Annotation sheet

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Supervisor: doc. Ing. Lukáš Krátký, Ph.D

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Submitter: Czech Technical University in Prague,
Faculty of Mechanical Engineering,
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Annotation - Czech: Práce se v první části věnuje shrnutí informací o možnostech decentralizované výroby vodíku, zejména pak parnímu reformingu a elektrolýze vody. Praktická část se věnuje hmotově-energetické bilanci procesů s důrazem na využití obnovitelných zdrojů energie včetně základní ekonomické rozvahy a citlivostní analýzy.

Keywords: Elektorýza, vodík, obnovitelné zdroje energie, parný reforming

Annotation - English: Detailed literature research on different hydrogen production technologies and selecting a few processes in a decentralized method such as Steam methane reforming and other technologies using electrolyzer. Based on this selection where complete mass, energy & Economic balance is created using MS Excel and creating sensitivity analyze for each process which helped us in knowing the profit & loss at different stages and also helped to find the best scenario in each case.

Keywords: Electrolyzer, steam methane reforming, hydrogen, renewables, grid

Utilization: Designing of hydrogen production technology.

MASTER'S THESIS ASSIGNMENT

I. Personal and study details

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II. Master's thesis details

Master's thesis title in English:

Decentralized hydrogen production technology

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Decentralizovaná technologie výroba vodiku

Guidelines:

1) Prepare an overview of hydrogen production technologies (methods of H2 production, the process set up, technical maturity, PFDs, schemes, process parameters, yields, energy demand). Perform a critical technical evaluation and assess their potential for usage in a decentralized mode of operation.
2) Process a technical study of suitable hydrogen production technologies.
3) Discuss their potential using sensitivity analysis.

Bibliography / sources:

According to the recommendation of the supervisor.

Name and workplace of master's thesis supervisor:

doc. Ing. Lukáš Krátký, Ph.D., Department of Process Engineering, FME

Name and workplace of second master's thesis supervisor or consultant:

Date of master's thesis assignment: **23.04.2019** Deadline for master's thesis submission: **07.06.2019**

Assignment valid until: ______________

doc. Ing. Lukáš Krátký, Ph.D. Supervisor's signature	prof. Ing. Tomáš Jirout, Ph.D. Head of department's signature	prof. Ing. Michael Valášek, DrSc. Dean's signature

III. Assignment receipt

The student acknowledges that the master's thesis is an individual work. The student must produce his thesis without the assistance of others, with the exception of provided consultations. Within the master's thesis, the author must state the names of consultants and include a list of references.

30-04-2019	S. Venkat Subramani
Date of assignment receipt	Student's signature

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Declaration

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In Prague on 2nd august, 2019 ....

Czech Technical University in Prague Faculty of Mechanical Engineering

Citation of this thesis

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1. INTRODUCTION

The introduction of greenhouse gases into the atmosphere due to the continuous burning of fossil fuels to the increase for more energy demand for satisfying the basic needs for human development, but continuous use of the fossil fuels that poses a serious threat to the global environment because these gases which trap heat and make the planet warmer which results in increases in melting of polar ice caps and raise the sea level also extreme weather change pattern occurring throughout the world. (Nikoladis, Poullikkas, 2017)

The main causes greenhouse effect in U.S are carbon di oxide which comprises 82% of the total percentage of greenhouse gases then methane 10%, nitrous oxide 6%, fluorinated gases 3% and remaining comprises of other pollutants. This high percentage of carbon di oxide is due to the burning of coal, natural gas and oil (Overview of Greenhouse Gases, 2019)

In order to reduce the amount of carbon di oxide in the atmosphere they are various methods and practices done also the technology is constantly developing to battle these pollutants to minimum and produce energy green in every possible way but due to very vast energy demand use of non-renewable sources is unavoidable to meets the needs. So, technology that is required to capture the above-mentioned gases are CCS (Carbon Capture and Storage) and CCU (Carbon Capture and Utilization)

In CCS method which specifically stands for capture and compression of the CO_2 emitted and its transported to a storage location creating a geological formation onshore or offshore. Usually the storage options which also includes amongst other deep saline aquifers, deep coal bed methane (enhanced), combined or used in Enhanced Oil Recovery (EOR), also in depleted oil/gas reservoirs. Using different alternatives, CCS is fundamental to achieve low carbon energy goals. According several studies carried out both in Europe and USA, 13% OF CO_2 Emissions can be avoided by means of this technology (Carbon capture and storage, 2019)

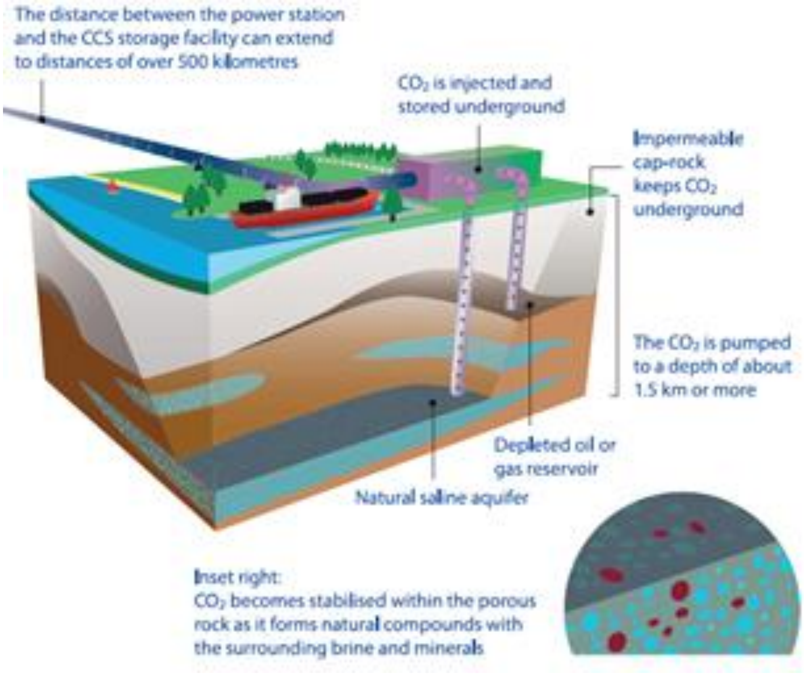


Figure 1: CCS (Carbon Capture and Storage)

1.1 Carbon Capture and Utilization

Carbon capture and utilization (CCU) stands for addition to the carbon capture storage, where the utilization of the carbon di oxide. The CO_2, as a source of carbon, has the possibility and the potential to be used in the manufacture of fuels, carbonates, polymers and chemicals. Being on development-to-demonstration phase, CCU represents a new economy for the carbon di oxide to be used as a raw material

Nowadays, the CO_2 are used in the beverage carbonation, food industry, medical applications, urea synthesis, rubber/ plastics or to mix gases/ aerosols among others (IHS CHEMICAL, 2015).

Capture, transport, CO_2 transformation and CO_2 product consumption represents the value chain of the CCU technology. (Carbon capture and utilization, 2019)

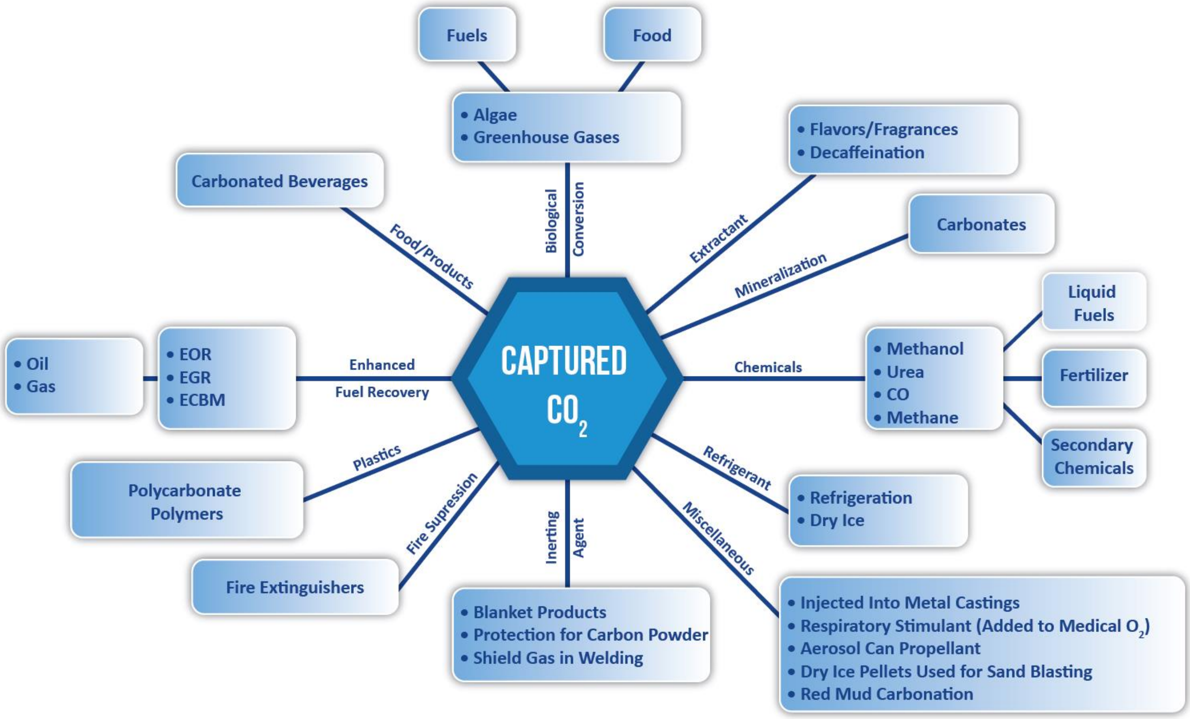


Figure 2: Classification of CO2 utilization (Carbon capture and utilization, 2019)

Converting CO_2 into methanol is considered the most important method to battle the pollutant gas into energy fuel for the energy needs

The catalytic hydrogenation of CO_2 with H_2 is considered to be the straightforward way for methanol. During the earliest methanol production plants were operated in the USA, which were using CO_2 and H_2 to produce methanol. Both heterogenous and homogenous catalysts have been studied by researchers for CO_2 hydrogenation process.

$$CO_2 + 3H_2 \leftrightarrow CH_3OH + H_2O \qquad \Delta H_{298K} = -11.9\,\frac{kcal}{mol}$$

Heterogenous catalytic conversion is the most preferred choice for chemical reaction due to the advantages of heterogenous catalysis. Even though homogenous catalysis is also used for methanol production from CO_2. In heterogenous which includes the easiest separation of fluid from the solid catalyst, convenient handling in the different types of reactors such as fixed or fluidized bed. In this method the used catalyst can be regenerated (Al-Saydeh, 2018). But in any cases the use and need of hydrogen H_2 is very essential.

1.2 Hydrogen

What is Hydrogen and why it is very essential? Hydrogen is a chemical element with the symbol H and with the atomic number 1 (smallest element in the periodic table). It consists of one proton and one electron. It is the most common element and it's just makes up staggering 75% of the mass of the entire universe. Even while the hydrogen abundant and covers the stars and other planets. In earth it is rarely available in naturally free state usually found in bonded state with other elements. For example, when with oxygen, it forms water H_2O.

Also, hydrogen is not a fuel or source of energy it's considered as an energy carrier. rather when the hydrogen burns, it reacts with the oxygen in the air to create heat. Then this heat is then used for energy.it stores energy first created elsewhere

Fortunately, there are many ways of producing hydrogen fuel but need to improve the ways that is required to produce such as using renewable and non-renewable energy sources

Hydrogen can be considered as an excellent alternate fuel because it has the following advantageous properties when compared to conventional fuels:

- Much higher calorific value (125000 kJ/kg) while being carbon free
- Exceptionally clean
- Lighter than air
- Odorless
- Non-toxic
- Safe and easy to produce
- Easy to store in large amounts
- Easily produced from many different sources

As a fuel, hydrogen has been used safely for many decades in a wide range of applications, including in the food, metal glass and chemical industries.

The global hydrogen industry is well established and produces more than 50 million tons of hydrogen per year (What is hydrogen, 2016)

2. LITERATURE RESEARCH

Hydrogen is abundantly available all over the universe, but only in sparse amounts in its natural form in Earth and is usually found to be bonded with other chemicals. Therefore, it needs to be separated from other elements in order to get pure hydrogen. Today, 95% of hydrogen is produced either from wood or from fossil fuels, such as natural gas and oil. Rest are from other renewable sources (Hydrogen Production, 2015)

Hydrogen can be produced using several different processes. But they are few major processes from which the hydrogen can be produced (Hydrogen production processes, 2019

- Thermochemical processes
- Electrolytic processes
- Direct solar water splitting processes
- Biological processes

2.1 Thermochemical Processes

In thermochemical processes which can use the energy from various resources, such as Natural gas, Coal, or biomass, to release the hydrogen from their molecular structure. List of thermochemical processes are as follows:

- Natural gas reforming
- Coal gasification
- Biomass gasification
- Biomass-derived liquid reforming
- Solar thermochemical hydrogen (STCH)

2.1.1 Natural gas reforming

Natural gas reforming is an advanced mature production process which that builds upon the existing natural gas pipeline delivery infrastructure. This process is a combination of process involving Synthesis gas, a mixture of hydrogen, carbon monoxide, and a few amounts of carbon dioxide when it is created with the help of high-temperature steam (Alternate fuel data center, 2019).

2.1.2 Coal gasification

Coal gasification is generally considered to be produced because since coal resource are generally abundant and domestically available in most of the countries worldwide it is one of the cheapest non-renewable resources and will also reduce the dependencies on the natural gas or other resource. Which is more expensive to extract and use for producing hydrogen.

Since coal is also a complex and highly variable substance which can be converted into a variety of products. In a one method which can produce power, liquid fuels, chemicals and hydrogen. Hydrogen is produced by reacting coal with oxygen and steam under high pressures and temperatures to form synthesis gas (Coal gasification, 2019).

Coal gasification reaction (unbalanced)

$$CH_{0.8} + O_2 + H_2O \rightarrow CO + CO_2 + H_2 + \text{other species}$$

2.1.3 Biomass gasification

Biomass gasification is a mature technology. Which is uses a controlled process that involves heat, steam and oxygen to convert biomass to hydrogen and other biproducts without combustion. Generally, the growing biomass removes carbon dioxide from the atmosphere, the net carbon emissions in this method can be low especially if it combined with the CCU technologies

Biomass is an organic resource which also includes the agriculture crop residues such as straw and corn Stover and specially grown crops for the energy purposes such as switch grass or willow trees. There is more biomass available than it is required for food and animal needs

Gasification process that converts organic or fossil- based carbonaceous material at high temperatures (>700°C) without combustion with a controlled amount of oxygen and steam into carbon monoxide which lets into water-gas shift reaction

Simplified example reaction for biomass gasification considering glucose as a surrogate for cellulose. Actual biomass has high variable composition (Biomass gasification, 2019)

$$C_6H_{12}O_6 + O_2 + H_2O \rightarrow CO + CO_2 + H_2 + \text{other products}$$

2.1.4 Biomass-Derived liquid reforming

Liquids derived from biomass resources which includes ethanol and bio oils can be reformed into producing hydrogen in a process like natural gas reforming and these can be transported more easily than the biomass feedstocks which allowing for semi-central production or possibly distributed hydrogen production

Biomass resource can be converted to cellulosic ethanol, bio-oils, or other liquid biofuels. Some of these liquids maybe transported at relatively low cost to produce hydrogen

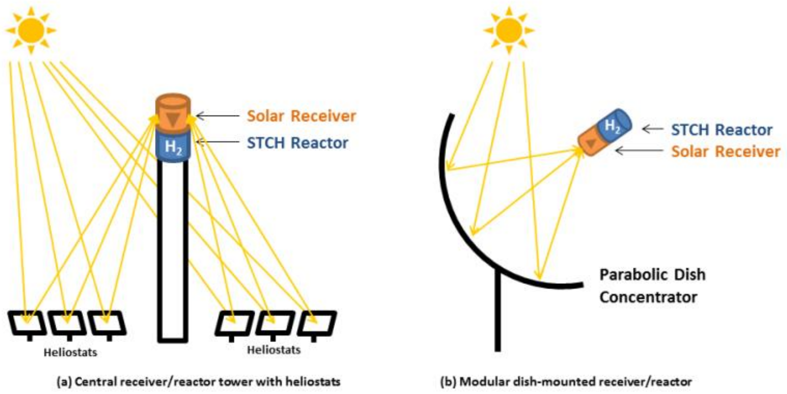
The process is similar to the previous process of using the water-gas shift reaction at the later stage but in the first stage the liquid fuel is reacted with steam at high temperatures in the presence of a catalyst to produce a reformate gas composed mostly of hydrogen and carbon monoxide (Biomass liquid reforming, 2019)

Steam reforming reaction (ethanol)

$$C_2H_5OH + H_2O\ (+\ \text{heat}) \rightarrow 2CO + 4H_2$$

2.1.5 Thermochemical water splitting

Thermochemical water splitting is a process which uses high temperature with the help from concentrated solar power or also uses the waste heat of the nuclear power in this process the main source will be water where it can able to produce the hydrogen and the oxygen and in the solar thermal energy which uses only the feedstock. Recently the nuclear reactor and solar sources have been emphasized. Nuclear power represents a high energy density that is restricted in operating temperature range because of the materials of construction needed to contain nuclear material. Solar power represents a low energy density source that can attain far higher temperatures through solar concentration (Perret Robert, 2011) Thermochemical water splitting processes use high-temperature heat (500°–2,000°C) to drive a series of chemical reactions that produce hydrogen. The chemicals used in the process are reused within each cycle, creating a closed loop that consumes only water and produces hydrogen and oxygen



(a) Central receiver/reactor tower with heliostats

(b) Modular dish-mounted receiver/reactor

Figure 3 STCH reactor (Thermochemical water splitting)

2.2 Electrolytic processes

Electrolytic processes generally uses the ion-exchange method where this process is so widely used in many production such as production of chlorine and caustic soda and mainly in the hydrogen and oxygen production usually the cell unit used in the process is composed of two electrodes separated by a cation-exchange membrane forming two compartments (Electrolytic processes, 2004).

2.3 Direct solar water splitting processes

This method directly refers to the method of photoelectrochemical (PEC) water splitting where the hydrogen is usually produced using water using sunlight and specialized semiconductors called photoelectrochemical materials, where the light energy is used. Usually the visible light has enough energy to split water into hydrogen and oxygen but fortunately the water is transparent and does not absorb this energy (Macqueen, 2019)

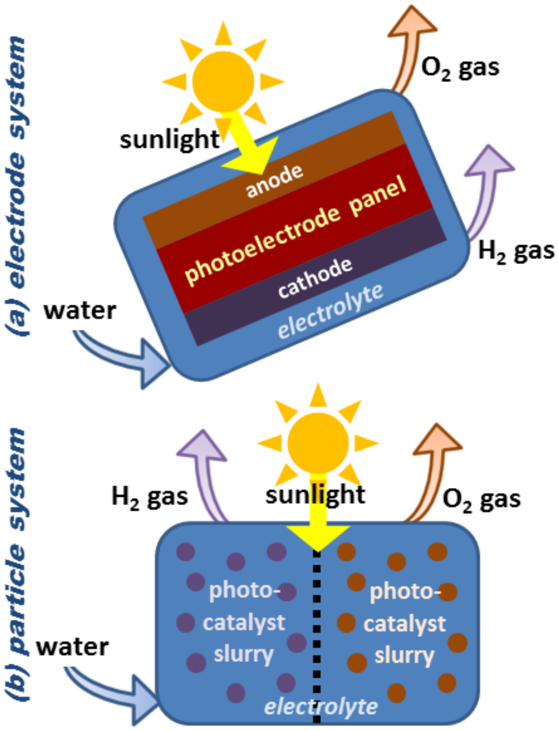


Figure 4 PEC photoelectrochemical approaches (Pec, 2019)

PEC reactors can be constructed in panel form where the application is like the photovoltaic panels as a slurry-based particle system or electrode system. To date, panel systems have been the most widely studies, owing to the similarities. Fortunately, these processes are in very early stages but offering a long-term potential for sustainable hydrogen production with low environmental impact.

2.4 Biological processes

Due to the increased attention to sustainable development and waste minimization, research in biological hydrogen production has substantially increased over the last several years. Most biological processes operate at ambient temperature and pressure. Thus, these processes are less energy intensive. Moreover, they utilize renewable energy resources which are inexhaustible, and they contribute to waste recycling as they can also use various waste materials as feedstock.

The major biological processes utilized for hydrogen gas production are direct and indirect bio photolysis, photo and dark fermentations and multistage or sequential dark and photo-fermentation. The feed for bio-hydrogen are:

water for photolysis where hydrogen is produced by some bacteria or algae directly through their hydrogenase or nitrogenase enzyme system and biomass for fermentative processes where the carbohydrate containing materials are converted to organic acids and then to hydrogen gas by using bio-processing technologies.

In direct bio-photolysis, green algae split water molecules to hydrogen ion and oxygen via photosynthesis. The generated hydrogen ions are then converted into hydrogen gas by hydrogenase enzyme. This enzyme is sensitive to oxygen and its necessary to maintain the oxygen content.

$$2H_2O + \text{light energy} \rightarrow 2H_2 + O_2$$

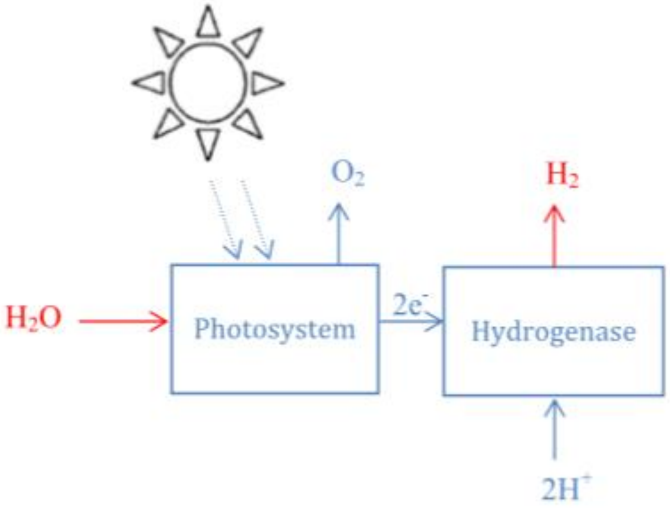


Figure 5 direct bio-photolysis process

In indirect bio-photolysis, the general reaction for hydrogen formation from water by cyanobacteria or blue-green algae can be represented as

$$12H_20 + 6CO_2 + \text{light energy} \rightarrow C_6H_6O_6 + 6CO_2$$

$$C_6H_{12}O_6 + 12H_2O + \text{light energy} \rightarrow 12H_2 + 6CO_2$$

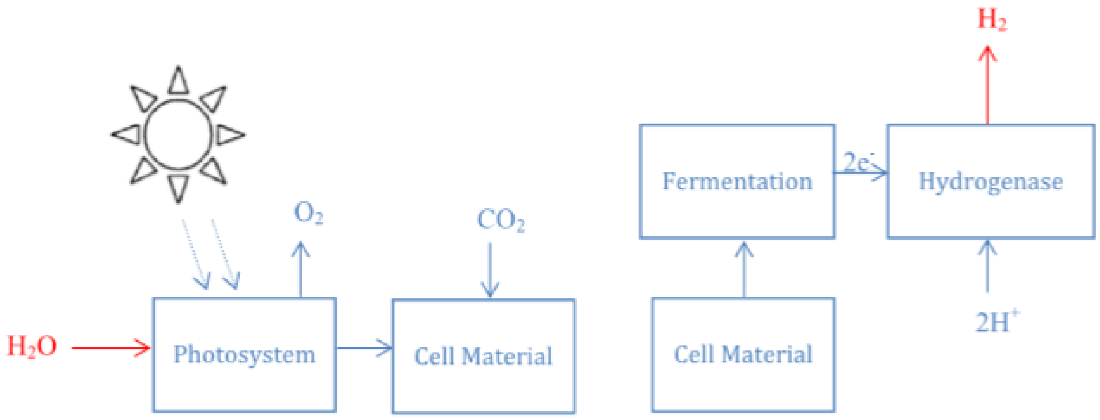


Figure 6 indirect bio-photolysis process

2.5 Types of production (quantity) methods

The type of production and usage generally depends on the type of material produced and its quantity. In this case, the production of hydrogen can be classified into:

- Distributed or Decentralized Production
- Centralized Production
- Semi-central Production

2.5.1 Distributed or Decentralized production

In this type of production where the hydrogen is usually produced in the smaller units and quantities it can be used in a small manner such as vehicle refueling stations which is also known as "Distributed Production ". This type of production maybe the most viable approach for the introducing hydrogen in the near term in part because usually the initial demand for the hydrogen is relatively low. Generally, these types are usually done for the reforming natural gas or liquid fuels and the small-scale water electrolysis.

2.5.2 Centralized production

In this type of production which defines as the name suggest it generally used for the large central hydrogen production facilities relatively (750,000 kg/day) which take advantage of the scale of economies that will be needed in the long term to meet the expected large hydrogen demand. This method of production which requires more capital investment than any other type of production also they require a detailed planning in the hydrogen transport and delivery infrastructure.

2.5.3 Semi-central production

This type of production usually falls between the quantity of (5,000-50,000 kg/day). These types of production unit are placed in the proximity to the point of use. These facilities can minimize hydrogen transport costs and infrastructure (Central vs distributed production, 2019).

2.6 Market Research

According to the report from the Market study, the hydrogen market is growing at the global level and anticipated that the growth at this rate will reach a significant value by the end of the year of assessment. During the 2012-2016 timeline, the hydrogen market has experienced steady growth. The CAGR (Compound Annual Growth Rate) of 6.1% throughout the period of assessment to reach a market value of more than US$ 200 Bn by the end of 2025 from the market valuation of about US$ 130 Bn in 2017. Hydrogen (H2) is a vital carrier of energy which can support the future requirement for clean energy across the globe. The factors that support the growth of the hydrogen market include increasing preference for onsite generation systems, increasing technological developments, also increasing the use of hydrogen across various industry verticals and introduction of green production technologies (Global Market Study, 2018).

2.6.1 Asia-Pacific

In the region of Asia Pacific is expected to be the largest with high market attractiveness. This region is characterized by high demand for hydrogen-based fuel vehicles in the countries such as Japan. The automotive manufacturers are planning to establish auto fueling stations in the region. These aspects are pushing the growth of the hydrogen market in the Asia Pacific. They hold more than one-third of the total market share in the coming years. In 2017, it was about US$35 Bn and it is estimated that to touch a valuation of more than US$70 BN by the end of the year (Global Market Study, 2018).

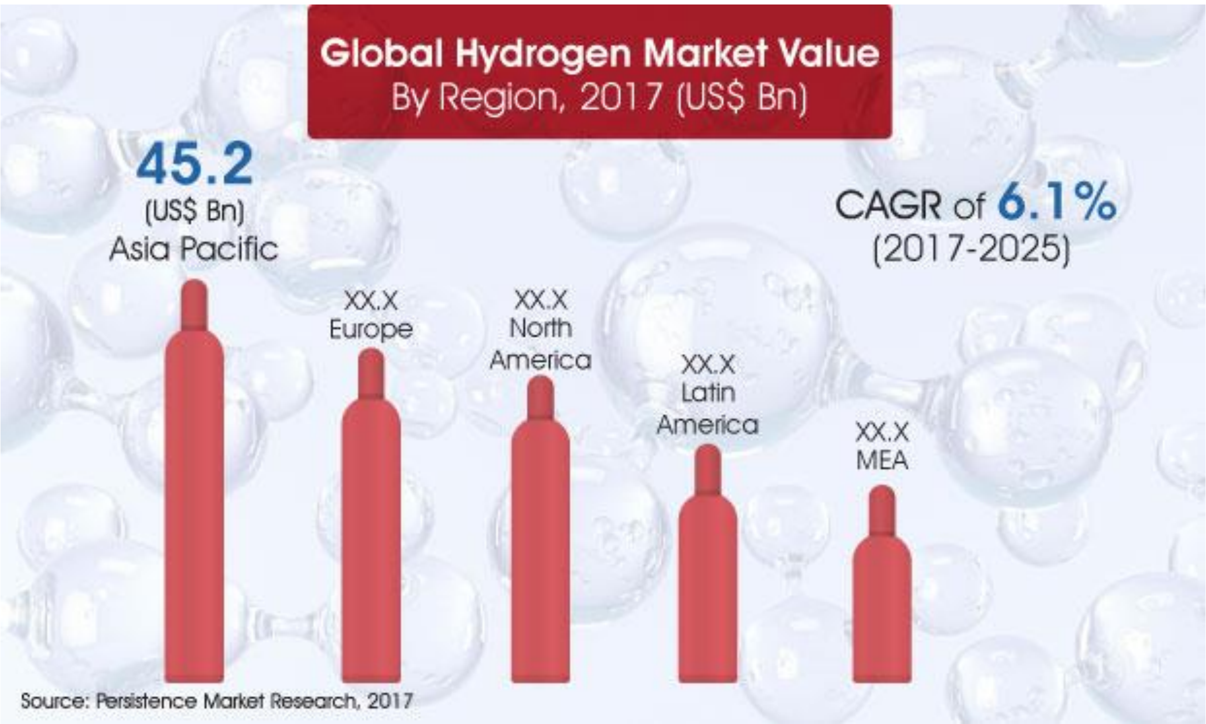


Figure 7: Hydrogen market value in Asia-Pacific (Global Market Study, 2018)

2.6.2 Europe

The hydrogen market in Europe is the second largest. The increasing adoption of hydrogen across various industries in Europe has presented potential opportunities for the growth of the global market. The hydrogen market is projected to grow at CAGR of 6.4% throughout the period of assessment (Global Market Study, 2018).

In order to use the Hydrogen as much as possible in many sectors such as power production, fuel, building heating and many other. The Europe's demand for the hydrogen will increase sevenfold, from 325 TWh in 2015 to 2,250 TWh in 2050. For this ambitious scenario an investment of roughly EUR 60 billion would be required by 2030. This fund includes both investments in infrastructure, as well as investments into R&D (Hydrogen roadmap, 2019).

3. OBJECTIVES

The main aim of the thesis is to set up few technologies in producing the hydrogen in decentralized methods which will be used in CCU technologies and comparing the results of each decentralized method and also having a detailed study of mass, energy balances and economic analysis

3.1 General objectives

- To design and analysis few decentralized hydrogens with full energy and economy balance the processes are:
- Hydrogen production by electrolyzer using renewable energy
- Hydrogen production by electrolyzer using grid energy
- Hydrogen production by methane steam reforming

3.2 Specific objectives

- To review the above-mentioned hydrogen production processes with working principle
- To make a literature research of process flow diagram of each mentioned processes
- To make using the flow diagram, an excel file of mass and energy balances for each process
- To perform the economical calculation such as detailed information on the Fixed Capital Investment, operating cost and cash flow of these processes
- To perform sensitivity analysis based on their economical balance
- To compare the all three processes utilization and most economical point of view

4. HYDROGEN PRODUCTION BY ELECTROLYSER USING RENEWABLE ENERGY

In this process of producing hydrogen it uses the modern technology to produce and it's a simple and easier process to produce than any other available process to create hydrogen this process uses the electrolytic processes from our literature research and here the detailed study will be discussed. The main technology here is water electrolyzer.

FLOWSHEET DIAGRAM

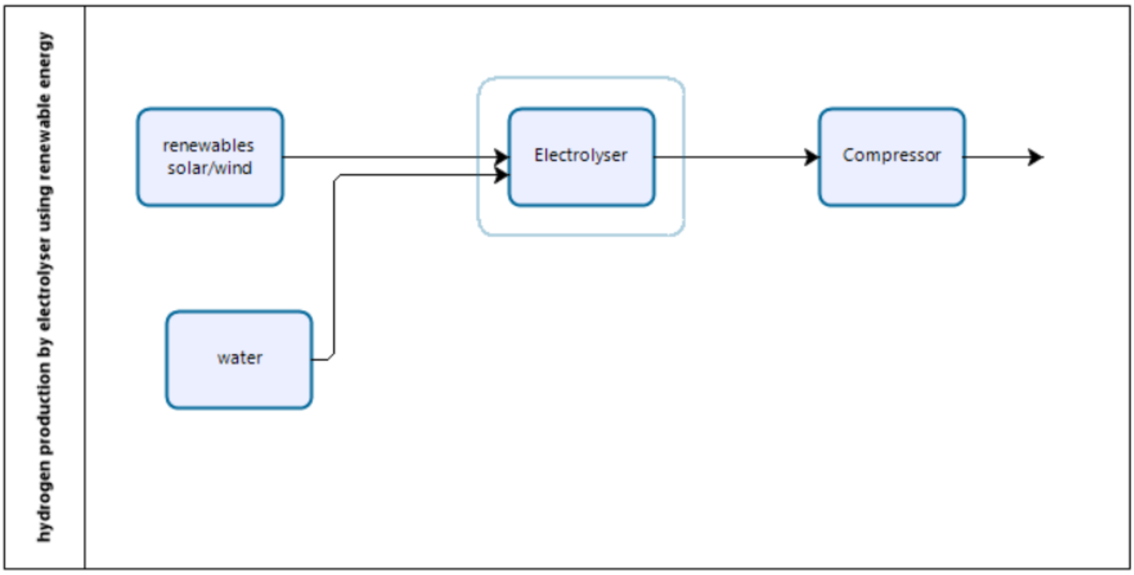
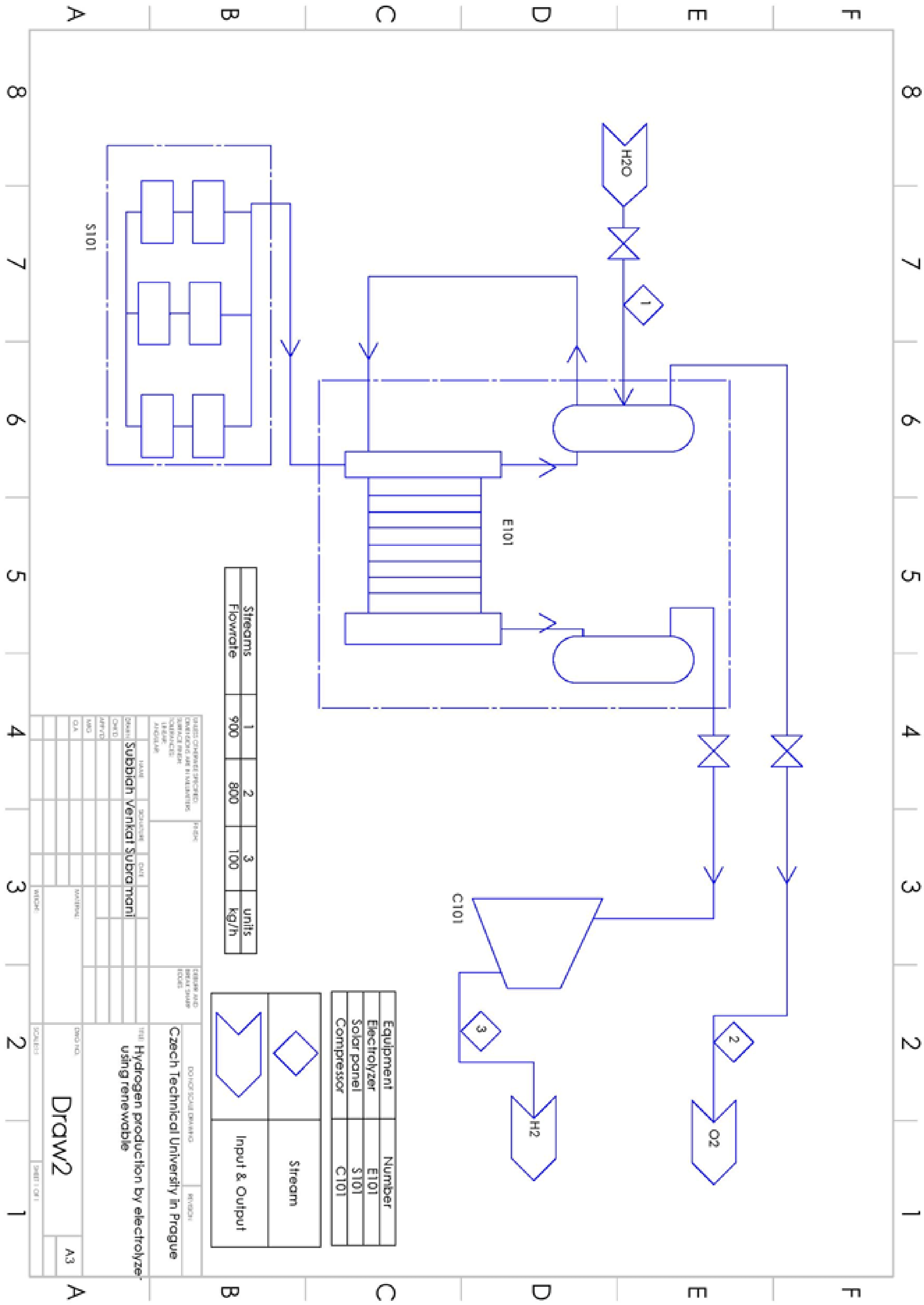


Figure 8 Flowsheet diagram for hydrogen production by electrolyzer (Renewable energy)



Streams	1	2	3	units
Flowrate	900	800	100	kg/h

Equipment	Number
Electrolyzer	E101
Solar panel	S101
Compressor	C101

Figure 9 PFD (renewable) by author

This process consists of few main components

- Solar Panels
- Electrolyzer
- Compressor

SOLAR PANEL

The Sun which is a producing a constant renewable source of energy in the form of light without any environmental pollution and noise. To make use of this abundant energy source these solar cells are presented in many categories and with different generation.

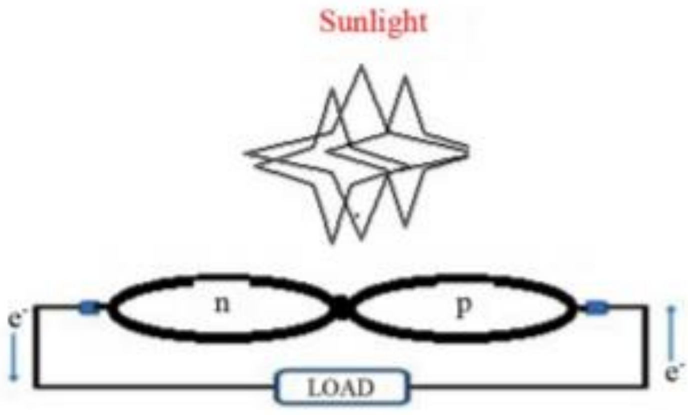


Figure 10 semiconductor p-n junction solar cell under load

There are totally three generation of solar cells available such as first, second & third and in the first generation which is oldest and the most popular technologies due to high power efficiencies. the first generation are divided into two subgroups such as Mono-crystalline silicon solar cell and Multi-crystalline silicon solar cell and similarly in the other two generation which is based on the thin film technology and emerging technologies such as Nano crystal, Polymer and Concentrated solar cells.

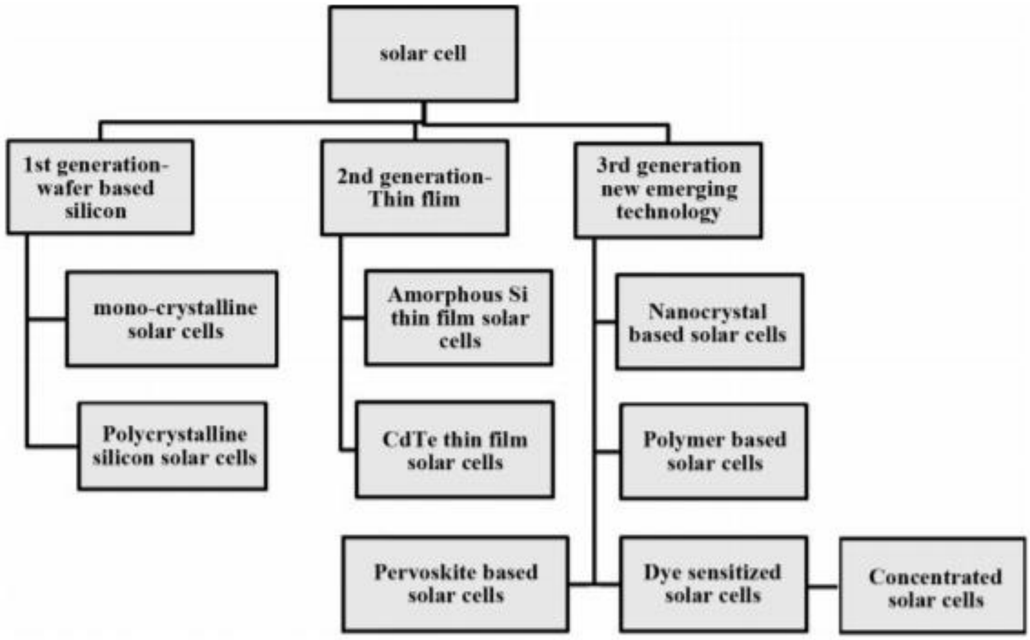


Figure 11 types of Solar cells (SHARMA, 2018)

For our current objectives we will be using the Polycrystalline/Multi-crystalline silicon panel as a source of renewable power to the electrolyzer.

ELECTROLYZER

To date the only few types of electrolyzer available in the market such as Solid Oxide Electrolysis cells (SOEC), Alkaline Electrolysis Cells (AEC) and Proton Exchange Membrane (PEM)

AEC is the most incumbent water electrolysis. Technology and theses are used widely for the centralized methods of producing hydrogen and in the industrial since early 1930s. These alkaline electrolyzer are readily available and durable with low capital cost because due to absence of noble metals and with relatively mature stack Components. However, the AEC have the low current density and the operating pressure negatively impact the system size and also the hydrogen production costs.

PEMEC or PEM these systems which are based on the solid polymer electrolyte these systems are generally created to overcome the drawbacks of the AEC and the PEM systems are generally used for small-scale applications such as for decentralized methods of producing hydrogen. Main advantages of PEM are high power density and much improved cell efficiency and provision for the pure and highly compressed hydrogen and also it has flexible operations. Using expensive catalyst, fluorinated membrane, and shorter lifetime are the disadvantages.

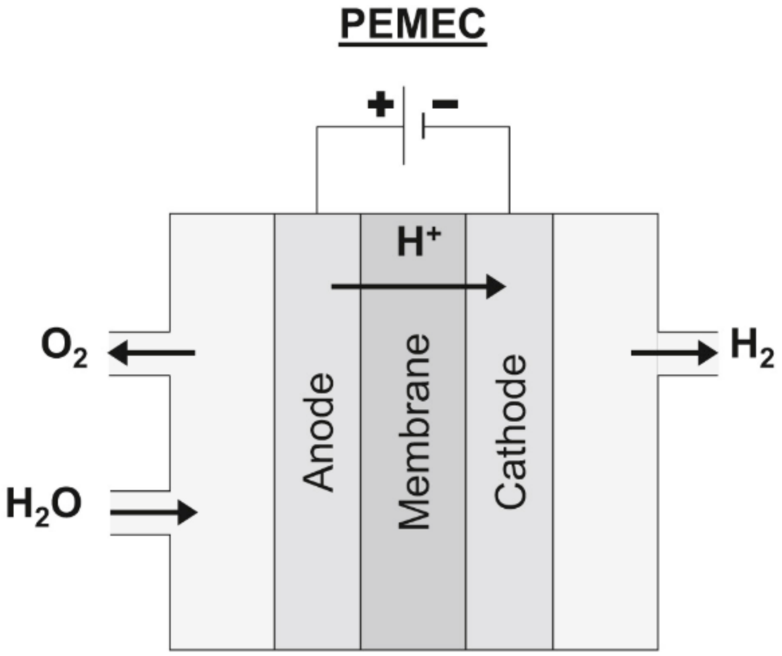


Figure 12 PEM

But to produce hydrogen in a decentralized or short scale application PEM will be the right choice to induct in the system because of their compact design and H_2-O_2 produced separately in different chambers.

4.1 Mass balance

We are going to create and build a hydrogen production using electrolyzer generating 100 kg/h. this is a simple mass balance where we need to find just the amount of water (inlet). So, with the help of Microsoft Excel I was able to derive the desired results

The chemical reaction which takes place inside the electrolyzer:

2H2O = 2H2 + O2

	Comp.	**Mols**	**Mass**
1	**H_2**	2	4
2	**O_2**	1	32
3	**H_2O**	-2	36

Table 1 Stochiometric coefficients – Electrolyzer

The table 1 shows us the amount of mols & mass number which are required in the reaction

Stream	**Kg/h**
Water (inlet)	900
Oxygen (outlet)	800
Hydrogen (outlet)	100

Table 2 Mass flow rates - Electrolyzer

The table 2 shows us the mass flow rates that will be flowing in & out of the electrolyzer. Where water is the only inlet which flows so 900kg/h of water in required and outlet is 800 kg/h and hydrogen is around is 100 kg/h. the efficiency of the electrolyser is considered as 100% since there is no additional material added in the process so even the left out excess water can be used for the process once again.

4.2 Capital cost

The capital cost is an important and essential concept in the final decision making. The capital cost is the cost usually given by the investors in order to start the project in our situation our investor will be bank where they invest in our project. While designing the capital cost every factor must be considered such as risk and contingencies, we need even include the direct and indirect cost which might affect the production plant.

Capital cost = total Purchased equipment cost (TPEC) + total installed cost (TIC) & total indirect cost

TOTAL PURCHASED EQUIPMENT COST

In this analysis of the TPEC we must be calculate the main required equipment which will be used in the process. So, such as solar panels, electrolyzer & compressor. The prices of the required equipment were taken with greater approximation from the internet.

As table 3 declares total purchased equipment costs are 1 685 000 dollars.

Equipment	**USD**
solar panels	1,500,000
electrolyser	125,000
compressor	60,000
Total	1,685,000

Table 3 Renewable - Total purchased equipment costs

TOTAL INSTALLED COST (TIC)

In this analysis of total installed cost where the cost of services after purchasing equipment and installation of the equipment & piping that will be required and for the building office use. Setting up the Instruments and controls for the installed equipment's and electrical systems even the purchase area for land where the entire process will be set up.

Total installed costs for producing hydrogen by renewable energy are 2 780 250 dollars.

Costs	USD	% of TPEC
Purchased equipment installation	168,500	10% of TPEC
Piping	252,750	15% of TPEC
Instrumentation and controls	252,750	15% of TPEC
Electrical systems	168,500	10% of TPEC
Land	1,516,500	90% of TPEC
Buildings (including services)	421,250	25% of TPEC

Total Installed Cost (TIC)	2,780,250

Table 4 Renewable - Total installed costs

TOTAL INDIRECT COST

In this analysis of total indirect cost where we calculate the cost of engineering, cost of constructing the plant and calculating the legal and contractor fess also employees hiring total cost. The most important cost for any project is having the contingency cost which is also added to the indirect cost. All indirect costs are described in table 5.

In this case are total indirect costs 1 263 750 dollars.

Costs	USD	% of TPEC
Engineering	252,750	15% of tpec
Construction	421,250	25% of tpec
Legal and contactor fees	168,500	10% of tpec
Employess total costs	168,500	10% of tpec
Project contigency	252,750	15% of tpec

Total Indirect Cost	1,263,750

Table 5 Renewable - Total indirect costs

4.3 Energy balance

The Energy balance is one of the important parts for designing any Industries even Hydrogen Production in this. In the Hydrogen production using electrolyzer finding the amount of Energy required for the process. In order to calculate we need to know the Mass flow rate, temperature that is used in the process and Specific heat of the Material flowing

ELECTROLYZER

It is the important part of the process where the main process of converting water into hydrogen occurs. The Average power consumption are taken from the online sources (Nel, 2019) to calculate the required power in electrolyzer.

Parameter	Value	Unit
Mass	100	kg
V1	1,416.48	m3
V2	1,210.04	Nm3 /h
Average Power Consumption	4.53	kWh/Nm3
Total required power	5,481.48	kWh
	5.50	MWh

Table 6 Renewable -Energy Balance - Electrolyzer

COMPRESSOR

In this process the compressor is required to compress the hydrogen from 8bar to 30 bars. The compressor is calculated using the online simulator (Checalc, 2015).

Parameter	Value	Unit
T1	100	C
P1	30.00	Bar
P2	50.00	Bar

Flowrate	1,210.04	Nm3/h
Polytropic efficiency	80.00	%
Accentric factor	-0.22	
Total power	**32.00**	**kW**

Table 7 Compressor energy balance

4.4 Economic balance

OPERATING COST

Operating cost is major task for the process since this cost make a process profitable or loss. So operating cost are carefully considered the major portion of the operating cost is buying of raw materials for the process. In our case of hydrogen production by electrolyzer using Renewable sources the main raw material will be water for the electrolyzer to convert into hydrogen. Using Mass Balance, we found out that to produce one kilogram of hydrogen we require nine kilograms of water.

Parameter	Value	Unit
Production of hydrogen	320	tons/year
Cost of compressor work	22,528	$/year
Required water per ton of H2	9	cu.m
Required water	2,880	cubic meter/year
Cost of water per cubic metre	2.17	$/cubic metre
Costs of water per year production	6,260.87	$/year
Operational cost	**28,788.87**	**$/year**

Table 8 Renewable - Operational costs

Also Operating cost (raw materials) is just one calculation in the "All cost" where we need to include the corporate cost which includes all kinds of cost such as laboratory, R&D and personal Cost. And in personal cost entire team of Direction, sales, marketing, accounting is included and then the Indirect operating cost is also considered such as Insurance, Consumable, Reserve and Maintenance cost and finally Distributional cost & Financial cost.

Costs for whole project with parameters are described in table 9. The project is financed by bank loan and it is forecasted for 15 years. Costs for that are in financial costs. Bank interests is calculated as 6.5% per year also I am calculating with owner's profitability what need for Cash Flow calculating is. That is giving overall picture about whole project.

All these expenses with each value are described on table 10. In this table is also visible total expenses and revenues in production hydrogen by renewable energy through one year. Table contains all kind of earnings which are explained under table – in next section.

Parameter	**Unit**	**Values**
Annaul production of hydrogen(in tonnes)	ton	320
Selling price of hydrogen	$/ton	15,000
Fix capital investment (CAPEX)	$	5,729,000
Total purchased equipment cost (TPEC)	$	1,685,000
Total installed cost (TIC)	$	2,780,250
Total indirect cost	$	1,263,750
Construction time - investment time	year	1
Life of the unit (= operating time)	year	15
Bank credit (bank loan)	$	5,729,000
The period of interest rate	year	15
Interest rate of the bank credit	%	6.5
Annuity	$	609,295
Bank draft overall	$	8,530,131
Interest rate	%	6.5
Owners profitability rate	%	5
Total asset depreciaton for year	$	176,925
Asset depreciation(for industrials) for year	$	64,592
Asset depreciation (for equipments) for year	$	112,333
Income tax	%	19

Table 9 Renewable – Project parameters

Parameter	**Unit**	**Variant B**
Proceeds from the sale of hydrogen (revenue from sales)	$/year	4,800,000
All costs	$/year	3,007,917
Direct operating costs	$/year	28,789
Raw materials	$/year	28,789
Corporate costs	$/year	1,100,000
Personal costs - Direction, sales, marketing, accounting	$/year	900,000
Laboratory	$/year	102,000
R&D	$/year	90,000
Electricity and water	$/year	8,000
Indirect operating costs	$/year	1,324,140
Personal costs – operation	$/year	680,400
Maintenance costs	$/year	326,400
Supervision	$/year	102,060.0
Consumables	$/year	65,280
Insurance	$/year	50,000
Reserve	$/year	100,000
Distributional costs	$/year	5,678.0
Transport	$/year	5,678.0
Financial cost	$/year	549,310
Interests costs	$/year	372,385
Assets depreciations	$/year	176,925
Earnings before Interest, Taxes, Depreciations and amortization Charges (EBITDA)	$/year	2,341,393
Earnings before Interest and Taxes (EBIT)	$/year	2,164,468
Earnings before Taxes (EBT)	$/year	1,792,083
Taxes (19%)	$/year	340,496
Earnings after Taxes (EAT)	$/year	1,451,587

Table 10 Renewable - Expenses and revenues

EBITDA

EBITDA is known as Earnings Before Interest, Taxes, Depreciation and Amortization it is a measure of overall company's Financial performance where it is used as an alternative to simple earning or net income the EBITDA for our process is around $ 2,341,393 per year (EBITDA,2019).

EBIT

EBIT is known as Earnings Before Interest and taxes. It's generally a measure of the company earning power through ongoing operations, equal to earnings before deduction of interest payments and it excludes the Depreciation and amortization activities also known as Operating profit (EBIT,2019). In our process of hydrogen production by electrolyzer using renewable it is $ 2,164,468 per year.

EBT

EBT is known as Earnings before Tax usually it is defined as the money which is retained by the company before removing or deducting the money due to be paid in as taxes. Operating and non-operating profits of a company before taxes are generally considered and these things quantify as EBT and also it holds the important significance for the Investment analyst to calculate and evaluate the performance of the entity. In our process of hydrogen production, the EBT is around $1,792,083 per year

EAT

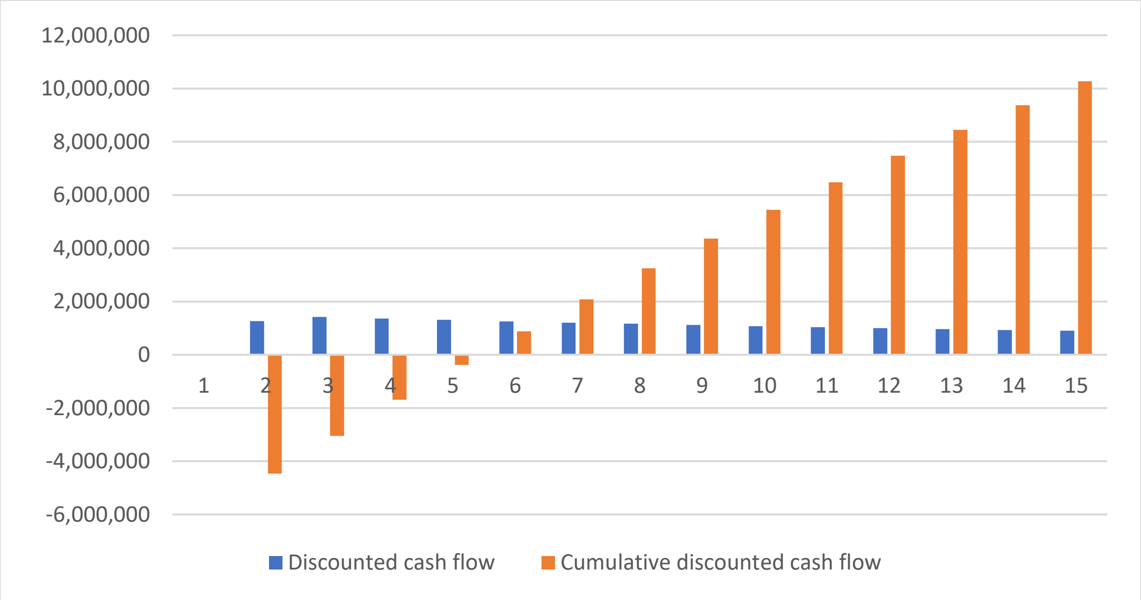
EAT is known as Earnings after Tax as the name suggest the earnings are calculated after the taxation it generally available for the distribution between the owners and the company (EAT,2019) EAT is also known as financial statement for an accounting period. In our process the EAT is calculated as $ 1,451,587.

The detailed definition of each parameter and also carried out information are included in the appendix section.

From the above table we can notice that the direct operating cost is less than the other cost because since in our process the raw material is which is used is just water. So, the cost of water in Czech Republic is around $ 2.17 per cubic meter and the cost of water for the office and building is not calculated in this Direct operating cost.

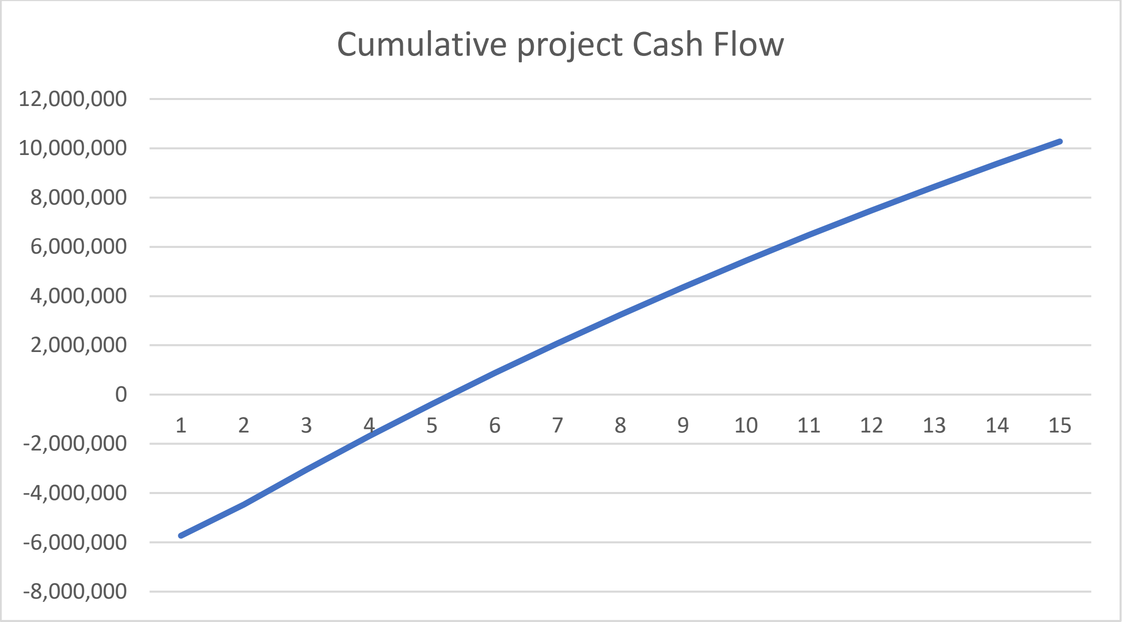
In investment assessment we considered indicators as cash flow, discounted cash flow (which calculate market risk and consider year period), payback period, net present value and Internal rate of return.

Discounted and cumulative discounted cashflow in years of project describes graph 1. It is visible that in sixth year of project we start making a profit. Which we are declaring also by calculating payback period which is also 6 years. Cashflow is calculated as EAT – amortization (bank loan part) + assets depreciations (because it is cost but not expense). Then is cashflow discounted by 5% rate.



Graph 1 Renewable - Discounted and Cumulative discounted cashflow

In graph 2 we can closely see when the project will start to make profit. Somewhere in half of the fifth year the project will be profitable. The trend describes the profit through 15 years.



Graph 2 Renewable - Payback period - Cumulative cash flow

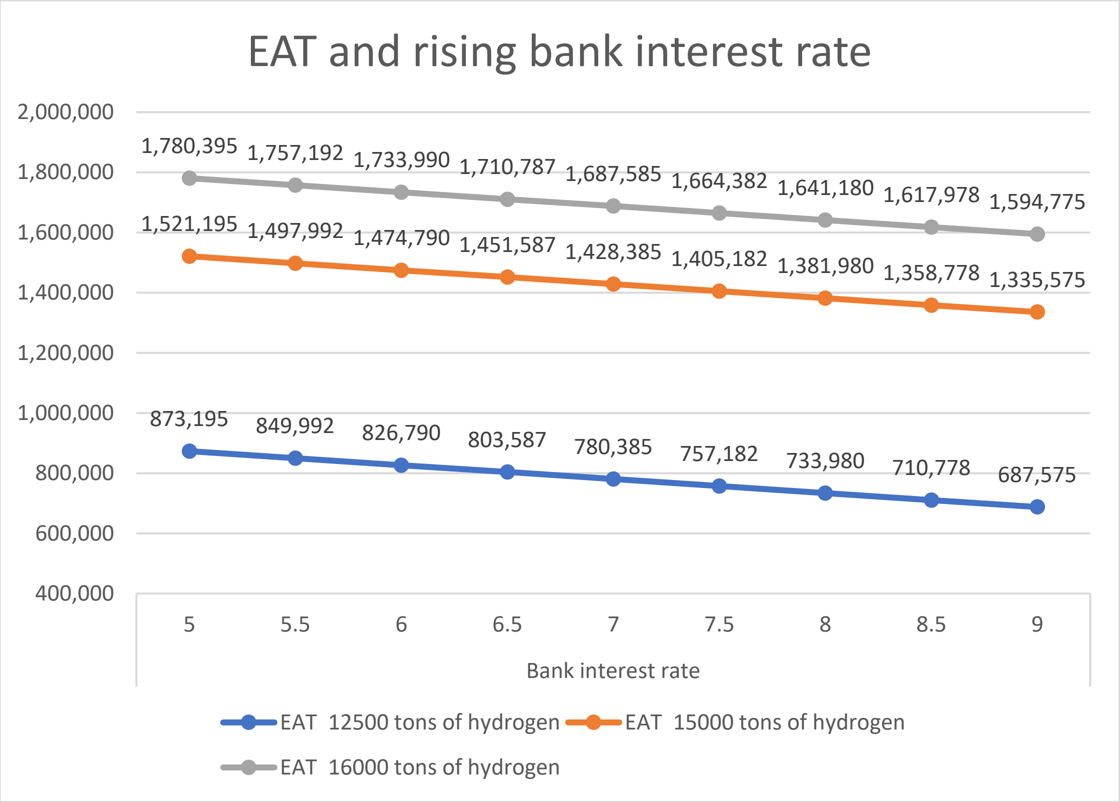
Overall in those above two graphs the payback period and the cumulative cash flow it is considered with 5% discount also it's known as owner's profitability rate. According to our calculation this amount of years it requires to reach the profitability stage is 5-6 years but when the discount rate will be increased the number of years to profits will decreases and in all our cases we have only considered only 15 years since the electrolyzer is a sensitive machine and the effectiveness gradually decreases over years.

Expected net present value (NPV) of project is 10 448 012 USD which declares that project will be profitable because it is more than 0. And so, it is convenient for investors.

IRR is calculated 28%.

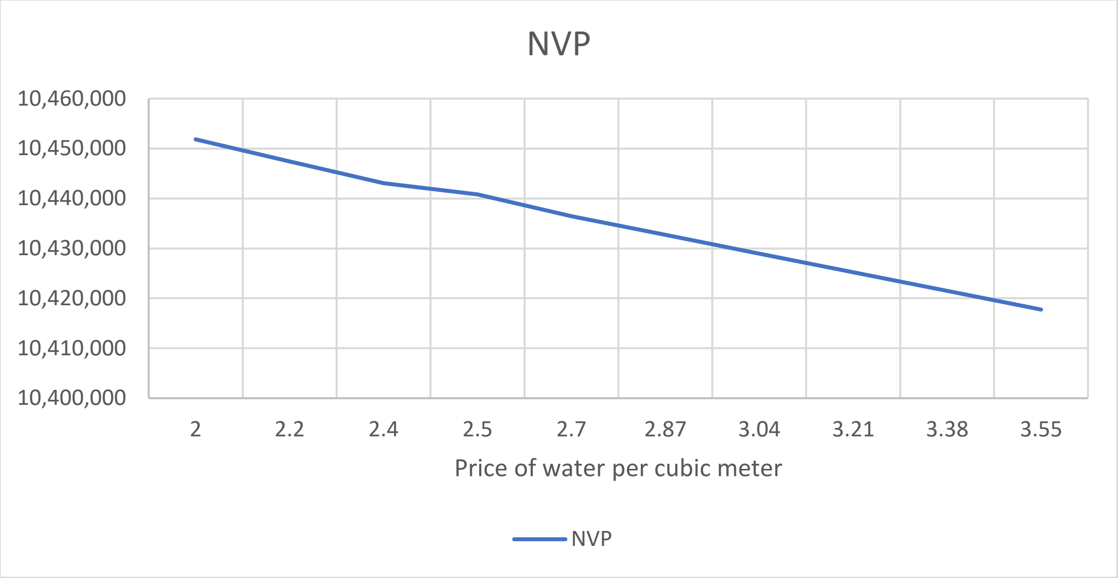
4.5 Sensitivity analysis

Sensitivity analysis represents tool which is used for seeing alternatives what can happen during project realization. It shows how sensitive is one parameter on others. For this case were chosen as parameters bank interest rate and selling price of hydrogen on EAT.



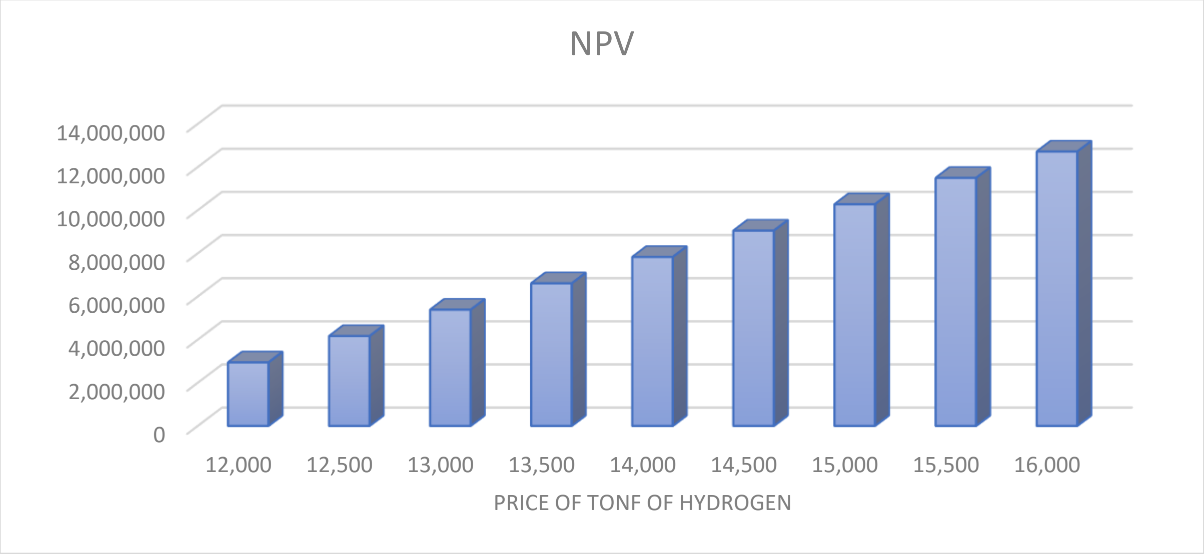
Graph 3 Renewable - Analysis for EAT and rising bank interest rate

In this above table which shows the sensitivity of the price of EAT on the interest rate by the price of hydrogen (in tons) graph 3 shows the detailed line graph for every $ 1000 change in the price of hydrogen the graph also indicates the gradual decrease of earnings when there is an increase in the rate of bank interest. Graph 3 describes 3 cases – ton of hydrogen will be selling for 12 500, 15 000 and 16 000 dollars.



Graph 4 Renewable - NPV and rising price of water

This above analysis is the comparison of the Net present value to the price of the water we considered $2.17 per cubic meter of water. In this graph we analyzed that when there is increase in cost of water the Net present value decreases gradually. Also, it is also visible that even if the price of water rises for more than one dollar per cubic meter the NPV will be till convenient for investors.



Graph 5 Renewable - EAT and rising price of Hydrogen

This above chart is the comparison of earning after taxes to the price per ton of hydrogen while checking for every increase of $500 dollars in price per ton there is significant increase in the EAT. Obviously, it increases when we will be selling hydrogen for higher price. This analysis was made for seeing the trend, in case of selling on ton of hydrogen for 1000 more expensive the EAT will be more than 1, 6 million USD.

5. HYDROGEN PRODUCTION BY ELECTROLYSER USING GRID

In this Hydrogen production process using grid is the same process as in using hydrogen production by electrolyzer using renewable energy source all the working & energy will be same. Except only change is using the grid as the source of energy the main reason for considering grid as separate entity or process is the cost of buying the solar panels which is not required here. But also consuming the power of grid so there will be significant increase in the operating costs of production.

In this given process of using grid we are not calculating the Mass & Energy balance due to using the same process only Economic balance is considered and the Sensitivity Analysis for this process.

FLOWSHEET DIAGRAM

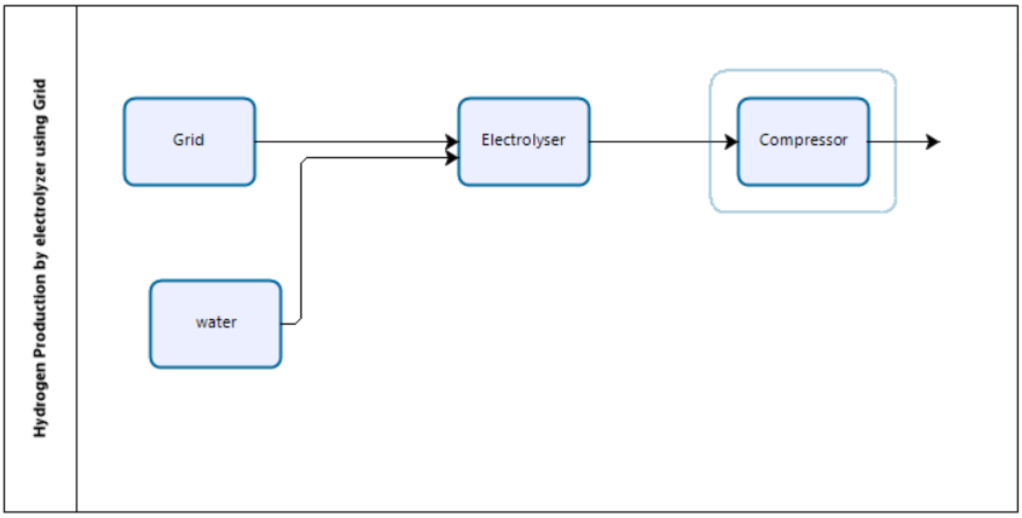


Figure 13 Flowsheet diagram for hydrogen production by electrolyzer (Grid energy)

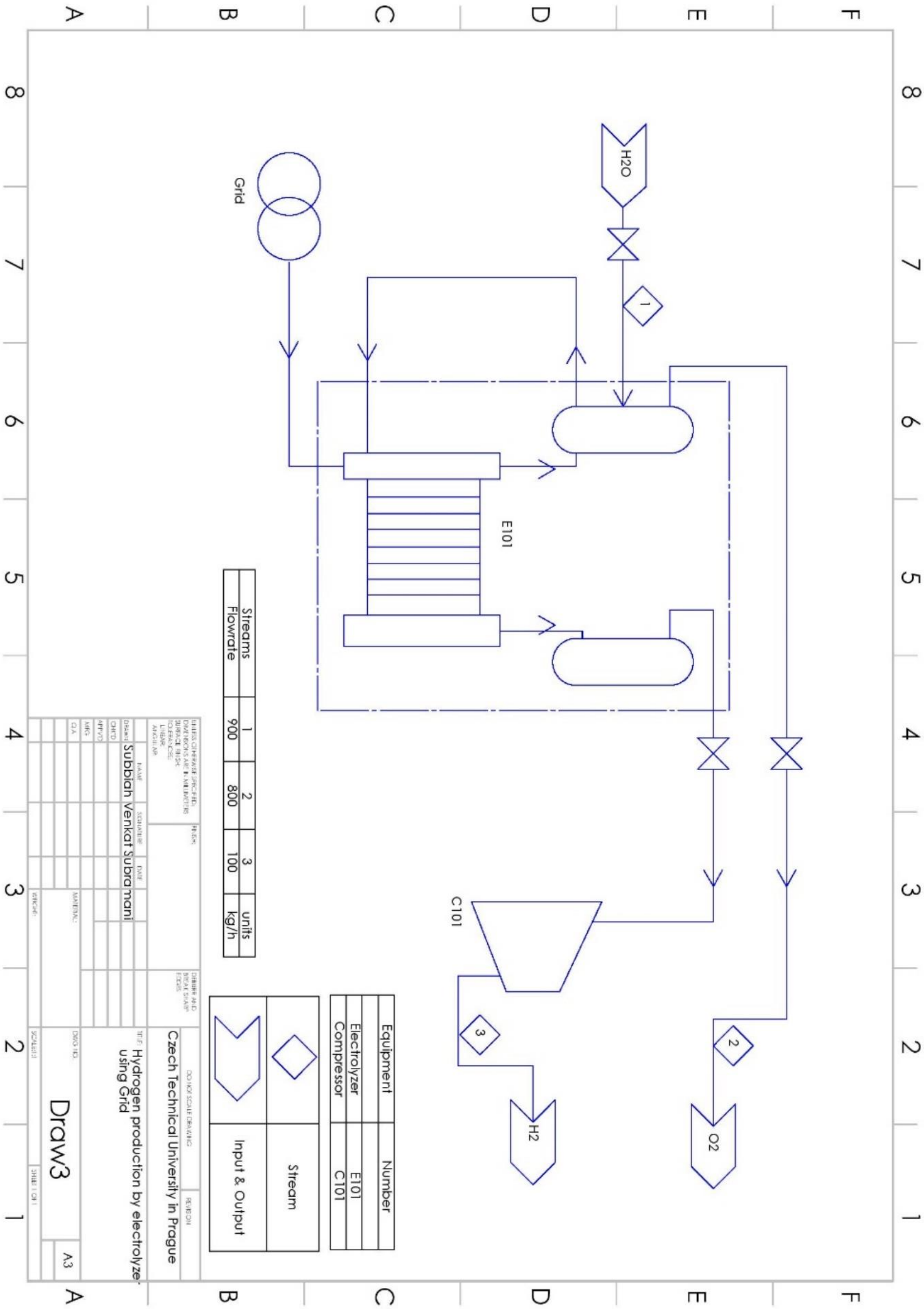


Figure 14 PFD (Grid) by author

5.1 Capital cost

In this process since the absence of using the Solar panels there will be a significant change in the cost of total purchased equipment but the other cost such as the total Installed cost and the total Indirect cost does not change and remains same as the preceding process even the cost of installation remains the same.

Equipment	USD
electrolyser	125,000
compressor	60,000
Total	185,000

Table 11 Grid - Total purchased equipment costs

TOTAL INSTALLED and TOTAL INDIECT COSTS

These costs are almost same as in case of producing hydrogen by renewable energy. They changed just in case of decreasing equipment costs. Changed values represents tables 12 and 13.

Parameter	USD	% of TPEC
Purchased equipment installation	18,500	**10% of tpec**
Piping	27,750	**15% of tpec**
Instrumentation and controls	27,750	**15% of tpec**
Electrical systems	18,500	**10% of tpec**
Land	166,500	**90% of tpec**
Buildings (including services)	46,250	**25% of tpec**

Total installed cost (TIC)		**305,250**

Table 12 Grid - Total installed costs

Parameter	USD	% of TPEC
Engineering	27,750	**15% of tpec**
Construction	46,250	**25% of tpec**
Legal and contactor fees	18,500	**10% of tpec**
Employess total costs	18,500	**10% of tpec**
Project contigency	27,750	**15% of tpec**

Total indirect cost	**138,750**

Table 13 Grid - Total indirect costs

5.2 Economic balance

OPERATING COST

In this process the operating cost will be the important factor as the use of grid power is used here than solar energy. The electricity cost in Czech Republic per kWh is around $ 0.22 and since there is lot of energy required for the use of electricity in the electrolyzer which is around 5 481 kWh

Parameter	Value	Unit
Production of hydrogen	320	tons/year
Cost of compressor work	22,528	$/year
Required water per ton of H2	9	cu.m
Required water	2,880	cubic meter/year
Cost of water per cubic metre	2.17	$/cubic metre
Costs of water per year production	6,260.87	$/year
Required electricity	5481,48	kWh
Cost of electricity per one ton of H2	12,059.00	$
Costs of electricity per year production	385,896.28	$/year
Operational cost	**414,673.88**	**$/year**

Table 14 Grid - Operational costs

This table 14 shows the clear increase in the cost the total operating cost for electrolyzer using grid is $ 414 673.

Parameters for project is almost same as in previous case. What is different is only bank loan as in this case we need less investment. So, in bank parameters we can see differences. Closer it is described in table 15. Then whole expenses and revenue with all kind of earnings for hydrogen production by using grid energy is in table 16.

Parameter	**Unit**	**Value**
Annaul production of hydrogen(in tonnes)	ton	320
Selling price of hydrogen	$/ton	15,000
Fix capital investment (*CAPEX*)	$	629,000
Total purchased equipment cost (TPEC)	$	185,000
Total installed cost (TIC)	$	305,250
Total indirect cost	$	138,750
Construction time - investment time	year	1
The percentage of capital investments made in the first year	%	110
Life of the unit (= operating time)	year	15
Bank credit (bank loan)	$	629,000
The period of interest rate	year	15
Interest rate of the bank credit	%	6.5
Annuity	$	66,896
Bank draft overall	$	936,543
Interest rate	%	6.5
Owners profitability rate	%	5
Total asset depreciaton for year	$	19,425
asset depreciation(for industrials) for year	$	7,092
asset depreciation (for equipments) for year	$	12,333
Income tax	%	19

Table 15 Grid - Project parameters

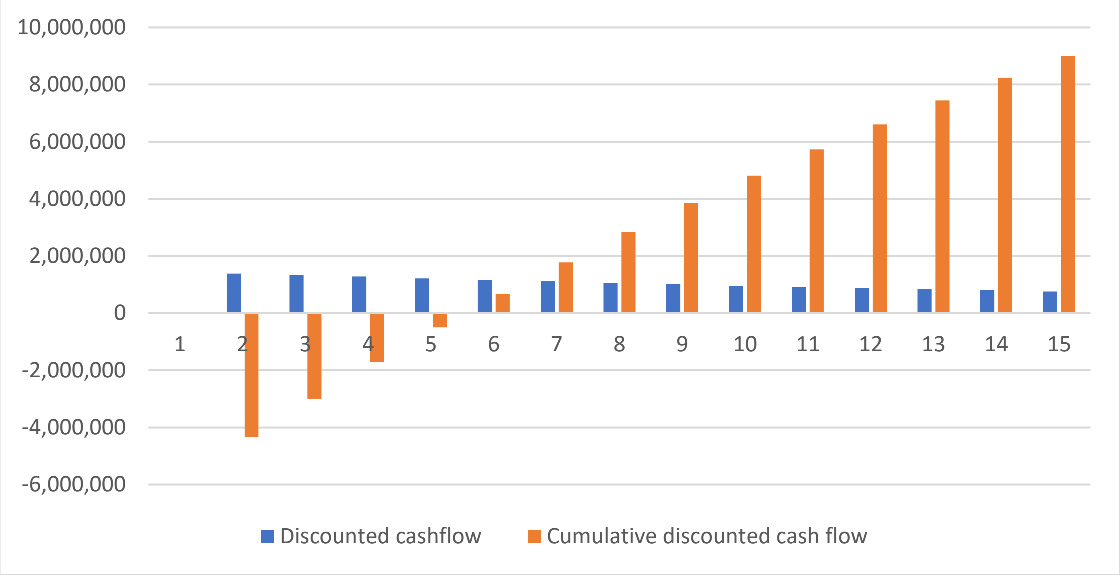
The below table have used the parameters to calculate the cost and the revenues. Due to higher operating cost you clearly notice the greater decrease in all of the EBITDA, EAT & other categories of revenue streams.

Parameter	**Unit**	**Value**
Proceeds from the sale of hydrogen(revenue from sales)	$/year	4,800,000
All costs	$/year	2,904,802
Direct operating costs	$/year	414,674
Raw materials	$/year	414,674
Corporate costs	$/year	1,100,000
Personal costs - Direction, sales, marketing, accounting	$/year	900,000
Laboratory	$/year	102,000
R&D	$/year	90,000
Electricity and water	$/year	8,000
Indirect operating costs	$/year	1,324,140
Personal costs – operation	$/year	680,400
Maintenance costs	$/year	326,400
Supervision	$/year	102,060.0
Consumables	$/year	65,280
Insurance	$/year	50,000
Reserve	$/year	100,000
Distributional costs	$/year	5,678.0
Transport	$/year	5,678.0
Financial cost	$/year	60,310
Interests costs	$/year	40,885
Assets depreciations	$/year	19,425
Earnings before Interest, Taxes, Depreciations and amortization Charges (EBITDA)	$/year	1,955,508
Earnings before Interest and Taxes (EBIT)	$/year	1,936,083
Earnings before Taxes (EBT)	$/year	1,895,198
Taxes (19%)	$/year	360,088
Earnings after Taxes (EAT)	$/year	1,535,110

Table 16 Grid - Expenses and revenues

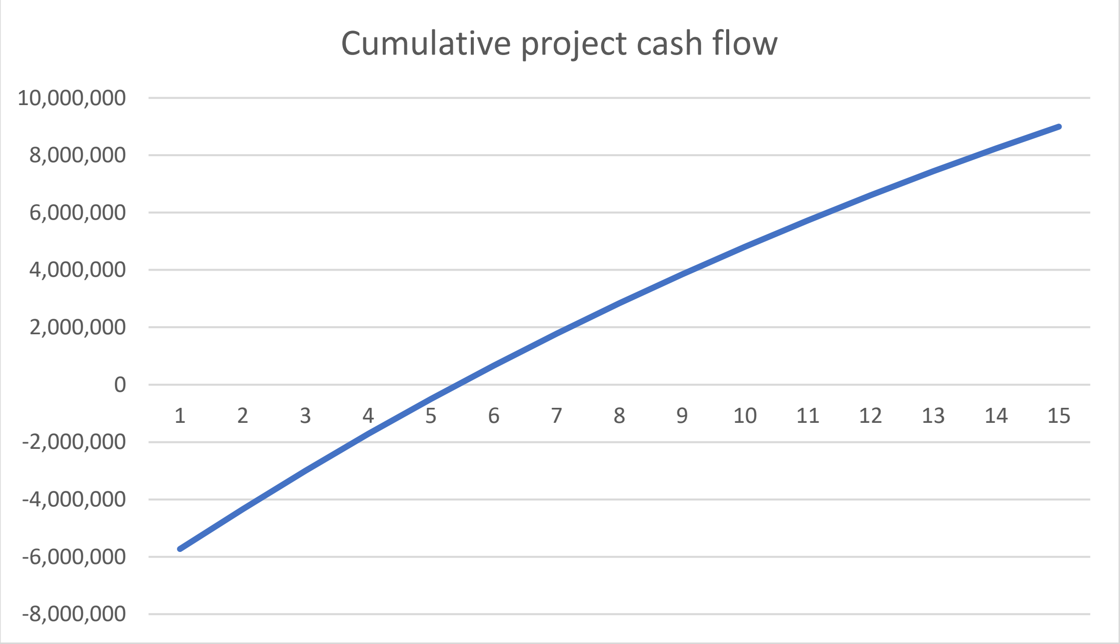
Income per year production and selling hydrogen by technology using grind energy is $ 4 800 000. After all cost which are $ 2 904 802 are earnings after taxes $ 1 535 110.

Investments assessments in this case is following. Cashflows are similar and the project is profitable after sixth year. Whole trend is on graph 6.



Graph 6 Grid - Discounted and Cumulative discounted cashflow

Closer trend of cumulative cash flow describes graph 7. It is visible that project will bring profit in the middle of fifth year of project season.



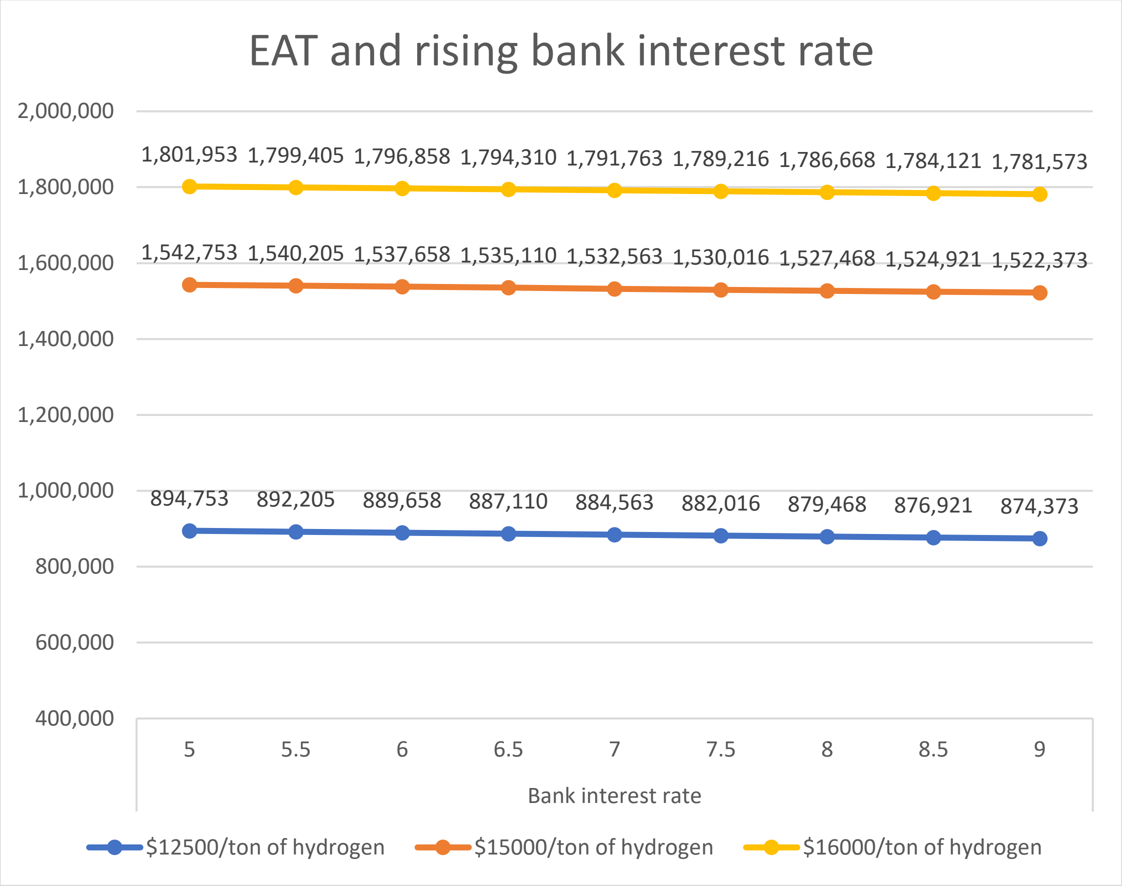
Graph 7 Grid - Cumulative cash flow

Expected net present value (NPV) of project where is for producing hydrogen used grid energy is 8 997 669 USD which declares that project will also be profitable because it is more than 0. And so, it is convenient for investors.

IRR is calculated 26%.

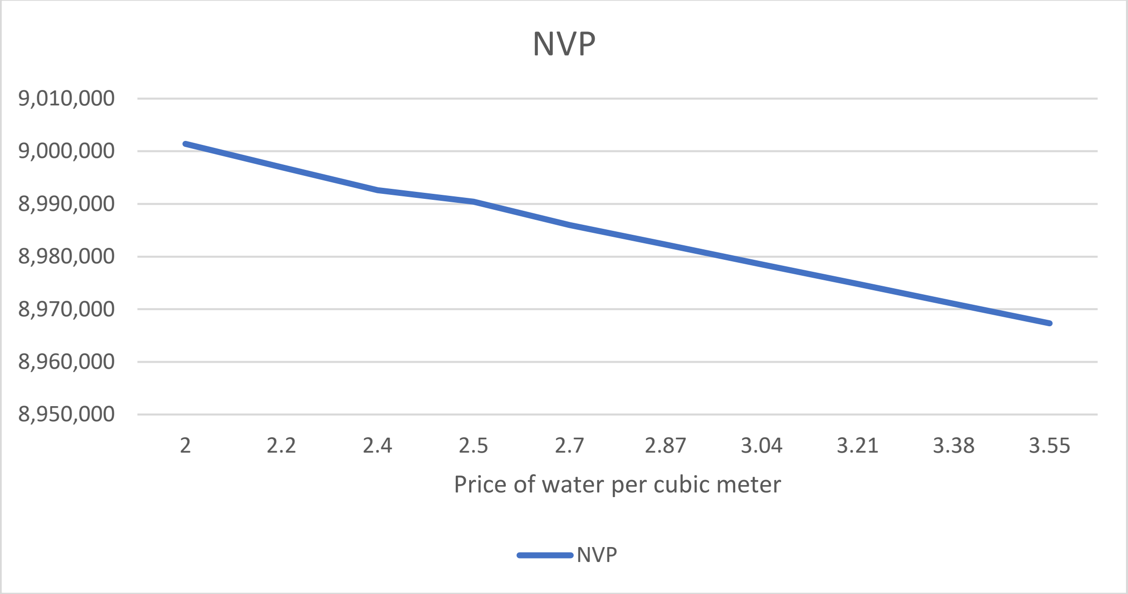
5.3 Sensitivity analysis

In this analysis we will be concentrating to parts which can affect the growth and development and we will also know the most profitable part. Which we can develop to maintain the Profit using the same process. For comparing uses we did analysis on the same parameters as in previous case.



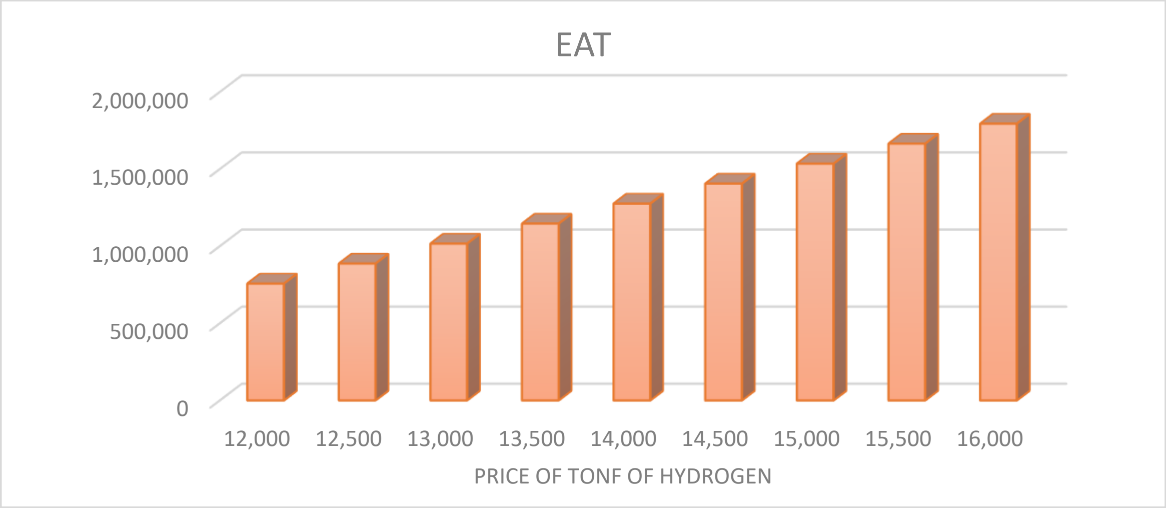
Graph 8 Grid - Analysis for EAT and rising bank interest rate

The above table indicts the change of earnings EAT when the interest rate changes, we also considered the three different hydrogen price changes. But comparing the previous method of using the renewable energy we can clearly see the there is no steep changes but only minimal changes in prices of the EAT.



Graph 9 Grid - NPV and rising price of water

Graph 9 is showing as is price of water sensitive on NPV and in case of increasing price of water for more than one dollar the project will be still profitable. The sensitivity is not that much significant in this case.



Graph 10 Grid - EAT and rising price of Hydrogen

On the other hand, if we increase the price of hydrogen, we produce for thousand dollars our earnings increase for 259 200 dollars. In case we will have to decrease price of hydrogen because of market conditions, to 12 000 dollars per ton, our EAT will be 757 510 $, what is still profitable incident.

6. HYDROGEN PRODUCTION BY METHANE STEAM REFORMING

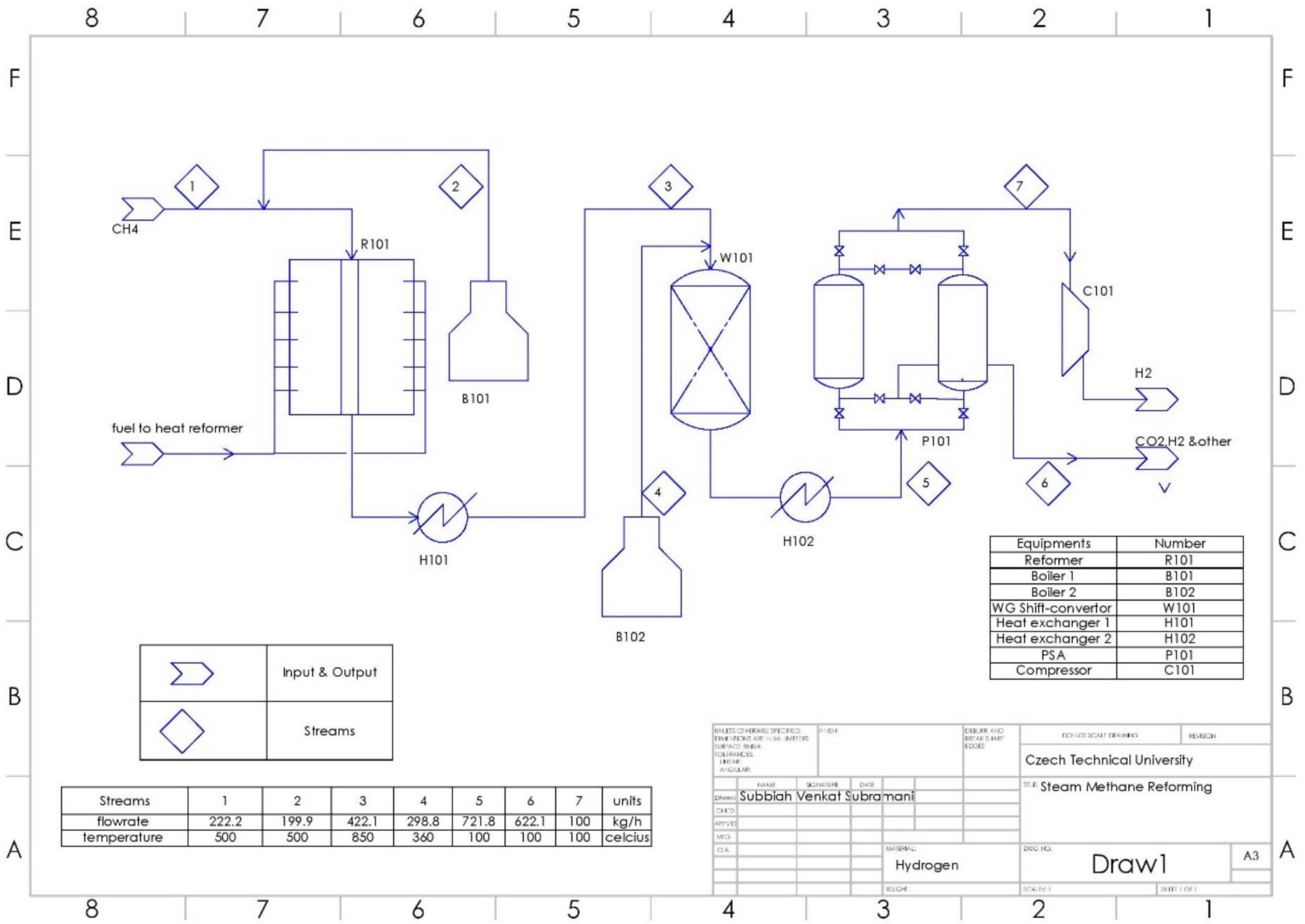
SMR is also known steam methane reforming which is a process that use methane from natural gas, and it is heated with steam generally with help of catalyst to produce hydrogen and carbon monoxide (SMR, 2019).

$$CH_4 + H_2O\ (+\text{heat}) \rightarrow CO + 3H_2$$

After this first process there is a lot of carbon monoxide which is then used to convert more Hydrogen and the remaining is converted to carbon di oxide so these syngas from the reformer is passed to multi-stage, fixed-bed reactor which also contains shift catalyst to convert CO theses process are generally known as water-gas shift (WGS) reaction (WGS, 2019).

$$CO + H_2O \rightarrow H_2 + CO_2$$

FLOWSHEET DIAGRAM



Streams	1	2	3	4	5	6	7	units
flowrate	222.2	199.9	422.1	298.8	721.8	622.1	100	kg/h
temperature	500	500	850	360	100	100	100	celcius

Equipments	Number
Reformer	R101
Boiler 1	B101
Boiler 2	B102
WG Shift-convertor	W101
Heat exchanger 1	H101
Heat exchanger 2	H102
PSA	P101
Compressor	C101

Figure 15 "SMR" PFD by the author

This above suggested process consists of different components

- Reformer
- Steam boiler
- Water-gas shift convertor
- Pressure swing adsorption
- Compressor

REFORMER

Steam reforming furnaces or commonly known as reformer which is used in most of the petrochemical industry mainly based on hydrogen. Reformer is also a heat exchanger where it heats the gas which passes through the tubes. They are several types of reformers also with different arrangement of tubes such as bottom fired, top fired, terrace wall and side fired

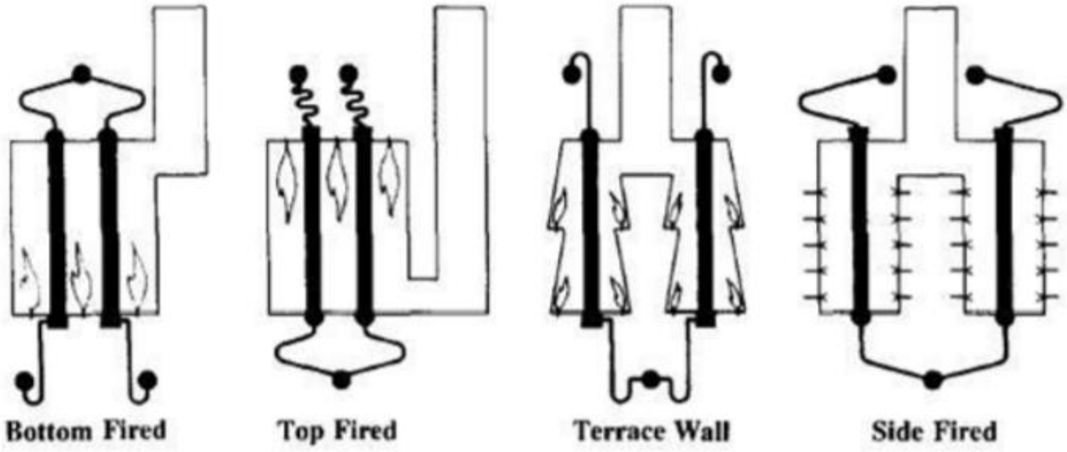


Figure 16 types of reformer

In this type the most preferred is the side fired reformer because it has the highest total heat flux possible combined with lowest heat flux where the tube skin temperature is at the highest also most effective design with the most flexible reformer in both operations and in design. The second-best type of reformer will be the bottom fired reformer (Wesenberg, 2006).

WATER-GAS SHIFT REACTOR

It's a reactor where the water-gas shift reaction occurs these reactor are mostly in two major process such as Haber-Bosch process for ammonia synthesis and the second process will be the steam methane reforming converting the carbon mono oxide and steam to hydrogen and carbon di-oxide generally the water-shift reaction occurs at $360^{\circ}C$ the catalyst which is used in this high-temperature WGS is CU promoted chromium-iron mixed oxide (Damma, 2019).

PRESSURE SWING ADSORPTION

Adsorption is the phenomenon of attraction that a molecule from fluid phase experiences when it's close to the surface of a solid called adsorbent. So, Pressure swing adsorption is a known gas separation technique which has great efficiency than any other techniques it is mostly used in the hydrogen purification separation. It has two cylinders filled with adsorbents when the gas is passed through the first cylinder only the purest hydrogen passes through rest gets adsorbed later its it released meanwhile second cylinder starts the cycle.

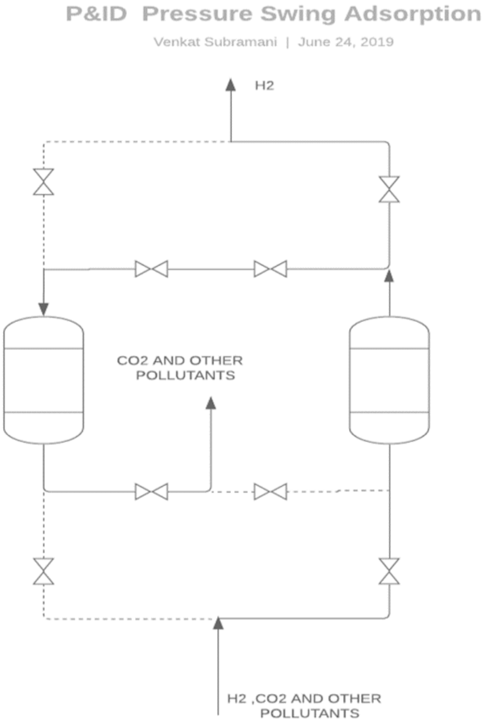


Figure 17 PSA

6.1 Mass balance

We are going to build a hydrogen production process of steam methane reforming we considered formula used in process and in order to have 100kg/h of hydrogen a standard which we have settled for all the three different process. To find the mass flow rate of the raw material and other products at different stages we are using the excel to establish the mass balance.

Reaction (r1)	$CH_4+H_20 = CO+3H_2$
Reaction (r2)	$CO+H_2O = CO_2+H_2$
Reaction(r3)	$CH_4+H_20 = CO+3H_2$

Figure 18 equations - SMR

For doing mass balance in excel we need to know the number of streams and components which are entering and exiting the process unit.

no	List of streams
1	Methane (CH_4)
2	Steam (H_2O)
3	Primary outlet ($CO + 3H_2+CH_4$)
4	Steam (H_2O)
5	Secondary outlet (CO_2+H_2)
6	Carbon di oxide CO_2+H_2
7	HYDROGEN H_2

Figure 19 list of streams

no	List of components	Mass number
1	CH_4	16
2	H_2O	18
3	CO	28
4	CO_2	44
5	H_2	2

Figure 20 list of components

Components and streams which flowing through the three process units are reformer, water-gas shift reactor and pressure swing adsorption

Stream; component	mass (kg/h)
m1;1	222.2
m2;2	199.9
m3;1	44.4
m3;3	311.1
m3;5	66.6
m4;2	298.8
m5;4	610.7
m5;5	111.1
m6;4	611.072
m6;5	11.1
m7;5	100

Figure 21 mass balance SMR

The above tables which shows the mass flowing through the process unit the first column in the table tell us the component present in that particular stream. Since we fixed the mass flow of hydrogen to 100 kg per hour. So, the rest of flow is showed and calculated this helps us to find the required amount of raw material and other sub products also it helps to calculate the operating cost for each required stream.

6.2 Capital cost

Capital cost is very important for any process and in this process, it is concentrated more to find the values of cost with greater approximation due to use of more equipment and greater complexity than other processes. Steam methane reforming is one of the old process to produce hydrogen and we have designed the process simpler as possible to attain the value with greater results

TOTAL PROJECT INVESTMENT (TPI) is $ 2,392,500.

TPI = Total purchased equipment cost + Total installed Cost + Total indirect cost.

TOTAL PURCHASED EQUIPMENT COST

Equipment	USD
Reformer	185,000
Water gas reactor	100,000
PSA	125,000
Steam producer 1&2	50,000
heat exchangers 1&2	50,000
compressor	40,000

Total purchased equipment cost (TPEC)	825,000

Table 17 SMR total purchase equipment cost

The cost of all equipment is approximately taken from the online sources. The costs of all this equipment are expensive than the other process since use of many reactors and boilers. The total cost estimated from steam methane reforming processes is $ 825000.

TOTAL INSTALLED COST

Costs	USD	% of TPEC
Purchased equipment installation	82,500	10% of tpec
Piping	123,750	15% of tpec
Instrumentation and controls	123,750	15% of tpec
Electrical systems	82,500	10% of tpec
Land	330,000	40% of tpec
Buildings (including services)	206,250	25% of tpec

Total installed cost (TIC)	948,750

Table 18 Steam reforming - Total installed costs

This table shows us the installation required for the steam reforming process we estimated the cost of the installation price based on the purchased equipment land & building are the major cost that are required. Total installed cost (TIC) is around $ 948750.

TOTAL INDIRECT COST

Costs	USD	% of TPEC
Engineering	123,750	15% of tpec
construction	206,250	25% of tpec
Legal and contactor fees	82,500	10% of tpec
Employess total costs	82,500	10% of tpec
project contigency	123,750	15% of tpec

otal indirect cost	618,750

Table 19 Steam reforming - Total indirect costs

Total indirect cost $ 618,750

6.3 Energy balance

Energy balance at steam reformer – inlet

Component	Flow Rate (kg/h)	Cp at 500℃ (kJ/kg)
CH_4	222.2	3.923
H_2O	199.9	2.147
Qin	650.43795	MJ/h

Figure 22 Balance at steam reformer - inlet

Energy balance at steam reformer – outlet

Component	Flow Rate (kg/h)	Cp at 850℃ (kJ/kg)
CH_4	44.4	4.708
CO	311.1	1.212
H_2	66.6	15.25
Qout	1361.47764	MJ/h

Figure 23 Balance at steam reformer - outlet

To find the energy difference between the inlet and outlet

$$\Delta Q = Q_{out} - Q_{in} \qquad 711.03969 \text{MJ/h}$$

Energy balance at steam generator 1

ΔT	500	℃
Specific heat	2.147	kJ/kg
Mass	198	kg/h
$\dot{Q}$(heat per hour)	212.553	MJ/h
efficiency	0.85	
Q	250.0624	MJ/h

Figure 24 Balance at steam generator 1

Energy balance at steam generator 2

ΔT	360	℃
Specific heat	2.047	kJ/kg.
Mass	299.88	kg/h
$\dot{Q}$(heat per hour)	220.9876	MJ/h
efficiency	0.85	
Q	259.9854	MJ/h

Figure 25 Balance at steam generator 2

Energy balance at shift convertor – inlet

Component	Flow Rate (kg/h)	Cp at 360℃ (kJ/kg)
CH_4	44.4	4.708
CO	311.1	1.212
H_2	66.6	15.25
H_2O	299.8	2.047

Figure 26 Balance at shift convertor - inlet

Calculating the energy balance of the shift convertor at inlet is found out to be 797.55 MJ/h

Energy balance at shift convertor – outlet

Component	Flow Rate (kg/h)	Cp at 360℃ (kJ/kg)
CO_2	611.1	1.102
H_2	111.1	14.7
Qout	830.376792	MJ/h

Figure 27 Balance at shift convertor - outlet

Energy balance at pressure swing adsorption – inlet

Component	Flow Rate (kg/h)	Cp at 100℃ (kJ/kg)
CO_2	611.1	0.918
H_2	111.1	14.46
Qin	216.74958	MJ/h

Figure 28 Balance at pressure swing adsorption - inlet

Energy balance at pressure swing adsorption – outlet 1 & 2

Component	Flow Rate (kg/h)	Cp at 100℃ (kJ/kg)
H_2	100	14.46
Qout1	144.6	MJ/h

Figure 29 Balance at pressure swing adsorption - outlet 1

Component	Flow Rate (kg/h)	Cp at 100℃ (kJ/kg)
CO_2	611.1	0.918
H_2	11.11	14.46
Qout2	72.16404	MJ/h

Figure 30 Balance at pressure swing adsorption - outlet 2

Energy balance of heat exchanger 1

This heat exchanger is used between the reformer and water-gas shift reactor

ΔT	490	℃
T1	850	℃
T2	360	℃
specific heat for CH_4	3.766	kJ/kg
specific heat for CO	1.126	kJ/kg
specific heat for H_2	14.65	kJ/kg
mass of CH_4	44.432	kg
mass of CO	311.08	kg
mass of H_2	66.6	kg
mass mixtures	422.112	kg
specific heat mixtures	3.53768	kJ/kg
Q	203.2543	kW

Figure 31 Balance of heat exchanger

To find the mass flow of the water flowing in the exchanger

The mass flow of rate of water is found using the formula M=Q/h where h is the specific enthalpy

M	1.93834	kg/s
specific enthalpy of water	104.86	kJ/kg

Figure 32 Mass flow rate

Energy balance of heat exchanger 2

ΔT	260	℃
T1	360	℃

T2	100	℃
specific heat for CO_2	1.046	kJ/kg
specific heat for H_2	14.53	kJ/kg
mass of CO_2	611.072	kg
mass of H_2	111	kg
mass mixtures	722.072	kg
specific heat mixtures	3.118818	kJ/kg
Q	162.6453	kW

Figure 33 Balance of heat exchanger 2

Mass flow of water flowing through the heat exchanger

M	1.551071	kg/s
specific enthalpy of water	104.86	kJ/kg

Figure 34 Mass flow of water

Energy balance of compressor

Compressor is used after the PSA to compress the hydrogen to 50bar the standard we used throughout all process to store the hydrogen

T1	100	℃
P1	8	Bar
P2	30	Bar
Flowrate	1210.04	Nm3/h
Polytropic efficiency	98	%
Acentric factor	-0.22	
Total power	77	kW

Figure 35 Balance for compressor

6.4 Economic balance

OPERATING COSTS

Operating cost of steam methane reforming considers all major parameters of operation that will be used in the production process such as natural gas for year, energy required for boilers and heating cost for reformer.

The total operating cost in a year is $ 918,799.78

Parameter	Value	Unit
Cost of methane without transport	2,029	$/ton
Cost of methane for one ton of hydrogen	2,251	$/ton
Cost of methane for hydrogen production	720,315	$/year
Total cost of energy required for boilers	99,264	$/year
Total cost of compressor work	54,208	$/year
Total cost of fuel for heating reformer	41,549	$/year
Required water per production	3,463	$/year
Operational costs	918,799.78	$/year

Table 20 Steam reforming - Operational costs

Project parameters

Project parameters in steam methane reforming is mostly same from those previous processes only the fix capital investment and the bank loan which is clearly showed in the below table

Parameter	Unit	Variant B
Annaul production of hydrogen(in tonnes)	ton	320
Selling price of hydrogen	$/ton	15,000
Fix capital investment (*CAPEX*)	$	2,392,500
Total purchased equipment cost (TPEC)	$	825,000
Total installed cost (TIC)	$	948,750
Total indirect cost	$	618,750
Construction time - investment time	year	1
The percentage of capital investments made in the first year	%	110
Life of the unit (= operating time)	year	15
Bank credit (bank loan)	$	2,392,500
The period of interest rate	year	15
Interest rate of the bank credit	%	6.5
Annuity	$	254,449
Bank draft overall	$	3,562,286
Interest rate	%	6.5
Owners profitability rate	%	5
Total asset depreciaton for year	$	61,875
asset depreciation(for industrials) for year	$	6,875
asset depreciation (for equipments) for year	$	55,000
Income tax	%	19

Table 21 Steam reforming - Project parameters

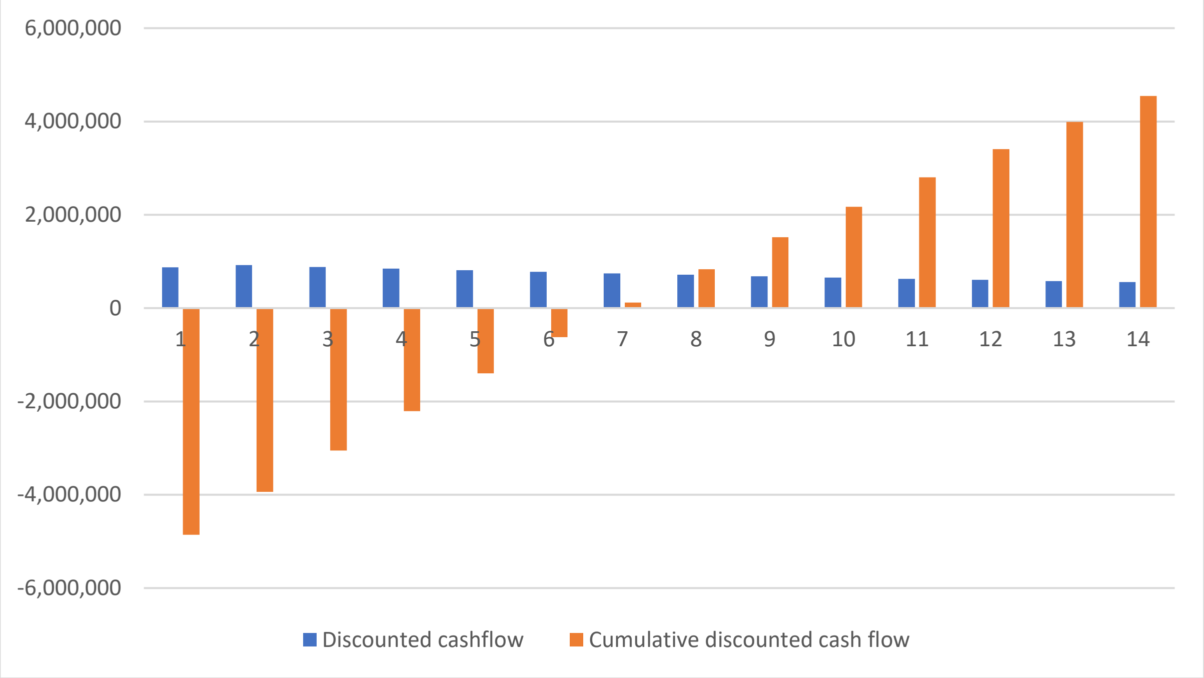
Expenses and revenues

The below table have used the parameters to calculate the cost and the revenues. Due to higher operating cost we can clearly see the decrease in the revenue than the other processes

Parameter	**Unit**	**Variant B**
Proceeds from the sale of hydrogen(revenue from sales)	$/year	4,800,000
All costs	$/year	3,566,005
Direct operating costs	$/year	918,800
Raw materials	$/year	918,800
Corporate costs	$/year	1,100,000
Personal costs - Direction, sales, marketing, accounting	$/year	900,000
Laboratory	$/year	102,000
R&D	$/year	90,000
Electricity and water	$/year	8,000
Indirect operating costs	$/year	1,324,140
Personal costs - operation	$/year	680,400
Maintenance costs	$/year	326,400
Supervision	$/year	102,060.0
Consumables	$/year	65,280
Insurance	$/year	50,000
Reserve	$/year	100,000
Distributional costs	$/year	5,678.0
Transport	$/year	5,678.0
Financial cost	$/year	217,388
Interests costs	$/year	155,513
Assets depreciations	$/year	61,875
Earnings before Interest, Taxes, Depreciations and amortization Charges (EBITDA)	$/year	1,451,382
Earnings before Interest and Taxes (EBIT)	$/year	1,389,507
Earnings before Taxes (EBT)	$/year	1,233,995
Taxes (19%)	$/year	234,459
Earnings after Taxes (EAT)	$/year	999,536

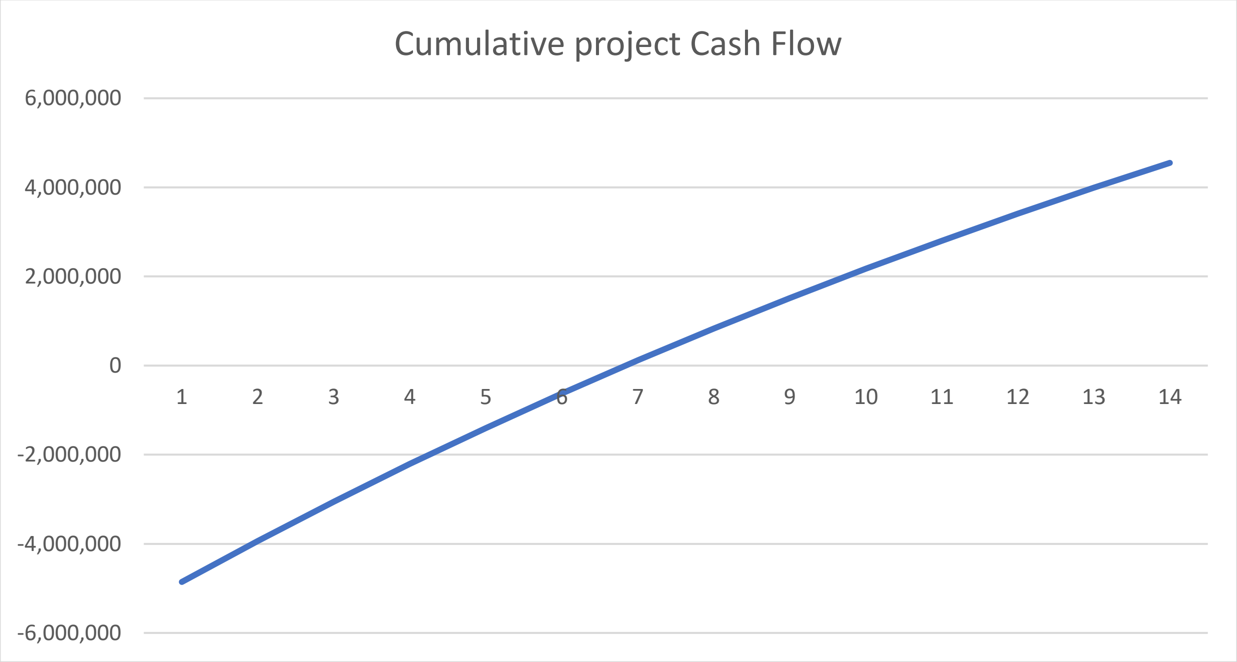
Table 22 Steam reforming - Expenses and revenues

Since the income per year production is same in all production that is $ 4,800,000 since we fixed the selling cost and the amount of production. In this SMR process we found out that earnings after taxes is 999,536.



Graph 11 Steam reforming - Discounted and Cumulative discounted cashflow

Pay back and cumulative cash flow view.

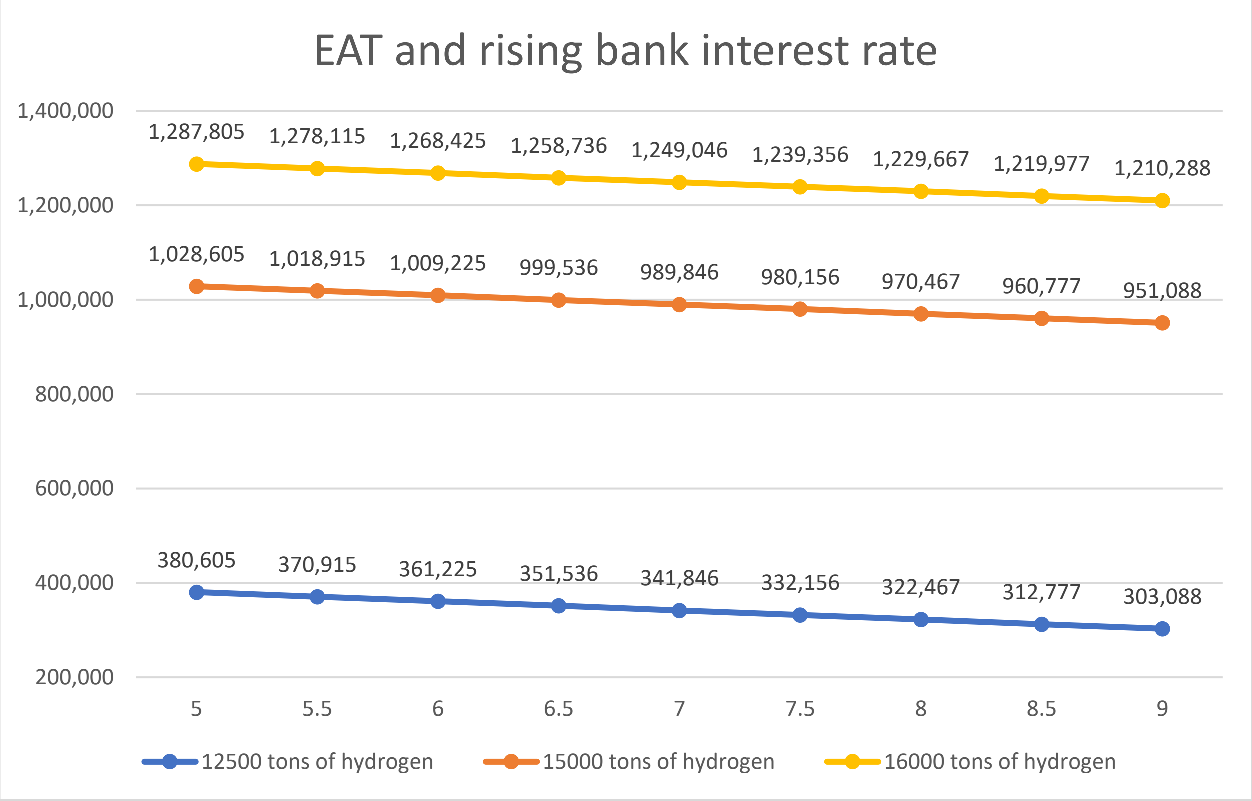


Graph 12 Steam reforming - Cumulative cash flow

Expected net present value (NPV) of project using Steam methane reforming is $ 4,755,793 which this graph also shows that project is profitable IRR is calculated at 26%

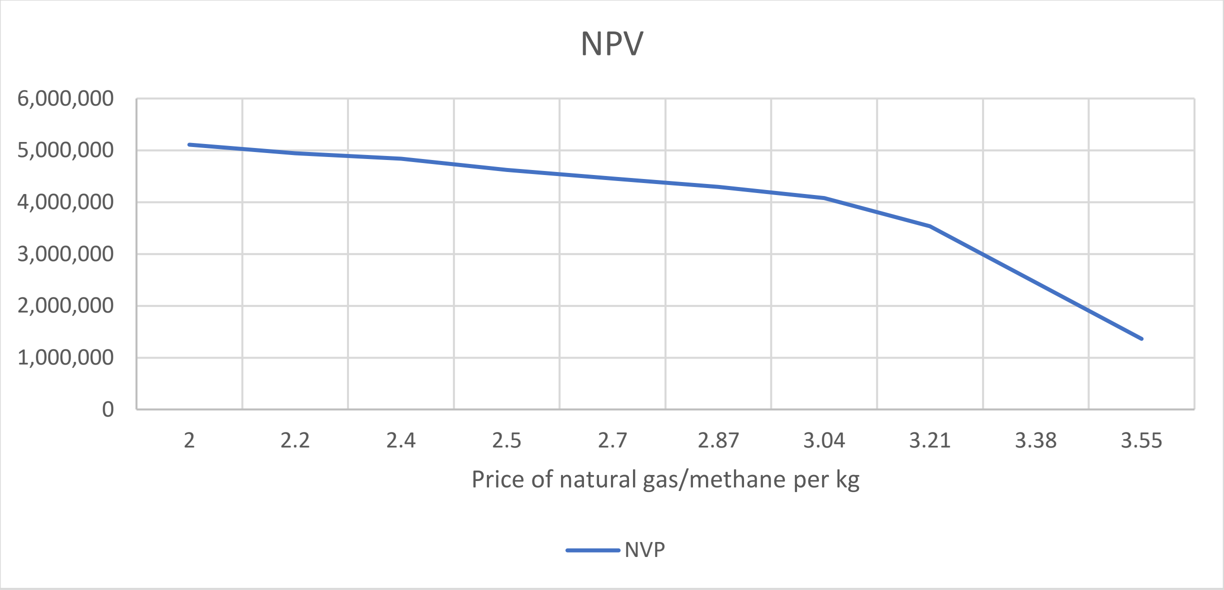
6.5 Sensitivity analysis

In this we will be concentrating on the same parts as other processes where we analyze the parts affecting the growth and development and we will also know the profitable part



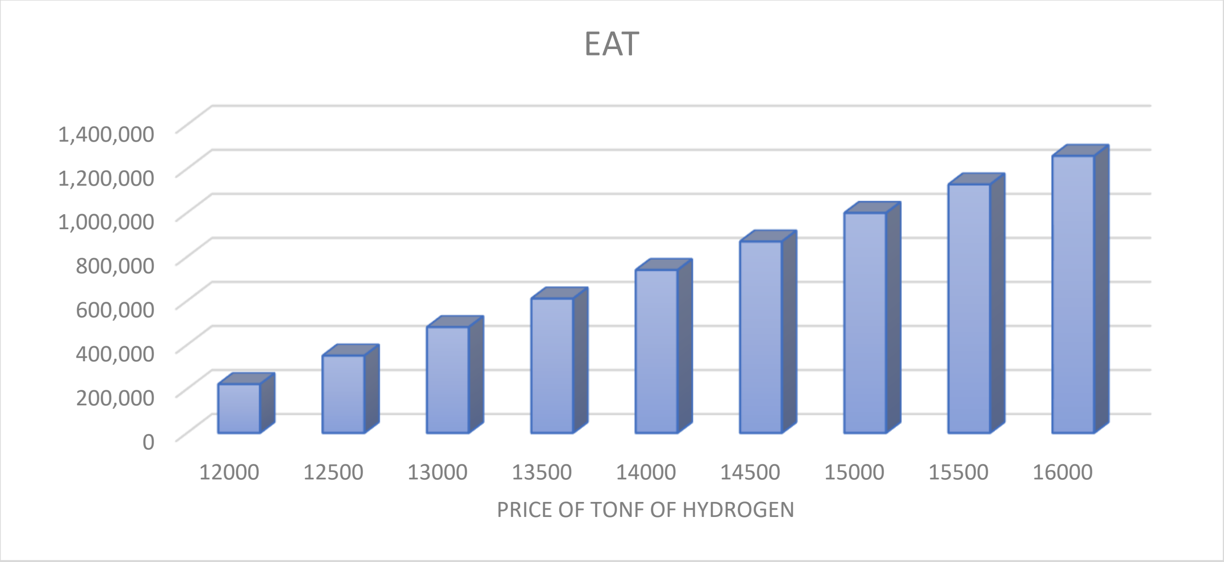
Graph 13 Steam reforming - Analysis for EAT and rising bank interest rate

How much change net present value even if will change price of natural gas per kg risen to 1.5 per kg project will still be profitable.



Graph 14 Steam reforming - NPV and rising price of natural gas

The above graph shows us the significance in the price of methane the graph curve falls on every few increases in the price of the methane



Graph 15 Steam reforming - EAT and rising price of Hydrogen

Analyzing the above graph we can clearly see that on increasing the $500 price of hydrogen per ton we can see a significant increase in our earnings Even in the case of selling hydrogen for 12 000 per ton, we will still make earnings more than 220,000 dollars which is really good because they can be some fluctuation in the hydrogen market.

DISCUSSION

We estimated the mass, energy, economic balance of all processes and we are comparing the results of those processes having the parameters as below

	Values
Annual production (pcs.)	320
Selling price of hydrogen ($)	15000
Project term (years)	15
Owners profitability rate	5%
Interest rate	6.5%
Tax	19%
Cost of water (cubic meter) ($)	2.17
Cost of Natural Gas (per kg) ($)	0.91

Table 23 Overall project parameters

Overall view of 3 possibilities of producing of hydrogen.

In case of all 3 projects have same conditions – bank rate, tax, and other cost such as water and natural gas.

Production/ Parameter	Rewenable	Grid	Steam Reforming
Investment (CAPEX) ($)	5,729,000	629,000	2,392,500
Costs ($)	3,007,917	2,904,802	3,566,259
Raw costs ($)	28,789	414,674	919,053
EBIT ($)	2,164,468	1,936,083	1,389,154
EAT ($)	1,451,587	1,535,110	999,330
NPV ($)	10,275,986	8,997,669	4,547,781
Payback period (years)	5	6	7
IRR	27%	26%	17%

Table 24 Economic balance for all types

On seeing the economic balance for all the process based on their operating and other we found the results is profitable in all three cases but having the production decentralized we find that the hydrogen production using electrolyzer by renewable sources is the most profitable comparing the results to others as shown in table above the payback year is less in renewable cases and simpler process than any other process. Since we are producing in hydrogen in decentralized method in order to use in Carbon Capture & Utilization. the main ideology of this technology is to convert carbon di oxide to methanol. So, using the steam methane reforming can't be used much since it requires heat for operation in reformer which results in burning the fuel also according to our results it's one of the most complicated, expensive processes.

Comparing all processes, we can confirm that the hydrogen production by electrolyzer using renewables is the best process. but using the hydrogen production process using grid is not bad since everything is same and taken from the first renewable process except the source of energy

CONCLUSION

During the work following sections were accomplished:

- Literature research showed us the different types of hydrogen production and allowed us to select three processes in decentralized methods in order to satisfy the requirements for CCU technologies
- Mass and energy balance were calculated for all streams and process units for chosen technology. Description of streams and positing are required in flowsheet.
- Simplified flowsheets are created for hydrogen production using electrolyzers and detailed flowsheet for the steam methane reforming process was prepared in SOLIDWORKS
- Using Mass & energy balance a detailed economic balance is created in MS Excel for all processes where capital cost is considered individually for each process
- Sensitivity Analysis is analyzed for each case such price of hydrogen against the Earnings after tax and many cases like these were discussed
- All the processes are finally compared with their best stats to check the best suitable and profitable processes line for decentralized production of hydrogen

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Subscript

CO – carbon mono oxide

CO_2 – carbon di oxide

CH_4 – methane

CH_3OH – methanol

CCU – carbon capture and utilization

CCS – carbon capture and storage

EBITDA – earnings before interests, taxes, depreciations and amortization charges

EBIT – earnings before interests and taxes

EBT – earnings before taxes

EAT – earnings after taxes

H_2O – water

H_2 – hydrogen

IRR – internal rate of return

NPV – net present value

SMR – steam methane reforming

Appendix

Appendix A. Thesis A

Appendix B. PFD of renewable

Appendix C. PFD of grid

Appendix D. PFD of SMR