline]	Capacity_of_Electrolysis[H2_Module_Alkaline]*Annual_Working_Hours_of_Electrolysis		MW*hour/year		
Produced_Hydrogen[PEM]	Capacity_of_Electrolysis[H2_Module_PEM]*Annual_Working_Hours_of_Electrolysis				
Produced_Hydrogen[SOEC]	Capacity_of_Electrolysis[H2_Module_SOEC]*Annual_Working_Hours_of_Electrolysis				
Produced_Hydrogen[Fossil_WO_CCS]	"Capacity_of_Fossil_Based_(Grey)"*Annual_Working_Hours_of_Fossil_Based_Hydrogen_Plants				

Produced_Hydrogen[Fossil_W_CCS]	"Capacity_of_Fossil_Based_(Blue)"*Annual_Working_Hours_of_Fossil_Based_Hydrogen_Plants				
Regional_Tilted_Irradiation_at_Optimum_Angle	2.500		MW*hour/square meter/year	https://globalsolaratlas.info	
Regionally_Average_Optimum_Panel_Tilt_Angle	29		deg	https://globalsolaratlas.info	
Required_Energy_Production_for_One_Year	Planning_Multiplier_to_Account_Delays_in_Constructions*(Scrapped_Energy_Units+(Global_Energy_Demand-Total_Produced_Energy))		MW*hour/year		
Required_Energy_to_Transmit_Hydrogen[H2_Market]	0.06 +0*(Multiplier_to_Change_Unit/Hydrogen_Lower_Heating_Value)*((Hydrogen_Transmission_Pressure_Drop+Required_Final_Pressure_of_Hydrogen_at_Demand_side- Delivery_Pressure_of_Hydrogen_at_Plants)/Hydrogen_Density)/Average_Efficiency_of_Hydrogen_Compressor		dmnl		
Required_Final_Pressure_of_Hydrogen_at_Demand_side	70		bar	(Drive, 2017) page 10	
Required_Land_per_MWh_of_new_Solar_PV	(Solar_PV_Efficiency/Global_Average_Tilted_Irradiation_at_Optimum_Angle)*(COS(Globally_Average_Optimum_Panel_Tilt_Angle*PI/180)+SIN(Globally_Average_Optimum_Panel_Tilt_Angle*PI/180)/TAN(Minimum_Sun_Angle_in_Winter_Solstice*PI/180))		square meter*year/MW/hour	For this calculation it was assumed that the solar PV farm is in a square shape. In one direction (to South) the rows of solar cells need to have enough space to prevent shading on other rows. In [*], it is stated that we have to give enough space between rows so that in winter solstice (from 10:00 to 14:00) we have no shadow on	

				solar cells. So the formula in the parenthesis is the summation of length required for PV (Cosine) and distance required for preventing the shadows on other PV cells. So, in one direction we have spacing and in the other, panels are close to each other. If we assume an almost square farm, we can use the written formula. (Sánchez-Carbajal & Rodrigo, 2019)	
Required_Land_per_MWh_of_new_Solar_PV_for_Electrolysis	(Solar_PV_Efficiency/Regional_Tilted_Irradiation_at_Optimum_Angle)*(COS(Regionally_Average_Optimum_Panel_Tilt_Angle*PI/180)+SIN(Regionally_Average_Optimum_Panel_Tilt_Angle*PI/180)/TAN(Minimum_Sun_Angle_in_Winter_Solstice*PI/180))		square meter*year/MW/hour	The same as "Required Land per MWh of new Solar PV"	
Required_Land_per_MWh_of_new_Solar_Thermal	(Solar_Thermal_Efficiency/Global_Average_Tilted_Irradiation_at_Optimum_Angle)*(COS(Globally_Average_Optimum_Panel_Tilt_Angle*PI/180)+SIN(Globally_Average_Optimum_Panel_Tilt_Angle*PI/180)/TAN(Minimum_Sun_Angle_in_Winter_Solstice*PI/180))		square meter*year/MW/hour	The same as "Required Land per MWh of new Solar PV"	
Required_New_Capacity_of_Green_Hydrogen	(New_Built_Hydrogen_Technologies_Market_Share[Alkaline]+New_Built_Hydrogen_Technologies_Market_Share[PEM]+New_Built_Hydrogen_Technologies_Market_Share[SOEC]) *Required_New_Hydrogen_Production_by_Market/Annual_Working_Hours_of_Electrolysis		MW		
Required_New_Hydrogen_Production_by_Market	New_Built_Hydrogen_Market_Share*Required_Energy_Production_for_One_Year		MW*hour/year		
Required_New_Power_for_Compression[H2_Market]	((New_Built_Hydrogen_Technologies_Market_Share*Required_Energy_to_Transmit_Hydrogen) *Required_New_Hydrogen_Production_by_Market/Annual_Working_Hours_of_Electrolysis)		MW		

Reverse_TEMP	1/"Global_Temperature_Above_the_Pre-Industrial_Period"		1/degree C		
S_all_H2	0.4		dmnl		
S_fossil	0.06		dmnl		
S_H2[Alkaline]	MIN(S_all_H2, 0.7)		dmnl		
S_H2[PEM]	MIN(S_all_H2, 0.7)				
S_H2[SOEC]	MIN(S_all_H2, 0.7)				
S_H2[Fossil_WO_CCS]	0				
S_H2[Fossil_W_CCS]	MIN(S_all_H2, 0.7)				
S_Hy	0.0044		dmnl		
S_PV	0.55		dmnl		
S_therm	0.098		dmnl		
S_Wind	0.345		dmnl		
Scale_of_Economy_for_Fossil_Based_Hydrogen[With_CC]	("Capacity_of_Fossil_Based_(Blue)"/INIT("Capacity_of_Fossil_Based_(Blue)"))^(Exponent_for_Scale_Economy_for_Fossil_Plants-1)		dmnl	Subtracting "1" from the equation's power is for this reason: The standard equation that is "capacity Ratio^scale exponent" is expressing the total cost ratio. Here we need to compare "cost/MW" not "cost". So the equation was changed.	
Scale_of_Economy_for_Fossil_Based_Hydrogen[Without_CC]	("Capacity_of_Fossil_Based_(Grey)"/INIT("Capacity_of_Fossil_Based_(Grey)"))^(Exponent_for_Scale_Economy_for_Fossil_Plants-1)				

Scenario_for_Future_Oil_Price	1		dmnl	1 means less sensitive to oil resource depletion 2 means more sensitive	
Scrapped_Electrolysis_Power	Scrapping_of_Blue_Hydrogen_Plants + Scrapping_of_Electrolysis[H2_Module_Alkaline] + Scrapping_of_Electrolysis[H2_Module_PEM] + Scrapping_of_Electrolysis[H2_Module_SOEC] + Scrapping_of_Grey_Hydrogen_Plants		MW/Years		SUMMING CONVERTER
Scrapped_Energy_Units	Energy_Lost_from_Scrapped_Electrolysis_in_one_year + Energy_Lost_from_Scrapped_Fossil_Based_Units_in_one_year + Renewable_Energies.Energy_Lost_from_Scrapped_Renewable_Energy_Units_in_One_Year		MW*hour/year		SUMMING CONVERTER
Simulation_Start_Year	2010		Year		
Solar_PV_Efficiency	LOOKUP(Historical_Efficiency_of_Solar_PV, STARTTIME)*((Accumulated_Experience_of_Electrolysis[Solar_PV]+Renewable_Energies.Accumulated_Experience_of_Solar_PV)/(INIT(Accumulated_Experience_of_Electrolysis[Solar_PV])+INIT(Renewable_Energies.Accumulated_Experience_of_Solar_PV)))^(-LOG10(1-Renewable_Energies.Efficiency_Learning_Rate_for_Solar_PV)/LOG10(2))		dmnl		
Solar_PV_Energy_Cost_for_Consumer	(1-Subsidy_Fraction_for_Solar_PV)*Renewable_Energies.Solar_PV_Electricity_Cost		USD/MW/hour		
Solar_PV_Market_Share	Renewable_Energies.Energy_From_Solar_PV/Estimated_Global_Energy_Demand		dmnl		
Solar_Thermal_Efficiency	LOOKUP(Historical_Efficiency_of_Solar_Thermal, STARTTIME)*(Renewable_Energies.Accumulated_Experience_of_Solar_Thermal/INIT(Renewable_Energies.Accumulated_Experience_of_Solar_Thermal))^(-LOG10(1-Renewable_Energies.Efficiency_Learning_Rate_for_Solar_Thermal)/LOG10(2))		dmnl		
Solar_Thermal_Energy_Cost_for_Consumer	(1-Subsidy_Fraction_for_Solar_Thermal)*Renewable_Energies.Solar_Thermal_Energy_Cost		USD/MW/hour		

Specific_Cost_of_Transportation_by_Ship	0.131		USD/ton/km	Cost of liquid hydrogen shipping for each kg of hydrogen per 10,000 km is 1.31. So, this number for one ton per km will be 0.131. Ref. (Wang et al., 2021)	
Specific_Emission_of_Fossil_Based_Hydrogen	9		ton/ton	Unit: ton(CO2)/ton(H2) https://greet.es.anl.gov/publication-smr_h2_2019#:~:text=The%20median%20CO2%20emission%20normalized,Rutkowski%20et%20al%20(2012).	
Specific_Emission_of_Fossil_Fuels	2.252		ton/ton	The unit is ton (CO2)/ton(natural gas) came from chemical equilibrium for natural gas. [https://ecoscore.be/en/info/ecoscore/co2] For coal it is a bit more (~2.42)	
Specific_Energy_Requirement_for_Desalination	LOOKUP(History_of_Specific_Energy_for_Desalination, Simulation_Start_Year)*(Accumulated_Experience_of_Electrolysis[Water_Purification]/INIT(Accumulated_Experience_of_Electrolysis[Water_Purification]))^(LOG10(1-Efficiency_Learning_Rate_for_Desalination)/LOG10(2))		MW*hour/m^3	AMTA (American Membrane Technology Association), Membrane Desalination Power Usage Put in Perspective, 2016	
Specific_Land_Requirement_for_Wind_Farm	3.45e5		square meter/MW	Based on data, it is 34.5 (+- 22.4) ha for each MW of wind turbine. (Denholm, Hand, Jackson, & Ong, 2009)	
Specific_Pressure_Drop_of_Hydrogen	0.1		bar/km	(Belfroid) Based on fig.9, I used D=30" and a	

				pressure of 60 bar which is relevant to our calculations.	
Spent_Money_for_Fossil_over_Year	New_Fossil_Based_Installation*Fossil_Fuel_Base_Energy_Cost*Average_Working_Hours_of_Fossil_Based_Plants*DT+ (Capacity_of_Fossil_Fuel_Based_Energy-New_Fossil_Based_Installation*DT)*Average_Working_Hours_of_Fossil_Based_Plants* PREVIOUS(SELF, INIT(Fossil_Fuel_Base_Energy_Cost)*INIT(Capacity_of_Fossil_Fuel_Based_Energy)*INIT(Average_Working_Hours_of_Fossil_Based_Plants))/ (PREVIOUS(Average_Working_Hours_of_Fossil_Based_Plants, INIT(Average_Working_Hours_of_Fossil_Based_Plants))*PREVIOUS(Capacity_of_Fossil_Fuel_Based_Energy, INIT(Capacity_of_Fossil_Fuel_Based_Energy)))		USD/year		
Spent_on_Hydrogen_for_Avoiding_CO2	IF Avoided_CO2_for_Hydrogen<1 THEN 0 ELSE Accumulated_Spent_Money_on_All_Hydrogen_Technologies/Avoided_CO2_for_Hydrogen		usd/ton		
Spread_of_All_Energies	0.0164934201628		dmnl		
Spread_of_Hydrogen	1.97845456511		dmnl		
Subsides_before_2020_for_Hydro_Power	GRAPH(TIME) Points: (2012.000, 0.004), (2017.000, 0.0044)		dmnl	Cost of electricity generated by hydro power was roughly 37 and 44 $/MWh in 2012 and 2017. Total energy production by them was 22778 and 25799 TWh in 2012 and 2017. So, the total paid money for hydro electricity were 842 and 1135 b$ for 2012 and 2017. The subsidies for renewable energies were 88 and 130 b$ in these two years. Hudro power absorbed near 5 b$ in 2017. As, I didn't found a reference for amount of global subsidies for each technology at 2012 that could be trustable, I used the same fraction (5/130) and estimated the subsidies for solar PV in 2012 as 3.4 b$. This leads to (3.4/842=) 0.004 and (	

				61/111=) 0.0044 for subsidies fraction for 2012 and 2017. Reference: - IRENA (2021), Renewable Power Generation Costs in 2020, International Renewable Energy Agency, Abu Dhabi - (Taylor, 2020) - IEA (International Energy Agency), World Energy Investment 2022 Reference: (Costs)	
Subsides_before_2020_for_Solar_PV	GRAPH(TIME) Points: (2012.000, 0.720), (2017.000, 0.550)		dmnl	Cost of electricity generated by solar PV was roughly 220 and 100 $/MWh in 2012 and 2017. Total energy production by them was 260.5 and 1115 TWh in 2012 and 2017. So, the total paid money for solar PV electricity were 57 and 111 b$ for 2012 and 2017. The subsidies for renewable energies were 88 and 130 b$ in these two years. Solar PV absorbed near 61 b$ in 2017. As, I didn't found a reference for amount of global subsidies for each technology at 2012 that could be trustable, I used the same fraction (61/130) and estimated the subsidies for solar PV in 2012 as 41 b$. This leads to (41/57=) 0.72 and (61/111=) 0.55 for subsidies fraction for 2012 and 2017. Reference: - IRENA (2021), Renewable Power	

				Generation Costs in 2020, International Renewable Energy Agency, Abu Dhabi - Taylor, Michael (2020), Energy subsidies: Evolution in the global energy transformation to 2050, International Renewable Energy Agency. - IEA (International Energy Agency), World Energy Investment 2022	
Subsides_before_2020_for_Solar_Thermal	GRAPH(TIME) Points: (2012.000, 0.1060), (2017.000, 0.0980)		dmnl	Cost of energy generated by solar thermal was roughly 70 and 53 $/MWh in 2012 and 2017. Total energy production by them was 269 and 382 TWh in 2012 and 2017. So, the total paid money for solar thermal were 18.8 and 20.3 b$ for 2012 and 2017. The subsidies for renewable energies were 88 and 130 b$ in these two years. Solar PV absorbed near 2 b$ in 2017. As, I didn't found a reference for amount of global subsidies for each technology at 2012 that could be trustable, I used the same value (2 b$) because we know that the solar thermal subsidies and so the motivation to have it is declined. This leads to (2/18.8=) 0.106 and (2/20.3=) 0.098 for subsidies fraction for 2012 and 2017. Reference: - IRENA (2021), Renewable Power Generation Costs in 2020, International Renewable Energy Agency, Abu Dhabi - Taylor, Michael (2020), Energy subsidies: Evolution in the global	

				energy transformation to 2050, International Renewable Energy Agency. - IEA (International Energy Agency), World Energy Investment 2022	
Subsides_before_2020_for_Wind_Power	GRAPH(TIME) Points: (2012.000, 0.410), (2017.000, 0.345)		dmnl	Cost of electricity generated by wind power was roughly 120 and 100 $/MWh in 2012 and 2017. Total energy production by them was 525 and 1127 TWh in 2012 and 2017. So, the total paid money for wind electricity were 63 and 113 b$ for 2012 and 2017. The subsidies for renewable energies were 88 and 130 b$ in these two years. Wind power absorbed near 39 b$ in 2017. As, I didn't found a reference for amount of global subsidies for each technology at 2012 that could be trustable, I used the same fraction (39/130) and estimated the subsidies for wind power in 2012 as 26 b$. This leads to (26/63=) 0.41 and (39/113=) 0.345 for subsidies fraction for 2012 and 2017. Reference: - IRENA (2021), Renewable Power Generation Costs in 2020, International Renewable Energy Agency, Abu Dhabi - Taylor, Michael (2020), Energy subsidies: Evolution in the global energy transformation to 2050, International Renewable Energy Agency. - IEA (International Energy Agency), World Energy Investment 2022	

Subsidies_for_Fossil_Based_Energy_before_2020	GRAPH(TIME) Points: (2010.00, 445300000000.0), (2011.00, 503600000000.0), (2012.00, 566000000000.0), (2013.00, 530300000000.0), (2014.00, 473300000000.0), (2015.00, 332500000000.0), (2016.00, 287200000000.0), (2017.00, 335400000000.0), (2018.00, 437700000000.0), (2019.00, 317600000000.0), (2020.00, 181900000000.0)		USD/year	(Gould et al., 2020)	
Subsidies_for_Hydrogen_before_2020	GRAPH(TIME) Points: (2012.000, 0.360), (2017.000, 0.400)		dmnl	This is rough estimation for subsidies on renewable energies. The first one is for 2010-2015, that is used the total investment on renewable energies at 2012 which was 244 b$. One year before (2011) the global subsidies on all renewable energies were 88 b$. This leads to a fraction of 0.36. For second 5 years period, 2015-2020, these numbers are 130 b$ and 326 b$. So, the fraction was 0.4. References: - Taylor, Michael (2020), Energy subsidies: Evolution in the global energy transformation to 2050, International Renewable Energy Agency. - IEA (International Energy Agency), World Energy Investment 2022	
Subsidies_Fraction_for_Fossil_Based_Energy_before_2020	Subsidies_for_Fossil_Based_Energy_before_2020/(0.81*History_of_Global_Energy_Demand*Fossil_Fuel_Base_Energy_Cost)		dmnl	As the share of fossil fuel on global energy basket was almost constant and equal to 81% during period of 2010 to 2020. Ref. IEA, Share of total primary energy demand by fuel, 2010-2019, IEA, Paris https://www.iea.org/data-and-statistics/charts/share-of-total-primary-	

				energy-demand-by-fuel-2010-2019, IEA. License: CC BY 4.0	
Subsidy_Fraction_for_Fossil_Based_Energy	IF TIME<=2020 THEN Subsidies_Fraction_for_Fossil_Based_Energy_before_2020 ELSE IF TIME<2025 THEN (Matrix_of_Subsidy_Fraction_for_Fossil_Based_Energy[1]-HISTORY(Subsidies_Fraction_for_Fossil_Based_Energy_before_2020, 2020))*((TIME-2020) MOD 5)/5/Per_year +HISTORY(Subsidies_Fraction_for_Fossil_Based_Energy_before_2020, 2020) ELSE (Matrix_of_Subsidy_Fraction_for_Fossil_Based_Energy[INT((TIME-2020-DT)/5/Per_year)+1]-Matrix_of_Subsidy_Fraction_for_Fossil_Based_Energy[INT((TIME-2020)/5/Per_year)])*((TIME-2020) MOD 5)/5/Per_year +Matrix_of_Subsidy_Fraction_for_Fossil_Based_Energy[INT((TIME-2020)/5/Per_year)]		dmnl		
Subsidy_Fraction_for_Hydro_Power	IF TIME<=2020 THEN Subsides_before_2020_for_Hydro_Power ELSE IF TIME<2025 THEN (Matrix_of_Subsidy_Fraction_for_Hydro_Power[1]-HISTORY(Subsides_before_2020_for_Hydro_Power, 2020))*((TIME-2020) MOD 5)/5/Per_year +HISTORY(Subsides_before_2020_for_Hydro_Power, 2020) ELSE (Matrix_of_Subsidy_Fraction_for_Hydro_Power[INT((TIME-2020-DT)/5/Per_year)+1]-Matrix_of_Subsidy_Fraction_for_Hydro_Power[INT((TIME-2020)/5/Per_year)])*((TIME-2020) MOD 5)/5/Per_year +Matrix_of_Subsidy_Fraction_for_Hydro_Power[INT((TIME-2020)/5/Per_year)]		dmnl		
Subsidy_Fraction_for_Hydrogen_Technologies[Alkaline]	IF TIME<=2020 THEN Subsidies_for_Hydrogen_before_2020 ELSE IF TIME<2025 THEN (Matrix_of_Subsidy_Fraction_for_Hydrogen_Technologies[Alkaline,1]-HISTORY(Subsidies_for_Hydrogen_before_2020, 2020))*((TIME-2020) MOD 5)/5/Per_year +HISTORY(Subsidies_for_Hydrogen_before_2020, 2020) ELSE (Matrix_of_Subsidy_Fraction_for_Hydrogen_Technologies[Alkaline,INT((TIME-2020-DT)/5/Per_year)+1]-Matrix_of_Subsidy_Fraction_for_Hydrogen_Technologies[Alkaline,INT((TIME-2020)/5/Per_year)])*((TIME-2020) MOD 5)/5/Per_year +Matrix_of_Subsidy_Fraction_for_Hydrogen_Technologies[Alkaline,INT((TIME-2020)/5/Per_year)]		dmnl		
Subsidy_Fraction_for_Hydrogen_Technologies[PEM]	IF TIME<=2020 THEN Subsidies_for_Hydrogen_before_2020 ELSE IF TIME<2025 THEN (Matrix_of_Subsidy_Fraction_for_Hydrogen_Technologies[PEM,1]-HISTORY(Subsidies_for_Hydrogen_before_2020, 2020))*((TIME-2020) MOD				

	5)/5/Per_year +HISTORY(Subsidies_for_Hydrogen_before_2020, 2020) ELSE (Matrix_of_Subsidy_Fraction_for_Hydrogen_Technologies[PEM,INT((TIME-2020-DT)/5/Per_year)+1]-Matrix_of_Subsidy_Fraction_for_Hydrogen_Technologies[PEM,INT((TIME-2020)/5/Per_year)])*((TIME-2020) MOD 5)/5/Per_year +Matrix_of_Subsidy_Fraction_for_Hydrogen_Technologies[PEM,INT((TIME-2020)/5/Per_year)]				
Subsidy_Fraction_for_Hydrogen_Technologies[SOEC]	IF TIME<=2020 THEN Subsidies_for_Hydrogen_before_2020 ELSE IF TIME<2025 THEN (Matrix_of_Subsidy_Fraction_for_Hydrogen_Technologies[SOEC,1]-HISTORY(Subsidies_for_Hydrogen_before_2020, 2020))*((TIME-2020) MOD 5)/5/Per_year +HISTORY(Subsidies_for_Hydrogen_before_2020, 2020) ELSE (Matrix_of_Subsidy_Fraction_for_Hydrogen_Technologies[SOEC,INT((TIME-2020-DT)/5/Per_year)+1]-Matrix_of_Subsidy_Fraction_for_Hydrogen_Technologies[SOEC,INT((TIME-2020)/5/Per_year)])*((TIME-2020) MOD 5)/5/Per_year +Matrix_of_Subsidy_Fraction_for_Hydrogen_Technologies[SOEC,INT((TIME-2020)/5/Per_year)]				
Subsidy_Fraction_for_Hydrogen_Technologies[Fossil_WO_CCS]	0				
Subsidy_Fraction_for_Hydrogen_Technologies[Fossil_W_CCS]	IF TIME<=2020 THEN Subsidies_for_Hydrogen_before_2020 ELSE IF TIME<2025 THEN (Matrix_of_Subsidy_Fraction_for_Hydrogen_Technologies[Fossil_W_CCS,1]-HISTORY(Subsidies_for_Hydrogen_before_2020, 2020))*((TIME-2020) MOD 5)/5/Per_year +HISTORY(Subsidies_for_Hydrogen_before_2020, 2020) ELSE (Matrix_of_Subsidy_Fraction_for_Hydrogen_Technologies[Fossil_W_CCS,INT((TIME-2020-DT)/5/Per_year)+1]-Matrix_of_Subsidy_Fraction_for_Hydrogen_Technologies[Fossil_W_CCS,INT((TIME-2020)/5/Per_year)])*((TIME-2020) MOD 5)/5/Per_year +Matrix_of_Subsidy_Fraction_for_Hydrogen_Technologies[Fossil_W_CCS,INT((TIME-2020)/5/Per_year)]				
Subsidy_Fraction_for_Solar_PV	IF TIME<=2020THEN Subsides_before_2020_for_Solar_PV ELSE IF TIME<2025 THEN (Matrix_of_Subsidy_Fraction_for_Solar_PV[1]-HISTORY(Subsides_before_2020_for_Solar_PV, 2020))*((TIME-2020) MOD		dmnl		

	5)/5/Per_year +HISTORY(Subsides_before_2020_for_Solar_PV, 2020) ELSE (Matrix_of_Subsidy_Fraction_for_Solar_PV[INT((TIME-2020-DT)/5/Per_year)+1]-Matrix_of_Subsidy_Fraction_for_Solar_PV[INT((TIME-2020)/5/Per_year)])*((TIME-2020) MOD 5)/5/Per_year +Matrix_of_Subsidy_Fraction_for_Solar_PV[INT((TIME-2020)/5/Per_year)]				
Subsidy_Fraction_for_Solar_Thermal	IF TIME<=2020 THEN Subsides_before_2020_for_Solar_Thermal ELSE IF TIME<2025 THEN (Matrix_of_Subsidy_Fraction_for_Solar_Thermal[1]-HISTORY(Subsides_before_2020_for_Solar_Thermal, 2020))*((TIME-2020) MOD 5)/5/Per_year +HISTORY(Subsides_before_2020_for_Solar_Thermal, 2020) ELSE (Matrix_of_Subsidy_Fraction_for_Solar_Thermal[INT((TIME-2020-DT)/5/Per_year)+1]-Matrix_of_Subsidy_Fraction_for_Solar_Thermal[INT((TIME-2020)/5/Per_year)])*((TIME-2020) MOD 5)/5/Per_year +Matrix_of_Subsidy_Fraction_for_Solar_Thermal[INT((TIME-2020)/5/Per_year)]		dmnl		
Subsidy_Fraction_for_Wind_Power	IF TIME<=2020 THEN Subsides_before_2020_for_Wind_Power ELSE IF TIME<2025 THEN (Matrix_of_Subsidy_Fraction_for_Wind_Power[1]-HISTORY(Subsides_before_2020_for_Wind_Power, 2020))*((TIME-2020) MOD 5)/5/Per_year +HISTORY(Subsides_before_2020_for_Wind_Power, 2020) ELSE (Matrix_of_Subsidy_Fraction_for_Wind_Power[INT((TIME-2020-DT)/5/Per_year)+1]-Matrix_of_Subsidy_Fraction_for_Wind_Power[INT((TIME-2020)/5/Per_year)])*((TIME-2020) MOD 5)/5/Per_year +Matrix_of_Subsidy_Fraction_for_Wind_Power[INT((TIME-2020)/5/Per_year)]		dmnl		
Sum_of_Apparent_Energy_Costs	Apparent_Cost_of_Fossil_Based + Apparent_Cost_of_Hydro_Power + Apparent_Cost_of_Hydrogen + Apparent_Cost_of_Nuclear_Power + Apparent_Cost_of_Solar_PV + Apparent_Cost_of_Solar_Thermal + Apparent_Cost_of_Wind_Power		USD/MW/hour		SUMMING CONVERTER
Sum_of_Exponential_Price_of_Energies	Exponential_Cost_of_Fossil_Fuel + Exponential_Cost_of_Hydro_Power + Exponential_Price_of_Hydrogen + Exponential_Cost_of_Nuclear_Power + Exponential_Price_of_Solar_PV + Exponential_Price_of_Solar_Thermal + Exponential_Price_of_Wind		dmnl		SUMMING CONVERTER
Sum_of_Exponential_Price_of_Hydrogen	SUM(Exponential_Price_of_Hydrogen_Technologies[*])		dmnl		SUMMING CONVERTER
Sum_of_Hydrogen_Prices	SUM(Hydrogen_Cost_of_New_Built_Plants_in_Tons[*])		USD/ton		SUMMING CONVERTER

Sum_of_New_Power_Required_for_Compression	SUM(Required_New_Power_for_Compression[*])		MW		SUMMING CONVERTER
Thermal_Solar_Market_Share	Renewable_Energies.Energy_From_Solar_Thermal/Estimated_Global_Energy_Demand		dmnl		
Time_00[H2_Market]	1950		year		
Total_Accumulated_Investment_on_All_Hydrogen	SUM(Accumulated_Investment_on_Hydrogen[*])		USD		SUMMING CONVERTER
Total_Annual_Energy_of_Fossil_Based	(Average_Working_Hours_of_Fossil_Based_Plants*Capacity_of_Fossil_Fuel_Based_Energy)		MW*hour/year		
Total_Annual_Expenditure_on_Non_Fossil	Average_Cost_of_Hydrogen_over_Year[Alkaline] + Average_Cost_of_Hydrogen_over_Year[Fossil_W_CCS] + Average_Cost_of_Hydrogen_over_Year[PEM] + Average_Cost_of_Hydrogen_over_Year[SOEC] + Total_Expenditure_on_Hydro_Power + Total_Expenditure_on_Nuclear_Power + Total_Expenditure_on_Solar_PV + Total_Expenditure_on_Solar_Thermal + Total_Expenditure_on_Wind_Power		USD/year		SUMMING CONVERTER
Total_Capacity_of_Fossil_Based_Hydrogen	"Capacity_of_Fossil_Based_(Blue)"+"Capacity_of_Fossil_Based_(Grey)"		MW		
Total_Energy_Consumption_for_Desalination	SUM(Water_Consumption)*Specific_Energy_Requirement_for_Desalination		MW*hour/year		
Total_Expenditure_on_Hydro_Power	Renewable_Energies.Hydro_Power_Electricity_Cost*Renewable_Energies.Energy_from_Hydro		USD/year		

Total_Expenditure_on_Nuclear_Power	Renewable_Energies.Nuclear_Power_Electricity_Cost*Renewable_Energies.Energy_from_Nuclear		USD/year		
Total_Expenditure_on_Solar_PV	Renewable_Energies.Solar_PV_Electricity_Cost*Renewable_Energies.Energy_From_Solar_PV		USD/year		
Total_Expenditure_on_Solar_Thermal	Renewable_Energies.Energy_From_Solar_Thermal*Renewable_Energies.Solar_Thermal_Energy_Cost		USD/year		
Total_Expenditure_on_Wind_Power	Renewable_Energies.Wind_Electricity_Cost*Renewable_Energies.Energy_from_Wind		USD/year		
Total_Hydrogen_Produced	SUM(Produced_Hydrogen[*])		MW*hour/year		SUMMING CONVERTER
Total_Investment_Rate	SUM(Investing_Rate_on_Hydrogen[*])		USD/year		SUMMING CONVERTER
Total_Power_Required_for_Desalination[Alkaline]	(Water_Consumption[Alkaline]/Annual_Working_Hours_of_Electrolysis)*Specific_Energy_Requirement_for_Desalination		MW		
Total_Power_Required_for_Desalination[PEM]	(Water_Consumption[PEM]/Annual_Working_Hours_of_Electrolysis)*Specific_Energy_Requirement_for_Desalination				
Total_Power_Required_for_Desalination[SOEC]	(Water_Consumption[SOEC]/Annual_Working_Hours_of_Electrolysis)*Specific_Energy_Requirement_for_Desalination				
Total_Power_Required_for_Desalination[Fossil_WO_CCS]	(Water_Consumption[Fossil_WO_CCS]/Annual_Working_Hours_of_Fossil_Based_Hydrogen_Plants)*Specific_Energy_Requirement_for_Desalination				

Total_Power_Required_for_Desalination[Fossil_W_CCS]	(Water_Consumption[Fossil_W_CCS]/Annual_Working_Hours_of_Fossil_Based_Hydrogen_Plants)*Specific_Energy_Requirement_for_Desalination				
Total_Power_Required_for_New_Installed_Compression	Sum_of_New_Power_Required_for_Compression		MW		
Total_Power_Required_for_New_Installed_Desalination	SUM(Power_Required_for_New_Installed_Desalination[*])		MW		SUMMING CONVERTER
Total_Power_Required_for_New_Installed_Electrolysis	SUM(Power_Required_for_New_Installed_Electrolysis[*])		MW		SUMMING CONVERTER
Total_Produced_Energy	Renewable_Energies.Energy_From_Solar_PV + Renewable_Energies.Energy_From_Solar_Thermal + Renewable_Energies.Energy_from_Hydro + Renewable_Energies.Energy_from_Wind + Total_Annual_Energy_of_Fossil_Based + Total_Hydrogen_Produced		MW*hour/year		SUMMING CONVERTER
Total_Produced_Energy_from_Non_Fossil	Renewable_Energies.Energy_From_Solar_PV + Renewable_Energies.Energy_From_Solar_Thermal + Renewable_Energies.Energy_from_Hydro + Renewable_Energies.Energy_from_Nuclear + Renewable_Energies.Energy_from_Wind + Total_Hydrogen_Produced		MW*hour/Years		SUMMING CONVERTER
Total_Required_New_Hydrogen_Production	(Growth_in_Hydrogen_Demand_for_Usual_Industrial_Application*Annual_Working_Hours_of_Electrolysis+Required_New_Hydrogen_Production_by_Market)		MW*hour/year		
Total_Required_New_Hydrogen_Production_1	(Growth_in_Hydrogen_Demand_for_Usual_Industrial_Application*Annual_Working_Hours_of_Fossil_Based_Hydrogen_Plants+Required_New_Hydrogen_Production_by_Market)		MW*hour/year		

Total_Water_requirement_for_Electrolysis	0.460		cubic meter/MW/hour	Minimum requirement: Water for the Hydrogen Economy Prepared by: Rain Saulnier, BSc, MASc, 2020	
Total_Water_requirement_for_Fossil_Based	0.39		cubic meter/MW/hour	Minimum requirement: Water for the Hydrogen Economy Prepared by: Rain Saulnier, BSc, MASc, 2020	
Variable_Costs[Alkaline]	Cost_of_Hydrogen_Transportation_by_Ships[Alkaline]		USD/MW/hour		
Variable_Costs[PEM]	Cost_of_Hydrogen_Transportation_by_Ships[PEM]				
Variable_Costs[SOEC]	Cost_of_Hydrogen_Transportation_by_Ships[SOEC]				
Variable_Costs[Fossil_WO_CCS]	Natural_Gas_Required_for_Producing_Hydrogen*Natural_Gas_Price/Natural_Gas_LHV + Cost_of_Hydrogen_Transportation_by_Ships[Fossil_WO_CCS]				
Variable_Costs[Fossil_W_CCS]	Natural_Gas_Required_for_Producing_Hydrogen*Natural_Gas_Price/Natural_Gas_LHV + Cost_of_Hydrogen_Transportation_by_Ships[Fossil_W_CCS]				
Water_Consumption[Alkaline]	Produced_Hydrogen[Alkaline]*Total_Water_requirement_for_Electrolysis		Meters^3/Years		
Water_Consumption[PEM]	Produced_Hydrogen[PEM]*Total_Water_requirement_for_Electrolysis				
Water_Consumption[SOEC]	Produced_Hydrogen[SOEC]*Total_Water_requirement_for_Electrolysis				
Water_Consumption[Fossil_WO_CCS]	Produced_Hydrogen[Fossil_WO_CCS]*Total_Water_requirement_for_Fossil_Based				

Water_Consumption[Fossil_W_CCS]	Produced_Hydrogen[Fossil_W_CCS]*Total_Water_requirement_for_Fossil_Based				
Water_Desalination_Capacity_for_Fossil_Based	("Capacity_of_Fossil_Based_(Grey)"+"Capacity_of_Fossil_Based_(Blue)")*Annual_Working_Hours_of_Fossil_Based_Hydrogen_Plants*Water_Requirement_for_Fossil_Based_Plants		Meters^3/Years		
Water_Requirement_for_Fossil_Based_Plants	0.195		cubic meter/MW/hour	Minimum requirement: Water for the Hydrogen Economy Prepared by: Rain Saulnier, BSc, MASc, 2020	
Water_Requirement_of_Electrolysis	0.27		cubic meter/MW/hour	the minimum requirement. Many said it need more because of cooling and process water.	
Weight_of_Each_ppm_of_CO2_in_the_Atmosphere	7.82e9		ton	https://en.wikipedia.org/wiki/Carbon_dioxide_in_Earth%27s_atmosphere	
Weight_of_One_Oil_Barrel	0.135		ton/barrel	A barrel of oil equals to 159 liters. Density of crude oil is normally in range of 800 to 900 kg/m3. Assuming 850, each barrel will be 135 kg	
Wind_Energy_Cost_for_Consumer	(1-Subsidy_Fraction_for_Wind_Power)*Renewable_Energies.Wind_Electricity_Cost		USD/MW/hour		
Wind_Market_Share	Renewable_Energies.Energy_from_Wind/Estimated_Global_Energy_Demand		dmnl		
Renewable_Energies:					

Accumulated_Experience_of_Hydro(t)	Accumulated_Experience_of_Hydro(t - dt) + (Experience_Gaining_of_Hydro) * dt	INIT Accumulated_Experience_of_Hydro = INIT(Capacity_of_Hydro)*(1+TIME-STARTTIME)	MW*year		NON-NEGATIVE
Accumulated_Experience_of_Nuclear_Plants(t)	Accumulated_Experience_of_Nuclear_Plants(t - dt) + (Experience_Gaining_of_Nuclear_Plants) * dt	INIT Accumulated_Experience_of_Nuclear_Plants = LOOKUP(History_of_Nuclear_Accumulated_Capacity, STARTTIME)	MW*year		NON-NEGATIVE
Accumulated_Experience_of_Solar_PV(t)	Accumulated_Experience_of_Solar_PV(t - dt) + (Experience_Gaining_of_Solar_PV) * dt	INIT Accumulated_Experience_of_Solar_PV = LOOKUP(History_of_PV_Accumulated_Capacity, STARTTIME)	MW*year		NON-NEGATIVE
Accumulated_Experience_of_Solar_Thermal(t)	Accumulated_Experience_of_Solar_Thermal(t - dt) + (Experience_Gaining_of_Solar_Thermal) * dt	INIT Accumulated_Experience_of_Solar_Thermal = LOOKUP(History_of_Solar_Thermal_Accumulated_Capacity, STARTTIME)	MW*year		NON-NEGATIVE
Accumulated_Experience_of_Wind(t)	Accumulated_Experience_of_Wind(t - dt) + (Experience_Gaining_of_Wind_Energy) * dt	INIT Accumulated_Experience_of_Wind = LOOKUP(History_of_Wind_Accumulated_Capacity, STARTTIME)	MW*year		NON-NEGATIVE
Capacity_of_Hydro(t)	Capacity_of_Hydro(t - dt) + (Installation_of_Hydro - Scrapping_of_Hydro) * dt	INIT Capacity_of_Hydro = LOOKUP(History_of_Hydro_Capacity, STARTTIME)	MW	https://www.statista.com/statistics/1179170/global-hydropower-capacity/#:~:text=Cumulative%20hydropower%20capacity%20reached%20approximately,1%2C000%20gigawatts%20had%20been%20installed.	NON-NEGATIVE
Capacity_of_Nuclear_Energy(t)	Capacity_of_Nuclear_Energy(t - dt) + (Installation_of_Nuclear_Plants - Scrapping_of_Nuclear_Plants) * dt	INIT Capacity_of_Nuclear_Energy =	MW	https://www.statista.com/statistics/263947/capacity-of-nuclear-power-plants-worldwide/#:~:text=In%202020%2C	NON-NEGATIVE

		LOOKUP(History_of_Nuclear_Capacity, STARTTIME)		%20the%20cumulative%20capacity,roughly%20396.6%20gigawatts%20in%202018.	
Capacity_of_Solar_PV(t)	Capacity_of_Solar_PV(t - dt) + (Installation_of_Solar_PV - Scrapping_of_Solar_PV) * dt	INIT Capacity_of_Solar_PV = LOOKUP(History_of_PV_Capacity, STARTTIME)	MW	Solar Heat Worldwide, Detailed Market Data 2019, AEE - Institute for Sustainable Technologies page 9	NON-NEGATIVE
Capacity_of_Solar_Thermal(t)	Capacity_of_Solar_Thermal(t - dt) + (Installation_of_Solar_Thermal - Scrapping_of_Solar_Thermal) * dt	INIT Capacity_of_Solar_Thermal = LOOKUP(History_of_Solar_Thermal_Capacity, STARTTIME)	MW		NON-NEGATIVE
Capacity_of_Wind(t)	Capacity_of_Wind(t - dt) + (Installation_of_Wind - Scrapping_of_Wind) * dt	INIT Capacity_of_Wind = LOOKUP(History_of_Wind_Capacity, STARTTIME)	MW	Solar Heat Worldwide, Detailed Market Data 2019, AEE - Institute for Sustainable Technologies page 9	NON-NEGATIVE
Experience_Gaining_of_Hydro	Capacity_of_Hydro		MW		UNIFLOW
Experience_Gaining_of_Nuclear_Plants	Capacity_of_Nuclear_Energy		MW		UNIFLOW
Experience_Gaining_of_Solar_PV	Capacity_of_Solar_PV		MW		UNIFLOW
Experience_Gaining_of_Solar_Thermal	Capacity_of_Solar_Thermal		MW		UNIFLOW
Experience_Gaining_of_Wind_Energy	Capacity_of_Wind		MW		UNIFLOW
Installation_of_Hydro	IF Capacity_of_Hydro<Technical_Potential_of_Hydro_Power THEN .Required_Energy_Production_for_One_Year*.New_Built_Hydro_Power_Market_Share/Average_Working_Hours_of_Hydro/Construction_Time_for_Hydro ELSE 0		MW/Year		UNIFLOW

Installation_of_Nuclear_Plants	.Required_Energy_Production_for_One_Year*.New_Built_Nuclear_Power_Market_Share/Average_Working_Hours_of_Nuclear_Plants/Construction_Time_for_Nuclear_Plants		MW/Year		UNIFLOW
Installation_of_Solar_PV	IF .Available_Land_for_Solar_Energy>0 THEN .Required_Energy_Production_for_One_Year*.New_Built_Solar_PV_Market_Share/Average_Working_Hours_of_Solar_Systems_in_Global_Scale/Construction_Time_for_Solar_PV_Systems ELSE 0		MW/Year		UNIFLOW
Installation_of_Solar_Thermal	IF .Available_Land_for_Solar_Energy>0 THEN (.Required_Energy_Production_for_One_Year*.New_Built_Solar_Thermal_Market_Share/Average_Working_Hours_of_Solar_Systems_in_Global_Scale)/Construction_Time_for_Solar_Thermal ELSE 0		MW/Year		UNIFLOW
Installation_of_Wind	IF .Available_Land_for_Wind_Energy>0 THEN .Required_Energy_Production_for_One_Year*.New_Built_Wind_Market_Share/Average_Working_Hours_of_Wind_Power/Construction_Time_for_Wind ELSE 0		MW/Year		UNIFLOW
Scrapping_of_Hydro	Capacity_of_Hydro/Lifetime_of_Hydro		MW/Year		UNIFLOW
Scrapping_of_Nuclear_Plants	Capacity_of_Nuclear_Energy/Lifetime_of_Nuclear_Plants		MW/Year		UNIFLOW
Scrapping_of_Solar_PV	Capacity_of_Solar_PV/Lifetime_of_Solar_PV_Systems		MW/Year		UNIFLOW
Scrapping_of_Solar_Thermal	Capacity_of_Solar_Thermal/Lifetime_of_Solar_Thermal		MW/Year		UNIFLOW
Scrapping_of_Wind	Capacity_of_Wind/Lifetime_of_Wind_Turbines		MW/Year		UNIFLOW
Average_Capacity_Factor_of_Hydro	0.44		dmnl	(Edenhofer et al., 2011)	
Average_Capacity_Factor_of	0.825		dmnl	Even though the capacity factor for nuclear power plants in US was more than 92% during the last decade [1],	

_Nuclear_Power_Plants				the World Nuclear Association stated that the average value over the world is 80.3% in 2020 [2]. [1]. https://www.statista.com/statistics/191201/capacity-factor-of-nuclear-power-plants-in-the-us-since-1975/ [2]. (Association, 2021)	
Average_Capacity_Factor_of_Solar	0.18		dmnl	0.18 is from table 6.2 of (Christensen, 2020) 0.138	
Average_Capacity_Factor_of_Wind	LOOKUP(Historical_Capacity_Factor_of_Wind_Power, STARTTIME)*(Accumulated_Experience_of_Wind/INIT(Accumulated_Experience_of_Wind))^(-LOG10(1-Capacity_Factor_Learning_Rate_for_Wind_Power)/LOG10(2))		dmnl		
Average_Cost_of_Hydro_over_Year	Spent_Money_for_Hydro_over_Year/(Capacity_of_Hydro*Average_Working_Hours_of_Hydro)		USD/MW/hour		
Average_Cost_of_Nuclear_over_Year	Spent_Money_for_Nuclear_over_Year/(Capacity_of_Nuclear_Energy*Average_Working_Hours_of_Nuclear_Plants)		USD/MW/hour		
Average_Cost_of_Solar_PV_over_Year	Spent_Money_for_Solar_PV_over_Year/(Capacity_of_Solar_PV*Average_Working_Hours_of_Solar_Systems_in_Global_Scale)		USD/MW/hour		
Average_Cost_of_Solar_Th	Spent_Money_for_Solar_Thermal_over_Year/(Capacity_of_Solar_Thermal*Average_Working_Hours_of_Solar_Systems_in_Global_Scale)		USD/MW/hour		

ermal_over_Year					
Average_Cost_of_Wind_Power_over_Year	Spent_Money_for_Wind_Power_over_Year/(Capacity_of_Wind*Average_Working_Hours_of_Wind_Power)		USD/MW/hour		
Average_Hydro_Power_O&M_Cost	11		USD/MW/Hour	The OPEX doesn't show a correlation with time. So I used the average value from 2010 to 2020. https://www.statista.com/statistics/195828/us-hydroelectric-power-plant-operating-expense-since-1998/	
Average_Working_Hours_of_Hydro	Hours_of_One_Year*Average_Capacity_Factor_of_Hydro		hour/year		
Average_Working_Hours_of_Nuclear_Plants	Hours_of_One_Year*Average_Capacity_Factor_of_Nuclear_Power_Plants		hour/year		
Average_Working_Hours_of_Solar_Systems_in_Global_Scale	Average_Capacity_Factor_of_Solar*Hours_of_One_Year		hour/year	In 2020: 707.5 GW 855725 GWh capacity factor=13.8 In 2018: capacity factor= 13.6 In 2014: = 13.15 https://ourworldindata.org/grapher/solar-pv-energy-consumption-vs-solar-pv-capacity	
Average_Working_Hours_of_Wind_Power	Hours_of_One_Year*Average_Capacity_Factor_of_Wind		hour/year	In 2020: Capacity 733 GW Generation: 1.59 million GWH Capacity Factor= 0.2475 In 2018: C.F.= 0.25.7 In 2014: C.F.=0.23 https://ourworldindata.org/grapher/win	

				d-energy-consumption-vs-installed-wind-energy-capacity	
Capacity_Factor_Learning_Rate_for_Wind_Power	0.117		dmnl	From data analysis.	
CAPEX_History_for_Solar_PV	GRAPH(TIME) Points: (2010.00, 2180000), (2011.00, 1417000), (2012.00, 1090000), (2013.00, 981000), (2014.00, 981000), (2015.00, 872000), (2016.00, 763000), (2017.00, 654000), (2018.00, 436000), (2019.00, 327000), (2020.00, 218000)		USD/MW	https://www.iea.org/data-and-statistics/charts/evolution-of-solar-pv-module-cost-by-data-source-1970-2020	
CAPEX_History_for_Solar_Thermal	GRAPH(TIME) Points: (2010.00, 1797400), (2011.11111111, 2117600), (2012.22222222, 1636600), (2013.33333333, 1283800), (2014.44444444, 1102000), (2015.55555556, 1472200), (2016.66666667, 1547400), (2017.77777778, 1464800), (2018.88888889, 1050600), (2020.00, 1154800)		USD/MW	Costs of 2020 is calculated based on 2019 from this ref: https://www.solar-payback.com/solar-heat-to-be-part-of-irena-cost-report-2021/	
CAPEX_History_for_Wind	GRAPH(TIME) Points: (2010.00, 1820896), (2011.00, 1694369), (2012.00, 1517962), (2013.00, 1425613), (2014.00, 1316661), (2015.00, 1186626), (2016.00, 1093261), (2017.00, 996114), (2018.00, 940553), (2019.00, 903324), (2020.00, 863612)		USD/MW	Land-Based Wind Market Report: 2021 Edition, DOE	
CAPEX_of_Hydro_Power	GRAPH(TIME) Points: (2010.00, 1249000), (2011.00, 1225000), (2012.00, 1302000), (2013.00, 1535000), (2014.00, 1607000), (2015.00, 1450000), (2016.00, 1861000), (2017.00, 1808000), (2018.00, 1462000), (2019.00, 1719000), (2020.00, 1870000)		USD/MW		
CAPEX_of_Nuclear_Power	GRAPH(TIME) Points: (2010.00, 6614650.436), (2011.00, 6055145.794), (2012.00, 5977176.92), (2013.00, 6000188.274), (2014.00, 6058247.691), (2015.00, 6206885.867), (2016.00, 6307562.649), (2017.00, 6383811.994), (2018.00, 6617651.184), (2019.00, 6639448.753), (2020.00, 6990097.961)		USD/MW	There are a lot of difference because of many different kinds of technologies. But I used average values between US and France: Lang, P. A. (2017). Nuclear power learning and deployment rates; disruption and global benefits forgone. Energies, 10(12), 2169.	

Construction_Time_for_Hydro	5.5		year	the average of the range 4-7 years [1]. This is correlated with the size of hydro power plant [2]. [1]. https://www.aqper.com/en/how-long-does-it-take-to-build-a-hydroelectric-power-station [2]. Kabanda, H., Romard, A., Yurtsever, F., Wadhera, A., Andrews, J., & Merrett, C. (2021). Construction Time Estimation Function for Canadian Utility Scale Power Plants. Energies, 14(17), 5421.	
Construction_Time_for_Nuclear_Plants	7		year	Page 11 of World Nuclear Performance Report 2021 COP26 Edition	
Construction_Time_for_Solar_PV_Systems	1		year	Linus, H. (2016). Impact of Time-of-Delivery Schemes on Optimum Solar Hybrid Power Plants-A Techno-Economic Study. page 84- Appendix B	
Construction_Time_for_Solar_Thermal	2		year	Linus, H. (2016). Impact of Time-of-Delivery Schemes on Optimum Solar Hybrid Power Plants-A Techno-Economic Study. page 84- Appendix B	
Construction_Time_for_Wind	1.5		year	It could be from less than 1 year to more than 5 years depending on the size of farm. Even in offshore it could be as high as 7-8 years. But as a rough value, I selected 1-2 years https://dbldkr.com/they-showed-up-over-night-a-true-timeline-to-build-a-wind-farm/ Based on below reference, a final	

				average value of 1.5 years seems more rational. D'ANGELO, M. A. R. T. A. (2020). Onshore Wind Energy Market Analysis: Of Sweden, Poland, and Romania.	
Cost_Learning_Rate_for_Hydro	-0.186		dmnl		
Cost_Learning_Rate_for_Nuclear	-0.11		dmnl	Before 1970. the learning rate was positive while the units built after 1970 had a negative learning rate. One of the reasons for the increased installation cost of nuclear plants could be spending more on safety. Based on my data analysis the value is -0.186	
Cost_Learning_Rate_for_Solar_PV	0.207		dmnl	IRENA (2021), Renewable Power Generation Costs in 2020, International Renewable Energy Agency, Abu Dhabi Table ES2, page 19	
Cost_Learning_Rate_for_Solar_Thermal	0		dmnl	There was no rational correlation. ================================ ==================== Here it is stated 0.36 for CSP that is different from solar thermal but I used it to be consistent with others. IRENA (2021), Renewable Power Generation Costs in 2020, International Renewable Energy Agency, Abu Dhabi Table ES2, page 19	

				Here it is 0.13 Werner J. Platzer, Frank Dinter, "A Learning Curve for Solar Thermal Power", AIP Conference Proceedings 1734, 160013 (2016); Figure 1	
Cost_Learning_Rate_for_Wind	0.247		dmnl	Based on data analysis.	
Cost_of_Hydro_Power	Economy_of_Scale_for_Hydro* Learning_for_Hydro*LOOKUP(CAPEX_of_Hydro_Power, STARTTIME)		USD/MW		
Cost_of_Nuclear_Power	Economy_of_Scale_for_Nuclear* Learning_for_Nuclear*(LOOKUP(CAPEX_of_Nuclear_Power, STARTTIME)+Overhead_Costs_for_Nuclear)		USD/MW		
Cost_of_Solar_PV	Economy_of_Scale_for_Solar_PV* Learning_for_Solar_PV*(LOOKUP(CAPEX_History_for_Solar_PV, STARTTIME)+Overhead_Costs_for_Solar_PV)		USD/MW		
Cost_of_Solar_Thermal	Economy_of_Scale_for_Solar_Thermal* Learning_for_Solar_Thermal*(LOOKUP(CAPEX_History_for_Solar_Thermal, STARTTIME)+Overhead_Costs_for_Solar_Thermal)		USD/MW		
Cost_of_Wind_Power	Economy_of_Scale_for_Wind* Learning_for_Wind*(LOOKUP(CAPEX_History_for_Wind, STARTTIME)+Overhead_Costs_for_Wind)		USD/MW		
Economy_of_Scale_for_Hydro	(Capacity_of_Hydro/INIT(Capacity_of_Hydro))^(Exponent_for_Economy_of_Scale_of_Hydro-1)		dmnl		
Economy_of_Scale_for_Nuclear	(Capacity_of_Nuclear_Energy/INIT(Capacity_of_Nuclear_Energy))^(Exponent_for_Economy_of_Scale_of_Nuclear-1)		dmnl		

Economy_of_Scale_for_Solar_PV	((Capacity_of_Solar_PV+.Capacity_of_Electrolysis[Solar_PV])/(INIT(Capacity_of_Solar_PV)+INIT(.Capacity_of_Electrolysis[Solar_PV])))^(Exponent_for_Economy_of_Scale_of_Solar_PV-1)		dmnl		
Economy_of_Scale_for_Solar_Thermal	(Capacity_of_Solar_Thermal/INIT(Capacity_of_Solar_Thermal))^(Exponent_for_Economy_of_Scale_of_Solar_Thermal-1)		dmnl		
Economy_of_Scale_for_Wind	(Capacity_of_Wind/INIT(Capacity_of_Wind))^(Exponent_for_Economy_of_Scale_of_Wind-1)		dmnl		
Efficiency_Learning_Rate_for_Solar_PV	0.036		dmnl		
Efficiency_Learning_Rate_for_Solar_Thermal	0.359		dmnl		
Energy_from_Hydro	Capacity_of_Hydro*Average_Working_Hours_of_Hydro		MW*hour/Years		
Energy_from_Nuclear	Average_Working_Hours_of_Nuclear_Plants*Capacity_of_Nuclear_Energy		MW*hour/Years		
Energy_From_Solar_PV	Average_Working_Hours_of_Solar_Systems_in_Global_Scale*Capacity_of_Solar_PV		MW*hour/year		
Energy_From_Solar_Thermal	Average_Working_Hours_of_Solar_Systems_in_Global_Scale*Capacity_of_Solar_Thermal		MW*hour/year		
Energy_from_Wind	Average_Working_Hours_of_Wind_Power*Capacity_of_Wind		MW*hour/year		
Energy_Lost_from_Scrapped_Renewable_Energy_Units_in_One_Year	Energy_Lost_from_Scrapped_Solar_Units_in_One_Year+Energy_Lost_from_Scrapped_Wind_Units_in_One_Year		MW*hour/Years		

Energy_Lost_from_Scrapped_Solar_Units_in_One_Year	Average_Working_Hours_of_Solar_Systems_in_Global_Scale*Scrapped_Units_of_Solar_Power*One_Year		MW*hour/Years		
Energy_Lost_from_Scrapped_Wind_Units_in_One_Year	Scrapping_of_Wind*Average_Working_Hours_of_Wind_Power*One_Year		MW*hour/Years		
Exponent_for_Economy_of_Scale_of_Hydro	1		dmnl	From data analysis	
Exponent_for_Economy_of_Scale_of_Nuclear	1		dmnl	Based on data analysis	
Exponent_for_Economy_of_Scale_of_Solar_PV	0.916		dmnl	From data analysis	
Exponent_for_Economy_of_Scale_of_Solar_Thermal	0.95		dmnl	The same as Electrolysis technologies, data analysis resulted to a value of 1 for this parameter because of a very poor correlation. So, I assumed a value of 0.95 that is something between the value obtained for wind and photo-voltaic.	
Exponent_for_Economy_of_Scale_of_Wind	1		dmnl	Based on data analysis.	
Extra_Price_due_to_Increase_in_Land_Co	.Additional_Land_Cost_for_Solar_PV/Energy_From_Solar_PV		USD/MW/hour		

st_for_Solar_PV					
Extra_Price_due_to_Increase_in_Land_Cost_for_Solar_Thermal	.Additional_Land_Cost_for_Solar_Thermal/Energy_From_Solar_Thermal		USD/MW/hour		
Extra_Price_due_to_Increase_in_Land_Cost_for_Wind_Energy	.Additional_Land_Cost_for_Wind_Farms/Energy_from_Wind		USD/MW/hour		
Fraction_of_Operating_Cost_for_Solar_Thermal	0.02		dmnl/year	It is argued that the O&M cost is 2% of the capital cost. Widyolar, B., Jiang, L., Bhusal, Y., Brinkley, J., & Winston, R. (2021). Solar thermal process heating with the external compound parabolic concentrator (XCPC)–45 m2 experimental array performance, annual generation (kWh/m2-year), and economics. Solar Energy, 230, 131-150.	
Historical_Capacity_Factor_of_Wind_Power	GRAPH(TIME) Points: (2010.00, 0.32502), (2011.00, 0.3615), (2012.00, 0.39283), (2013.00, 0.40791), (2014.00, 0.40623), (2015.00, 0.41687), (2016.00, 0.41491), (2017.00, 0.42177), (2018.00, 0.42403), (2019.00, 0.4152), (2020.00, 0.425)		dmnl	Ref. Land-Based Wind Market Report: 2021 Edition, DOE	
History_of_Hydro_Accumulated_Capacity	GRAPH(TIME) Points: (2010.00, 2805000), (2011.00, 3765000), (2012.00, 4725000), (2013.00, 5743000), (2014.00, 6779000), (2015.00, 7843000), (2016.00, 8939000), (2017.00, 10055000), (2018.00, 11181000), (2019.00, 12332000), (2020.00, 13500000)		MW*Year	Reference: https://www.statista.com/statistics/275419/hydropower-and-renewable-energy-worldwide/	
History_of_Hydro_Capacity	GRAPH(TIME) Points: (2010.00, 935000), (2011.00, 960000), (2012.00, 960000), (2013.00, 1018000), (2014.00, 1036000), (2015.00, 1064000), (2016.00, 1096000), (2017.00, 1116000), (2018.00, 1126000), (2019.00, 1151000), (2020.00, 1168000)		MW	Reference: https://www.statista.com/statistics/275	

				419/hydropower-and-renewable-energy-worldwide/	
History_of_Nuclear_Accumulated_Capacity	GRAPH(TIME) Points: (2010.00, 10501036), (2011.00, 10838176), (2012.00, 11170691), (2013.00, 11504571), (2014.00, 11841895), (2015.00, 12188036), (2016.00, 12540149), (2017.00, 12896785), (2018.00, 13267292), (2019.00, 13639092), (2020.00, 14031692)		MW*Year	Reference: https://www.worldnuclearreport.org/The-World-Nuclear-Industry-Status-Report-2019-HTML.html	
History_of_Nuclear_Capacity	GRAPH(TIME) Points: (2010.00, 370329), (2011.00, 337140), (2012.00, 332515), (2013.00, 333880), (2014.00, 337324), (2015.00, 346141), (2016.00, 352113), (2017.00, 356636), (2018.00, 370507), (2019.00, 371800), (2020.00, 392600)		MW	Reference: https://www.worldnuclearreport.org/The-World-Nuclear-Industry-Status-Report-2019-HTML.html	
History_of_PV_Accumulated_Capacity	GRAPH(TIME) Points: (2010.00, 103798.0264), (2011.00, 175838.0264), (2012.00, 277288.0264), (2013.00, 412968.0264), (2014.00, 584558.0264), (2015.00, 802018.0264), (2016.00, 1093318.026), (2017.00, 1477768.026), (2018.00, 1960688.026), (2019.00, 2541448.026), (2020.00, 3248948.026)		MW*year	Reference: https://ourworldindata.org/grapher/installed-solar-pv-capacity	
History_of_PV_Capacity	GRAPH(TIME) Points: (2010.00, 40130), (2011.00, 72040), (2012.00, 101450), (2013.00, 135680), (2014.00, 171590), (2015.00, 217460), (2016.00, 291300), (2017.00, 384450), (2018.00, 482920), (2019.00, 580760), (2020.00, 707500)		MW	Reference: https://ourworldindata.org/grapher/installed-solar-pv-capacity	
History_of_Solar_Thermal_Accumulated_Capacity	GRAPH(TIME) Points: (2010.00, 1330205.279), (2011.00, 1609970.674), (2012.00, 1935483.871), (2013.00, 2308504.399), (2014.00, 2716715.543), (2015.00, 3151319.648), (2016.00, 3605278.592), (2017.00, 4075073.314), (2018.00, 4553665.689), (2019.00, 5037536.657), (2020.00, 5533724.34)		MW*Year	Reference: Solar Heat Worldwide. Global Market Development and Trends (2021)	
History_of_Solar_Thermal_Capacity	GRAPH(TIME) Points: (2010.00, 237536.6569), (2011.00, 279765.3959), (2012.00, 325513.1965), (2013.00, 373020.5279), (2014.00, 408211.1437), (2015.00, 434604.1056), (2016.00, 453958.9443), (2017.00, 469794.7214), (2018.00, 478592.3754), (2019.00, 483870.9677), (2020.00, 496187.6833)		MW	Reference: Solar Heat Worldwide. Global Market Development and Trends (2021)	
History_of_Wind_Accumulated_Capacity	GRAPH(TIME) Points: (2010.00, 864200), (2011.00, 1102300), (2012.00, 1385200), (2013.00, 1703900), (2014.00, 2073800), (2015.00, 2506500), (2016.00, 2993800), (2017.00, 3532900), (2018.00, 4123900), (2019.00, 4773900), (2020.00, 5518900)		MW*Year	Reference: GWEC | GLOBAL WIND REPORT 2022	
History_of_Wind_Capacity	GRAPH(TIME) Points: (2010.00, 198000), (2011.00, 238100), (2012.00, 282900), (2013.00, 318700), (2014.00, 369900), (2015.00, 432700), (2016.00, 487300), (2017.00, 539100), (2018.00, 591000), (2019.00, 650000), (2020.00, 745000)		MW	Reference: GWEC | GLOBAL WIND REPORT 2022	

Hours_of_One_Year	8760		hour/year		
Hydro_Power_Electricity_Cost	Cost_of_Hydro_Power/(Average_Working_Hours_of_Hydro*Lifetime_of_Hydro) +Average_Hydro_Power_O&M_Cost		USD/MW/Hour		
Learning_for_Hydro	(Accumulated_Experience_of_Hydro/INIT(Accumulated_Experience_of_Hydro))^ (LOG10(1-Cost_Learning_Rate_for_Hydro)/LOG10(2))		dmnl		
Learning_for_Nuclear	(Accumulated_Experience_of_Nuclear_Plants/INIT(Accumulated_Experience_of_Nuclear_Plants))^ (LOG10(1-Cost_Learning_Rate_for_Nuclear)/LOG10(2))		dmnl		
Learning_for_Solar_PV	((Accumulated_Experience_of_Solar_PV+.Accumulated_Solar_PV_of_Electrolysis)/(INIT(Accumulated_Experience_of_Solar_PV)+INIT(.Accumulated_Solar_PV_of_Electrolysis)))^ (LOG10(1-Cost_Learning_Rate_for_Solar_PV-Efficiency_Learning_Rate_for_Solar_PV)/LOG10(2))		dmnl		
Learning_for_Solar_Thermal	(Accumulated_Experience_of_Solar_Thermal/INIT(Accumulated_Experience_of_Solar_Thermal))^ (LOG10(1-Cost_Learning_Rate_for_Solar_Thermal-Efficiency_Learning_Rate_for_Solar_Thermal)/LOG10(2))		dmnl		
Learning_for_Wind	(Accumulated_Experience_of_Wind/INIT(Accumulated_Experience_of_Wind))^ (LOG10(1-Cost_Learning_Rate_for_Wind)/LOG10(2))		dmnl		
Learning_Rate_for_Nuclear_Power_O&M_Cost	0.65		dmnl	From data analysis	
Learning_Rate_for_Solar_PV_O&M_Cost	0.25		dmnl	The experience rate (learning rate) is correlated with cumulative energy production but as I use a constant hour per year operation for solar systems over the entire simulation period, I used accumulative capacity instead. Ref. Steffen, B., Beuse, M., Tautorat, P., & Schmidt, T. S. (2020). Experience curves for operations and maintenance	

				costs of renewable energy technologies. Joule, 4(2), 359-375.	
Learning_Rate_for_Wind_Turbine_O&M_Cost	0.08		dmnl	I used the data from below reference for 2005 and 2017 to find the learning rate for O&M cost. Ref. Steffen, B., Beuse, M., Tautorat, P., & Schmidt, T. S. (2020). Experience curves for operations and maintenance costs of renewable energy technologies. Joule, 4(2), 359-375.	
Lifetime_of_Hydro	50		year	(Gallagher, Styles, McNabola, & Williams, 2015)	
Lifetime_of_Nuclear_Plants	40		year	Krivanek, R. (2020). Factors limiting lifetime of nuclear power plants with pressurized-water reactors. Nuclear Engineering and Design, 370, 110872.	
Lifetime_of_Solar_PV_Systems	15		year	Although Solar PV last longer (normally more than 250 or 25 years) because of short lifetime of storage batteries, the value is lower than what I used for solar PV in the electrolysis where I assumed that they don't have any batteries. I calculated roughly this lifetime based on cost breakdown and lifetime of component. Assuming 30% of cost is for battery and all those with less lifetime (21% is for batteries), and a 8 years lifetime for them, while 25 years for others, the average lifetime of the investment will be close to 15 years.	
Lifetime_of_Solar_Thermal	20		year	SOLAR HOT WATER SYSTEM SPECIFICATIONS AND	

				REQUIREMENTS, EPA, 2014 (and also) Linus, H. (2016). Impact of Time-of-Delivery Schemes on Optimum Solar Hybrid Power Plants-A Techno-Economic Study. page 84- Appendix B here it was stated 30 years" Košiˇcan, J.; Pardo Picazo, M.Á.; Vilˇceková, S.; Košiˇcanová, D. Life Cycle Assessment and Economic Energy Efficiency of a Solar Thermal Installation in a Family House. Sustainability 2021, 13, 2305. https://doi.org/10.3390/su13042305	
Lifetime_of_Wind_Turbines	20		year	Wind turbine blade material in the United States: Quantities, costs, and end-of-life options, Resources, Conservation and Recycling, Volume 168, May 2021, 105439	
Nuclear_O&M_Cost	LOOKUP(OPEX_History_for_Nuclear_Power, STARTTIME)*(Accumulated_Experience_of_Nuclear_Plants/INIT(Accumulated_Experience_of_Nuclear_Plants))^(LOG10(1-Learning_Rate_for_Nuclear_Power_O&M_Cost)/LOG10(2))		USD/MW/hour		

Nuclear_Power_Electricity_Cost	Cost_of_Nuclear_Power/(Average_Working_Hours_of_Nuclear_Plants*Lifetime_of_Nuclear_Plants) +Nuclear_O&M_Cost		USD/MW/hour		
One_Year	1		year		
OPEX_History_for_Nuclear_Power	GRAPH(TIME) Points: (2010.00, 39.83), (2011.00, 42.47), (2012.00, 44.57), (2013.00, 42.0), (2014.00, 40.0), (2015.00, 38.45), (2016.00, 36.11), (2017.00, 35.03), (2018.00, 32.91), (2019.00, 30.41), (2020.00, 30.41)		USD/MW/hour		
OPEX_History_for_Solar_PV	GRAPH(TIME) Points: (2010.00, 24997.768), (2011.00, 21237.88342), (2012.00, 18043.51862), (2013.00, 15329.61442), (2014.00, 13023.90534), (2015.00, 11064.99521), (2016.00, 9400.722432), (2017.00, 7986.770943), (2018.00, 6785.490217), (2019.00, 5764.892698), (2020.00, 4897.802038)		USD/MW/year	This obtained from: Ref. Steffen, B., Beuse, M., Tautorat, P., & Schmidt, T. S. (2020). Experience curves for operations and maintenance costs of renewable energy technologies. Joule, 4(2), 359-375.	
OPEX_History_for_Wind_Power	GRAPH(TIME) Points: (2010.00, 17.6502055), (2011.00, 17.14100985), (2012.00, 16.6763765), (2013.00, 16.26609994), (2014.00, 15.8861844), (2015.00, 15.52813446), (2016.00, 15.19980346), (2017.00, 14.90005211), (2018.00, 14.62536818), (2019.00, 14.37011626), (2020.00, 14.12161107)		USD/MW/hour	This obtained from: Ref. Steffen, B., Beuse, M., Tautorat, P., & Schmidt, T. S. (2020). Experience curves for operations and maintenance costs of renewable energy technologies. Joule, 4(2), 359-375.	
Overhead_Costs_for_Nuclear	16500000		USD/MW	This overhead was obtained from other available data to match the calculated energy cost with the historical one (at 2010).	
Overhead_Costs_for_Solar_PV	GRAPH(TIME) Points: (2010.00, 5840000), (2011.00, 6210000), (2012.00, 4930000), (2013.00, 4370000), (2014.00, 4370000), (2015.00, 3980000), (2016.00, 3980000), (2017.00, 3750000), (2018.00, 3890000), (2019.00, 3880000), (2020.00, 3950000)		USD/MW	In addition to CapEx of solar panel, there are other costs such as inverter, electrical, structural, soft cost, ... These cost didn't drop as much as PV panel from 2010 to 2020. According to Figure 52, they were almost halved during this 10 years. Using the values for "commercial rooftop PV" that is	

				almost median between residential and utility solar PVs, the overhead cost was 3.39 $/W at 2010 that decreased to 1.5 $/W by 2020. Then the obtained curve was adjusted to match calculated and historical electricity costs. Feldman, D., Ramasamy, V., Fu, R., Ramdas, A., Desai, J., & Margolis, R. (2021). US solar photovoltaic system and energy storage cost benchmark (Q1 2020) (No. NREL/TP-6A20-77324). National Renewable Energy Lab.(NREL), Golden, CO (United States).	
Overhead_Costs_for_Solar_Thermal	2000000		USD/MW	This overhead was obtained from other available data to match the calculated energy cost with the historical one (at 2010).	
Overhead_Costs_for_Wind	5120000		USD/MW	From two report of NREL (2010 and 2020) it is obvious that the amount of overhead costs including BOS (electrical, structural, ...) and soft cost didn't change too much. For example, for offshore wind turbines, the overhead price decreased from 3.9 $/W to 2.9 $/W roughly during 2010-2020. The value for onshore is less but the change over time also was not too much. So, I assumed that the overhead cost is constant and roughly equal to 3.4 $/W that is the average value of offshore and onshore.	

				Ref. -Tegen, S., Hand, M., Maples, B., Lantz, E., Schwabe, P., & Smith, A. (2012). 2010 cost of wind energy review (No. NREL/TP-5000-52920). National Renewable Energy Lab.(NREL), Golden, CO (United States). - Stehly, T., & Duffy, P. (2021). 2020 Cost of Wind Energy Review (No. NREL/TP-5000-81209). National Renewable Energy Lab.(NREL), Golden, CO (United States).	
Scrapped_Units_of_Solar_Power	Scrapping_of_Solar_PV + Scrapping_of_Solar_Thermal		MW/Years		SUMMING CONVERTER
Solar_PV_Electricity_Cost	Cost_of_Solar_PV/(Average_Working_Hours_of_Solar_Systems_in_Global_Scale*Lifetime_of_Solar_PV_Systems) +Solar_PV_O&M_Cost/Average_Working_Hours_of_Solar_Systems_in_Global_Scale +Extra_Price_due_to_Increase_in_Land_Cost_for_Solar_PV		USD/MW/hour		
Solar_PV_O&M_Cost	LOOKUP(OPEX_History_for_Solar_PV, STARTTIME)*(Accumulated_Experience_of_Solar_PV/INIT(Accumulated_Experience_of_Solar_PV))^(LOG10(1-Learning_Rate_for_Solar_PV_O&M_Cost)/LOG10(2))		USD/MW/year		
Solar_Thermal_Energy_Cost	Cost_of_Solar_Thermal/(Average_Working_Hours_of_Solar_Systems_in_Global_Scale*Lifetime_of_Solar_Thermal) +Solar_Thermal_Operating_Cost/Average_Working_Hours_of_Solar_Systems_in_Global_Scale +Extra_Price_due_to_Increase_in_Land_Cost_for_Solar_Thermal		USD/MW/Hour		
Solar_Thermal_Operating_Cost	Fraction_of_Operating_Cost_for_Solar_Thermal*Cost_of_Solar_Thermal		USD/MW/year		

Spent_Money_for_Hydro_over_Year	Installation_of_Hydro*Hydro_Power_Electricity_Cost*Average_Working_Hours_of_Hydro*DT+ (Capacity_of_Hydro-Installation_of_Hydro*DT)*Average_Working_Hours_of_Hydro* PREVIOUS(SELF, INIT(Hydro_Power_Electricity_Cost)*INIT(Capacity_of_Hydro)*INIT(Average_Working_Hours_of_Hydro))/ (PREVIOUS(Average_Working_Hours_of_Hydro, INIT(Average_Working_Hours_of_Hydro))*PREVIOUS(Capacity_of_Hydro, INIT(Capacity_of_Hydro)))		USD/year		
Spent_Money_for_Nuclear_over_Year	Installation_of_Nuclear_Plants*Nuclear_Power_Electricity_Cost*Average_Working_Hours_of_Nuclear_Plants*DT+ (Capacity_of_Nuclear_Energy-Installation_of_Nuclear_Plants*DT)*Average_Working_Hours_of_Nuclear_Plants * PREVIOUS(SELF, INIT(Nuclear_Power_Electricity_Cost)*INIT(Capacity_of_Nuclear_Energy)*INIT(Average_Working_Hours_of_Nuclear_Plants))/ (PREVIOUS(Average_Working_Hours_of_Nuclear_Plants, INIT(Average_Working_Hours_of_Nuclear_Plants))*PREVIOUS(Capacity_of_Nuclear_Energy, INIT(Capacity_of_Nuclear_Energy)))		USD/year		
Spent_Money_for_Solar_PV_over_Year	Installation_of_Solar_PV*Solar_PV_Electricity_Cost*Average_Working_Hours_of_Solar_Systems_in_Global_Scale*DT+ (Capacity_of_Solar_PV-Installation_of_Solar_PV*DT)*(Average_Working_Hours_of_Solar_Systems_in_Global_Scale)* PREVIOUS(SELF, INIT(Solar_PV_Electricity_Cost)*INIT(Capacity_of_Solar_PV)*INIT(Average_Working_Hours_of_Solar_Systems_in_Global_Scale))/ (PREVIOUS(Average_Working_Hours_of_Solar_Systems_in_Global_Scale, INIT(Average_Working_Hours_of_Solar_Systems_in_Global_Scale))*PREVIOUS(Capacity_of_Solar_PV, INIT(Capacity_of_Solar_PV)))		USD/year		
Spent_Money_for_Solar_Thermal_over_Year	Installation_of_Solar_Thermal*Solar_Thermal_Energy_Cost*Average_Working_Hours_of_Solar_Systems_in_Global_Scale*DT+ (Capacity_of_Solar_Thermal-Installation_of_Solar_Thermal*DT)*(Average_Working_Hours_of_Solar_Systems_in_Global_Scale)* PREVIOUS(SELF, INIT(Solar_Thermal_Energy_Cost)*INIT(Capacity_of_Solar_Thermal)*INIT(Average_Working_Hours_of_Solar_Systems_in_Global_Scale))/ (PREVIOUS(Average_Working_Hours_of_Solar_Systems_in_Global_Scale, INIT(Average_Working_Hours_of_Solar_Systems_in_Global_Scale))*PREVIOUS(Capacity_of_Solar_Thermal, INIT(Capacity_of_Solar_Thermal)))		USD/year		
Spent_Money_for_Wind_Po	Installation_of_Wind*Wind_Electricity_Cost*Average_Working_Hours_of_Wind_Power*DT+ (Capacity_of_Wind-		USD/year		

wer_over_Year	Installation_of_Wind*DT)*Average_Working_Hours_of_Wind_Power* PREVIOUS(SELF, INIT(Wind_Electricity_Cost)*INIT(Capacity_of_Wind)*INIT(Average_Working_Hours_of_Wind_Power))/ (PREVIOUS(Average_Working_Hours_of_Wind_Power, INIT(Average_Working_Hours_of_Wind_Power))*PREVIOUS(Capacity_of_Wind, INIT(Capacity_of_Wind)))				
Technical_Potential_of_Hydro_Power	3721e3		MW	Edenhofer, O., Pichs-Madruga, R., Sokona, Y., Seyboth, K., Matschoss, P., Kadner, S., ... & von Stechow, C. (2011). IPCC special report on renewable energy sources and climate change mitigation. Prepared By Working Group III of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, UK.	
Total_Capacity_of_Renewable_Energies	Capacity_of_Hydro + Capacity_of_Nuclear_Energy + Capacity_of_Solar_PV + Capacity_of_Solar_Thermal + Capacity_of_Wind		MW		SUMMING CONVERTER
Wind_Electricity_Cost	Cost_of_Wind_Power/(Average_Working_Hours_of_Wind_Power*Lifetime_of_Wind_Turbines) +Wind_O&M_Cost +Extra_Price_due_to_Increase_in_Land_Cost_for_Wind_Energy		USD/MW/hour		
Wind_O&M_Cost	LOOKUP(OPEX_History_for_Wind_Power, STARTTIME)*(Accumulated_Experience_of_Wind/INIT(Accumulated_Experience_of_Wind))^(LOG10(1-Learning_Rate_for_Wind_Turbine_O&M_Cost)/LOG10(2))		USD/MW/hour		

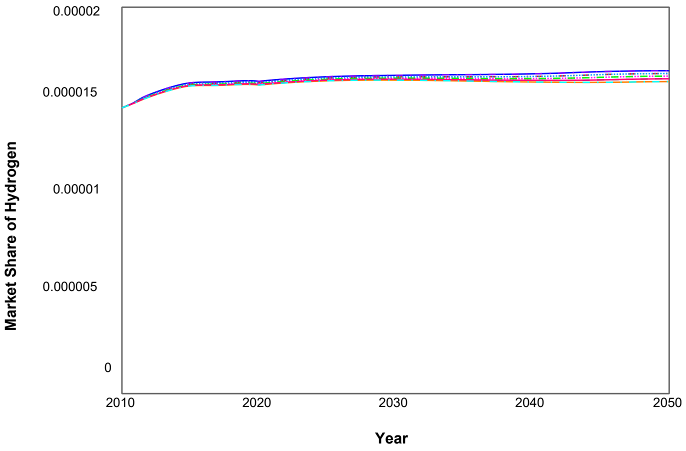
Total	Count	Including Array Elements
Variables	536	798
Modules	1	
Sectors	9	
Stocks	33	48
Flows	45	65
Converters	458	685
Constants	111	153
Equations	392	597
Graphicals	64	64

Run Specs	
Start Time	Simulation Start Year
Stop Time	2050
DT	1/200
Fractional DT	True
Save Interval	0.005
Sim Duration	0.1
Time Units	Year
Pause Interval	0
Integration Method	Euler
Keep all variable results	True
Run By	Run
Calculate loop dominance information	False

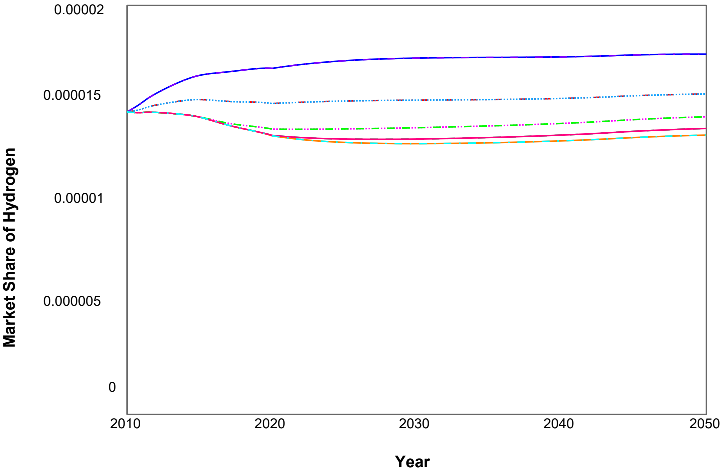
Array Dimension	Indexed by	Elements
Energies	Label (7)	Hydrogen Solar_PV Solar_Thermal Wind Hydro Nuclear Fossil
Fossil_Hydrogen	Label (2)	With_CC Without_CC
H2_Market	Label (5)	Alkaline PEM SOEC Fossil_WO_CCS Fossil_W_CCS
Subsidy_Time_Steps	Number	6
SubTech_Elect	Label (6)	Solar_PV Water_Purification Compression H2_Module_Alkaline H2_Module_PEM H2_Module_SOEC

Appendix B: (Sensitivity Analysis)

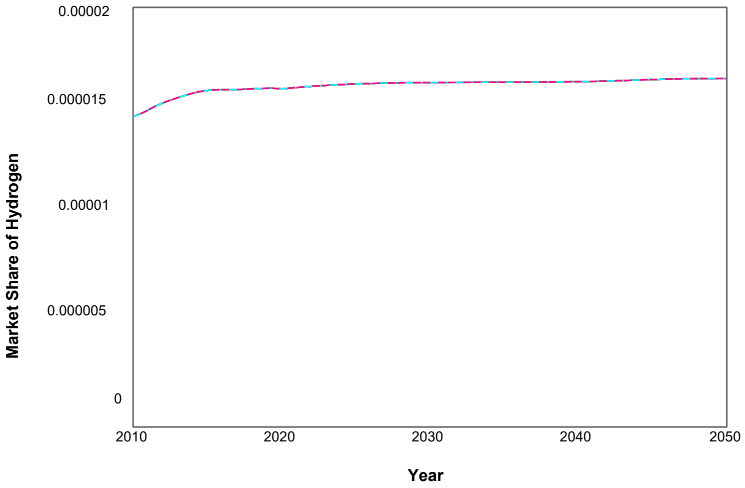
Outcomes for sensitivity analysis of some of parameters used in the model are presented in this appendix as graphs. The range of each parameter is stated below each figure. These graphs were only obtained for a specific set of the subsidies.



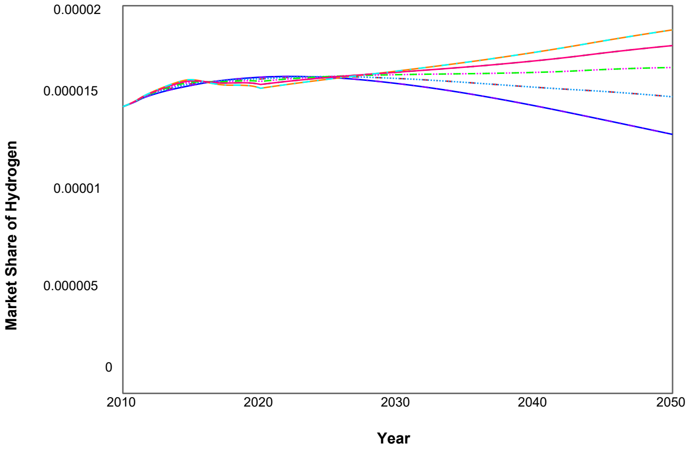
Appendix Figure 1. Sensitivity of hydrogen market share to distance between production and demand (200-5000 km)



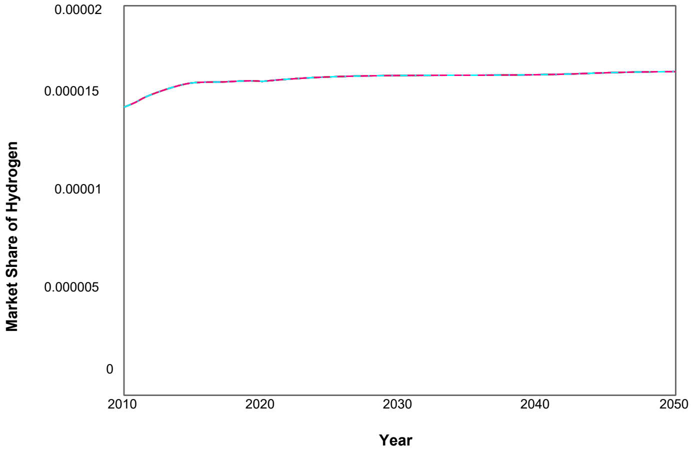
Appendix Figure 2. Sensitivity of hydrogen market share to fraction of fossil based hydrogen units planning to be equipped with CCS every year (1-10%)



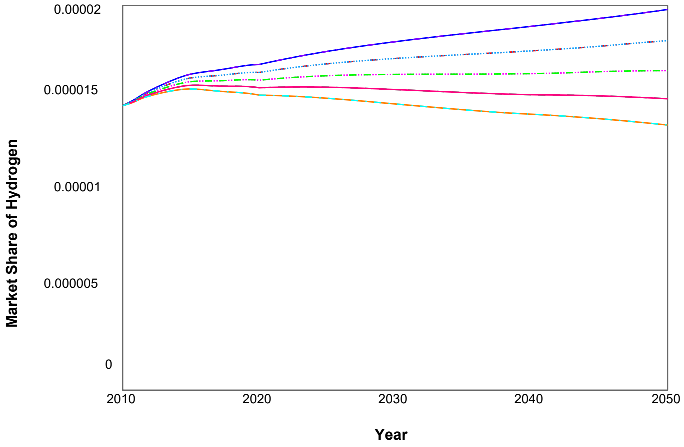
Appendix Figure 3. Sensitivity of hydrogen market share to the average land cost (0.03-0.6 $/acre)



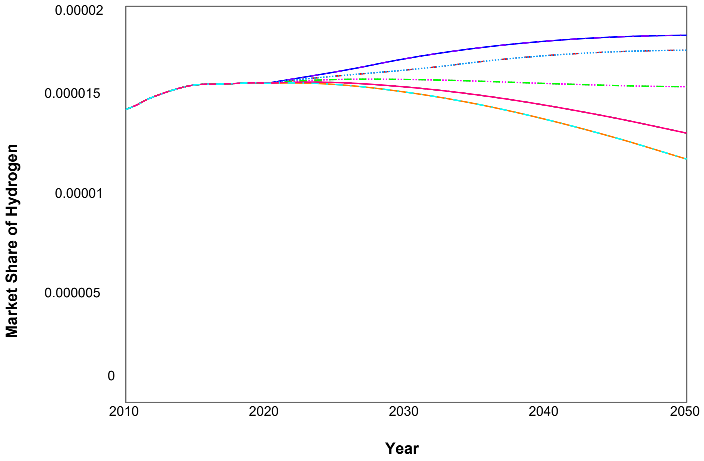
Appendix Figure 4. Sensitivity of hydrogen market share to elasticity of global energy demand (-0.01 to -1.12) while a value of -0.524 is used in the model



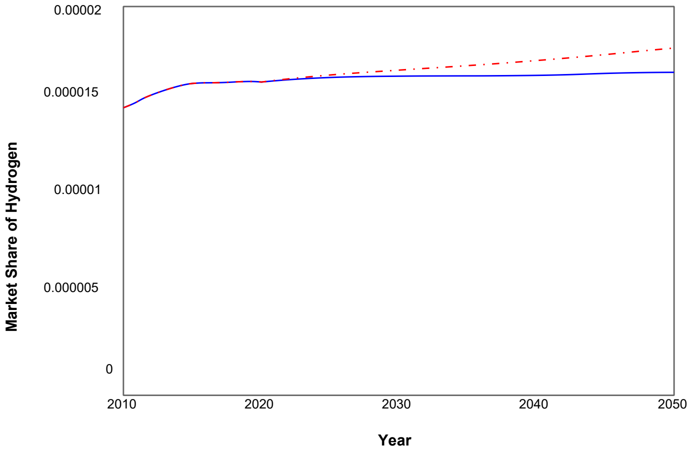
Appendix Figure 5. Sensitivity of hydrogen market share to solar irradiation at the region the green hydrogen units are going to e installed (0.5-3.5 MWh/(m^2.year))



Appendix Figure 6. Sensitivity of hydrogen market share to annual growth rate of global energy demand (1-2%)



Appendix Figure 7. Sensitivity of hydrogen market share to rate of annual oil exploration (1E9-15E9 ton/year)



Appendix Figure 8. Sensitivity of hydrogen market share to the how much oil producers will react to their resource depletion. Blue-solid line represents less increase in fossil fuel price by being close to their depletion.