Recycling of CO₂, the perfect biofuel?

Marco Kauw

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Supervised by: Dr. R.M.J. Benders (IVEM)
               Dr. C. Visser (IVEM)

University of Groningen
CIO, Center for Isotope Research
IVEM, Center for Energy and Environmental Studies
Nijenborgh 4
9747 AG Groningen
The Netherlands

http://www.rug.nl/fmns-research/cio
http://www.rug.nl/fmns-research/ivem
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SUMMARY (ENGLISH)

Most of the fossil fuels are currently used for transportation, to generate electricity or used for heating purposes. Mainly due to the increasing world population and the economic development of countries, the energy demand will increase rapidly. If society will still use fossil fuels in the future to supply this demand, we are going to be faced with major fossil fuel shortfalls and increasing CO₂ emissions. The Icelandic company Carbon Recycling International (CRI) think they have the answer for both major global problems and developed a way to recycle CO₂ into biofuel, which can act as a replacement for fossil fuels. CRI only uses geothermal power, water and CO₂ to convert this in methanol. They claim that, on a short term, this technique can replace fossil fuels and they think it is possible to decrease CO₂ emissions to pre-industrial levels. But is it technically possible to recycle CO₂ and are the claims of CRI correct?

An important fact is that also hydrogen is required to convert CO₂ into methanol. Converting CO₂ into methanol is not a new technique and already developed by BASF in 1905 when CO₂ and hydrogen were obtained from fermentation gases. What is new is the way of producing hydrogen with the electrolysis of water and capturing CO₂ by only using geothermal power. Iceland has a large potential of geothermal and hydropower. Furthermore, CO₂ can efficiently be captured from geothermal power plants. Both reasons, give CRI the opportunity to produce large amounts of renewable methanol.

Only electricity is required to convert CO₂ to methanol. Unfortunately, the total energy efficiency from electricity to methanol is relatively low with 42 up to 55%. This depends on where the process is located, how CO₂ is captured and how the electricity is generated (geothermal, solar, wind et cetera). In this process, CO₂ is basically a temporary feedstock because, with the combustion of methanol itself, captured CO₂ will be released again. Therefore, no CO₂ will be recycled by CRI. The situation is even worse, it will cost CO₂ when new geothermal power plants are used to produce renewable methanol.

The only realistic option to recycle CO₂ is when it is captured from fossil fuel power plants or from industry. In this situation, captured CO₂ is converted to methanol and with the use of this methanol, the same amount of CO₂ will be released again. The best option that CRI can achieve is to create a closed-loop of CO₂ when it is captured from atmospheric air. This means, when it is applied on a large scale, it can actually stabilize CO₂ level. However, it is untrue that CO₂ levels could decrease to pre-industrial levels. Also too few information is available about the actual energy consumption of a large scale implementation of this kind of methanol production.

The total potential of Iceland is not large. Using the maximum available geothermal power and CO₂, the potential is limited up to about 350 million litres of methanol a year. This is large enough to supply the Icelandic demand of methanol when this is used as a replacement for conventional gasoline in passenger cars. Exporting this amount to the Netherlands would not even supply 3% of all gasoline cars in the Netherlands. The potential could be five times larger when also potential hydropower is used and extra CO₂ is captured from the industry. In this case, CO₂ will be recycled but the potential is still relatively small. Furthermore, the production costs will be even higher than the current estimated production price of 600-1200 euro/ton of methanol in combination with old geothermal power or hydropower plants. To compete with the current fossil fuel-based methanol market prices of 300 euro/ton, the production of renewable methanol has not to be taxed or the production has to be subsidised.

When this methanol process is applied on a global scale, the maximum potential of geothermal power could almost replace current demand of methanol. This would actually save about 30 Mton of CO₂ a year, which is about 0.1% of all annual global CO₂ emissions. Unfortunately, the second claim of CRI is also not true. The use of only the available geothermal power and CO₂ cannot replace the global demand for fossil fuels.

A positive fact about this technique is that it can store electricity and can therefore function as a potential energy buffer. If a country tries to install unpredictable and variable renewable energy sources such as wind and solar, at some moments, more electricity can be generated than is actually needed. This oversupply can be used to produce methanol to buffer energy. The most ambitious plan of the Dutch government is to implement 6 GW of offshore wind, 4 GW of onshore wind and 4 GW of solar PVs by the year 2030. When this scenario is simulated in PowerPlan (a medium term program that simulate the
electricity supply and demand of a country), the result is that the oversupply of electricity in the Netherlands is too small. Besides renewables, the Netherlands also invests in more flexible fossil fuel power plants. These will be used to minimize the occurrence of a electricity oversupply. Therefore, methanol production in the Netherlands by the year 2030 cannot advantageously be used as a potential energy buffer. Perhaps it can be used in countries such as Germany that are trying to invest more in solar and wind power and are therefore faced with larger electricity oversupplies than the Netherlands.
SAMENVATTING (DUTCH)

De meeste fossiele brandstoffen worden gebruikt in de transport sector, om elektriciteit op te wekken of voor verwarmingsdoeleinden in huizen. Door de toenemende wereldbevolking en de economische ontwikkeling van vele landen zal de vraag naar energie in de komende jaren alleen maar stijgen. Als wij in de toekomst nog steeds gebruik maken van fossiele brandstoffen voor eerder genoemde toepassingen, zouden we te maken krijgen met energietekorten en stijgende globale CO\textsubscript{2} niveaus. Het IJslandse bedrijf Carbon Recycling International (CRI) denkt het antwoord gevonden te hebben voor deze twee toekomstige grote problemen en ontwikkelde een manier om CO\textsubscript{2} te recyclen naar een biobrandstof waarna deze gebruikt kan worden als vervanging voor de fossiele variant. CRI gebruikt alleen geothermische energie, water en CO\textsubscript{2} om methanol te produceren en claimt dat op korte termijn dit fossiele brandstoffen in zijn geheel kan vervangen en dat het CO\textsubscript{2} niveau naar een pre-industriële waarde verlaagd kan worden. Is dit technisch mogelijk en kan CRI de claims waar maken?

Naast CO\textsubscript{2} is ook waterstof nodig voor dit proces. De productie van methanol met waterstof en CO\textsubscript{2} is niet nieuw en was al in 1905 ontwikkeld door BASF. Wat wel nieuw is, is de manier waarbij waterstof en CO\textsubscript{2} verkregen zijn. CRI maakt namelijk alleen gebruik van geothermische energie en vangt hierbij ook CO\textsubscript{2} af. Waterstof is verkregen door de elektrolyse van water met behulp van elektriciteit. Helaas is de energie efficiëntie van het gehele proces, waarbij enkel elektriciteit benodigd is, erg laag met zo’n 42 tot maximaal 55%. Het verschil lijkt waar het proces zich plaats vindt, hoe CO\textsubscript{2} verkregen is en met welke bron van energie de benodigde elektriciteit is geproduceerd (wind-, zonne-, geothermische- of waterkracht energie). CO\textsubscript{2} is eigenlijk een soort grondstof welke weer tijden s het verbranden van methanol in zijn geheel uitgestoten wordt. Om deze reden wordt er in zijn totaliteit geen CO\textsubscript{2} geregycled in de methanol fabriek van CRI. Het is zelfs zo dat het CO\textsubscript{2} kost omdat nieuwe geothermische putten geslagen moeten worden en er CO\textsubscript{2} uitgestoten zal worden. Aan de andere kant, deze extra emissies vallen bijna in het niet vergeleken met de natuurlijke CO\textsubscript{2} uitstoot van IJsland door zijn vele geisers en vulkanen.

De enige mogelijk manier om daadwerkelijk CO\textsubscript{2} te recyclen is om het af te vangen bij fossiele energiecentrales of de industrie. Hierbij wordt de afgevangen CO\textsubscript{2} gebruikt om methanol te produceren en zal bij het gebruik ervan in het in zijn geheel afnemend uitgepost worden. De best mogelijke situatie kan door CRI bereikt worden door CO\textsubscript{2} af te vangen uit de lucht. Bij grootschalige implementatie is het theoretisch mogelijk om het CO\textsubscript{2} niveau daadwerkelijk te stabiliseren. Het is echter onjuist dat men met dit proces het niveau kan verlagen en zeker niet tot pre-industriële waarden. Verder is er op dit moment weinig eenduidige informatie verkrijgbaar over de haalbaarheid van dit proces op grote schaal.

De totale methanol potentie van IJsland is niet erg groot. Het gebruik van alle mogelijk beschikbare geothermische energie en beschikbare CO\textsubscript{2} zou een productiecapaciteit opleveren van 350 miljoen liter/jaar. Dit is genoeg om alle benzine auto’s in IJsland te voorzien van methanol en zal bij het gebruik ervan in zijn geheel afnemend uitgestoten worden. De beste mogelijke situatie kan door CRI bereikt worden door CO\textsubscript{2} af te vangen uit de lucht. Bij grootschalige implementatie is het theoretisch mogelijk om het CO\textsubscript{2} niveau daadwerkelijk te stabiliseren. Het is echter onjuist dat men met dit proces het niveau kan verlagen en zeker niet tot pre-industriële waarden. Verder is er op dit moment weinig eenduidige informatie verkrijgbaar over de haalbaarheid van dit proces op grote schaal.

Toepassing van dit proces op het gehele globale potentieel van geothermische energie leidt ertoe dat de huidige fossiele productie van methanol bijna vervangen kan worden door deze productie methode van methanol. Dit zou jaarlijks ongeveer 30 megaton CO\textsubscript{2} besparen (0.1% van alle globale CO\textsubscript{2} emissies). Maar ook de tweede claim van CRI kan niet waar gemaakt worden. Bij gebruik van alleen de beschikbare geothermische energie en CO\textsubscript{2}, kan deze techniek niet zo groot worden dat het compleet kan voldoen aan de vraag naar fossiele brandstoffen. Wellicht is het wel in de toekomst mogelijk deze techniek toe te passen met CO\textsubscript{2} uit de lucht en geconcentreerde zonne-energie in bijvoorbeeld de woestijn.

Toch is er iets positiefs aan deze methode, namelijk dat het gebruikt kan worden om elektriciteit grootschalig op te slaan. Stel dat een land besluit om te investeren in wind- en zonne-energie, dan zou het kunnen dat op bepaalde momenten meer elektriciteit gegenereerd gaat worden dan er daadwerkelijk nodig is. Dit overschot aan elektriciteit kan in dit geval gebruikt worden om methanol van te produceren.
waardoor het fungeert als een energiebuffer. Het meest ambitieuze plan van de Nederlandse overheid is om 6 GW\textsubscript{e} offshore wind, 4 GW\textsubscript{e} on-shore wind en 4 GW\textsubscript{e} aan zonnepanelen te installeren voor het jaar 2030. Met behulp van het computerprogramma PowerPlan (een medium-term programma voor simulatie van vraag en aanbod van elektriciteit) is berekend dat in dit geval te weinig overschot gegenereerd zal worden. Dit omdat naast wind en zonne-energie ook geïnvesteerd wordt in flexibele gas gestookte energie centrales waardoor in bijna alle gevallen, de door wind en zon gegenereerde elektriciteit, gebruikt kan worden. Het is daarom voor Nederland niet zinvol om methanol als energiebuffer te gebruiken in combinatie met het hierboven genoemde ambitieuze plan voor 2030. Echter het kan voor andere landen, zoals bijvoorbeeld Duitsland, waar men grootschaliger investeert in duurzame energie bronnen eventueel een toekomstige optie bieden omdat deze landen naar alle waarschijnlijkheid te maken zullen krijgen met grote overschotten aan elektriciteit.
CHAPTER 1 INTRODUCTION

Most of the world’s fossil fuels, for example oil, natural gas and coal, are currently used for transportation, to generate electricity or are burned for heating purposes. Currently, we are consuming more than 11 million tons of oil a day and this demand for energy will increase in the coming decades due to, among others, the increasing world population (International Energy Agency, 2011a). According to the medium projections by the United Nations, the world population will reach 9.3 billion in 2050. This is an increase of more than 32% (United Nations, 2004). Not only the population growth, but also the economic development of countries and the increasing standard of living will affect the total demand for energy in the future (Ohla et al., 2006). The International Energy Agency (IEA) estimated that the current world energy demand of 120 PWh/yr would increase to about 190 PWh in 2025 and to 280 PWh in 2050 (Energy Information Administration, 2011). If society still will use only fossil fuels in the future for the above-mentioned purposes, we are going to face major resource shortfalls and increased CO$_2$ emissions due to the combustion of fossil fuels.

Throughout the industrial revolution, from 1750 up to now, human activity has increased the total amount of carbon dioxide (CO$_2$) emissions in the atmosphere by almost 33% (Energy Protection Agency, 2007), to about 393 ppm (CO$_2$ Now, 2012). Three-quarter of this increase is caused by the combustion of fossil fuels. The rest is mainly caused by land use changes such as deforestation (Intergovernmental Panel on Climate Change, 2007). The earth’s natural processes can recycle about half of the anthropogenic CO$_2$ emissions but the rest will go into the atmosphere where they act as greenhouse gases (Energy Information Administration, 2012). Combusting fossil fuels (energy) yield both CO$_2$ and water. Producing fossil fuels, with for example the use of photosynthesis, is unfortunately not possible within a human lifetime and can therefore not be seen as a source of renewable energy. However, the Icelandic company Carbon Recycling International (CRI) has found a method to recycle CO$_2$ into a fuel, namely methanol, using only geothermal or hydropower.

Currently, about 85% of all the produced methanol (76,000 million l/yr) uses natural gas as a feedstock. The reasons are the relatively high hydrogen content of natural gas, the low energy consumption during the production and the relatively low investments costs (Ohla et al., 2006). Furthermore, coal can also be used as a feedstock for methanol production. This method is commonly used in China. The problem however, is that both techniques still require the use of fossil fuels and still emit CO$_2$ during the production. CRI claims that they can use CO$_2$ as a feedstock and therefore produce methanol without emitting extra CO$_2$ emissions (Carbon Recycling International, 2012). This process also requires hydrogen (H$_2$) as a feedstock (figure 1.1).

![Methanol production with CO$_2$ and H$_2$ as a feedstock. Figure based on: Carbon Recycling International, 2012.](image-url)

At the moment, CRI is building a commercial methanol power plant with a production capacity of 50 million litres of methanol a year (Carbon Recycling International, 2012). Most of the currently produced methanol is being used in the chemical industry but methanol also has the potential to replace fossil fuels. It is obviously no coincidence that this innovative method is applied in Iceland. This country has a large potential for producing inexpensive renewable energy. The current production is 12 TWh$_{th}$/yr of which 80% comes from hydropower and the rest from geothermal power plants (Ingason et al., 2008). Furthermore, the theoretical potential of hydropower in Iceland is 187 TWh$_{th}$/yr, of which it is estimated that 30 TWh$_{th}$/yr can be used sustainable. The 18 (high temperature) geothermal reservoirs in Iceland have a theoretical potential of 59 TWh$_{th}$/yr of which 20 TWh/yr can be converted into electricity (Bardardottir and Sturludottir, 2006).
All geothermal power plants in Iceland emit CO₂ due to the degassing of volcanic magma. CO₂ from these plants can easily be stored and used for methanol synthesis. Due to the available renewable energy and CO₂, Iceland can produce methanol on a large scale (Graves et al., 2010). However, building new methanol plants in Iceland require new geothermal wells for supplying the energy (thermal and electricity) and the required CO₂. When not all of the newly released CO₂ from these wells is captured and used for methanol production, more CO₂ is released into the atmosphere than maybe was necessary. The production process of CRI has to be analysed to calculate the actual recycled CO₂ or even emissions.

CRI is ambitious and wants to extent their production capacity. Some quotes of the company make it clear that recycling of CO₂ is, according to CRI, the solution for the decreasing fossil fuel reserves and the increasing CO₂ levels.

Quote 1: “Possible to decrease CO₂ to pre-industrial levels” (CRI, 2012; Down to earth, 2011)

Quote 2: “On short-term, the production of fossil fuels can be stopped to prevent additional CO₂ from being released” (CRI, 2012)

Furthermore, the company claims that methanol production, with the use of CO₂ and hydrogen, can also be accomplished by other (variable) renewable energy sources such as wind, solar, tidal, wave power and from biomass. Therefore, this methanol production method is also possible in other regions, such as the Netherlands, that do not have renewable energy sources with a constant power output such as hydro or geothermal energy. In this research, the potential of Iceland and the Netherlands will be investigated.

Why methanol?
To produce methanol, also hydrogen is used as a feedstock. Methanol as an energy carrier has several advantages to hydrogen, whether this would be in a compressed or liquid stage. It can be stored easily at ambient temperatures and atmospheric pressure and existing infrastructures can be used for transporting the fuel to, for example, filling stations for passenger cars. Furthermore, CO₂ can be used as a feedstock, which is not possible with only hydrogen as a future energy carrier. In theory, this could help to stabilize CO₂ emissions. The energy consumption of producing renewable methanol has to be researched together with the potential CO₂ savings or emissions of this production. Furthermore, it is important to investigate the supply and demand of methanol and whether methanol can replace fossil fuels in for example the transport sector.

Methanol can in fact be used as a replacement for fossil fuels in cars. It can directly be used in gasoline cars or, by converting methanol into dimethyl ether (DME), the fuel for diesel cars (Breure, 2005). Furthermore, methanol can be used in fuel cells to convert it into electricity. However, in the future methanol can also play a large role as an energy carrier for different purposes (electricity production, heating et cetera, Breure, 2005).

Research design
In order to stop the ever-increasing human energy demand in the future, fossil fuels will be exhausted and yield large amounts of CO₂ emissions caused by the combustion of it. According to CRI, recycling of CO₂ into methanol is challenging but technically possible. However, this process will require large amounts of hydrogen, which have to be produced in a sustainable way. Furthermore, electric and thermal energy are needed to convert CO₂ and hydrogen into methanol. In this research the complete process of CRI will be analysed applied for Iceland and the Netherlands.
Therefore the main question of this research is: *Is methanol production a way to recycle CO$_2$?*

The aim of this research is to analyse the methanol process developed by CRI. Besides to the energy consumption, the potential CO$_2$ savings by recycling CO$_2$ have to be examined.

Sub question 1: *What are the energy and resource requirements of methanol synthesis and what are possible suitable energy sources for this process?* The energy requirements have to be researched to calculate the energy efficiency of producing methanol with different energy sources. Also the role of thermal energy for the production of hydrogen (electrolysis) has to be examined as well as suitable sources, such as cooling water from a coal-fired power plant. Besides hydrogen as a feedstock, CO$_2$ is required and therefore also it is possible sources have to be investigated.

Sub question 2: *Is sustainable production of methanol possible in Iceland and to what extent?* CRI, located in Svartsengi, claims that the required energy is only used from geothermal or hydropower and that in 2013 a production capacity of 50 million litres a year can be achieved. Svartsengi is not the only location in Iceland that is suitable for producing methanol. The sustainability of large-scale methanol production in Iceland has to be examined together with the possible locations.

Sub question 3: *Is sustainable production of methanol possible in the Netherlands and can this production act as an energy buffer for renewable energy surpluses?* Theoretically, the production of methanol is possible only using renewable energy sources like solar-, wind-, hydropower, et cetera. In the Netherlands there is not a constant and reliable renewable energy source like hydro- or geothermal power. By using variable renewable energy sources, at some moments an imbalance between the electricity supply and demand can occur. Is it possible, when an oversupply appears, to use this energy to produce methanol and therefore act as an energy buffer? Or will this variable oversupply of energy, significantly affect the efficiency of methanol production? To what extent is buffering energy in the form of methanol possible? Furthermore, the possibilities of CO$_2$ capturing, thermal energy sources and hydrogen production have to be examined.

Sub question 4: *Can methanol, which is produced in Iceland, play a role in replacing fossil fuel use in the Netherlands and to what extent?* The potential of Iceland, calculated in sub question 3 will be used to investigate whether this potential is large enough to replace for example the fossil fuel demand in the transport sector or not.

**Methodology**

Scientific literature will be used to find the relevant data needed for calculating the required energy and emitted CO$_2$ emissions of producing, transporting and converting methanol. When all possible paths are researched, the most optimal and realistic production technique (used resources, power supply, et cetera) will be extrapolated to a larger extent (both Iceland and the Netherlands). Up-scaling advantages or disadvantages will be taken into account.

All data will be implemented into an Excel model for both energy/CO$_2$ analysis and the comparison between different locations. Furthermore, PowerPlan will be used to simulate and calculate the potential oversupply of renewable energy (solar and wind) in the Netherlands that can be used for methanol production.
CHAPTER 2 METHANOL SYNTHESIS

Robert Boyle already discovered methanol in 1661, but no evidence exists that it had any purpose at that time. The first records of methanol use were only after the 19th century. In 1834, the molecular identity of methanol was confirmed by Dumas and Peligot. The first successful process of methanol synthesis was already accomplished in 1857 with wood as a feedstock (Ohla et al., 2006). From then, large improvements have been made in the synthesis of methanol to use as for example a replacement for conventional gasoline (Lee, 1990).

2.1 Process description

The first idea of using synthesis gas (CO and H₂) for producing methanol was found by Paul Sabatier in 1905. Eight years later, the first synthesis patent was given to the Badische Anilin und Soda Fabrik (BASF; Cheng et al., 1994). The synthesis process developed by BASF, operates at an temperature between 573 and 673 K and a pressure between 100 and 250 bar over sulfur-resistant ZnO/Cr₂O₃ catalyst. Ten years later, the first commercial methanol synthesis plant was build. For many years this was the only, but not energy-efficient technique, to produce methanol. In this exothermic process, synthesis gas is converted into methanol (equation 2.1).

\[
\text{CO} + 2\text{H}_2 \rightarrow \text{CH}_3\text{OH} \quad - \Delta H = 91 \text{ kJ/mole} \quad (2.1)
\]

\[
\text{CO}_2 + 3\text{H}_2 \rightarrow \text{CH}_3\text{OH} + \text{H}_2\text{O} \quad - \Delta H = 49 \text{ kJ/mole} \quad (2.2)
\]

In 1927, methanol was produced for the first time by using CO₂ instead of CO, and H₂, both obtained as fermentation gases (Edmonds, 1932). This exothermic reaction is shown in equation 2.2. In the same year, DuPont improved the BASF process with a more efficient zinc/copper catalyst. Both processes, with coal as a feedstock, continued to produce methanol up to 1940, when natural gas became abundant. From this time on, only the reforming of natural gas was used to produce methanol because natural gas as a feedstock was economical more beneficial (Lee, 1990).

The first real breakthrough for energy-efficient production of methanol was in 1966 by Imperial Chemical Industries (ICI, now Synetix), which developed a Cu/ZnO/Al₂O₃ catalyst (Weissermel, 2003). This process operates at relatively low pressures (50 – 100 bar) and lower temperatures (523 – 573 K). In this process, the first time only 10-15% of the new inlet gasses will be converted into methanol and water (equation 1.2), the rest remains unreacted. To achieve high conversion rates, and therefore a higher energy efficiency, ICI developed a process in which the unreacted gasses were recycled and put back into the catalyst of the reactor. Another improvement was that the inlet gasses and the recycled gasses were preheated by a heat exchanger before they were inserted into the reactor vessel. The exothermic heat that was generated by the conversion process was recovered in the reactor vessel and used to preheat the feed water from the boiler. This new process of methanol synthesis was the end of the inefficient methanol production techniques developed by BASF and DuPont (Lee, 1990). A few years later, the Lurgi low-pressure process was developed which uses overall the same type of catalyst. The difference with the ICI process is that the temperature of the inlet gasses are regulated by boiling water in the reactor instead of preheating the synthesis gas outside the reactor vessel.

Currently commercial production plants only use fossil fuels to produce methanol. Natural gas is the most commonly used feedstock because of the relatively high hydrogen content and the lowest energy consumption compared to other feedstocks such as coal and oil. Also, natural gas has fewer impurities like sulphur (Ohla et al., 2006). The commercial methanol production techniques, together with their operating temperature and pressures are shown in table 2.1.
Table 2.1: Methanol production techniques with operating temperatures and pressures (Lee, 1990; Ohla et al., 2006; Forschungszentrum Jülich, 2004).

<table>
<thead>
<tr>
<th>Catalyst</th>
<th>Temperature (K)</th>
<th>Pressure (bar)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BASF/DuPont</td>
<td>CuO/ZnO/Al₂O₃</td>
<td>573 - 673, 100 - 250</td>
</tr>
<tr>
<td>ICI</td>
<td>CuO/ZnO/Al₂O₃</td>
<td>523 - 573, 50 - 100</td>
</tr>
<tr>
<td>Lurgi</td>
<td>CuO/ZnO/(Al₂O₃)</td>
<td>503 - 523, 40 - 50</td>
</tr>
</tbody>
</table>

In 2006, 60% of the commercial methanol was produced by the process of ICI and 27% by the Lurgi process (Ohla et al., 2006). The rest was generally produced by the Kellog process or in laboratories. According to the patents of the Icelandic company CRI, they are using the Lurgi methanol processes with H₂ and CO₂ as feedstock. H₂ is produced by the electrolysis of water and CO₂ is recovered from a geothermal power plant located in Svartsengi. These two streams are compressed to approximately 50 bars and a temperature around 498 K. After the reactor vessel, a mixture of unreacted H₂/CO₂, methanol and water (by-product), flows through a heat exchanger to preheat the inlet gasses. After that, this mixture flows to a preheater for the distillation system and then methanol is condensed in a condenser. (Global CCS institute, 2011; Forschungszentrum Jülich, 2004; Carbon Recycling International, 2012). In the following paragraphs several possibilities and the required energy to obtain H₂ and CO₂ are discussed. Besides this, a process and energy analysis is developed.

2.2 Electricity sources

In this report, several energy sources are discussed that could generate the required electricity that is needed for methanol production. All of these mentioned sources are suitable for electricity generation.

Hydropower (Iceland)

Hydropower is derived from moving water to produce electricity. It is the world’s largest renewable energy source for electricity production. Currently, about 2.2% of the total primary energy supply (TPES) is generated by hydropower, which is equal to 17% of all produced electricity in the world (IEA Renewable information, 2011b). Only 18% of the potential of hydropower is in use today. However, the Netherlands does not have a large hydropower potential and for this reason only the hydropower potential in Iceland is researched.

Geothermal power (Iceland)

Electricity can also be generated from geothermal energy. This is currently used in 24 countries with a total capacity of about 11 GWₑ. Geothermal power can be seen as a renewable source of energy because the heat that is extracted from the earth is only a small part of the total heat content of the entire earth (Geothermal Energy Association, 2010). The main environmental drawback of large-scale electricity generation from geothermal energy (specifically in volcanic area’s) is that the wells contain high amounts of CO₂, derived from metamorphism of carbonate with worldwide average emissions of 122 g CO₂ per generated kWhₑ (Armannsson et al. 2005). A detailed research of emissions from geothermal energy sources is described in chapter 3. Because the Netherlands does not have a large scale potential of geothermal electricity generation from high temperature reservoirs, only geothermal electricity generation in Iceland is discussed in this research.

Wind (off- and onshore)

Currently, wind power is the fastest growing renewable energy source, especially in Europe. For example, in Denmark, over 20% of the demand for electricity is generated by wind power. Because Iceland has a large potential of inexpensive production of electricity using geothermal and hydropower, only the implementation of wind power in the Netherlands is discussed. According to the Central Bureau of Statistics (CBS, 2012), a total capacity of 2237 MWₑ is currently installed in the Netherlands, of which is only 10% is offshore. In the coming decades, the Netherlands is planning to expand the capacity of both on- and offshore wind turbines. This is discussed in more detail in chapter 4.
Solar power (photovoltaics)

Photovoltaic (PV) solar panels convert solar radiation into electricity by using semiconductors. Commonly used materials in PVs are monocrystalline silicon, polycrystalline silicon, amorphous silicon, cadmium telluride, and copper indium gallium selenide/sulphide. Currently, in about 100 countries a total electrical capacity of 67 GW is installed which generated over 80 billion kWh in 2011 (European Photovoltaic Industry Association, 2012). Besides wind energy, the Netherlands is planning to implement large amounts of solar power. This is discussed in more detail in chapter 4.

2.3 Hydrogen production

CRI produce methanol with the Lurgi process by only using a mixture of CO₂ and H₂. In this paragraph, the possibilities of hydrogen production are discussed together with the energy requirements. Current demand for commercial H₂ is still limited to a few niche markets such as space facilities, feedstocks for the chemical industries and fuel for new transportation alternatives.

Techniques for hydrogen production are steam methane reforming (SMR, with natural gas a feedstock), coal gasification, oil reforming and water electrolysis. In 2005, about 96% of all hydrogen was produced by the use of fossil fuels (figure 2.1). Although this is currently the most inexpensive method for hydrogen production, large amounts of CO₂ and other greenhouse gasses are emitted during this process. Furthermore, fossil fuel reserves will decline. Today, the only large scale clean and relatively efficient technique for producing hydrogen is electrolysis of water, using electricity generated from renewable energy sources. The advantage of this method is the high purity of hydrogen, which cannot be achieved by any other production technique. Due to high costs, this production technique only accounts for 4% of all worldwide commercially produced hydrogen (Ewan & Allen, 2005).

In this research, only hydrogen production from the electrolysis of water is discussed, because in all other production techniques fossil fuels are used. The required energy for the electrolysis process is generated by renewable energy sources, which were discussed in paragraph 2.2. The idea of using renewable energy for producing hydrogen is not new and was already mentioned as an option in 1975 (Eisenstadt, 1975). However, the interest in renewable hydrogen production only started in the 1990s, when people became concerned about climate change and the diminishing fossil fuel reserves.
2.3.1 Electrolyser technologies

The only commercial electrolysis technologies for hydrogen production are currently Alkaline water electrolysis (uni- or bipolar) and Proton exchange membrane (PEM) electrolysis. Other types exist but these will not be discussed (Teledyne, 2004; National Renewable Energy Laboratory, 2004; Larminie & Dicks, 2003). Alkaline electrolysers were first produced in 1928 by Norks Hydro in Norway (now NEL) with an aqueous solution of potassium hydroxide (KOH) because of its high conductivity. In an unipolar version, the electrodes are connected parallel, in the bipolar version these are installed in series, which results in a higher production capacity. NEL is currently the world leading company that provide alkaline electrolysers for large scale hydrogen production (National Renewable Energy Laboratory, 2004). PEM electrolysers are the best option for small scale commercial hydrogen production (Tolga Baltaa, 2009).

2.3.2 Energy consumption

At this moment, only Stuart, Teledyne, Proton, H2 Logic, Hydrogenics, Avalence Hydrofiller and NEL build industrial large scale electrolysis units. In this report, 41 large scale hydrogen electrolysers are researched and compared to each other. The capacity of these units varies between 0.3 and 380 tons of H2 a year. Proton only build PEM electrolysers, Avalence Hydrofiller build unipolar electrolysers and the other five companies build bipolar electrolysers. A complete list of the 41 electrolysis units is reported in appendix A.

All of the mentioned electrolyser units only require raw water (at ambient temperature) and electricity as an input. A flow chart of a unit is shown in figure 2.2. The purification of raw water and the separation of oxygen, hydrogen and unreacted water are included in the energy requirements of an electrolyser unit. In table 2.2, the specifications and energy consumptions of the largest capacity unit of each company are shown. Detailed information is given for each column in the table.

1. **Conversion efficiency**: the efficiency of converting water into hydrogen and oxygen. Water that has not been used in the electrolysis process is recycled. A lower conversion efficiency means a higher energy consumption. Commonly, PEM electrolysers have higher conversion efficiencies than alkaline electrolysers (National Renewable Energy Laboratory, 2004).
2. **Energy consumption**: the overall energy consumption in kWh/kgH2 that is given by the manufacturers of electrolyser units. Energy consumption values mainly vary because the endproduct (hydrogen) has a specific endpressure.
3. **Product pressure**: the hydrogen endpressure given in bars before it is stored. In an electrolyser unit, compression of atmospheric hydrogen is in some cases included.
4. **Energy efficiency (incl. pressure)**: the energy efficiency given by the manufacturers. This is including the compression of hydrogen for some electrolysers.
5. **Energy consumption without compression**: to fairly compare the energy consumption for hydrogen production, the end pressure has to be equal for each electrolyser unit because hydrogen compression is energy intensive. In this column, the energy consumption is given in kWh/kg\(H_2\) at atmospheric pressure. For this justification, assumed is a polytrophic compression of hydrogen with an overall mechanical efficiency of 72%. Detailed information of this calculation is discussed in paragraph 2.5.

6. **Energy efficiency (excl. pressure)**: the energy efficiency of hydrogen production with an atmospheric end pressure (ATM).

7. **Lifetime**: the lifetime of an electrolyser unit given in years. This information could be used for further research to investigate for example the costs of hydrogen production or the environmental impact of building electrolysers. In this research, both examples will not be discussed.

![Flow chart of a PEM or Alkaline electrolyser.](image)

**Figure 2.2: Flow chart of a PEM or Alkaline electrolyser.**

**Table 2.2: Specifications and energy consumptions of each electrolyser unit**

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Avalence Hydrofiller 175</td>
<td>10</td>
<td>3622</td>
<td>Unipolar alkaline electrolyser</td>
<td>0.89</td>
<td>60.5</td>
<td>414</td>
<td>65.2%</td>
<td>55.8</td>
<td>70.7%</td>
<td>N/A</td>
</tr>
<tr>
<td>Proton HOGEN 380</td>
<td>22</td>
<td>7875</td>
<td>Proton exchange membrane electrolyser</td>
<td>0.95</td>
<td>70.1</td>
<td>13.8</td>
<td>56.2%</td>
<td>68.9</td>
<td>57.2%</td>
<td>5-7</td>
</tr>
<tr>
<td>Hydrogenics HySTAT-15-10</td>
<td>32</td>
<td>11732</td>
<td>Bipolar alkaline electrolyser</td>
<td>N/A</td>
<td>54.8</td>
<td>ATM</td>
<td>71.8%</td>
<td>54.9</td>
<td>71.8%</td>
<td>N/A</td>
</tr>
<tr>
<td>Teledyne EC-750</td>
<td>91</td>
<td>33069</td>
<td>Bipolar alkaline electrolyser</td>
<td>0.8</td>
<td>62.3</td>
<td>4.1</td>
<td>63.3%</td>
<td>61.8</td>
<td>63.3%</td>
<td>15</td>
</tr>
<tr>
<td>H₂ Logic 64.00D</td>
<td>91</td>
<td>33335</td>
<td>Bipolar alkaline electrolyser</td>
<td>N/A</td>
<td>56.7</td>
<td>ATM</td>
<td>69.5%</td>
<td>56.7</td>
<td>69.5%</td>
<td>N/A</td>
</tr>
<tr>
<td>Stuart IMET 1000, 4 cell stack, 1000 cm³</td>
<td>194</td>
<td>70863</td>
<td>Bipolar alkaline electrolyser</td>
<td>0.8</td>
<td>53.4</td>
<td>24.8</td>
<td>73.8%</td>
<td>51.9</td>
<td>76.0%</td>
<td>10</td>
</tr>
<tr>
<td>NEL Atmospheric Type No.5040 (5150 Amp DC)</td>
<td>1046</td>
<td>381864</td>
<td>Bipolar alkaline electrolyser</td>
<td>0.8</td>
<td>53.5</td>
<td>30.0</td>
<td>73.7%</td>
<td>51.8</td>
<td>76.1%</td>
<td>7-10</td>
</tr>
</tbody>
</table>

* ATM = Atmospheric pressure of 100 kPa, N/A = Not Available

Despite the lower conversion efficiency of bipolar alkaline electrolysers that are shown in table 2.2 [1], they are the most energy efficient with a consumption of around 52-54 kWh/kg\(H_2\). PEM electrolysers have a higher energy consumption, which is around 70 kWh/kg\(H_2\). As already mentioned, PEM electrolysers are more suitable for small scale use (Tolga Baltaa, 2009). In conclusion, a unipolar alkaline electrolyser (Avalence Hydrofiller) has an energy efficiency of around 70%. A bipolar large scale alkaline electrolyser (NEL) has an energy efficiency of around 76% and a PEM electrolyser (Proton HOGEN) an efficiency around 57%. It is not known which type or brand electrolyser unit the Icelandic company CRI
uses for its production of renewable methanol. However, in a recent project of Shell and the Icelandic government, they had built the world’s first commercial hydrogen facility (for transport purposes) with an electrolyser from NEL (Rifkin, 2004). In this research, it is assumed that CRI also uses the highly efficient electrolysers from NEL in new commercial methanol production facilities.

2.3.3 Thermal energy for hydrogen production

Electrolysis of water at relatively low temperatures (293 K) is faced with a limited theoretical efficiency of 83% (see textbox 1). However, the performance can be improved by using partly thermal energy. This results in a lower electricity consumption during the production of hydrogen. According to Sigurvinsson et al., (2007): “Because the conversion efficiency of heat to electricity is low compared to using heat directly, the energy efficiency can be improved by supplying the system with energy in the form of heat rather than electricity.” In this paragraph, four different processes of using thermal energy for hydrogen production are discussed together with their maximum improvement potentials.

Case 1: Water electrolysis with a raw water inlet temperature of 293 K. This process, and the energy consumption of hydrogen production were already discussed in paragraph 2.3.2. Basically, any source of electricity can be used in this case.

Case 2: Water electrolysis with preheated raw water from waste heat or from geothermal steam. When fossil fuel power plants are used to generate electricity, waste heat is available. In this situation, this is used for preheating the raw inlet water. The inlet water can also be preheated with geothermal energy (no waste heat; Sigurvinsson et al., 2007).

Case 3: High temperature water electrolysis from geothermal energy sources. Only geothermal thermal energy is used for producing hydrogen. Because the inlet temperature of geothermal sources is lower than the required temperature for HTE electrolysis, heat exchangers are required to bring water to a temperature of at least 1273 K. This process is currently under development and according to Sigurvinsson et al., (2007) this will be operational in the coming ten years.

Case 4: High temperature water electrolysis from nuclear power. HTE electrolysis with thermal energy generated from nuclear power plants. This technique is already commercially used and operational in new nuclear power plants. Because no new nuclear power plants are planned in Iceland or in the Netherlands, this case is not further discussed in this report.
Using the data and calculations of Sigurvinsson et al., (2007), the potential improvements of using thermal energy for hydrogen production are calculated. In table 2.3, a summary of the electrical energy efficiency of each electrolyser that is discussed in paragraph 2.3.2 is shown, applied with the case 1, 2 & 3. As already mentioned, case 3 is still under development and will perhaps be possible in the coming decades. Nevertheless, as an indication, these results are also shown in the table. Case 4 will not be discussed.

Table 2.3: Energy efficiency electrolyzers applied with case 1, 2 & 3. Calculations based on Sigurvinsson et al., (2007).

<table>
<thead>
<tr>
<th>Electrolyser</th>
<th>Case 1</th>
<th>Case 2</th>
<th>Case 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Avalence Hydrofiltrer 175</td>
<td>70.7%</td>
<td>74.3%</td>
<td>85.2%</td>
</tr>
<tr>
<td>Proton HOGEN 380</td>
<td>57.2%</td>
<td>60.1%</td>
<td>68.9%</td>
</tr>
<tr>
<td>Hydrogenics HySTAT-15-10</td>
<td>71.8%</td>
<td>75.5%</td>
<td>86.6%</td>
</tr>
<tr>
<td>Teledyne EC-750</td>
<td>63.8%</td>
<td>67.0%</td>
<td>76.9%</td>
</tr>
<tr>
<td>H2 Logic 64.00D</td>
<td>69.5%</td>
<td>73.1%</td>
<td>83.8%</td>
</tr>
<tr>
<td>Stuart IMET 1000, 4 cell stack, 1000 cm³</td>
<td>76.0%</td>
<td>79.9%</td>
<td>91.6%</td>
</tr>
<tr>
<td>Norsk Atmospheric Type No.5040 (5150 Amp DC)</td>
<td>76.1%</td>
<td>80.0%</td>
<td>91.7%</td>
</tr>
</tbody>
</table>

In conclusion, the efficiency of hydrogen production can relatively easy (technical and economic) be improved by a few percent (difference case 2 and 1) by using partly thermal energy. The potential source in Iceland is geothermal steam/water and in the Netherlands waste heat from fossil fuels power plants. By using renewable energy sources such as solar and wind power, the efficiencies in case 1 are used.

2.3.4 Variable energy sources

The electrical output from geothermal and hydropower plants can be controlled and is therefore predictable. This is not the case with other renewable energy source like solar and wind. Existing electrolyzers require a constant and reliable source of electricity for producing hydrogen. With the implementation of renewable energy sources in, for example the Netherlands, this could result in less efficient hydrogen production (Gandía et al., 2007).

One of the ideas of producing renewable methanol in the Netherlands is that methanol could function as an energy buffer for storing surpluses of electricity that are generated by wind or solar energy. The main drawback of this oversupply is the unpredictability and the non-constant output. None of the currently produced electrolyzers can officially handle these two drawbacks. Little information is known about consequences of large scale hydrogen production with variable energy inputs such as solar and wind. Wind energy in combination with hydrogen production is more realistic than solar energy from an economic point of view and for this reason more experimental information in literature is available.

In the last ten years, experiments with existing electrolyzers and electricity that is generated by wind have been performed. These show that it is technically possible for an electrolyser to handle unpredictable and variable energy input from wind. In a study described by Gandía et al., (2007), hydrogen is produced with an alkaline electrolyser (bipolar) from the manufacturer Hydrogenics. Wind patterns from Sierra del Perdon (Spain) are used to simulate a realistic electricity output. The efficiency of the electrolyser decreased on average by 9% when using this pattern.

Wind energy in combination with hydrogen production is more realistic than solar energy from an economic point of view and for this reason more experimental information in literature is available.

The advantage of solar power (PV) is the generation of direct current (DC) power instead of alternating current (AC). In electrolyzers, first AC is converted into DC before the process begins. Using DC instead of AC could increase the efficiency of hydrogen production by a few percentages (Sherif et al., 2005). According to Ursúa et al., (2010), using solar power in combination with a DC/DC maximum power point tracker (MMPT), the efficiency drop is 6-7% depending on the solar radiation (direct or indirect sunlight). Little literature is available on other calculations and experiments with variable energy sources and hydrogen production but on average these results are in line with the efficiencies drops calculations from Gandía et al., (2007) and Ursúa et al., (2010). For this reason, these numbers will be used in this report.
2.4 CO₂ Recovery

Nearly all produced methanol is based on synthesis gas from coal, oil or natural gas. In this report, the focus is on renewable methanol production that only requires concentrated streams of H₂ and CO₂ as a feedstock. As described in the previous paragraph, H₂ can be produced in a sustainable way via the electrolysis of water in combination with renewable energy sources. However, CO₂ has to be recovered from other sources. In this paragraph, the possibilities of recovery are discussed together with their energy requirements.

2.4.1 CO₂ sources

The used CO₂ sources that will be discussed in this report are:
- Flue gas from existing natural gas (NG) electricity power plants
- Flue gas from new or existing coal-fired electricity power plants
- CO₂ emissions from integrated gasification combined cycle (IGCC) power plants
- Geothermal media (Iceland)
- Atmospheric air

The standard overall energy efficiency of existing NG power plants is about 55 up to 58%. For existing (old) coal-fired power plants this is about 33 up to 37% and for new coal-fired power plant about 41 up to 45%. An important fact is that CO₂ recovery from power plants reduces the overall efficiency of electricity generation largely because capture CO₂ is energy-intensive (Intergovernmental Panel on Climate Change, 2005). This would also affect the total energy requirement of renewable methanol production. Also, CO₂ can be recovered from geothermal fluids that have relatively high concentrations of CO₂ compared to atmospheric air (Cleanindex, 2012; Armansson & Dereinda, 2010). The last option is recovery from atmospheric air. The CO₂ concentrations (by volume) of each discussed source are important to investigate the required energy for the recovery. In table 2.4, these concentrations are shown and will be used for further calculations.

![Table 2.4: CO₂ concentrations by volume of various sources.](image)

<table>
<thead>
<tr>
<th>Source</th>
<th>CO₂ Concentration by volume [%]</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flue gas Coal-fired / IGCC</td>
<td>12 - 15</td>
<td>IEA GHG, 2002</td>
</tr>
<tr>
<td>Flue gas NG</td>
<td>3 - 10</td>
<td>IEA GHG, 2002</td>
</tr>
<tr>
<td>Geothermal media (Iceland)</td>
<td>0.4 - 6</td>
<td>Cleanindex, Armansson &amp; Dereinda, 2010</td>
</tr>
<tr>
<td>Atmospheric air</td>
<td>0.0384 - 0.0400</td>
<td>Lackner, 2009; Bockris, 2010</td>
</tr>
</tbody>
</table>

2.4.2 Recovery systems in power plants

CO₂ can be recovered from power plants with three different techniques: post-combustion recovery, pre-combustion recovery and oxy-fuel combustion. These techniques will briefly be discussed in this paragraph.

2.4.2.1 Post-combustion recovery

Post-combustion recovery is basically the first technique that was developed for the recovery from power plants. After the combustion of natural gas or coal, flue gasses will not go directly into the atmosphere but will pass through a CO₂-separation unit. Commonly, a chemical absorbent (discussed in paragraph 2.4.3) is used to separate CO₂ from the rest of the flue gasses. This technique of recovery can be installed in NG or in coal-fired power plants (Intergovernmental Panel on Climate Change, 2005).

2.4.2.2 Pre-combustion recovery

A relatively new technique is recovery before the combustion in IGCC power plants. Coal reacts with oxygen, air or steam to form synthesis gas (CO and H₂). CO reacts in a reactor with steam and is converted into CO₂. This CO₂ will be chemically absorbed and separated (Intergovernmental Panel on Climate Change, 2005). Due to high capital costs, these systems are not commonly used. According to the IEA World energy outlook (WEO), in 2010 only 0.1% of all installed coal-fired power plants make use of this pre-combustion technique (International Energy Agency, 2010).
2.4.2.3 Oxy-fuel combustion recovery
For this technique almost pure oxygen is used for the combustion of fossil fuel. This results in high temperatures and therefore the flue gasses almost only consist of CO$_2$ and H$_2$O. After the combustion, the recovery will be the same as described with a post-combustion system. This recovery is still under development and not applied in large scale power plants (Intergovernmental Panel on Climate Change, 2005) For this reason, this technique will not be discussed in this report.

2.4.3 Recovery technology
After the combustion of fossil fuels, whether this is with a pre- or post-combustion system, CO$_2$ must be separated from other flue gasses. From geothermal fluids, CO$_2$ must be separated mainly from H$_2$S (Dunstall & Graeber, 1997). The challenge of CO$_2$ recovery from atmospheric air is the relatively low CO$_2$ concentrations (Lackner, 2009; Bockris, 2011). CO$_2$ can be recovered by passing a CO$_2$-containing medium through a solid or liquid absorber. This absorber has to be capable of capturing only CO$_2$ and no other components in this CO$_2$-containing medium. Figure 2.4 shows a simple scheme of this process. When CO$_2$ is absorbed in system a, with a specific absorption efficiency, it is separated in system b, which results in a high concentrated sources of CO$_2$. The absorbers can be reused in system a.

Figure 2.4: Simple scheme of CO$_2$ recovery with an absorber. Figure based on Intergovernmental Panel on Climate Change, 2005

Used absorbers for CO$_2$ recovery in large scale recovery facilities are:
- Monoethanolamine (MEA)
- Methyl diethanolamine (MDEA)
- Sodium hydroxide (NaOH)
- Magnesium oxide (MgO)

The problem with CO$_2$ recovery is the large flow between system a and b which results in large equipments when high concentrations of CO$_2$ have to be captured. Therefore, this could be a problem when install CO$_2$-recovery systems in existing power plants. Furthermore, a large amount of electricity is needed for recovery, which is significant for already existing low-efficient coal-fired power plants. Other technologies for CO$_2$ recovery such as the separation by membranes or by cryogenic debilitation are only used at a small scale or are under development and therefore not discussed in this report.

2.4.4 Energy consumption
Only a few power plants have an option for the recovery of CO$_2$. In this section, the energy consumption of CO$_2$ recovery is investigated. On a basis of gathering studies that actually measured the required energy for CO$_2$ recovery, average energy consumptions are calculated. In table 2.5, these results are shown together with the references that are used.

Flue gas from electricity power plants (NG and coal-fired power plants)
NG power plants do have relatively clean flue gasses compared to coal-fired power plants, which is more beneficial for CO$_2$ recovery. This results in an average recovery electric energy consumption of 1.69 MJ/kgCO$_2$. For coal-fired power plants this is slightly more with an average 1.77 MJ/kgCO$_2$. 

19
\textit{CO}_2 \textit{from integrated gasification combined cycles (IGCC) power plants}

CO\textsubscript{2} recovery from coal before electricity is generated consumes less energy due to less impurities. The average consumption is 1.30 MJ/kgCO\textsubscript{2}.

\textit{Geothermal steam (Iceland)}

Geothermal steam in Iceland consists basically of water, CO\textsubscript{2} and H\textsubscript{2}S. Other components in these streams are neglected in this report. According to Cleanindex, (2012) and Dunstall & Graeber, (1997), average geothermal steam contains about 0.4\% CO\textsubscript{2} and 0.075\% of H\textsubscript{2}S (by volume). CO\textsubscript{2} and H\textsubscript{2}S are absorbed by MDEA and both are separated afterwards. The energy consumption of this process is around 1.16 MJ/kgCO\textsubscript{2} with a recovery efficiency up to 90\% (Carbon Recycling International, 2012; Dunstall & Graeber, 1997).

\textit{Atmospheric air}

An ambitious way of CO\textsubscript{2} recovery is the extraction of it from ambient air. In power plants, preferred is that at least 85-90\% of CO\textsubscript{2} from flue gasses will be recovered. The advantage of CO\textsubscript{2} recovery from air is that it does not have to recover high amounts of CO\textsubscript{2} from a specific air stream, which results in a lower energy consumption compared to a recovery system from a power plant. According to Stolaroff \textit{et al.}, (2008), the minimum thermodynamic energy that is required to capture 1 kg of CO\textsubscript{2} from air with a NaOH absorber is only 0.45 MJ. However, in practice this varies between 1.1 and 8.2 MJ/kgCO\textsubscript{2} (Bockris, 2010; Luckner, 2009; Specht \textit{et al.}, 2000). Furthermore, large surfaces are needed to recover only a small amount of CO\textsubscript{2}. 
Table 2.5: Summary of CO\textsubscript{2} recovery specification for selected sources. Information is based on: Intergovernmental Panel on Climate Change, 2005 *

<table>
<thead>
<tr>
<th>CO\textsubscript{2} Source</th>
<th>Existing NG Plant</th>
<th>Existing Coal-fired Plant</th>
<th>New Coal-fired Plant</th>
<th>New IGCC Plant</th>
<th>Geothermal steam</th>
<th>Atmospheric air</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Min.</td>
<td>1.59</td>
<td>1.70</td>
<td>0.97</td>
<td>-</td>
<td>Min.</td>
</tr>
<tr>
<td></td>
<td>Max.</td>
<td>1.90</td>
<td>1.84</td>
<td>1.49</td>
<td>-</td>
<td>Max.</td>
</tr>
<tr>
<td></td>
<td>Avg.</td>
<td>1.69</td>
<td>1.77</td>
<td>1.30</td>
<td>-</td>
<td>Avg.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Energy consumption (MJ/kgCO\textsubscript{2})</td>
<td>379</td>
<td>351</td>
<td>520</td>
<td>521</td>
<td>1.16</td>
<td>Min.</td>
</tr>
<tr>
<td>Reference Capacity (MW\textsubscript{e})</td>
<td>327</td>
<td>275</td>
<td>408</td>
<td>455</td>
<td>-</td>
<td>Max.</td>
</tr>
<tr>
<td>Reference PP Net efficiency</td>
<td>47.4%</td>
<td>21.6%</td>
<td>34.9%</td>
<td>39.0%</td>
<td>-</td>
<td>Avg.</td>
</tr>
<tr>
<td>Recovery PP Capacity (MW\textsubscript{e})</td>
<td>429</td>
<td>275</td>
<td>329</td>
<td>457</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Recovery PP Net efficiency</td>
<td>47.9%</td>
<td>21.6%</td>
<td>30.1%</td>
<td>31.3%</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>More fuel input</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Recovery efficiency</td>
<td>85.0%</td>
<td>80.0%</td>
<td>88.0%</td>
<td>89.0%</td>
<td>90.0%</td>
<td></td>
</tr>
<tr>
<td>Absorber</td>
<td>MEA</td>
<td>MEA</td>
<td>MEA</td>
<td>MEA</td>
<td>MDEA</td>
<td>N/A</td>
</tr>
</tbody>
</table>

* Min/Max = Minimal or Maximum energy consumption for capturing CO\textsubscript{2} that is found in literature

CO\textsubscript{2} recovery from geothermal streams seems to be the most energy-efficient source. This is because these streams generally only consist of CO\textsubscript{2} and H\textsubscript{2}S, which are in practice relatively easy to separate (CO\textsubscript{2} and H\textsubscript{2}S have a different solubility in water). The energy that is required for the recovery in fossil fuel power plants is slightly higher due to less pure flue gases. However, in both situations, CO\textsubscript{2} will be absorbed by an absorber (whether this would be MDEA or MEA). All the energy consumption results from geothermal and fossil fuel power plants that are shown in table 2.5 are generally between 1.0 and 2.0 MJ/kgCO\textsubscript{2}, which is in most literature used as a ‘standard’.

The recovery from atmospheric air is completely different. Due to low concentrations of CO\textsubscript{2} in the air, other absorbers are needed (commonly NaOH). Furthermore, to achieve a high production capacity (kgCO\textsubscript{2}/hour), large airflows are needed. This is commonly achieved by using large fans, which consume electricity. Little information is available about the practical energy consumption of this recovery technique and therefore ranges between 1.10 and 8.20 MJ/kgCO\textsubscript{2}. The largest advantage of the recovery of CO\textsubscript{2} from air is that CO\textsubscript{2} concentration in the air actually could decrease with these techniques.
2.5 Energy and material analysis
Methanol synthesis from CO₂ and H₂ is an exothermic reaction. For this process, no extra electricity is needed. The only requirement for this process is that the inlet gases (H₂/CO₂) have to be at the correct temperature of 503 K and pressure of 50 bars. Thermal energy can be used to achieve this relative high inlet temperature or, when no thermal energy is available, electricity. In this paragraph, the methanol synthesis process according to the Lurgi system is analysed.

2.5.1 Flowchart
In figure 2.5, a flowchart of the methanol synthesis process is shown. The process begins with new, at ambient temperature and atmospheric pressure, input of H₂ [1] and CO₂ [2]. These gases have to be compressed to a pressure of 50 bar before they flow into the reactor. After compression [3], these are mixed with gases that were not used the first time in the synthesis reactor (explained below). This mixture [4] is preheated in [CONDENSOR1] and in heat exchangers before they flow into the reactor [5-6]. The first heat exchanger [HX1] is fed by exothermic energy from the conversion (equation 2.2). The second heat exchanger [HX2] uses, when necessary, external thermal energy to achieve the required inlet temperature of at least 503 K. After the [REACTOR] with a Cu/ZnO/(Al₂O₃) catalyst [7], part of the H₂ and CO₂ have been converted into methanol and H₂O. Assumed in this research is a conversion ratio of 7.9, which is equal to 12.7% (Mignard, 2003). In other words, only a small part of the gases will be converted into methanol the first time. During this exothermic process, the gases reach a temperature of about 558 K. A part of this energy is transferred by the first heat exchanger [HX1] to the inlet gases [5]. Afterwards, the gases [8] still have a large energy potential and in the [PREHEATER] another part of this energy is transferred to feed water/steam for the [DISTILLATION] column. After the [PREHEATER], this mixture [9] is still in a gaseous phase (methanol as well as CO₂, H₂ and H₂O). To achieve high conversion efficiency, unreacted H₂ and CO₂ have to be recycled and brought back into the reactor. Therefore, other fluids (methanol and H₂O), have to be separated. This mixture [9] flows into the [CONDENSOR1] to condensate only methanol and H₂O. The other gases will remain in a gaseous phase. This mixture [10], at a pressure of 45 bars and a temperature of about 300 K, flows to the [SEPARATOR]. Unreacted CO₂ and H₂ [11] will be recycled and compressed from 45 to 50 bars and will join the new input stream [3]. This difference in pressure before and after the entire process is caused by temperature differences, heat exchange efficiencies, equipment losses et cetera. Liquid methanol and H₂O are separated in the [DISTILLATION] column. For this process, thermal energy is required. Methanol has a boiling point of about 338 K and first will be preheated by waste water of the distillation column in the heat exchanger number 3 [HX3]. Methanol and H₂O will flow into the [DISTILLATION] column at a pressure of 1.5 bars [14]. In this column, preheated water/steam from the preheater is used to raise the temperature of this mixture [14] above 338 K. Furthermore, external thermal energy is required to vaporize methanol. H₂O, which will stay liquid in this column, is a waste product but is still used in [HX3] to preheat the inlet mixture [12]. Afterwards, this waste H₂O can be recycled for hydrogen production. The vaporized methanol [16] is condensed in [CONDENSOR2] with the use of cooling water. Methanol is stored at ambient temperatures and at an atmospheric pressure [17]. A complete list of specification (temperature, pressure et cetera) of each stream that is shown in figure 2.5 can be found in appendix B.
2.5.2 Mass balance

Equation 2.3 (Reactor) shows the reaction in the reactor vessel. The required H\(_2\) is obtained from the electrolysis of water (equation 2.4). Water that is formed as a by-product in the reactor vessel can be recycled and used again for electrolysis to form H\(_2\). The energy balance that is discussed in this paragraph is on a basis of one kilogram of methanol. Methanol has a molecular weight of 32.04 g/mol, which means that 1 kg of methanol is equal to about 31.21 mol. The equation can be written as:

\[
\text{CO}_2 + 3 \text{H}_2 \rightarrow \text{CH}_3\text{OH} + \text{H}_2\text{O}
\]

Reactor (2.3)

\[
2\text{H}_2\text{O} \rightarrow 2\text{H}_2 + \text{O}_2
\]

Electrolysis (2.4)

For producing 1 kg of methanol, 1.374 kg CO\(_2\) and 0.187 kg H\(_2\) is required.

For producing 1 kg of methanol, 1.374 kg of CO\(_2\) and 1.124 kg of water (1.685-0.562) is required.
2.5.3 Energy consumption

In this paragraph, the main components that are discussed by the flowchart (figure 2.5) of renewable methanol production are investigated for their energy consumption.

Compression of gasses

Compression of gasses will consume energy. In this report, the compression of CO$_2$ and H$_2$ is performed separately with new inlet gasses and simultaneous with recycled gasses. The first compression step for inlet gasses is from an atmospheric pressure up to 50 bars. The second step is to compress the unreacted gasses from the reactor. The gasses have to be recycled multiple times to achieve a high conversion efficiency. The recycle ratio that is used in this report is 7.9 (Mignard, 2003). Assumed is a polytrophic compression with an efficiency of 72%. According to formula 3.3, the electrical Work ($W$) for the compression of gasses can be calculated.

$$W = \left(\frac{n}{n-1}\right) \cdot P_2 \cdot V_1 \cdot \left[\left(\frac{P_2}{P_1}\right)^{(n-1)/n} - 1\right]$$  \hspace{1cm} (3.3)

The $n$ is the specific heat ratio ($C_p/C_v$). For hydrogen $n = 1.410$ and for CO$_2$ $n = 1.289$. Furthermore, the initial pressure is important. In this report is assumed that the new inlet gasses have a pressure of 1 bar (100 kPa) and the recycled gasses a pressure of 45 bar (4,500 kPa). Both end pressures are 50 bar (5,000 kPa). Besides the specific heat ratio, the inlet volume with the specific temperature ($V_1$) is needed in $m^3/kg$. In this case CO$_2$ has a specific volume of $V_1 = 0.547 m^3/kg$ and for hydrogen $V_1 = 11.11 m^3/kg$. Hydrogen is the lightest element and therefore it has a large specific volume, which results in a high energy consumption for compression. In figure 2.6, both energy consumptions are shown in MJ/kg. For example, compressing 1 kg of atmospheric pressurised hydrogen up to a pressure of 300 bars, will require about 16 MJ/kg. For CO$_2$, the compression energy is significantly lower at about 0.6 MJ/kg.

Reactor

In the reactor, H$_2$ and CO$_2$ are converted into methanol and water as a by-product (formula 3.1). This process is exothermic with the correct inlet temperature and pressure. The energy that is released from this reaction can be calculated with formula 2.2. Heat that is involved with this process is $\Delta H = -49.7 kJ/mol$ of methanol. This results in: $-49.7 kJ \cdot 31.21 mol = -1.55 MJ/CH_3OH$

Distillation

In the distillation column, raw methanol and water are separated. The inlet temperature of this mixture [14] is approximately 333 K and it has a pressure of 1.5 bars. For separating both fluids, methanol will be vaporized and water remains in a liquid phase. For this process, energy from the [PREHEATER] and external thermal energy is used. The total energy consumption of the distillation column, including losses, pumping and condensation of methanol in the [CONDENSOR2], is estimated around 1.96 MJ/kg. This is in line with conventional distillation columns in methanol production facilities with natural gas as a feedstock (Methanex, 2006).

Auxiliary & losses

On a basis of specifications of four different power plants, the average electrical energy consumption of all equipment’s and losses of a methanol factory are calculated. An electric energy consumption of 0.96 MJ/kgCH$_3$OH is used as an average in this research (Parsons, 2002b).
CHAPTER 3 ICELAND

Iceland has a total area of 103,000 km², which is about 2.5 times larger than the Netherlands. It has a population of about 320,000 with a density of about 3.1/km². Iceland is geologically very active and has many volcanoes such as the Hekla, Eldgjá, Herðubreið and the Eldfell. Geothermal activity, rivers and waterfalls are largely available in Iceland, which gives Iceland the unique opportunity to generate inexpensive amounts of electricity and use thermal energy for district heating. In this chapter, overall information about the primary energy use, electricity generation and CO₂ emissions of Iceland are discussed. This is necessary for further calculations such as investigating the energy potential of this country, load factors of electricity production, the supply and demand of energy et cetera that are reported in the second part of this chapter.

3.1 Energy statistics

Figure 3.1a shows that currently in Iceland, more than 85% of all primary energy consumption is generated by renewable energy sources (66% geothermal and 19% hydro power). Iceland has a large potential of generating inexpensive electricity for its power intensive industry (mainly aluminium production). Furthermore, geothermal energy can also be used for heating purposes. In the primary energy use, geothermal power is the dominant source of energy.

Figure 3.1a (left): Primary energy consumption of Iceland from 1940 up to 2010 Based on: Orkustofnun/National Energy Authority of Iceland, 2012a. Figure 3.1b (right): Electricity production of Iceland by source from 1940 up to 2010 based on: Orkustofnun/National Energy Authority of Iceland, 2012b.

In figure 3.1b, the electricity production of Iceland is shown. In this case, hydropower is dominant. This can be explained because electricity production from hydropower is significantly more energy-efficient than the use of geothermal energy. Only a part of the geothermal energy (heat) can be converted into electricity (Kanoglu, 2010). Also, a part (45%) of geothermal energy is actually used for heating purposes (Orkustofnun, 2011). For this reason, the energy consumption share of geothermal energy, shown in figure 3.1, is larger than the hydropower share.

The largest purchaser of all the electricity is the aluminium industry with more than 12,000 GWh/yr. The rest is for private use, public services, agriculture et cetera (Orkustofnun, 2011). A complete list of purchasers of the electricity that is produced in Iceland can be found in appendix C1. Concluded is that the use of renewable energy sources are more than doubled in the last five years. Especially the installed capacity of hydropower has increased enormously. Renewable resources also have a limit. In the following paragraphs, the potential of electricity generation of Iceland is investigated.
3.2 Energy potentials

Currently, 55 hydropower plants are installed in Iceland, which generated 12.6 TWh$_e$ of electric power in 2010 (Iceland energy portal, 2012). A complete list of all the installed hydro power plants with their specifications, such as building year and capacity, can be found in appendix C1. On a basis of the total installed capacity and the electricity that is generated, an overall capacity factor is calculated. For the year 2010 this was 0.753. This number is used to investigate the potential of new hydropower plants. According to Bardardottir et al. (2006), the theoretical thermodynamic potential of hydropower in Iceland is 187 TWh$_e$/yr. Technically, 64 TWh$_e$/yr can be used by installing hydro power plants. In practice, without damaging the environmental too much and to keep it economically feasible only 30 TWh$_e$/yr can be used.

Seven geothermal power plants are currently installed in Iceland with a total capacity of 505 MW$_e$ (appendix C2). In 2010 these power plants generated a total amount of about 4,038 GWh$_e$ (Orkustofnun/National Energy Authority of Iceland, 2012b). This results in an overall capacity factor of 0.913. Geothermal power has a lower future potential for electricity generation compared to that of hydropower. Estimated by Bardardottir et al. (2006) is a potential production of 20 TWh$_e$/yr with a total capacity of 2400 MW$_e$. This potential is divided over the 18 potential (high temperature) reservoirs across Iceland.

However, these calculations of Bardardottir et al. (2006) are very rough estimations and only a few environmental and economic factors are taken into account. For the Icelandic government this was, among others, a reason to decide that they have to develop a master plan to investigate the future of renewable electricity production in Iceland. In this plan, next to environmental and economic aspects also social subjects are taken into account such as human impact for flora and fauna, vegetation, fishing in rivers, agriculture, geological formations, economic activity, employment and regional development et cetera. A steering group was appointed by the ministry of industry and the ministry of environment, which has been supported by more than 50 experts (Ingason, 2008; Landvernd, 2012).

After two years, the master plan was finished and the group reported that the maximum capacity of future hydropower plant is around 1200 MW$_e$. This potential capacity, which is shown in table 3.1, would be divided over 12 power plants across the country (figure 3.2). Combining this with the calculated capacity factor of 0.753 results in a potential electricity generation potential of 8,200 GWh$_e$/yr. For geothermal, the potential was slightly more with a capacity of 1400 MW$_e$ divided over 11 power plants (table 3.1). Combining this capacity with the earlier calculated capacity factor of 0.913, results in an electricity potential of 11,210 GWh$_e$/yr. These geothermal and hydropower potentials are used for further calculations in this report for the potential production of renewable methanol.

![Installed and potential hydro and geothermal power plants in Iceland](image)

<table>
<thead>
<tr>
<th>Hydropower plant</th>
<th>Capacity (MW&lt;sub&gt;e&lt;/sub&gt;)</th>
<th>Energy (GWh&lt;sub&gt;e&lt;/sub&gt;/yr)</th>
<th>Geothermal power plant</th>
<th>Capacity (MW&lt;sub&gt;e&lt;/sub&gt;)</th>
<th>Energy (GWh&lt;sub&gt;e&lt;/sub&gt;/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hvitaa</td>
<td>227</td>
<td>1,499</td>
<td>Krafla</td>
<td>240</td>
<td>1,922</td>
</tr>
<tr>
<td>Skattastadur</td>
<td>184</td>
<td>1,215</td>
<td>2 ðvarfðróður</td>
<td>240</td>
<td>1,922</td>
</tr>
<tr>
<td>Skaffa</td>
<td>140</td>
<td>924</td>
<td>3 Þeistareykid</td>
<td>200</td>
<td>1,601</td>
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<tr>
<td>Urðafoss</td>
<td>120</td>
<td>792</td>
<td>Krisuvik</td>
<td>240</td>
<td>1,922</td>
</tr>
<tr>
<td>Markarfljótt</td>
<td>106</td>
<td>700</td>
<td>Hellisheiði</td>
<td>200</td>
<td>1,601</td>
</tr>
<tr>
<td>Hrafnabjörg</td>
<td>89</td>
<td>588</td>
<td>Brennisteinsfjöll</td>
<td>80</td>
<td>641</td>
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<tr>
<td>Hólt</td>
<td>77</td>
<td>508</td>
<td>Þagðbúrgur</td>
<td>60</td>
<td>480</td>
</tr>
<tr>
<td>Dúpa</td>
<td>75</td>
<td>495</td>
<td>Bjarnafjöll</td>
<td>40</td>
<td>320</td>
</tr>
<tr>
<td>Þólsámá</td>
<td>73</td>
<td>482</td>
<td>Nesjavellir</td>
<td>40</td>
<td>320</td>
</tr>
<tr>
<td>Bjallar</td>
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<td>462</td>
<td>Reykjanes</td>
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<td>240</td>
</tr>
<tr>
<td>Hvammur</td>
<td>48</td>
<td>317</td>
<td>Svartsengi</td>
<td>30</td>
<td>240</td>
</tr>
<tr>
<td>Villinganes</td>
<td>33</td>
<td>218</td>
<td></td>
<td>11,210</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Total</td>
<td>1,400</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>11,210</td>
<td></td>
</tr>
</tbody>
</table>

3.3 CO<sub>2</sub> emissions

CO<sub>2</sub> emissions from geothermal power plants have always been seen as the main drawback even when it is emitting significantly less CO<sub>2</sub> per generated kWh<sub>e</sub> electric power than fossil fuel power plants. Power plants use thermal energy by drilling wells to high depths. Plants in Iceland are located in volcanic areas that contain high amounts of CO<sub>2</sub> derived from metamorphism of carbonate rock. In this case, CO<sub>2</sub> will be released in the atmosphere when it is not recovered by the power plant itself (Armannsson et al., 2005). The Icelandic organisation Orkustofnun monitored the total CO<sub>2</sub> emissions per geothermal power plant from 1977 up till now. To give an indication, the total CO<sub>2</sub> emissions in 2010 from geothermal power plants were about 168 kton. A detailed dataset of the emissions of each specific power plant can be found in appendix C3. Using the last data (2010) of the emissions and the electricity that is generated in these power plants, the emissions per kWh<sub>e</sub> can be calculated. These results are shown in table 3.2.

Table 3.2: Current installed geothermal power plants with their specifications and CO<sub>2</sub> emissions. Calculations based on: Orkustofnun/National Energy Authority of Iceland, 2012 b,d *.

<table>
<thead>
<tr>
<th>Place</th>
<th>Opening year</th>
<th>Capacity [kW&lt;sub&gt;e&lt;/sub&gt;]</th>
<th>Power Plant Name</th>
<th>Electricity [GWh&lt;sub&gt;e&lt;/sub&gt;/yr]</th>
<th>CO&lt;sub&gt;2&lt;/sub&gt; [tons/yr]</th>
<th>gCO&lt;sub&gt;2&lt;/sub&gt;/kWh</th>
</tr>
</thead>
<tbody>
<tr>
<td>Krafla</td>
<td>1971</td>
<td>60,000</td>
<td>Kröfluvirkjun</td>
<td>480</td>
<td>44,515</td>
<td>92.7</td>
</tr>
<tr>
<td>Hellisheiði</td>
<td>2006</td>
<td>213,358</td>
<td>Hellisheiðavirkjun</td>
<td>1708</td>
<td>32,937</td>
<td>19.3</td>
</tr>
<tr>
<td>Nesjavellir</td>
<td>1998</td>
<td>120,000</td>
<td>Nesjavellavirkjun</td>
<td>961</td>
<td>20,201</td>
<td>21.0</td>
</tr>
<tr>
<td>Svartsengi</td>
<td>1977</td>
<td>76,400</td>
<td>Orkuverðöð Svartsengi</td>
<td>612</td>
<td>61,182</td>
<td>100.0</td>
</tr>
<tr>
<td>Bjarnafjöll</td>
<td>1969</td>
<td>32,000</td>
<td>Aflastbóð Bjarnarfjöll</td>
<td>256</td>
<td>962</td>
<td>N/A</td>
</tr>
<tr>
<td>Reykjanes</td>
<td>1977</td>
<td>500</td>
<td>Reykjanes á Suðurnesjum</td>
<td>4</td>
<td>24,310</td>
<td>N/A</td>
</tr>
</tbody>
</table>

* N/A = Not Available

Remarkable is that old power plants (Kröfluvirkjun & Orkuverðöð Svartsengi where CRI is located) emit the largest amounts of CO<sub>2</sub> per generated kWh<sub>e</sub>. Newer power plants such as Hellisheiðavirkjun & Nesjavellavirkjun from respectively 2006 and 1998, emit 5 less CO<sub>2</sub> per kWh<sub>e</sub>. The fact is that they are using the same thermal energy from almost the same geographically area.

This phenomenon can partly be explained by the higher energy efficiency of these newer power plants (Kanoglu, et al., 2010). In other words, less CO<sub>2</sub>-containing steam is required for generation the same amount of electric power. Furthermore, it is difficult to estimate the CO<sub>2</sub> concentrations from drilled wells. For example, in figure 3.3 the CO<sub>2</sub> concentrations of the wells that are used in the Svartsengi power plant are shown. These CO<sub>2</sub> concentrations (by volume) range between 0.4 and almost 6% in a specific period. The latest wells generally have CO<sub>2</sub> concentrations between 0.4 and 1.0%. This makes it difficult to estimate the CO<sub>2</sub> emissions of new geothermal power plants in volcanic areas. The emissions of new geothermal power plants described in table 3.2 emit between 19.3 and 21 gCO<sub>2</sub>/kWh. These emissions are in line with a recent CO<sub>2</sub> survey study of Bertani & Thain, 2002. Worldwide CO<sub>2</sub> emissions from geothermal power plants are discussed in more detail in chapter 7.
Are these amounts of geothermal power plants significant compared to the total anthropogenic CO$_2$ of Iceland? In figure 3.4, the total Icelandic anthropogenic CO$_2$ emissions are shown (blue line). In 2010 this was about 2,300 kton. In the same year, the Netherlands emitted 78 times more CO$_2$ (about 174 Mton/yr). The distribution of 2010 CO$_2$ emissions in Iceland can be found in the pie diagram in the same figure. $7\%$ of all anthropogenic CO$_2$ is emitted by geothermal power plants; other emissions are mainly from fishing (boats), the industry or road transport (Orkustofnun/National Energy Authority of Iceland, 2010). The emissions of geothermal power plants increased in the last years but never exceed a share of more than $10\%$ (red line).

Maybe more important are the natural emissions of geothermal activity in Iceland. In Iceland, natural emissions far exceed anthropogenic CO$_2$ emissions from geothermal power plants (Seaward & Kerrick, 1996; Delgado et al., 1998; Bertani & Thain, 2002). Armannsson, (2005) reported in a review that this natural CO$_2$ flux in Iceland is between 1,000 and 2,000 kton per year. This 2,000 line is also shown in the figure (black dotted). These emissions have to be added to the anthropogenic CO$_2$ emissions (blue line). This means that the emissions of geothermal power plants in Iceland (red line) can almost be neglected.

Figure 3.3: CO$_2$ concentration by volume of geothermal wells at the Svartsengi power plant (Armannsson & Dereinda, 2010).

Figure 3.4: CO$_2$ emissions Iceland from 1970-2010 Information based on: Trading economies, 2012; Orkustofnun/National Energy Authority of Iceland, 2009; Orkustofnun/National Energy Authority of Iceland, 2012b,c. PP = power plant
3.4 Scenarios methanol production

In this paragraph, five scenarios of renewable methanol production in Iceland are investigated. For each scenario, the following relevant subjects will be discussed:

- Energy requirements of producing renewable methanol (MJ/kgCH$_3$OH)
- Average CO$_2$ emissions (weighted) for methanol production (gCO$_2$/kgCH$_3$OH)
- Maximum potential (l/yr)
- Maximum recovered CO$_2$ (kg/yr)
- Required electrolysers (#)
- Estimated total building area (m$^2$)

**Scenario 1a: CRI 5M.** After havening built a pilot methanol plant, CRI is currently using an industrial scale plant with a maximum capacity of 5 million litres of methanol a year. According to CRI, the facility requires a plot size of about 1000 m$^2$. The required CO$_2$ will be captured with the MDEA absorption technique with a maximum of 90%. Hydrogen in this industrial scale plant is produced with a relatively low efficiency of 65%. The reason for this low efficiency is not known. (Global CCS Institute, 2011; Carbon Recycling International, 2012).

**Scenario 1b: CRI 50M.** The second methanol plant in Iceland has to be operational in 2013-2014. This one has to be built at the Kröfluvirkjun geothermal power plant in Krafla. This would be the first commercial renewable methanol plant with an annual production capacity of 50 million litres. According to CRI, this is a standard plant that can be installed at every power plant in the world. In this case, the CO$_2$ is recovered from the Kröfluvirkjun power plant with a maximum recovery efficiency of 90%. Assumed is that the required hydrogen is produced with the NEL Atmospheric Type No.5040 electrolyser with an energy efficiency of 76% and a water inlet temperature of 293 K (case 1, table 2.3). The reason for this assumption is that Iceland already has installed an efficient electrolyser from NEL for hydrogen production. This hydrogen is currently used for the limited amounts of fuel cell cars in Iceland (Rifkin, 2004).
Scenario 2: Geothermal. In this scenario it is assumed that all the potential geothermal power plants, described in table 3.1, would produce renewable methanol. The required CO₂ is recovered by the geothermal power plants with a maximum recovery efficiency of 90% (MDEA technique). Hydrogen can be produced by PEM electrolysers (Proton HOGEN 380), unipolar electrolysers (Avalence Hydrofiller 175) or bipolar electrolysers (NEL Atmospheric Type No.5040). Furthermore, the possibility of using partly thermal energy for hydrogen production is included (case 2, table 2.3).

Scenario 3: Hydro. In this scenario, it is assumed that all the potential hydropower plants that are described in table 3.1, will produce renewable methanol. Because no CO₂ source is available at hydropower plants, this has to be recovered by currently installed geothermal power plants with a maximum recovery efficiency of 90% (MDEA technique). Hydrogen can be produced by PEM electrolysers (Proton HOGEN 380), unipolar electrolysers (Avalence Hydrofiller 175) or bipolar electrolysers (Norsk Atmospheric Type No.5040).

Scenario 4: Geothermal & Hydro. This scenario is basically a combination of scenario 2 & 3. All potential geothermal and hydropower plants would produce renewable methanol. The required CO₂ is recovered by the new and existing (when necessary) geothermal power plants with a maximum recovery efficiency of 90% (MDEA technique). Furthermore, hydrogen is produced in the same way as described in scenario 2 or 3 and the electrolyser is located at each power plant to minimize transport losses.

Scenario 5: CO₂ as a limit. When only CO₂ from geothermal power plants can be captured and used in the production process, the available CO₂ is a limiting factor. The availability in existing geothermal power plants is calculated on the basis of current annual emissions. New geothermal power plants will emit less CO₂ per generated kWhₑ, which is explained in paragraph 3.3. The total available CO₂ in existing geothermal power plants is 168 kton, when the recovery efficiency of 90% is taken into account. In potential new geothermal power this is 202 kton (Orkustofnun/National Energy Authority of Iceland, 2012 b, d).

In table 3.3, a summary of each scenario is shown. The most energy-efficient scenario is the production of renewable methanol in combination with geothermal power. In this case, partly thermal energy can be used for the production of the required hydrogen. In figure 3.6, the energy requirements of each stage can be found from a specific scenario. It can be concluded that most of the energy is required for the production of hydrogen (between 80 and 84%). The individual energy requirements range between 42 (scenario 1 & 2 bi-polar) and 55 MJ/kgCH₃OH (scenario 3 PEM). Therefore, the energy efficiency results between 56% and 43% (electricity to methanol).
Table 3.3: Summary of five scenarios of renewable methanol production in Iceland.

<table>
<thead>
<tr>
<th>Energy consumption (MJ/kgCH$_3$OH)</th>
<th>PEM</th>
<th>Alkaline unipolar</th>
<th>Alkaline bipolar</th>
<th>PEM</th>
<th>Alkaline unipolar</th>
<th>Alkaline bipolar</th>
</tr>
</thead>
<tbody>
<tr>
<td>1a: CRI 5M</td>
<td>-</td>
<td>-</td>
<td>53.5 (51.2)</td>
<td>54.7</td>
<td>54.0 (52.7)</td>
<td>53.5 (51.2)</td>
</tr>
<tr>
<td>1b: CRI 50M</td>
<td>-</td>
<td>-</td>
<td>44.6 (42.8)</td>
<td>45.8</td>
<td>45.1 (44.0)</td>
<td>44.6 (42.8)</td>
</tr>
<tr>
<td>2: Geothermal*</td>
<td>47.9</td>
<td>41.95</td>
<td>42.0 (40.2)</td>
<td>43.1</td>
<td>42.4 (41.5)</td>
<td>42.0 (40.2)</td>
</tr>
<tr>
<td>3: Hydro</td>
<td>-</td>
<td>-</td>
<td>42.4% (44.8%)</td>
<td>40.1%</td>
<td>41.4% (42.8%)</td>
<td>42.4% (44.8%)</td>
</tr>
<tr>
<td>4: Geothermal &amp; Hydro*</td>
<td>47.4</td>
<td>54.07%</td>
<td>54.1% (56.4%)</td>
<td>50.3%</td>
<td>52.50% (53.8%)</td>
<td>54.1% (56.4%)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Energy efficiency (Power-Methanol)</th>
<th>PEM</th>
<th>Alkaline unipolar</th>
<th>Alkaline bipolar</th>
<th>PEM</th>
<th>Alkaline unipolar</th>
<th>Alkaline bipolar</th>
</tr>
</thead>
<tbody>
<tr>
<td>1a: CRI 5M</td>
<td>-</td>
<td>-</td>
<td>42.4% (44.8%)</td>
<td>42.0%</td>
<td>43.1% (41.5)</td>
<td>42.0% (40.2)</td>
</tr>
<tr>
<td>1b: CRI 50M</td>
<td>-</td>
<td>-</td>
<td>25.9%</td>
<td>28.7%</td>
<td>32.1%</td>
<td>25.9%</td>
</tr>
<tr>
<td>2: Geothermal*</td>
<td>-</td>
<td>-</td>
<td>50.8% (53.0%)</td>
<td>47.5%</td>
<td>49.4% (49.4%)</td>
<td>50.8% (53.0%)</td>
</tr>
<tr>
<td>3: Hydro</td>
<td>47.4</td>
<td>54.07%</td>
<td>54.1% (56.4%)</td>
<td>50.3%</td>
<td>52.50% (53.8%)</td>
<td>54.1% (56.4%)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Potential (10$^6$l/yr)</th>
<th>PEM</th>
<th>Alkaline unipolar</th>
<th>Alkaline bipolar</th>
<th>PEM</th>
<th>Alkaline unipolar</th>
<th>Alkaline bipolar</th>
</tr>
</thead>
<tbody>
<tr>
<td>1a: CRI 5M</td>
<td>-</td>
<td>-</td>
<td>2,010 (2,064)</td>
<td>-</td>
<td>-</td>
<td>338</td>
</tr>
<tr>
<td>1b: CRI 50M</td>
<td>-</td>
<td>-</td>
<td>1,671 (1,716)</td>
<td>-</td>
<td>-</td>
<td>8034</td>
</tr>
<tr>
<td>2: Geothermal*</td>
<td>5</td>
<td>50</td>
<td>1,195 (1,249)</td>
<td>27</td>
<td>61,788 (64,564)</td>
<td>17,458</td>
</tr>
<tr>
<td>3: Hydro</td>
<td>-</td>
<td>-</td>
<td>815</td>
<td>-</td>
<td>-</td>
<td>166</td>
</tr>
<tr>
<td>4: Geothermal &amp; Hydro*</td>
<td>5</td>
<td>50</td>
<td>1,671 (1,716)</td>
<td>27</td>
<td>625 (653)</td>
<td>166</td>
</tr>
<tr>
<td>5: CO$_2$ as a limit</td>
<td>-</td>
<td>-</td>
<td>2,427</td>
<td>-</td>
<td>-</td>
<td>67,500</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>CO$_2$</th>
<th>PEM</th>
<th>Alkaline unipolar</th>
<th>Alkaline bipolar</th>
<th>PEM</th>
<th>Alkaline unipolar</th>
<th>Alkaline bipolar</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max. Recovered CO$_2$</td>
<td>5.4</td>
<td>54.4</td>
<td>1,448</td>
<td>979</td>
<td>2,427</td>
<td>367</td>
</tr>
<tr>
<td>(kton/yr)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total g(CO$_2$/kgCH$_3$OH)</td>
<td>1501</td>
<td>1492</td>
<td>1395</td>
<td>1373</td>
<td>1386</td>
<td>1395</td>
</tr>
<tr>
<td>Production (gCO$_2$/kgCH$_3$OH)</td>
<td>127.6</td>
<td>118.3</td>
<td>21.4</td>
<td>0</td>
<td>12.4</td>
<td>21.4</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Area</th>
<th>PEM</th>
<th>Alkaline unipolar</th>
<th>Alkaline bipolar</th>
<th>PEM</th>
<th>Alkaline unipolar</th>
<th>Alkaline bipolar</th>
</tr>
</thead>
<tbody>
<tr>
<td>Required plot area (m$^2$)</td>
<td>1,000</td>
<td>10,000</td>
<td>266,200</td>
<td>180,000</td>
<td>448,200</td>
<td>67,500</td>
</tr>
</tbody>
</table>

* Between brackets are values when partly thermal energy is used for hydrogen production (case 2, table 2.3).

The total maximum potential of Iceland (Scenario 4) is 2,200 million litres of methanol a year. This is hardly 4.5% of the current worldwide methanol demand (Lund et al., 2011). The total potential demand of Iceland or the Netherlands will be discussed in more detail in chapter 5. To achieve this production, a minimum of about 1,100 large scale electrolysers (NEL Atmospheric Type No.5040) are required. This is technically possible but this type of electrolyser has only been built once and the costs of purchase are extremely high. Also, the required CO$_2$ for this potential (2,427 kton/yr) is significantly larger than is available from only geothermal power plants. Keep in mind that the total emissions from currently installed geothermal power plants is ‘only’ 168 kton/yr. The geothermal capacity of electricity generation can be more than doubled, but the available CO$_2$ for recovery is estimated at around 367 kton/yr. The rest of the required CO$_2$ has to come from another source like the aluminium industry. (Note that the energy requirements of CO$_2$ recovery from other sources than mentioned in this report may be significantly higher than the recovery from geothermal fluids). The direct plus indirect emissions of methanol production and the use of it are around 1,400-1,600 gCO$_2$/kgCH$_3$OH depending on the recovery efficiency, used electrolysers and the source of CO$_2$. Using methanol would generate approximately 1,373 gCO$_2$/kgCH$_3$OH (paragraph 2.5.2). A detailed life cycle assessment of CO$_2$ emissions per produced unit of renewable methanol and the use of it can be found in chapter 7.
3.5 Conclusion

The electricity generation of Iceland can be more than doubled according to the Icelandic master plan of future use of renewable energy sources. By using this potential, a maximum amount of about 2,200 million litres of methanol can be produced every year. The largest challenges to achieve this potential are the required hydrogen and CO$_2$. Recovery of CO$_2$ from only geothermal power plants is not enough and therefore other sources have to be investigated. This can increase the energy consumption for the production, which results in a lower energy efficiency. On a small scale, the recovery of the required CO$_2$ will give no direct problems (scenario 1a & 1b).

CRI claims that they can recycle CO$_2$ by producing renewable methanol but the truth is that extra electricity must be generated to provide the necessary energy for renewable methanol production. This extra electricity will cost additional CO$_2$ when geothermal power plants are used. Furthermore, only 90% of the emitted CO$_2$ can be recovered and the rest is directly released into the atmosphere. The recovered CO$_2$ will be used as a feedstock for renewable methanol production. Keep in mind that this ‘stored’ CO$_2$ in the form of methanol will be released when the methanol is combusted, whether this will be in a fuel cell or in an internal combustion engine (ICE). At the end, all the released CO$_2$ from geothermal power plants will end up in the atmosphere when it is not recycled again in the form of methanol.

CRI claims that they can “close the CO$_2$ life cycle loop” because they assume that the emitted CO$_2$ from the use of methanol (fuel cell or in an ICE) can 100% be recovered and used again for the production of renewable methanol (figure 1.1). The first problem with this theory is that only renewable energy sources are suitable for this production technique. In other words, it is not a solution for decreasing CO$_2$ emissions from fossil fuels power plants. Second, it is technically impossible to capture 100% of the CO$_2$ from geothermal fluids or flue gasses from fossil-fuelled power plants. In practice, a maximum of 90% can hardly be achieved. The rest is directly emitted into the atmosphere. Third, recovery of emitted CO$_2$ by the use of methanol in internal combustion engines is currently impossible but it is possible to recover high percentages of CO$_2$ when methanol is used in a stationary fuel cell. However, these are faced with extremely high costs. Fourth, CRI neglects the fact that the produced methanol or the recovered CO$_2$ has to be transported. This will cost energy and, therefore, in some cases, CO$_2$. Overall, it is currently not correct to say that this type of renewable methanol production is a process that can recycle CO$_2$. It is just a good step forwards for decreasing emissions compared to the use of fossil fuels in for example the transport sector. In the future, it is perhaps possible to completely recycle CO$_2$ and therefore stabilize or even decrease anthropogenic CO$_2$ emissions. In this situation, the entire society has to switch to a complete renewable energy supply. Furthermore, a technique for 100% recovery of methanol production and the use of it has to be developed, without these improvements or developments this type of energy storage will probably not be completely renewable.
CHAPTER 4 THE NETHERLANDS

CRI claims that a standard methanol facility of 50 million litres/year can be located everywhere in the world. In this chapter, the feasibility of this statement will be investigated. As concluded in the previous chapters, renewable energy sources are needed for the production of renewable methanol. In the Netherlands, assumed is that (large scale) wind and solar energy can be used for this process. The required CO$_2$ will be recovered from (existing or new) fossil-fuelled power plants. First, the current state of electricity production will be researched and implemented in a computer program called PowerPlan. Then, scenarios are developed in this program to research the effects of implementing solar and wind energy on a large scale. When a potential oversupply of renewable electricity occurs, this could be used for the production of renewable methanol. This way, the feasibility of buffering energy in the form of methanol production will be investigated, together with the maximum capacity of it.

4.1 Electricity production up to 2030

The current electricity mix of the Netherlands is mainly based on fossil fuels. In 2011, only 4.9% of all electricity was generated by renewable energy sources such as waste, wind, hydro, solar et cetera (IEA Monthly Energy Update, 2012). The Dutch government developed scenarios for renewable energy generation up to the year 2030. A drawback of this large scale implementation of renewable energy power plants could be the potential oversupply of energy. Renewable energy sources like wind and solar are unpredictable in their power output and therefore it is complex to match the demand with the supply. When the demand for electricity is low, for example at 4 A.M., the output of large scale wind farms could be relatively high. The problem is partly the flexibility of base load power plants. Base load power plants, especially coal-fired ones, always have to deliver a certain output (must run capacity) due to a low flexibility. With the use of the computer program PowerPlan, the potential oversupply of renewable electricity production in the Netherlands is examined. In PowerPlan, the medium term electricity supply of a country is simulated with the use of present-day information. This program gives an indication about the consequences of implementation of specific power plants in combination with their produced electricity during a certain period. First, the current state of electricity production in the Netherlands is discussed and implemented in this program. Then, several scenarios of renewable electricity production up to 2030 will be discussed.

4.1.1 Current state and expected growth

To investigate future effects of implementing large scale renewable energy in the Netherlands, the current state of electricity generation has to be set. The in 2012 installed capacity for electricity generation by different types of power plants is shown in figure 4.1 (Tennet, 2011a; Energie Nederland, 2011). This information was checked, and edited when necessary, with up-to-date website information of each power plant licence holder such as EON, Essent, RWE et cetera. This is basically a baseline scenario for further calculations. A detailed list of currently installed and announced power plants, together with energy efficiencies and operation dates, is reported in appendix D1.

![Figure 4.1: Current electricity capacity 2012. Based on: Tennet, 2011a; Energie Nederland, 2011](image-url)
The total installed capacity of the Netherlands in this baseline scenario is 21.1 GW\textsubscript{e}. The peak demand is estimated around 13.5 GW\textsubscript{e} and is based on the ratio between the installed capacity and the peak load of 2011 (Energie Nederland, 2011). In the coming years, the demand for electricity will increase. Based on information of Tennet, 2011b, the peak load growth in 2012-2013 is estimated at 1.5% a year. From 2014-2017 this growth would be 1.25% a year. The following years from 2018-2025, a higher growth of 1.5% a year is estimated and after 2026 an annual growth of 1.25% is expected.

4.1.2 Scenarios electricity production
Tennet is a cross-border grid operator in Europe and the premier electricity transmission operator of the Netherlands. They give information about planned electricity networks, power plants and possible further scenarios up till the year 2030 which are set by the Dutch government (Tennet, 2011b). These 2030 plans of the Dutch government are:

Scenario 1: Green revolution. Europe’s target for 2030 is that CO\textsubscript{2} emissions of electricity production have to decrease with 60% compared to 1990 levels. For the Netherlands this results in a large scale investment of on- and offshore wind energy and photovoltaic (PV) solar power. The total installed capacity in 2030 would be 6 GW\textsubscript{e} offshore and 4 GW\textsubscript{e} onshore wind power. Furthermore, 4 GW\textsubscript{e} of PVs will be installed.

Scenario 2: Sustainable Transition. In this scenario, great emphasis lies on energy-saving measures rather than the generation of renewable energy. This would result in lower installed capacities than in the first scenario with both 3.5 GW\textsubscript{e} off- and onshore wind energy and 4 GW\textsubscript{e} of PVs.

Scenario 3: Money is important. Renewable power plants are expensive and therefore in this scenario assumed is that most of the energy will be imported from other countries to supply the increasing demand in 2030. Large scale implementation of PVs will not occur and wind energy is limited to a capacity of 2 GW\textsubscript{e} for offshore and 3 GW\textsubscript{e} for onshore.

For each of the scenarios, the potential oversupply will be examined. Instead of exporting this potential surplus, it will be used to produce renewable methanol. This can be seen as an ‘energy buffer’. As an indication, and to put these scenarios in perspective, a fourth scenario is added:

Scenario 4: Methanol economy. In 2030, 6 GW\textsubscript{e} offshore, 4 GW\textsubscript{e} onshore wind power and 4 GW\textsubscript{e} PVs are installed to produce primarily renewable methanol. These renewable power plants will not deliver any electricity to the grid. This scenario gives an idea about the potential methanol capacity of the Netherlands by implementing large scale renewable energy sources like solar and wind.

Assumed is that the implementation of renewable energy sources in these scenario would be linear up to 2030. Furthermore, the lifetime of renewable power plants (20 years) are taken into account. Detailed information about the implementation of these scenarios from 2012 up to 2030 can be found in appendix D2.
4.2 Potential electricity oversupply
To investigate the potential oversupply of electricity by renewables, the mentioned scenarios are simulated in PowerPlan. The wind and sun patterns were included in the electricity output calculations. Furthermore, demand patterns are included. As mentioned earlier, coal-fired power plants have a certain minimum power output (must run capacity). These base load power plants cannot be shut down rapidly and are not flexible in shifting their capacity. This results in a minimum power output that always has to be generated and delivered to the grid.

An example of a specific period (hour 7570-7720) of a certain year is shown in figure 4.2. The blue line is the demand in a certain period shown in GW_e. The red line is the must run capacity (basically from coal-fired power plants) and the green line shows the renewable electricity that is generated which is added to the must run capacity. An oversupply in this figure occurs for example between hour 7657 and 7661. When the demand is higher than the must run supply and the electricity that is generated with renewables, the other installed power plants in the Netherlands will be used to supply the rest of the demand. For each scenario that is discussed in paragraph 4.1.2, the annual accumulated oversupply of electricity (GWh_e) will be calculated using this method.

![Figure 4.2: Example of investigating a potential oversupply of electricity in the Netherlands.](image)

In table 4.1, the potential oversupply of each scenario is shown. In the Green Revolution scenario, the oversupply in 2030 is 3.6 GWh, but in the other two scenarios (Sustainable Transition & Money is important) no oversupply in 2030 occurs. This can be explained by the fact that more gas-fired power plants, which do not have a must run capacity, will be built in the coming years and that coal-fired power plants, with a high must run capacity, will be shut down (see graphs in appendix D2). With a lower to non must run capacity, unpredictable renewable electricity that is generated can always be used. The rest of the demand will be supplied mainly by gas-fired power plants, which are more flexible in their capacity. It can be concluded that, when the Dutch government decides to implement up till 3 GW_e onshore, 3 GW_e offshore and 4 GW_e solar power, no oversupply of renewable energy occurs. This is positive for future implementation of renewable energy in the Netherlands and it means that no methanol facilities are needed as a potential energy buffer.

Table 4.1: Potential oversupply of electricity in 2030

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Capacity Offshore wind (GW_e)</th>
<th>Capacity Onshore wind (GW_e)</th>
<th>Capacity Solar PV (GW_e)</th>
<th>Oversupply 2030 (GWh_e)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Green Revolution</td>
<td>6.0</td>
<td>4.0</td>
<td>4.0</td>
<td>3.6</td>
</tr>
<tr>
<td>2 Sustainable Transition</td>
<td>3.0</td>
<td>3.0</td>
<td>4.0</td>
<td>0.0</td>
</tr>
<tr>
<td>3 Money is important</td>
<td>2.0</td>
<td>3.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>4 Methanol Economy</td>
<td>6.0</td>
<td>4.0</td>
<td>4.0</td>
<td>30,030</td>
</tr>
</tbody>
</table>

35
4.3 Scenarios methanol production

3.6 GWh\textsubscript{e} is generated as an oversupply in the \textit{Green Revolution} scenario. In this paragraph, the potential methanol production of this amount of energy will be examined. As an indication, also the \textit{Methanol Economy} scenario, which generates about 30,000 GWh\textsubscript{e}/yr is included. The production of renewable methanol in the Netherlands can have two potential benefits. First, potential oversupply of electricity can be ‘stored’ and advantageous be used for future purposes (chapter 5). Second, this is a reason for fossil power plants to capture CO\textsubscript{2} and to use it for methanol production. This will decrease the CO\textsubscript{2} emissions of electricity production in the Netherlands.

In the discussed scenarios the following measures are taken into account:

- Efficiency drops for hydrogen production because unpredictable renewable energy sources are used. These efficiency drops can be found in chapter 2.
- A renewable methanol facility is located next to a potential CO\textsubscript{2} source; potential transport losses of CO\textsubscript{2} or H\textsubscript{2} are neglected.
- The use of efficient alkaline bi-polar electrolysers from Hydrogenics (HySTAT-15-10) in the \textit{Green Revolution} scenario. Gandía et al., 2007, have intensively tested this electrolyser with existing wind pattern. For the \textit{Methanol Economy} scenario, a large electrolyser has to be used (NEL Atmospheric Type No.5040 5150 Amp DC).
- CO\textsubscript{2} emissions of electricity generation from various types of fossil fuel power plants are used from Armannsson \textit{et al.}, 2005. Assumed is that an existing coal-fired power plant (subcritical) produces 1,300 gCO\textsubscript{2}/kWh\textsubscript{e}. New coal-fired power plants (supercritical) produce 900 gCO\textsubscript{2}/kWh\textsubscript{e} and an IGCC power plant (ultra supercritical) only 600 gCO\textsubscript{2}/kWh\textsubscript{e}. NG power plants (combined cycle) are assumed to produce 400 gCO\textsubscript{2}/kWh\textsubscript{e}. The average energy consumption values and efficiencies of CO\textsubscript{2} recovery are used which were shown in table 2.5.

Table 4.2: Results of renewable methanol production in the Netherlands.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Potential oversupply (GWh\textsubscript{e}/yr)</th>
<th>CO\textsubscript{2} Source</th>
<th>Energy consumption (MJ/kgCH\textsubscript{3}OH)</th>
<th>Energy efficiency (Power-Methanol)</th>
<th>Potential (million l/yr)</th>
<th>Required electrolysers (#)*</th>
<th>Recovered CO\textsubscript{2} (kton/yr)</th>
<th>Production (gCO\textsubscript{2}/kgCH\textsubscript{3}OH)</th>
<th>Total (gCO\textsubscript{2}/kgCH\textsubscript{3}OH)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Green Revolution 3.6</td>
<td>3.6</td>
<td>NG</td>
<td>50.86</td>
<td>42.94%</td>
<td>0.32</td>
<td>5</td>
<td>0.350</td>
<td>22</td>
<td>1395</td>
</tr>
<tr>
<td>Existing Coal-fired</td>
<td>50.95</td>
<td>42.87%</td>
<td>0.32</td>
<td>5</td>
<td>0.349</td>
<td>64</td>
<td>1437</td>
<td></td>
<td></td>
</tr>
<tr>
<td>New Coal-fired</td>
<td>50.36</td>
<td>43.35%</td>
<td>0.33</td>
<td>5</td>
<td>0.353</td>
<td>36</td>
<td>1409</td>
<td></td>
<td></td>
</tr>
<tr>
<td>IGCC</td>
<td>50.36</td>
<td>43.35%</td>
<td>0.33</td>
<td>5</td>
<td>0.353</td>
<td>24</td>
<td>1397</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Air</td>
<td>53.38</td>
<td>40.98%</td>
<td>0.31</td>
<td>5</td>
<td>0.333</td>
<td>0</td>
<td>1373</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Methanol Economy 30,030</td>
<td>30,030</td>
<td>NG</td>
<td>50.86</td>
<td>42.94%</td>
<td>2685</td>
<td>1317</td>
<td>2920</td>
<td>22</td>
<td>1395</td>
</tr>
<tr>
<td>Existing Coal-fired</td>
<td>50.95</td>
<td>42.87%</td>
<td>2680</td>
<td>1314</td>
<td>2915</td>
<td>64</td>
<td>1437</td>
<td></td>
<td></td>
</tr>
<tr>
<td>New Coal-fired</td>
<td>50.36</td>
<td>43.35%</td>
<td>2711</td>
<td>1330</td>
<td>2949</td>
<td>36</td>
<td>1409</td>
<td></td>
<td></td>
</tr>
<tr>
<td>IGCC</td>
<td>50.36</td>
<td>43.35%</td>
<td>2711</td>
<td>1330</td>
<td>2949</td>
<td>24</td>
<td>1397</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Air</td>
<td>53.38</td>
<td>40.98%</td>
<td>2558</td>
<td>1254</td>
<td>2782</td>
<td>0</td>
<td>1373</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Note: \textit{Green Revolution} scenario electrolyser = Hydrogenics HySTAT-15-10, \textit{Methanol Economy} scenario electrolyser = NEL Atmospheric Type No.5040.

Due to unpredictable renewable electricity generation, the energy efficiency from electricity-to-methanol in the Netherlands is relatively low (± 42%) compared to the same production process in Iceland (± 52%). An advantage of the production in the Netherlands could be the lower CO\textsubscript{2} production emissions, which will not exceed 64 gCO\textsubscript{2}/kgCH\textsubscript{3}OH, because wind or solar power is cleaner than geothermal electricity generation.
The potential of both scenarios within the Netherlands is completely different. In the Green Revolution scenario, only a potential oversupply of 3.6 GWh was available. Converting this electricity into renewable methanol would result in an amount of about 0.31-0.33 million litres of methanol a year (depending on the source of CO$_2$). This can almost be neglected when it is compared to the annual worldwide methanol production of 76,000 million litres. In the Methanol Economy scenario, a potential between 2,558 and 2,711 million litres of methanol a year can be achieved which is significant. This scenario is not realistic however, because it will be more beneficial from an energy point of view to connect these renewable energy sources directly to the grid. Therefore, this scenario only function as an indication of what the potential would be. In chapter 5, the demand for methanol in the Netherlands will be discussed to examine whether this potential of 0.3 million litres a year is enough to for example replace the Dutch transportation fossil fuels.

CRI argued that a facility with an annual potential of 50 million litres, which is currently built in Krafla, would be a ‘standard facility’ that can be installed in every country in combination with for example wind or solar power. It was concluded that the potential of the Green Revolution scenario only has a potential of about 0.3 million litres a year. The question arises how many renewables are required to achieve this potential amount of 50 million litres with only the occurrence of an electricity oversupply. By using PowerPlan, the potential oversupply of electricity can be calculated by implementing a certain amount of renewable energy. This can be translated into a potential amount of methanol. The implementation of onshore, offshore and PV solar energy was examined with a capacity between 1 and 20 GW$_e$. These results are shown in figure 4.3. Energy losses due to the temporary storage of hydrogen and CO$_2$ are included, because an oversupply is unpredictable and not constant in output. In these calculations ‘boil off’ losses of 2% a day are assumed (Ohla et al, 2006).

![Figure 4.3: Required implementation of renewable energy sources in the Netherlands for methanol production as an energy buffer. Note: The M3 demand line (purple) and the RMFC demand line (orange) will be explained in chapter 5.](image)

Up to a capacity of about 10 GW$_e$, with any source of renewable energy, no oversupply occurs. An annual production of 50 million litres (red dotted line) can be achieved by implementing at least 13.5 GW$_e$ offshore wind, 14.6 GW$_e$ onshore wind or 16.2 GW$_e$ solar PVs. Less offshore wind has to be installed compared to for example onshore wind, because the capacity factor of offshore wind is higher than onshore and solar PVs. To achieve the same capacity of Iceland (350 million litres/yr), at least 19 GW$_e$ offshore wind, 22 GW$_e$ onshore wind or 25 GW$_e$ solar PVs has to be installed. Keep in mind that the capacity of all power plants in the Netherlands is currently about 21 GW$_e$. If the Netherlands wants to
produce methanol on a large scale with a ‘standard’ methanol factory of 50 million litres, our capacity has
to increase heavily in the coming years.
Also shown in the figure (right axis) is the CO$_2$ reduction gained by producing methanol. By installing for
example a 50 million-litre factory, the reduction is about 0.06 Mton a year. This is small compared to the
annual CO$_2$ emissions of the Netherlands of almost 174 Mton. CO$_2$ saving by producing renewable
methanol in the Netherlands will not have a significant effect and therefore methanol as an energy buffer
is perhaps not the most ideal option from a CO$_2$ point of view. Furthermore, the buffering efficiency of
electricity-to-methanol is relatively low. Perhaps other energy buffer systems are more beneficial to
implement in the Netherlands rather than the production of methanol.

4.4 Conclusion
The overall energy efficiency of renewable methanol production is lower in the Netherlands than in
Iceland. The highest efficiency in the Netherlands can be achieved by using CO$_2$ from a new coal-fired
(super critical) or an IGGC power plant. Using CO$_2$ from atmospheric air would result in a lower
efficiency but an advantage is that direct CO$_2$ emissions from the production of methanol are zero. This
will be explained in more detail in chapter 7. The potential CO$_2$ saving by using methanol as an energy
buffer for the Netherlands is not significant. Therefore, the argument of CRI to decrease CO$_2$ emissions of
a country by installing a renewable methanol factory is not true for the Netherlands. Furthermore, to
achieve an annual production of 50 up to 350 million litres methanol, the capacity of renewable energy
sources have to be increased to 13.5 up to 23 GW$_e$. This would mean that the current capacity of the
Netherlands has to increase with 65% by implementing offshore wind or up to 125% by implementing
PVs. This is very unlikely to happen before the year 2030 because the most extreme scenario that is
developed by the Dutch government is an implementation of the Green Revolution scenario (6 GW$_e$
offshore, 4GW$_e$ onshore and 4 GW$_e$ PVs)

In chapter 5, the demand of methanol of the Netherlands will be discussed in more detail to examine
whether for example the production of 50 up to 350 million litres methanol is enough to replace the Dutch
fossil fuels in the transport sector.
CHAPTER 5 METHANOL DEMAND AND SUPPLY

Methanol can replace fossil fuels in the transport sector by combusting it in conventional internal combustion engines (ICE) or by using it in a fuel cell to convert it into electricity. However, methanol is generally used in other markets and not as a replacement for transport fuel. In this chapter the demand of methanol is researched. The aim is to investigate the current methanol demand of the Netherlands. Furthermore, scenarios are developed to show the potential demand in the Netherlands and Iceland for the transport sector.

5.1 Global demand and production

The demand for methanol is rapidly increasing. The demand in 1990 was only 22,000 million litres/yr but this increased with more than 300% to about 76,000 million litres/yr in 2011 (figure 5.1). IHS, a global information company which works in different fields, developed a forecast scenario for the future demand of methanol. In the coming years, the demand will further increase up to about 120,000 million litres/yr.

![Figure 5.1: Historical and future methanol demand since 1990 up to 2016. Information based on IHS Chemicals, 2012a; Ohla et al., 2006.](image)

The production of methanol is currently divided over more than 100 methanol facilities across the world, which uses natural gas, biomass or coal as a feedstock. In the last years, due to higher natural gas prices in Europe, the production of methanol has shifted to other regions. Especially the Middle East and Asia have increased their export and production capacity. In figure 5.2, the capacity and the production of methanol by different regions is shown. In 2011, the installed capacity was 84,000 million litres/yr. The production was estimated around 76,000 million (IHS Chemicals, 2012b).

![Figure 5.2: Methanol installed capacity (left) and production (right) in 2011. (IHS Chemicals, 2012b)](image)
In Asia, the capacity factor of methanol production is very low compared to other regions, which explains the difference between the installed capacity and the actually produced methanol. All methanol that is produced in Europe, CIS and the Baltic States comes from the reforming of natural gas. Methanol production in Asia is partly from the gasification of coal and the rest of reforming natural gas. For understanding the estimated increase of the demand for methanol, the purpose of it has to be investigated. This is completely different in each region of the world. Only the largest consumers of methanol will be discussed (United States, West Europe and Northeast Asia). These regions account for more than 75% of the total demand for methanol.

In the United States, more than 90% of the used methanol is imported, mainly from exporting countries such as Asia, Oman, Saudi Arabia, Iran, Chile and Trinidad. In West Europe, 65% is imported and in Northeast Asia only 35%. IHS is the only large scale company that provides detailed information about the production and the use of methanol in each region.

It is difficult or maybe impossible to investigate how many methanol is used for each specific product or process and in which exact country. On the other hand, information of direct methanol use (mainly the transport sector) is well known per region and therefore estimations could be made what the demand would be in for example Iceland or in the Netherlands. It can be concluded that most of the produced methanol is used as a feedstock for chemical processes or for producing consumer goods. Direct use of methanol only occurs at a very small scale in the transport sector but could increase by applying large scale renewable methanol production in Iceland. In the following paragraphs, the potential demand of Iceland and the Netherlands is compared to the demand in the transport sector.
5.2 Methanol as a transport fuel
In this paragraph, the potential options of replacing conventional gasoline for the transport sector are examined. First, the option of using methanol in current passenger cars is researched and afterwards possible future options in the form of a fuel cell are investigated.

5.2.1 M15 & M85 fuel
Methanol can be used in a mixture with conventional gasoline, as an alternative fuel in current gasoline passenger cars.

- The first option is to use small amounts of methanol in a mixture in normal ICE gasoline passenger cars. Up to about 15% methanol can be added to conventional gasoline without adjustments to the gasoline engine. This type of fuel is called M15 and is used as a standard in the automotive industry (15% methanol and 85% conventional gasoline by volume).

- Another automotive standard is a mixture of 85% methanol and 15% gasoline (M85). 100% use of methanol in IC engines is not recommended because of technical barriers such as cold-start problems and problems with the air/fuel ratio. Gasoline engines have to be modified to cope with M85. These modifications are, for example, the installation of larger injectors and a methanol fuel tank.

Advantages:
- Running on M85 requires only small technical changes in new or existing ICE gasoline vehicles. This would result in little extra costs for the car manufacturers to adjust cars for methanol use. These vehicles are flexible and are able to run on a mixture of methanol between 0 and 85%, the rest will be conventional gasoline (Alternative fuels, 2012).

- The current infrastructure is able to handle both M15 as M85. Furthermore, small changes to fuel stations have to be carried out. Converting an existing fuel station into a methanol fuelling station would cost between $60,000 and $65,000. This is significantly lower than a new hydrogen fuel station with costs that are estimated around $1 million per station (Ohla et al, 2006).

Disadvantages:
- The automotive industry is currently more interested in ethanol (E85) rather than methanol (M85). The reason for this is explained in paragraph 5.2.2. (Alternative fuels, 2012).

- Methanol is more corrosive that conventional gasoline. In older passenger car, especially cars with carburettors and lead-coated fuels tanks (terne plate), this could cause engine problems or even car accidents (E85, 2012).

- Due to a lower energy density of 19.7 MJ/kg compared to 47.2 MJ/kg for gasoline, a large fuel tank has to be installed to compete with current standard vehicle ranges up to 800 km.

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**Textbox 3: Fuel economy methanol ICE cars**

The fuel consumption of a very efficient new Toyota Prius 2012, 1.8L, 4 cylinder gasoline passenger car is about 4.63 l/100 km (100% gasoline). Due to the lower energy density of methanol, the fuel consumption would change. Running on 100% methanol, would result in a consumption of 10.1 litre CH3OH/100 km (Bell Fuels, 2012; Kauw, 2012; Fuel economy, 2012).
5.2.2 Blending percentages conventional gasoline

To achieve lower CO\textsubscript{2} emissions and to support the use of biofuels in the European Union, a target of blending biofuels with conventional gasoline and diesel are set. In 2020, in each country at least 10\% of all transport fuels has to come from renewable sources (EU, 2009). The Dutch government translated this into a short term target of 4.0\% in 2011 and 5.5\% in 2014 (IenM, 2011). For Iceland, no specific targets are set up to the year 2020. However, they also have to achieve the 10\% target in 2020 (EU, 2009).

Interesting are the limitations that are set by the EU of biofuel-blending percentages for gasoline. In directive 2009/30/EC of the European parliament, a limitation of 3\% by volume is set for blending methanol with conventional gasoline. For ethanol, this is higher with 10\% by volume because blending ethanol is less toxic and dangerous than methanol. This is the reason why fuel companies and the automotive industry are more interested in ethanol rather than in methanol as a future transport fuel. In conclusion, for the European market, only 3\% methanol can be blended into conventional gasoline. This type of gasoline fuel is called M3. To achieve the biofuel-blending percentages that are set by the EU, other biofuels are needed besides methanol.

5.2.3 Direct Methanol Fuel Cell

Methanol can direct be used in a proton exchange-based fuel cell for generating electricity to use in an electric car. In this direct-methanol fuel cell (DMFC), methanol is reformed into electricity, water, heat and \text{CO}_2 according to the following equations:

\begin{align*}
\text{Anode:} & \quad \text{CH}_3\text{OH} + \text{H}_2\text{O} \rightarrow 6\text{H}^+ + 6\text{e}^- + \text{CO}_2 \\
\text{Cathode:} & \quad \frac{3}{2}\text{O}_2 + 6\text{H}^+ + 6\text{e}^- \rightarrow 3\text{H}_2\text{O} \\
\text{Overall:} & \quad \text{CH}_3\text{OH} + \frac{3}{2}\text{O}_2 \rightarrow 2\text{H}_2\text{O} + \text{CO}_2
\end{align*}

The working temperature of this DMFC is between 323 and 393 K, which is equal to a PEM fuel cell with hydrogen as a fuel. The biggest limitation of this type of fuel cell is the capacity, which is currently not larger than 5 kW\textsubscript{e}. This makes DMFCs not suitable for vehicle purposes, which require a minimum capacity of 80 kW\textsubscript{e} (Kauw, 2012). DMFCs could be ideal for forklifts, mobile phones, military purposes et cetera (Dohle \textit{et al.}, 2002; Ohla \textit{et al.}, 2006; The Seattle Times, 2009). An alternative is a reformed methanol fuel cell (RMFC), which is larger in capacity and can therefore function as a replacement for the internal combustion engine in our current passenger cars.

5.2.4 Reformed Methanol Fuel Cell

To overcome the problem of the limited capacity of DMFCs, RMFCs can be used. In these cells, first hydrogen is generated from methanol. Afterwards, the generated hydrogen is converted into electricity, water and heat. The conversion of methanol into hydrogen is relatively energy-efficient (70\%). However, high temperatures are required (523 – 623 K), which is the main drawback when these cells are used in passenger vehicles (Romm, 2004; Ohla \textit{et al.}, 2006). The fuel cell efficiency is estimated around 39\% in combination with on-board methanol reforming. Combining this with a drive-chain efficiency of 95\% results in an overall energy efficiency of 26\% (methanol-to-wheel). A battery electric car has a energy-efficiency (electricity-to-wheel) from around 90\% and an ICE car (gasoline-to-wheel) of about 15-20\%. (Ananthachar & Duffy, 2005; Kauw, 2012).

\textbf{Textbox 4: Fuel economy RMFC cars}

Calculation of the fuel consumption of RMFC vehicles: assumed is a basic car with a weight of 1100 kg and an energy consumption of 200 Wh/km. Converting 1 kg of methanol into hydrogen results in 0.187 kg H\textsubscript{2}. With a conversion efficiency of 70\% this is only 0.131 kg H\textsubscript{2}. The electricity that can be generated with 1 kg of methanol, including a drive-chain efficiency of 95\% and a fuel cell efficiency of 39\%, is about 5.2 kWh\textsubscript{e}. This is equal to a fuel consumption of 25.8 km/kgCH\textsubscript{3}OH or 4.9 litre CH\textsubscript{3}OH/100 km. Thus, using methanol in a RMFC is more energy-efficient than combusting it directly in an ICE engine. (Kauw, 2012; Campanari, 2009).
5.3 Methanol demand/supply
In this paragraph, the demand for methanol in combination with the mentioned transportation options is examined. As concluded in the previous paragraph, it is not allowed to blend more than 3% methanol by volume with gasoline within the European Union (EU, 2009). Therefore, M15, which is a mixture of 15% methanol and 85% gasoline, is not allowed. According to the EU, M85 with 85% methanol and 15% gasoline is not a blending product of gasoline but it is seen as a complete new type of fuel which is allowed within Europe. For this reason only the demand for M85 and M3 (3% methanol and 95% gasoline) are discussed. RMFCs are discussed to install in future passenger cars.

In the Netherlands, there are 7.9 million passenger cars. Besides an annual diesel consumption of about 7,500 million litres, about 5,600 million litres gasoline is consumed (CBS, 2012). A complete datasheet of transport fossil fuel consumption in amount of litres, PJ or kg of the Netherlands can be found in Appendix E.

In Iceland, the amount of cars is significant lower than in the Netherlands with 205,000 in 2010. The fuel consumption for automotive purposes was 287 kton of oil equivalent. Unfortunately, no information is known about the specific fuel consumption use of diesel or gasoline cars (Statistics Iceland, 2012). Assuming the same share of gasoline passenger cars compared as that of the Netherlands, this would result in a total gasoline demand of 162 million litres a year.

Assumed in the following methanol demand scenarios is that the fuel consumption of passenger cars in both Iceland as in the Netherlands will stay constant as well as the amount of passenger cars.

- M85: Every gasoline passenger car in Iceland or in the Netherlands will run on M85.
- M3: Every gasoline passenger car in Iceland or in the Netherlands will run on M3.
- RMFC: All passenger cars (gasoline and diesels) will use RMFCs. The entire private transport sector is running on methanol in combination with a RMFC.

In table 5.1, the demand and supply results of each above-mentioned scenario are shown. The demand in Iceland is combined with the five potential supply scenarios that are described in chapter 3 (scenario 1a-5), which are shown in red. In the Netherlands, the Green revolution and the Methanol Economy are discussed together with a 50 and 350 million litre example scenario. In the last two cases, methanol is produced from an oversupply of electricity from large scale implementation of offshore wind or solar PVs. These results are shown in blue.

The potential supply scenarios of Iceland are also applied to the demand in the Netherlands. These Icelandic scenarios are export scenarios and are added because, among other reasons, CRI will build more commercial renewable methanol plants for exporting produced methanol to, for example, the Netherlands. The reason for this is that the domestic demand for methanol in Iceland is too small. The potential losses due to transportation from Iceland to the Netherlands are neglected in this research.
Table 5.1: Annual supply and demand of methanol in the transport sector.

<table>
<thead>
<tr>
<th>Demand Scenarios</th>
<th>Supply Scenarios</th>
<th>Potential (million litres)</th>
<th>M3</th>
<th>M85</th>
<th>RMFC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Iceland the Netherlands</td>
<td>Demand (million litres)</td>
<td>10550</td>
<td>372</td>
<td>13490</td>
<td></td>
</tr>
<tr>
<td>Iceland (% of potential)</td>
<td>1a: CRI 5M</td>
<td>5</td>
<td>2%</td>
<td>47%</td>
<td>1%</td>
</tr>
<tr>
<td></td>
<td>1b: CRI 50M</td>
<td>50</td>
<td>17%</td>
<td>100%</td>
<td>12%</td>
</tr>
<tr>
<td></td>
<td>2: Geothermal</td>
<td>1331</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
</tr>
<tr>
<td></td>
<td>3: Hydro</td>
<td>865</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
</tr>
<tr>
<td></td>
<td>4: Geothermal &amp; Hydro</td>
<td>2196</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
</tr>
<tr>
<td></td>
<td>5: CO2 as a limit</td>
<td>338</td>
<td>100%</td>
<td>100%</td>
<td>88%</td>
</tr>
<tr>
<td>the Netherlands (% of potential)</td>
<td>Green Revolution</td>
<td>0.33</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td></td>
<td>Methanol Economy</td>
<td>2711</td>
<td>26%</td>
<td>100%</td>
<td>20%</td>
</tr>
<tr>
<td></td>
<td>Offshore Wind (13.5 GW_e)</td>
<td>50</td>
<td>0%</td>
<td>13%</td>
<td>0%</td>
</tr>
<tr>
<td></td>
<td>Solar PV’s (25 GW_e)</td>
<td>350</td>
<td>3%</td>
<td>94%</td>
<td>3%</td>
</tr>
<tr>
<td></td>
<td>4: Geothermal &amp; Hydro</td>
<td>2196</td>
<td>21%</td>
<td>100%</td>
<td>16%</td>
</tr>
<tr>
<td></td>
<td>5: CO2 as a limit</td>
<td>338</td>
<td>3%</td>
<td>91%</td>
<td>3%</td>
</tr>
</tbody>
</table>

a: Iceland M3. CRI accomplished to build a 5 million litre factory in 2012. About half of the gasoline passenger cars in Iceland can therefore run on M3. The factory that CRI is currently building in Krafla can supply an annual amount of 50 million litres a year. This would be large enough to supply all Icelandic gasoline passenger cars with M3. The rest can be used for export purposes.

b: Iceland M85. To supply all gasoline passenger cars in Iceland with M85, large amounts of new methanol factories have to be built. The maximum potential of Iceland, with the available CO2 (338 million litres/yr) can fully supply the demand of M85 in Iceland.

c: Iceland RMFC. The supply of CO2 would be a limiting factor for the production in Iceland. When CO2 will only be captured from geothermal power plants, the potential is 338 million litres/year. This is almost enough to supply all potential RMFC passenger cars.

d: the Netherlands Green Revolution. The renewable scenario that is set by the Dutch government to implement 6 GW_e offshore, 4GW_e onshore and 4 GW_e PVs will barely produce an electricity oversupply. This means that it cannot even supply 1% of the methanol demand in each scenario.

ev: the Netherlands M3. By installing large amounts of renewables (for example 13.5 GW_e offshore wind) to obtain an electricity oversupply, only 13% of the gasoline passenger cars can be supplied with M3. In figure 5.3, this demand scenario is also shown. To supply every gasoline passenger car in the Netherlands with M3, unrealistic amounts of renewables have to be implemented.

f: the Netherlands RMFC. When in the future every passenger car is a RMFC car, the demand for methanol is so large that it cannot be supplied by any of the discussed supply scenario. Figure 5.3 from the previous paragraph shows which amount of renewables is required to supply the demand when 2% of all passenger cars are RMFC cars. Just like for the M3 fuel, unrealistic amounts of renewables have to be implemented before the year 2030. For this reason, this type of future transportation technology is not the most optimal solution and is very unlikely to happen.

g: Export methanol Iceland to the Netherlands. CRI want to build more commercial renewable methanol factories to export their methanol to other European countries. In the most optimistic situation, when Iceland will produce about 2,200 million litres of methanol a year, it can only supply up to 16% of the demand for the Netherlands when all the passenger cars are RMFC cars.
5.4 Conclusion

Iceland can become independent of fossil fuels for the entire passenger transportation sector. When CO_2 is also captured from other sources than geothermal power plants, it can supply enough methanol for current ICE gasoline passenger cars. However, it has to be examined whether this future transportation solution for passenger cars is the most optimal one for Iceland. Perhaps full electric, hybrid or hydrogen passenger cars are more beneficial to apply in Iceland from an economic, social, environmental and energy point of view.

The Netherlands has no benefits by installing a methanol factory that can function as an energy buffer. To produce 350 million litres methanol a year, at least 19 GW\textsubscript{e} offshore wind, 22 GW\textsubscript{e} onshore wind or 25 GW\textsubscript{e} solar PVs has to be installed. With this amount, barely half of the current gasoline ICE passenger cars can be supplied with M3 fuel. In the future, when we perhaps all have RMFC cars, less than 3% can be supplied. Even when Iceland will export all produced methanol, the potential is too small. In conclusion, the potential of methanol as an energy buffer is too small to replace the Dutch transportation fossil fuel use. Even when all of the methanol potential of Iceland is imported, the Netherlands cannot become independent.
CHAPTER 6 ECONOMICS
An important aspect of renewable methanol production is the potential market price. If CRI wants to export their produced methanol on a short term, the prices have to compete with currently produced methanol from, for example, natural gas or coal. In this chapter, the current and historical market prices are examined and compared to the estimated methanol production prices of renewable methanol in Iceland and in the Netherlands.

6.1 Market prices and production costs
Oil prices are fluctuating rapidly and have been more than tripled since the year 2000. This generally means that the prices of other energy resources such as coal and natural gas have risen the last years. Commonly, methanol is produced from natural gas but in the last years, especially in China, coal is also used. Both methanol feedstocks are very sensitive to energy price changes, which influence methanol market prices. In figure 6.1, the global crude oil market price is shown in dollars per barrel of oil (red line). The blue line in the figure represents the historical methanol price since 2000 up to now. The ethanol price is generally ahead of crude oil prices and fluctuated in the last ten years between 200 and 700 €/Ton.

![Figure 6.1: Historical methanol and crude oil prices. Based on: IHS Chemicals, 2012b; Ohla et al., 2006.](image)

From the year 2000 up to 2005, the methanol prices are relatively constant but from then on, the prices highly fluctuated. In the last years from 2009 up to now, the methanol market price has been around € 300 per ton. The production costs of methanol are different for each used feedstock. Generally, methanol is produced from natural gas as a feedstock. On average, this will represent two-thirds of the total production cost of methanol. The rest are capital, maintenance and labour costs. When methanol is produced from coal, the feedstock costs are only 25% but the rest are generally high maintenance and capital costs. The average production prices of methanol production with different feedstocks are shown in table 6.1.

<table>
<thead>
<tr>
<th>Feedstock</th>
<th>Production price (€/Ton)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural gas</td>
<td>102</td>
<td>Williams et al. 1995; Roan et al. 2004</td>
</tr>
<tr>
<td>Coal</td>
<td>255</td>
<td>Roan et al. 2004</td>
</tr>
<tr>
<td>Coal (IGCC)</td>
<td>154</td>
<td>DOE, 2003</td>
</tr>
<tr>
<td>Renewable Biomass</td>
<td>428</td>
<td>Williams et al. 1995; Specht et al. 1998</td>
</tr>
</tbody>
</table>
6.2 Methanol production

Iceland

Producing renewable methanol will consume large amounts of electricity. Iceland has the benefits of producing inexpensive electricity with geothermal or hydropower plants. However, the costs of electricity have also been rising, especially in the last five years. In figure 6.2, the average consumer electricity prices from 1980 up to now are shown. Due to the economic problems in Iceland, in 2007, prices almost doubled. Not only electricity prices went up but also diesel and geothermal heat prices for heating purposes went up. These are also shown in the figure as an indication.

Figure 6.2: Current and historical electricity and heat prices in Iceland (Statistics Iceland, 2012)

- Geothermal power plant electricity generation range between $0.045/kWh and $0.074/kWh (2012 US dollars, exchange rate 1.32 $/EUR).
- Hydropower plants are less expensive with costs that range between $0.030/kWh and $0.050/kWh (2012 US dollars, exchange rate 1.32 $/EUR; Worldwatch Institute, 2012).

Based on information of Huisman, 2011; Ingason, 2008 and Barranon, 2006, assumed is that the costs of renewable methanol production consist of 20% capital costs, 8% maintenance costs and 6% staff costs. The rest are electricity costs, which is basically the only feedstock. In table 6.2, the estimated costs of renewable methanol production in Iceland are shown. The lowest costs can be achieved by using a large scale energy-efficient electrolyser (76%). The highest costs represent the current production in the methanol facility of CRI with an electrolyser efficiency that is estimated around 65% (Global CCS Institute, 2011).

<table>
<thead>
<tr>
<th>Energy Feedstock</th>
<th>Production price (EUR/Ton)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geothermal power</td>
<td>948 - 1127</td>
</tr>
<tr>
<td>Hydropower</td>
<td>610 - 724</td>
</tr>
</tbody>
</table>

Table 6.2: Estimated costs of renewable methanol production in Iceland.
The Netherlands

Large scale renewable methanol production in the Netherlands can only be realised in combination with wind or solar power. In 2009, the European Wind Energy Association (EWEA) published the book: “Wind Energy – The Facts” which is currently pointed out as the most important reference in the world for information about wind energy. It presents detailed information about social, economic and environmental aspects of implementing wind energy. The reported costs of implementing onshore wind energy range between €0.07-0.10/kWh in low wind speed areas (<1900 wind hours a year) and €0.05-0.065/kWh in coastal areas (>2500 wind hours a year), with an average of €0.07/ kWh. These costs estimations are based on a lifetime of 20 years. Offshore wind turbines are more costly than onshore and accounts for less than 1% of all wind capacity in the world. EWEA estimated that the costs of offshore wind are about €0.14/ kWh. PV solar power is currently the most expensive form of renewable electricity generation. Estimated is that current prices range between €0.13 and €0.48/kWh, depending on the type of PV (mono crystalline silicon, polycrystalline silicon, amorphous silicon and others; Timilsina, 2012).

Comparison

In figure 6.3, the estimated production costs of methanol from different energy sources are shown. Currently, the production of methanol with fossil fuels as a feedstock is less expensive than renewable methanol production from hydro, geothermal, wind or solar power. Hydropower is one of the most inexpensive techniques to produce electricity but due to the high energy consumption of methanol production, it can currently not compete with production prices of methanol from fossil fuels.

It can be concluded that renewable methanol production can only compete with fossil fuel methanol production when the production will not be taxed or when the production will be subsidised (Williams et al., 1995; Specht et al., 1998; Roan et al., 2004). The motivation of building a large scale commercial renewable methanol power plant in Iceland is not known. In 2005, CRI invested in this 20 million dollar project with only private money from different stakeholders. In 2005 the energy prices were about half of current electricity prices in Iceland. On the other hand, even with the estimated electricity costs of old existing geothermal power plants ($0.045/kWh), the production of renewable methanol could not be lower than € 600/ton.
CHAPTER 7 GLOBAL RENEWABLE METHANOL PRODUCTION

Electricity generation from geothermal sources has a history of over hundred years. The first ‘power plant’ was installed in Italy (Larderello) to generate small amounts of electricity. Ten years later, the first commercial 250 kW$_e$ power plant was built and connected to the national grid. Currently, over more than 10 GW$_e$ of geothermal electric power is installed. In this chapter, the potential of this source of electricity generation is discussed and applied to potential renewable methanol production.

7.1 Global geothermal potential

Different types of geothermal power plants exist with each a certain global potential. All currently installed power plants have one thing in common: they all generate electricity with a steam turbine. Dry Steam power plants use high temperature, vapour dominant reservoirs to directly generate electricity from the available steam. About 27% of all worldwide installed geothermal power capacity uses this technique. The most common type, with a share of 41%, is Single Flash power plants, which are more flexible because they can cope with lower temperatures and liquid dominant thermal reservoirs. In these power plants, a mixture of liquid and steam is separated and afterwards the steam can be used to generate electricity. In a Double Flash power plant, which have a share of 20%, the used steams in the first turbine is recycled and re-used in a lower pressure steam turbine to achieve higher energy efficiencies. The last and newest technology is Binary power plants, which represent 12% of all geothermal power plants. These plants can handle reservoir temperatures that are lower than 423 K. Geothermal fluids are only used in heat exchangers to increase the temperatures of the working fluid for generating electricity in a steam turbine. These systems can also be installed in existing, less efficient, geothermal power plants to increase the efficiency (Chamorro et al., 2011).

In figure 7.1 (left), the top 10 countries that installed geothermal power plant are shown. The blue bars represent the in 2010 installed electric capacity and the red bars the short term potential in each country. The total worldwide potential in 2050 of geothermal electricity production in an optimistic view is a future capacity of 70 GW$_e$ (red line in figure 7.1 right) using a capacity factor of 0.95. A less optimistic scenario (yellow line) would be a capacity of 40 GW$_e$ in 2050 which is based on the first scenario of Bertani, 2012. Both scenarios will be used to examine the worldwide potential of renewable methanol production. The current share of plant types (dry steam, double flash et cetera) is assumed to be the same in 2050.

A complete new technology, which is currently under development, is an Enhanced Geothermal System (EGS). This closed-loop system can be installed in a low temperature reservoir and compared to conventional geothermal power plants these will emit no CO$_2$. The potential of electricity generation of EGS’s is estimated to be 70 GW$_e$ in 2050. This type of geothermal electricity generation could not be used for renewable methanol production because no CO$_2$ is available at this source of energy. For this reason, only the potential of methanol production in combination with today’s geothermal technology is examined.

Figure 7.1: Left: Current types of geothermal power plants. Right: Future potential geothermal capacity (Bertani, 2012)
7.2 CO₂ emissions
In all installed geothermal power plants, CO₂ will be released with the production of electricity. This CO₂ is can be used for renewable methanol production. In chapter 3, it was concluded that the CO₂ emissions of geothermal power plants in Iceland are too small compared to the electricity that is generated. In other words, CO₂ is the limiting factor in Iceland when it is not captured from other sources such as the industry. When the worldwide potential of methanol production is examined, CO₂ could also be a limiting factor. Iceland is transparent in providing data about each power plant and their emissions. However, not every country provides this information because emissions could sometimes be extremely high and exceed the emission from natural gas or coal-fired power plants. In a CO₂ survey study of Bertani & Thain (2002), data is collected of plants, which represented 85% of the worldwide geothermal capacity. These results (summary) are shown in figure 7.2. No specific information is available such as locations, sizes, type of plants et cetera, because this data is kept confidential, primarily for commercial reasons. Figure 7.2 shows that most of the installed capacity (73%) has a CO₂ intensity lower than 149 g/kWhₑ. The worldwide average (weighted) CO₂ emissions from geothermal power plants is 122 gCO₂/kWhₑ.

In the most optimal situation, when thermal energy is partly used for the production of methanol, 40.24 MJ/kgCH₃OH is required (table 3.3). This will consume about 1.53 kgCO₂/kgCH₃OH when 90% is recovered. Converting this into CO₂ per generated kWh results in minimal required emissions of 120 gCO₂/kWhₑ. This means that the required emissions for renewable methanol production are about equal to the worldwide averages. It can be concluded that on average CO₂ emissions are large enough to not be a limitation for the production of methanol. However, for many geothermal power plants, the real emissions will be lower than the require emission (see figure 7.2). Unfortunately, no data is available about the exact locations of these power plants. In the following scenario, when the potential of the 40 and 70 GWₑ scenarios is examined, it is assumed that CO₂ will not be a limitation.

7.3 Potential methanol production
Using the same share in geothermal power plant types in 2050 with the including of energy efficiencies would result in a potential electricity generation of 583 TWhₑ/yr for the 70 GWₑ scenario. For the 40 GWₑ scenario this results in an electricity production of 333 TWhₑ/yr; calculations based on energy efficiencies and capacity factors of Chamorro et al., 2011). The total production potential of these scenarios are shown in figure 7.3 and table 7.1.
The 2050 potential production in the 70 GW_e scenario is about 66,000 million litres a year and with the 40 GW_e scenario about 38,000 million litres. Both potentials are lower than the currently produced amount of methanol with generally natural gas as a feedstock (76,000 million litres, black line in figure 8.3). It can be concluded that when all worldwide geothermal potential is used, in the optimistic scenario, it would not even be able to replace current demand for methanol.

In figure 7.3, the current estimated methanol demand for 4% of all global passenger cars is shown. Keep in mind that the total amount of passenger cars is expected to increase with more than 100% by the year 2050 (Kauw, 2012). As an indication, the M85 demand for Iceland and the Netherlands is shown when these counties will use M85 as a transport fuels (blue and orange dotted lines).

<table>
<thead>
<tr>
<th>Installed capacity (GW_e)</th>
<th>Produced electricity (TWh_e)</th>
<th>Recovered CO_2 (Mton)</th>
<th>Methanol potential (million litres) without CO_2 limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>70</td>
<td>583 (2.9%*)</td>
<td>72</td>
<td>± 66,000</td>
</tr>
<tr>
<td>40</td>
<td>333 (1.7%*)</td>
<td>41</td>
<td>± 38,000</td>
</tr>
</tbody>
</table>

* Share of worldwide produced electricity in 2012.

The captured CO_2 with the 70 and 40 GW_e scenario is respectively 72 and 41 Mton/yr (table 7.1). These emissions can be seen as anthropogenic and will be released upon the use of methanol itself. However, these emissions can almost be neglected compared to the annual worldwide CO_2 emissions of approximately 30,000 Mton; United Nations Statistics Division, 2012). On a worldwide scale, CO_2 can also not be recycled.

7.4 CO_2 savings

Producing methanol with geothermal power plants is not CO_2 free, but it can function as a substitution for methanol that is produced with fossil fuels. This will save some emissions because reforming natural gas into methanol also costs energy and therefore CO_2. In this paragraph, the actual global savings are researched when the industry, the transport sector or other sectors use renewable methanol, produced from geothermal power, instead of fossil methanol.

Figure 7.4 shows the CO_2 emissions of using methanol together with the estimated production emissions are shown. When a certain amount of methanol is used, CO_2 will be released, no matter if this would be in a combustion engine or in a fuel cell. The only variation is the way that methanol is produced. When natural gas is reformed into methanol, a certain part of energy is lost, which results in potential CO_2 emissions. Generally, methanol produced from natural gas has an energy-efficiency around 75% (CFR, 2004). The production emissions of methanol produced from coal are significantly higher because combustion of coal is more pollutant than natural gas (Tiax, 2005). Current capturing technology is only able to capture 90% of CO_2 from geothermal power plants. The rest (10%) cannot be captured and is therefore directly released into the atmosphere. These emissions can be seen as production emissions. The actual captured CO_2 will be converted into methanol and released upon the use of methanol itself. When CO_2 is recycled, only the production emissions (10%) will be emitted during the lifetime of methanol.
production. In a closed-loop situation, CO₂ will be captured from atmospheric air. All of this captured CO₂ will be used to convert it into methanol. After the use of this methanol, the ‘stored’ CO₂ will be released again. This means that the production of this type of renewable methanol will emit no CO₂ during the production or use of methanol. A closed-loop can only be achieved when the required electricity is generated with renewable energy sources other than geothermal.

Mainly all worldwide produced methanol use natural gas a feedstock. The actual savings of producing methanol with geothermal power and CO₂ instead of using natural gas is about 10 gCO₂/MJ of methanol (difference of red bars in figure 7.4). The difference with coal as a feedstock is around 140 gCO₂/MJ of methanol. Assuming that 85% of all methanol is currently produced with natural gas and 15% with coal, this would actually save 31.1 Mton CO₂/yr. It can be concluded that using geothermal power to produce methanol releases additional CO₂ into the atmosphere but this produced methanol can function as a replacement for methanol that is produced with fossil fuels. This means that CO₂ is reduced. However, these reductions are small compared to the annual emissions of approximately 30,000 Mton of CO₂/yr.
CHAPTER 8 CONCLUSION, DISCUSSION AND RECOMMENDATIONS

8.1 Conclusion
In the Icelandic company CRI, CO\textsubscript{2} from a geothermal power plant is converted into methanol. For this process not only CO\textsubscript{2} is required but also hydrogen. CRI claimed this was a new technique but converting these two feedstocks into methanol was already developed in 1927 by BASF, who converted CO\textsubscript{2}, and H\textsubscript{2}, obtained from fermentation gasses, into methanol with the use of a copper zinc oxide based catalyst. What is new is the method of producing methanol where CO\textsubscript{2} is obtained from a geothermal power plant and hydrogen is produced from the electrolysis of water in combination with electricity that is generated with renewable energy sources. At CRI, CO\textsubscript{2} and H\textsubscript{2} are compressed to the required pressure and temperature and converted into methanol and water as a by-product by using a CuO/ZnO/Al\textsubscript{2}O\textsubscript{3} catalyst. For this process, only electricity is required of which 90% is used to produce the required hydrogen and put it at the required pressure of 50 bars. What basically is accomplished in this factory is converting electricity, generated by a geothermal power plant, into methanol with the use of CO\textsubscript{2} as feedstock. The only advantage of Iceland is that they are able to use inexpensive amounts of renewable energy (geothermal or hydropower) to make this happen. The overall energy efficiency from electricity to methanol is around 50 – 55%.

For geothermal power plants located in Iceland, it can be concluded that more electricity will be generated than the required CO\textsubscript{2} for methanol production. If CRI wants to extend their production capacity and use the available CO\textsubscript{2} from potential new geothermal power plants, the methanol production is limited to 350 million litres/yr. This potential is large enough to supply all gasoline vehicles in Iceland with M85 instead of conventional gasoline. However, this production is relatively small when it exported to large countries with a potentially large demand for methanol such as the Netherlands. As an indication, 350 million litres can only supply 3% of all Dutch gasoline vehicles. The potential of Iceland could become larger when the required CO\textsubscript{2} is captured from for example the industry. Combining this with the maximum potential of geothermal and hydropower results in a maximal production of 2,200 million litres/yr. This is unlikely to happen because the costs and the energy consumption of capturing CO\textsubscript{2} from the industry are significantly higher than capturing it from geothermal power plants.

It is correct to say that this type of methanol production also can be achieved by other renewable energy such as solar and wind. These sources generate a variable and unpredictable source of electricity. The problem is that no hydrogen electrolyser exist that officially can handle with this input. Small scale experiments are realized with existing electrolyser (Hydrogenics HyStat 15-10) in combination with an unpredictable source (wind turbine). The result is that it is technically possible but, according to all electrolyser manufactures, it is not safe and therefore not allowed. Furthermore, the efficiency of hydrogen production will decrease on average with 9%. Because hydrogen production is responsible for at least 80% of all consumed energy in converting CO\textsubscript{2} into methanol, this will extremely affect the total energy efficiency of producing renewable methanol.

No CO\textsubscript{2} will be recycled in the CRI methanol factory, because deep in the ground volcanic magma is degassed into CO\textsubscript{2}, which will be released into the atmosphere by using this thermal energy to generate electricity or produce methanol. When a new geothermal power plant is built, additional CO\textsubscript{2} will be released into the atmosphere. This is on average ten times less than a coal-fired power plant but still significant. CRI claims that they are able to capture this CO\textsubscript{2} and recycle it into methanol but the truth is that this captured CO\textsubscript{2} will still be released upon the use of methanol itself. This is less and may not happen in Iceland but in another country when they try to export the methanol where it will function, as for example, an alternative for conventional gasoline.

The only way to recycle CO\textsubscript{2} is when it is captured from a fossil fuel power plant or from the industry. This is possible in the Netherlands in combination with solar or wind power where methanol production could function as an energy buffer. The most ambitious plan of the Dutch government is to implement 14
GW_e of renewables in 2030. In this scenario, moments exist in which more electricity will be generated than is required due to the unpredictability and variability of solar and wind power. Methanol production, according to the CRI process, gives the Netherlands the opportunity to use it as an energy buffer. The potential is however not large, mainly because of the limited oversupply. The Netherlands will largely invest in gas-fired power plants, which are flexible in their demand. This means that generally all electricity that is generated with renewable energy source can be supplied. It can be concluded that at least 17 GW_e of renewable energy sources have to be implemented before methanol production in the Netherlands can become feasible and create a potential methanol production of around 50 million litres a year. Furthermore, the theoretical energy efficiency, which is around 42%, is relatively low due to the inefficient hydrogen production in combination with solar and wind power. The recycled amount of CO_2 (± 0.01 Mton per million litre methanol) is extremely small and can therefore be neglected compared to the annual Dutch CO_2 emissions of 174 Mton. Due to the low energy efficiency, the small potential, the technical problems with hydrogen production from solar/wind power and the small amounts of recycled CO_2, this method is not optimal to store energy and to recycle CO_2.

If the only purpose of implementing solar and wind energy in a country is to produce methanol, the costs are currently at least 15 times higher compared to methanol production from natural gas as a feedstock. Renewable methanol production can only compete with the fossil fuel-based production when the production will not be taxed or the production will be subsidised. Therefore, producing renewable methanol can only be achieved in countries, which have the opportunity to use large amounts of inexpensive renewable energy sources.

From a CO_2 point of view, the best option that can be achieved is to create a closed loop when CO_2 is capture from air and used to produce methanol. This captured CO_2 will be released again when it is used. Capturing CO_2 from air is a relative new technique and only little research is performed about this subject. Therefore, only small scale prototypes are developed and the energy consumption is still relatively high and not well-known in literature. In theory, when the entire society uses methanol as a replacement for fossil fuel, CO_2 levels could stabilize but cannot decrease to for example pre-industrial levels as mentioned by CRI. Furthermore, the global potential of producing renewable methanol with geothermal power is too small to replace fossil fuel use and it is even too small to replace current demand for methanol that is produced with fossil fuels. But, using the maximum global potential can actually save some CO_2 because renewable methanol production is less pollutant than with any other fossil fuel feedstock such as coal and natural gas.

CRI made a correct choice to produce methanol from the large energy potential of Iceland. It is currently a better option for an energy carrier than hydrogen. It has an existing infrastructure, it can directly be used as a replacement for conventional gasoline and it can easily be transported and stored at ambient pressures and temperature. None is currently the case with hydrogen as an energy carrier. However, it is untrue to claim that CRI on short-term can produce large amounts of methanol that completely can supply the current global demand of fossil fuels (quote 2 on page 6).

8.2 Discussion
In the discussion the most important assumption points are discussed. These are not mentioned in this research thus far and could influence the results and the conclusion of this research.

Energy efficiency
CRI is a small company that gives little information about their methanol production process. By using the most recent patents of CRI, it was assumed that they are using the Lurgi system based on a CuO/ZnO catalyst. It may be that they developed their own system, which is more energy-efficient than the one is calculated in this report. On 1 June 2012, a news article appeared on the website of CRI. Information about their methanol process was given and it was concluded that their energy-efficiency was around 58% (electricity-to-methanol). In this research, it was calculated that with the Lurgi system, a maximum energy-efficiency of 54.1% was feasible. So it seems that they use a slightly different process in reality.
Potential Iceland
A lot of information is available about the potential of the Icelandic renewable energy sources. In this research, data from the Icelandic government are used. The government developed a future master plan for implementing new geothermal and hydropower plants. The total potential of geothermal power was estimated around 11 TWh/yr and for hydropower 8.2 TWh/yr. However, in some literature, the total (technical) potential is estimated to be much larger with at least 20 TWh/yr for geothermal and 30 TWh/yr for hydropower.

Available CO$_2$
CO$_2$ from geothermal power plants is used by CRI to produce renewable methanol. It is assumed that by building new geothermal power plants, the same amounts of CO$_2$ will be released as with existing geothermal power plants, built after the year 2006. However, it is not completely well known what the actual available CO$_2$ from new geothermal power plants is and which amount can be used for methanol production. This could positively or negatively influence the estimated potential of Iceland.

Power plants in the Netherlands
Tennet provides detailed data about the implementation of new power plants up to the year 2020 for the Netherlands. The trend of the last years is that mainly gas-fired power plants were installed instead of coal-fired power plants. Because no data about new plant after the year 2020 are available, it is assumed that from 2020 up to 2030 only new gas-fired power plants would be installed. Gas-fired power plants are flexible in their demand, which is beneficial when also large capacities of renewables are installed. This means that generally all electricity that is generated by wind and solar power can be used. However, when after 2020, the Dutch government decides to invest in less flexible plants, such as nuclear power, the potential oversupply of electricity could be much larger than is indicated in this report. Therefore, methanol production in the form of an energy buffer may become feasible to use in the Netherlands.

These discussion points could influence the results in this report, but the overall conclusion will be the same. The claims of CRI are not correct. Currently no CO$_2$ will be recycled in Iceland and the potential of Iceland is too small to replace all global fossil fuels. Methanol can perhaps be used as an energy buffer in the Netherlands when the Dutch government decides to implement more renewable or less flexible power plants then are assumed in this report.

8.3 Recommendations
 Methanol synthesis
 The methanol production potential of Iceland is estimated around 338 million litres/yr with the available CO$_2$ and geothermal power. In the most extreme case, more than a thousand large scale bi-polar electrolyser are needed to produce the required amounts of hydrogen. The feasibility of this has to be examined because the company NEL has only built such a large electrolyser once. Furthermore, the (environmental) impact of building new methanol factories, including the required number of electrolyser, is not included in this report but it may be significant towards the impact of producing methanol itself.

Energy buffer
In the Netherlands, the potential of methanol as an energy buffer is limited. Only when more capacity will be installed than is mentioned in the most ambitious plan of the Dutch government (6 GW$_e$ offshore wind, 4 GW$_e$ onshore wind and 4 GW$_e$ PVs) a methanol factory can become feasible. Larger countries that will heavily invest in renewables such as Germany will be faced with larger oversupplies of electricity than in the Netherlands. In this situation perhaps methanol can (economical and technical) function as an energy buffer. This is maybe not the most efficient method of storing electricity but it can be applied on a large scale which is currently technically not possible with for example Li-ion batteries. Maybe the largest barrier/challenge for methanol production, used as an energy buffer, is the method to produce the required
hydrogen. In most literature, it is assumed that hydrogen easily can be produced by an oversupply of electricity. However, no electrolyzers exist that can handle with an unpredictable and variable source of energy which will be generated from solar and wind power. Electrolyser manufactures such as NEL and H₂logic have to research the possibilities of combining solar and wind energy with the variable production of hydrogen. If this is technically not possible or maybe energy inefficient, CRI can probably built no new methanol factories in countries that only have the possibility to implement solar PVs or wind power. Perhaps an option to overcome this technical barrier is to use Concentrated Solar Power (CSP) in high solar radiation areas. New CSP systems exists that can generate a constant and predictable output of electricity which can be used for the production of renewable methanol. The only technical challenge in this situation is to obtain clean water for hydrogen production and to capture large amounts of CO₂ from atmospheric air.

**CO₂ uptake from air**
The best option that can be achieved by CRI is to create a closed loop for CO₂ by capturing it from air. Too little information is available about the actual energy consumption of a large scale implementation of this kind of methanol production. Small scale lab experiments are developed but the energy consumption seems to be too optimistic when it is compared to CO₂ capturing from geothermal fluids. Currently, capturing CO₂ from air in an old cooling tower develops a medium scale experiment. The data is not yet available but it will be more accurate than current lab experiments. Furthermore, the potential of these techniques has to be examined to investigate the feasibility of stabilising global CO₂ emissions by introducing methanol production from atmospheric air.

**Geothermal emissions**
In figure 3.4 it was concluded that emissions from geothermal power plants, compared to other anthropogenic CO₂ emissions are very small. Applying large scale electricity generation of geothermal energy source could increase these emissions up to about 0.3 Mton/yr. This would be a significant part of the total anthropogenic CO₂ emissions of Iceland. Already was concluded that, natural emissions exceed far anthropogenic CO₂ emissions from geothermal power plants. The conflict with the use of geothermal energy is the contribution of human activity to this type of electricity generation. According to Armannsson & Dereinda et al., (2010): “The main controversy is whether the emissions from geothermal plants is an addition of gas to the atmosphere or whether it is just a transfer from natural emissions to plant emissions”. This could mean that CO₂ emissions of methanol production by CRI could be far lower than calculated in this report and that they are actually able to recycle CO₂ into methanol. In Iceland they currently see emissions from geothermal power plants as a human activity. However, in Italy they report these emissions as natural fluxes (Armannsson & Dereinda et al., 2010; IPPC, 2007). In future, more research has to be performed on emissions from geothermal power plants and their contribution to the atmosphere.

**Demand**
In this report, methanol is used in the transport sector as a replacement for conventional gasoline to indicate how large the potentials of Iceland and the Netherlands were. Using methanol in a passenger car is maybe not the best purpose from an energy point of view. The use of methanol is most efficient in a stationary methanol fuel cell where waste heat is recovered and used for potential heating purposes. The actual future methanol demand in Iceland or the Netherlands, other than the transport sector, has to be investigated to use methanol in the most optimal way.
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### APPENDIXES

#### A: Specifications of 41 industrial electrolysers

<table>
<thead>
<tr>
<th>Model</th>
<th>Capacity [kg/day]</th>
<th>Capacity [kg/yr]</th>
<th>Type</th>
<th>Conversion efficiency [-]</th>
<th>Energy consumption [kWh/kg H₂]</th>
<th>Product pressure [bar]</th>
<th>Energy efficiency (incl. pressure) [-]</th>
<th>Energy consumption without compression [kWh/kg H₂]</th>
<th>Energy efficiency (excl. pressure) [-]</th>
<th>Lifetime [years]</th>
</tr>
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<td>AvalancheHydrofiller 15</td>
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<td>315</td>
<td>Unipolar</td>
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<td>Bipolar</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>15 years</td>
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<td>2364</td>
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<td></td>
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<td></td>
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### B: Methanol synthesis specifications

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C1: Electricity consumption of Iceland 2010

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C2: Power Plants Iceland

### Hydro power plants

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| Total [MW] | 1907    |
| Electricity production 2010 [GWh] | 12592 |
| Load Factor | 0.753 |
## Geothermal power plants

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**Total**                  **504258**          **159797**

**Total [MW]**              **504**

**Total [GWh/yr]**          **4037.7**

**Load Factor**             **0.913**

### C3: Emissions from geothermal power plants Iceland

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D2: Implementation of renewable energy sources the Netherlands

Scenario 1: Green revolution

Scenario 2: Sustainable Transition

Scenario 3: Money is important
## E: Dutch fuel consumption 2010 – 2011

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