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Content

Editorial

By **COL Romualdas Petkevičius (LTU-AF)**
Director of the NATO ENSEC COE

Climate change is, without a doubt, one of the biggest challenges facing the world, a defining issue of our time. We may not always see or feel the effect of climate change directly, but it affects us all.

NATO, its partners and the military sector are no exceptions to this rule. Climate change is the ultimate "threat multiplier" and in the coming years it will have a negative impact for military operations, personnel and installations. In response to the growing climate movement across most of the West, NATO militaries will also likely become increasingly involved in efforts to reduce CO_2 emissions.

This issue of Energy Highlights is a direct response to these challenges we face. It provides a timely overview of the governmental and institutional dilemmas that stem from the need to tackle climate change-related environmental threats. It also looks at the technological and the economic prospects of using innovative low-carbon fuels as more climate-friendly alternatives to fossil fuels.

In their article Ms. Camille Fourmeau and Dr. Reiner Zimmermann examine the Australian military's difficult balancing act of defending the country from external threats and responding to devastating natural disasters such as the 2019–20 bushfire crisis, all while reducing its carbon footprint and becoming "greener". As global temperatures continue to rise, there is little doubt that decision makers across the world will be facing a greater number of similar environmental challenges, and more frequently, too. Therefore, it would be prudent to monitor the developments in Australia and draw valuable lessons from its experiences.

While it is necessary to be prepared to adequately respond to climate change-induced natural disasters, it is arguably even more important to tackle one of its root causes: the burning of fossil fuels. To this end, Dr. Jutta Lauf has written two distinct, but related articles, which examine the potential of hydrogen and synthetic fuels.

In her first contribution, Dr. Lauf examines the potential of using hydrogen as a versatile energy source. She argues that hydrogen may play an important role in mitigating climate change as it can be used for heating and as fuel in the transport and mobility sector. Moreover, Dr. Lauf looks at the available hydrogen production technologies and breaks down their costs in the case study of Germany.

In her second article, Dr. Lauf explains how power-to-liquid technologies can produce synthetic fuels, which can make a positive contribution to the environment. She argues that synthetic fuel has the potential to provide an alternative to NATO's F-34 kerosene fuel and, by doing so, reduce the alliance's dependency on fossil fuels, cut its carbon footprint and potentially even help stabilize NATO's partners and vulnerable neighbors.

Granted, despite the clear environmental benefits of these innovative synthetic fuels it is not yet clear if they will be able to compete with fossil fuels anytime soon. If the low oil price environment persists for the foreseeable future, it is rather difficult to expect that synthetic fuel or hydrogen would be able to carve out a greater share of the energy market. Similarly, in light of the global COVID-19 economic recession, it is also hard to imagine that most governments would be overly keen to spend additional funds on costlier fuels, at least in the short run.

In the end, while there is little doubt that innovative synthetic fuels are the future, it remains to be seen when and under what circumstances will they make their grand debut.

Can military forces do it all?
Climate change, a national energy security issue for Australia and its Defence Force

by **Camille Fourmeau and Reiner Zimmermann**

ABSTRACT

Australia experienced a significant increase in average annual temperatures in the 20th century bringing extreme weather events and devastating bushfires. The ensuing rescue and relief missions were strongly supported by the Australian Defence Forces (ADF). Yet, the country and its governments have shown little concern regarding the mitigation of climate change which hampers Australia's international commitment and efforts to curb Green House Gas emissions. This denial has led to problematic choices in the energy sector where coal is still the main source of energy used despite a significant potential for renewable energy. With most countries taking the climate change issue into their core policy, especially in the Indo-Pacific region where climate change is a grave concern, Australia is becoming gradually isolated in international negotiations and cooperation. Australia's political indifference in these matters is not without consequence for the Australian Forces which must maintain cooperation to protect Australia's strategic needs and national security. In addition, climate change related environmental threats as well as resulting rescue and relief missions strain the ADF's infrastructure, equipment and above all military operability. ADF's military capabilities are increasingly being torn between home defence, international operations and disaster relief. In addition, ensuring the maritime safety of Australia's trade and supply routes - especially for fuel imports - is a core part of the national Defence. With tarnished relations in the Indo-Pacific region due to Australia's poor performance on climate change mitigation the ADF's capability to tackle core defence tasks might become an issue.

by **Camille Fourmeau and Reiner Zimmermann**

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INTRODUCTION

The emerging consequences of climate change are increasingly affecting civil and military energy security of nations and are a determinant element of national security. Australia as a nation that spans an entire continent is already facing negative effects of global warming like severe droughts and uncontrolled bushfires. These natural disasters are beginning to stretch the capacity of civil society and military forces involved in disaster relief and rescue activities and are threatening the private and public infrastructures. In the past years Australia's government has always invoked the Australian Defence Force for crisis and disaster management. But should the military really take on all these additional tasks and roles? Since Australia's economy and national budget very much depend on the revenues from mineral and raw material exports while its energy supply strongly depends on international imports, any disruption of production and transportation infrastructure will make the country vulnerable to energy security and its ability to cope with future crises. Australia has two major challenges to address in order to solve its climate and energy dilemma. First, respond to climate change related environmental challenges and the international demand for decarbonisation while taking into account its dependence on a carbon-based economy and second, to maintain energy security for the civil and military sectors under increasing threats from climate change. In this paper we will address the threats to Australia's national security caused by climate change and focus on Australia's climate policies and position on the Paris Climate agreement to understand the impacts on national energy security and the Australian Defence Force.

FROM CLIMATE CHANGE INACTION TO A NATIONAL SECURITY ISSUE

In 1998, Australia signed the Kyoto Protocol[1] but did not ratify it until 2007. Australia met and exceeded its carbon emission reduction target for the first commitment period but fell short of keeping up the positive result. In the COP 15 Copenhagen agreement of 2009, Australia pledged a voluntary 5% reduction by 2020 compared with the year 2000 emission levels for their second commitment period of the Kyoto Protocol, but missed this target [14]. In August 2015, Australia presented its "nationally determined contribution" (NDC) to the Paris Agreement[2] under the Liberal Prime Minister Tony Abbott known for his anti-climate position. The pledge promised a 26-28% reduction of emissions by 2030 compared to 2005 levels, which equals to a 22–25% cut below 1990 levels, including the effects of land use changes. However, if land use is excluded, the target will be equal to a 3-6% rise in emissions as land use is currently acting as a net carbon sink[3] in Australia.

Today, Australia is not on track to meet its climate targets even though the Australian Government has repeatedly insisted on the contrary in its annual emission projection reviews released by the department of Environment and Energy[4] [7] [8]. Emissions were trending down from 2007 to 2015 but increased ever since. In June 2018 emissions had increased by 0.6% compared to the previous year, pushing Australia's emissions to be the highest since 2011 (see Figure 1). A report released in December 2019 by the Department of the Environment and Energy [5] shows that Australia's greenhouse gas emissions in 2020 are estimated to be just 1.6% below their

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[1] The Kyoto Protocol was an instrument made under the United Nations Framework Convention on Climate Change in 1997 to force some developed countries to reduce their greenhouse gas (GHG) emissions. First agreed on in 1992 and following growing global concern about climate change, the Convention defines a framework aimed at stabilising atmospheric concentrations of GHG to prevent 'dangerous anthropogenic interference with the climate system'. The UNFCCC entered into force in 1994, and now has a near universal membership of 197 countries having ratified the Convention. Parties to the Convention meet regularly, including at the annual Conference of the Parties (COP), where they make decisions to promote the effective implementation of the Convention and adopt other instruments.

[2] The Paris Agreement (December 2015) was designed to replace the Kyoto Protocol after the year 2020. It set a long-term temperature goal to keep the increase in global average temperature to well below 2° C above pre-industrial levels and to pursue efforts to limit the increase to 1.5° C. Each country was asked to determine, plan, and regularly report on the contribution that it undertakes to mitigate global warming. No mechanisms to force a country to set a specific emissions target by a specific date were implemented, but it was asked that each new target set should go beyond previously set targets. The 2° C level was chosen based on the Intergovernmental Panel on Climate Change 's (IPCC) result: "global warming of more than 2° C would have serious consequences, such as an increase in the number of extreme weather events".

[3] Photosynthetic uptake of atmospheric CO^2 by existing forests and other vegetation.

2000 level. Based on this estimate, Australia will possibly meet its target in 2030 instead of 2020.

The lack of political action on reducing carbon emissions and thus mitigating climate change will not go without consequences as Australia will lose its international credibility and suffer from its choices. Abiding to the Paris Agreement is critical to limit devastating climate impacts on public health, the national economy and natural ecosystems, - all these concerns were already raised by the 2008 Garnaut Review.[5] The Climate Action Tracker (CAT) [4], an independent scientific analysis produced by four international research organizations, warns that if other countries were to adopt climate policies similar to Australia then global average temperature could rise by up to 4° C, posing serious challenges for human survival. Global temperature has already risen by 1° C over the past millennium's average and yet the results are already felt in Australia with worsening heat waves, bushfires, intense rainfall events, and rising sea levels - all inducing serious national security issues[6] [1].

Climate change considerably affects the risk perception and assessment [15] of the Australian public since they are particularly proud of their unique and fragile ecosystems and biodiversity. Yet, the relation of climate and environment with national security, even though recognised, is still seen as a matter of lesser importance.

The idea of balancing environmental concerns with the social system and the economy is sometimes seen as a dilemma because it is generally assumed that addressing climate change challenges will hamper the economy, Australia's government's first concern. This perception has prevented Australia from designing a national security framework which considers climate change effects, and establishing a policy on environmental security beyond environment protection, which is largely implemented by states and territories. The truth is that economic security as a well-accepted part of national security is itself challenged by climate change. This is highlighted by the fact that the Australian Business Roundtable for Disaster Resilience and Safer Communities estimates the cost of natural disasters to reach AUD 39 billion per year by 2050. During the 2019-2020 bushfires, many called on Australia's Prime Minister to step up his response to the catastrophe and demanded that emergency management in Australia needs to be restructured because the threat is now a "national security issue".

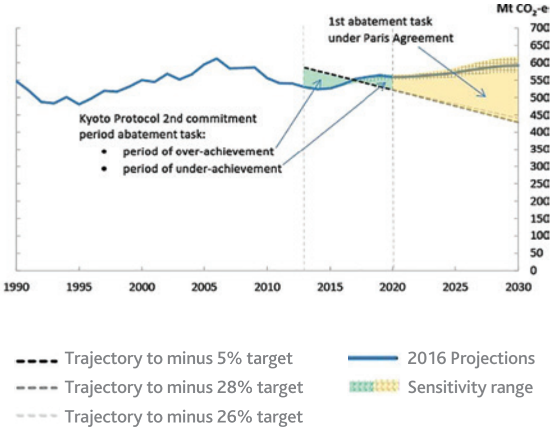

Figure 1: Australia's emission projections for 1990 to 2030 and the 2030 emission reduction target, based on 2016 projections. Source: ANAO (Australian National Audit Office) adapted from the Department of the Environment and Energy, Australia's emissions projections 2016.

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[4] The relatively positive document has been criticised by many. First because Australia uses its good state of land use as a net sink to reduce the GHG emitted and taking credits for a large decline in deforestation that happened before the Paris Agreement was signed. Second, because Australia is trying to carry forward credit for overachieving on its Kyoto targets, using the surplus to meet its Paris goals. Lastly, because their own emissions projections curves show a gap between the level required by the pledge and the current trend.

[5] Released on September 2008 the report was written by Ross Garnaut, one of Australia's most distinguished and well-known economists. Garnaut was commissioned by all of the Governments of Australia's Federation to examine the impacts of climate change on Australia and to recommend policy frameworks for improving the prospects of sustainable prosperity. The report was criticised by the Australian Chamber of Commerce and Industry for the implied negative economic impacts if greenhouse gas emissions were to be reduced.

[6] In the Australian Bureau of Meteorology's annual climate statement, the year 2019 has been recorded as the warmest and driest. The annual national mean temperature was measured to have been 1.52° C above average, the nationally averaged annual rainfall 40% below average and a widespread severe fire hazard due to weather conditions throughout the year was noted. This trend is projected to worsen in the coming years.

THE AUSTRALIAN DEFENCE FORCE AND CLIMATE CHANGE

The apparent lack of response by the national security decision makers to the new environmental and climate security paradigm induces uncertainties for the military as the guardian of national security [12]. Australia's 2009 and 2013 Defence White Papers mentioned climate change very briefly. In 2009, it was stated that strategic consequences of climate change were unlikely to be felt until after 2030, whereas in 2013, climate change was considered as a vague national security threat only. The 2016 Defence White Paper marks a change when climate change was referred to as one of the six key strategic drivers of Australia's security environment to 2035 and its impacts were named as a "threat multiplier".

The majority of Australia's population is concentrated near the coast. Further sea level rise, storm surges and coastal erosion endangers the cities and impact low-lying military bases, national energy infrastructure, as well as ports and airfields (see Figure 2) Australian Navy's Admiral Barrie[7] [11] suggested in 2018 that defence planners should consider new locations for military and civilian airfields situated in such threatened areas. On an international scale, rising seas could inflame terrorism and maritime disputes in the Asian Pacific region as competition for resources and military control may intensify. This could also overwhelm the Australian Navy's security role at border control to regulate the expected surge in climate-driven migration.

The ADF is being more and more mobilised in the air, at sea and on land for climate change related missions. The recent bushfire crisis was one of its largest operations in years [18]. At least three

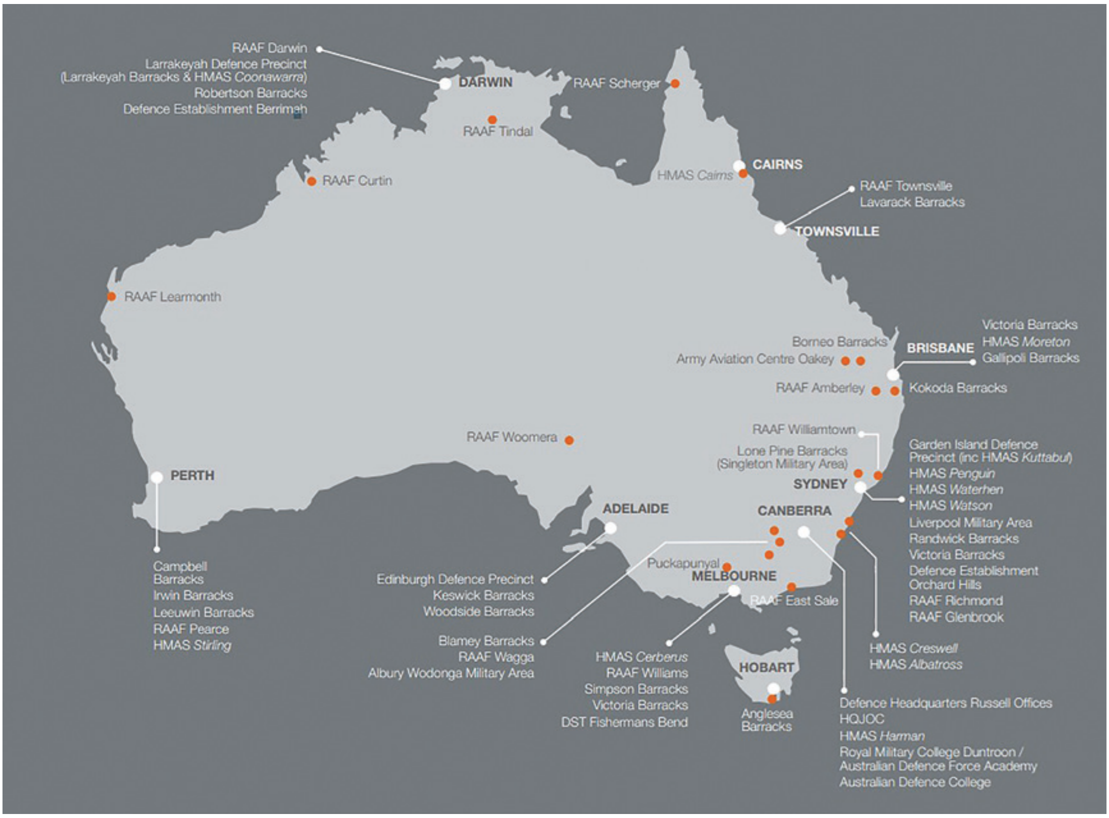

Figure 2: Military base locations of the Australian Defence Force. Source: Department of Defence annual report 2018-2019 [10]

thousand army reservists were activated to help deliver aid and to evacuate victims. The Australian Air Force was transporting personnel and firefighting equipment, army helicopters carried victims from isolated rural areas unable to evacuate on their own and navy ships evacuated over a thousand people trapped by bushfires along the coast shores being unable to evacuate by road. New Zealand and Singapore also offered military resources to assist.

"War" became a national metaphor used by Australians to refer to the black summer of 2019. This raises the question whether the ADF should be expected to continue fighting "climate change war" and whether 'security risks' include climate change. If so, the ADF will need to reorganise in order to address the complex issues emerging in both, Australia and in neighbouring countries. The advantage of the ADF over civilian institutions is their long-term view on planning. The ADF is well trained and equipped and is known for its designing capabilities and effectiveness in risk and mitigation assessment. However, if as argued by John Blaxland[8], climate-fuelled disasters on the scale experienced in 2019 become the norm, Australia's military would not be large enough to meet its security obligations[9] around the world and the capability to support relief operations at home.

The high operational level required by the bushfires in 2019 showed how climate change could challenge military capacities which were originally designed for traditional military missions. The bushfires also stretched the ability to meet security requirements and the unpredictable demands of new climate-fuelled disasters at home and in allied countries. For example ADF logistical terrestrial transport units, navy evacuation vessels and military air support could be requested by Australia's government as permanent rescue assets rather than tools of war. Such could be the case for the two largest vessels in Australia's fleet, the HMAS Choules being Australia's only landing ship and the HMAS Adelaide one of its two helicopter carriers. If the ADF is to play a greater role in climate change mitigation, the government will need to provide the necessary means for new equipment and forces to adapt them to new environmental conditions in order to ensure Australia's sovereignty[10] and national security.

Today, climate change is an issue taken seriously by the Australian military. In June 2019 in a speech to managers from government departments and agencies, the current Defence Force Chief Gen. Angus Campbell warned of the threats climate change poses to Australia's military and deployments. He predicts for the next years that the military will have to cope with more disaster relief efforts and peace-keeping missions and that climate change has the potential to exacerbate existing or future conflicts. In his speech he also warned the Federal Government that their actions on climate change could affect the relationship with Pacific island nations, which have pushed for the inclusion of the 1.5° C target in the Paris Agreement and are asking Australia to do more to reduce emissions. If Australia keeps ignoring their call, the ability to influence their choices for support in the region could be altered.[11] This would hinder the Australian Indo-Pacific strategy, which aims to place Australia as the military guardian of the area.

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[7] Admiral Christopher Alexander Barrie is a retired senior officer of the Royal Australian Navy who served as Chief of the Defence Force from 4 July 1998 to 3 July 2002.

[8] Head of strategic and defence studies at Australian National University.

[9] The Australian military is involved in at least thirteen ongoing operations around the world mostly in the Middle East, Africa, and the Western Pacific, not counting periodic tasking and occasional operations.

[10] The 2019-2020 bushfires have questioned Australia's ability to cope on its own with the problem. The reliance on contracting American firefighting aircrafts raised many questions. With large fires now happening year-round in Australia and in North America, Australia risks to be left without firefighting aircrafts in times of dire need.)

[11] In 2018, the Federal Government signed the Boe Declaration, a Pacific-wide declaration stating that climate change is the single largest threat to security in the region. However, during the 2019 Pacific Islands Forum leaders meeting in Tuvalu the coalition was put on hiatus over its refusal to take stronger action to combat climate change.

IGNORING THE INDO-PACIFIC'S CALL ON CLIMATE WILL AFFECT ENERGY SECURITY IN AUSTRALIA

Australia's retired Air Vice Marshal John Blackburn[12] [9] speaks of energy security as "the association between national security and the availability of natural resources for energy consumption". Energy plays an important role in the national security of any given country as it is necessary to power the economy. Energy security is about reliability, affordability and environmental protection but also implies ensuring the security of energy supply.

The uneven distribution of mainly fossil energy supplies among countries has led to the internationalisation of the energy trade. This causes sovereignty and vulnerability issues over strategic energy resources and transport routes. Threats to energy security emerge from political instability of several energy producing countries, market manipulations of energy supplies, competition over energy resources, and overreliance on foreign countries. Terrorism or open warfare with attacks on energy infrastructure as well as accidents and natural disasters aggravate significantly the threats to energy security. Even in peacetime, energy exports or imports may have political or economic motives to limit their foreign energy sales and purchases or even cause disruptions in the supply chain by cutting off supplies, putting embargoes and applying pressure during economic negotiations [16].

Australia is globally the 10th richest country in natural resources, but is greatly depending on crude oil and petroleum imports [6]. This puts the country at risk as its natural resources could be coveted in the future by other nations and oil imports could be disrupted. Thus, Australia ironically greatly depends on energy imports for its resource extraction and exports. One security concern is the safety of the Strait of Hormuz supply route, which accounts for more than 40% of the world's oil transit. The South China Sea and the Indonesian islands are also regions of concern

Figure 3: Main round-the-world sailing routes for LNG and petrol and the location of trouble spots for energy transport security. Source: International Maritime Bureau

as they are key shipping routes for Australian fuel imports. These areas have become a growing security concern as 50% of Australia's refined diesel and 75% of its refined jet fuel imports transit via these routes [3] (see Figure 3). Thus, providing protection to Australian's imported and exported goods, especially for fossil fuel products, is one of the ADF's concerns when securing sea lines and communication [13].

With the Indo-Pacific region becoming economically, demographically, and strategically more contested and central to the global power balance, Australia's interests are at a growing risk. The Indian Ocean is already supplanting the Atlantic as the world's busiest shipping highway and maritime routes through the Western Pacific Ocean, including the disputed waters of the South and East China Seas are becoming more and more important [20].

The continuing economic growth in Asia will result in an increased and acute dependence on sea-borne energy supplies for Australia. Changes in energy cooperation and importance of supply routes within the Indo-Pacific region highlight how the baseline of Australian defence planning has to shift. The "energy risk pivot" to Asia will introduce new strategic tensions as China, South Korea, Japan, India, and Singapore jostle to ensure continuity of supply. Australia will be a critical regional exporter as it is the biggest provider of LNG and coal in the region, sources of energy that are widely used in Indo-Pacific countries. Moreover, if Australia transitions to clean energy, it could also become an important green energy export nation and a net exporter of mineral essential for energy transition such as lithium. This role could put Australia's resources and routes supply at risk as they might become more and more sought-after in the current changing climate.

All countries of the Indo-Pacific share to some extent Australia's energy security challenges. The developing economies in the Asia-Pacific region are expected to account for almost two-thirds of global growth in energy demand between now and 2040. These economies will increasingly rely on energy imports, especially of oil and gas, to sustain economic growth. Given their geographical location, deepening regional cooperation seems to be the best solution to the energy challenge. Understanding evolution patterns of energy interdependence, and the motivations behind national energy strategies can help find more appropriate answers and promote interstate cooperation, while reducing the risk of energy shortages. Otherwise, a climate of energy insecurity can lead to resource nationalism and potential conflict over the control of resources. Given that the Indo-Pacific is home to both supplier and consumer nations, mechanisms that promote transparent, rules-based, and liquid markets will be an advantage for ensuring the region's energy security and smoothen sovereignty claims on land and resources.

Any such project might result in the loss of some energy independence as the diverse sources of energy of the participating countries would become more interlinked. Countries of the ASEAN have made arrangements to increase energy resilience and supply each other in case of crisis. In 1997, the ASEAN heads of states first agreed to develop the ASEAN Power Grid (APG) to ensure energy security in the region through investment in regional power interconnections. The Trans-ASEAN Gas Pipeline (TAGP) is an example of a project aiming to create a single integrated gas pipeline grid. For now, the TAGP remains incomplete and has been slowed down by the general environment of energy insecurity and uncertainty, which is felt by Asian governments.

Even though the ADF does contribute to the preservation of regional security and stability in South East Asia through the auspices of Operation GATEWAY[13], Australia has been invest-

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[12] Air Vice-Marshal John Blackburn AO (Retired) is the Board Chair of the Institute for Integrated Economic Research (IIER)–Australia and a Fellow of both the Institute for Regional Security and the Sir Richard Williams Foundation. He is now a consultant on defence and national security, including energy security. (The IIER-Australia is exploring the challenges of linked transformation of economic, environmental and energy systems).

[13] Under Operation GATEWAY, the Australian Defence Force provides maritime surveillance patrols in the North Indian Ocean and South China Sea, contributing to the bilateral defence relationship between Australia and Malaysia. The operation has endured since the 1980s.

ing more in cooperation with the United States than with the Indo-Pacific region. In February of 2018 the Trump and Morrison administrations launched the Australia-U.S.-Strategic Partnership on Energy in the Indo-Pacific. However, this US-Australia energy cooperation weakens possible energy cooperation with Australia's nearest neighbours. To prevent Australia from becoming politically isolated from the Indo-Pacific countries, the ADF has chosen to increase cooperation in the region. In July 2020, the ADF has stated in its 2020 Defence Strategic Update the importance of its nearer region the Indo-Pacific and its willingness to deepen cooperation [19]. Yet, for this to happen, Australia will need to improve on its poor performance on GHG emission reduction and poor interest in climate change mitigation which are threatening the Australian-Indo-Pacific region and the political relations.

CONCLUSIONS

Today, the ADF is deployed in more places at the same time and has a greater panel of activity than ever before. This brings up the question on how fit the Australian military is to provide national security with its capability to simultaneously support global, regional and domestic operations (see Figure 4) The ADF, like the armies of all countries, must face new military challenges. In addition to protecting the country from external threats, it is asked to protect strategic supply routes and infrastructures, protect the country from natural disaster and also to get "greener" [2]. To fulfil all these tasks, the ADF will need substantial government funding to build, repair and operate (also even greener) equipment with improved performance.

But should the military take on all these challenges and tasks as its genuine future roles? The public opinion in Australia is divided:

For some, ADF's core business in the future will be to tackle climate change related issues like natural disaster aid at home and internationally as well as securing supplies of water, food, and energy. In their view climate change is "the most imminent" threat to national security because unlike the potential threats from rising nations like China or India, climate change is already happening. Therefore, instead of spending the defence's budget on weapons systems that might be used in the unlikely case that Australia gets involved in a conflict, the defence budget should be used for what could become the new task of national defence.

Many reject this idea. They believe that the Australian Government has other departments dealing with climate change, energy security and border control. They refer to the Department of Industry, Science, Energy and Resources, the Department of Infrastructure, Transport, Regional Development and Communications, the Australian Federal Police, and the Australian Border Force. If the ADF is to spend more time in Australia's territory responding to climate change it will leave aside a role that no other agency can do which is to develop and, if necessary, apply all military capabilities to deter and defeat the nation's potential adversaries. Consequently, they argue that for countering the consequences of climate change an appropriate budget, equipment, and training should be given to the responsible entities or to a newly created special unit.

Therefore, Australia needs a new natural security framework that takes into account climate change and its capacity to affect the nation's energy security and the security of food and water supply. The 2019-2020 bushfires have shown how Australia needed a national mitigation plan for climate change disaster to coordinate efforts between states. A harmonisation will help reduce the need for the ADF to intervene. What remains sure is that it will not be the ADF's role to curb Australia's GHG emissions – this is the Australian nation's task as a whole because no military alliance, deployment of troops or new weapon system will adequately protect Australia from climate change.

Australia's defence heavily relies on close cooperation with international partners. Climate change is a new shaper of inter-countries relations and commercial exchange. Australia's choice to either ignore climate change or to pro-

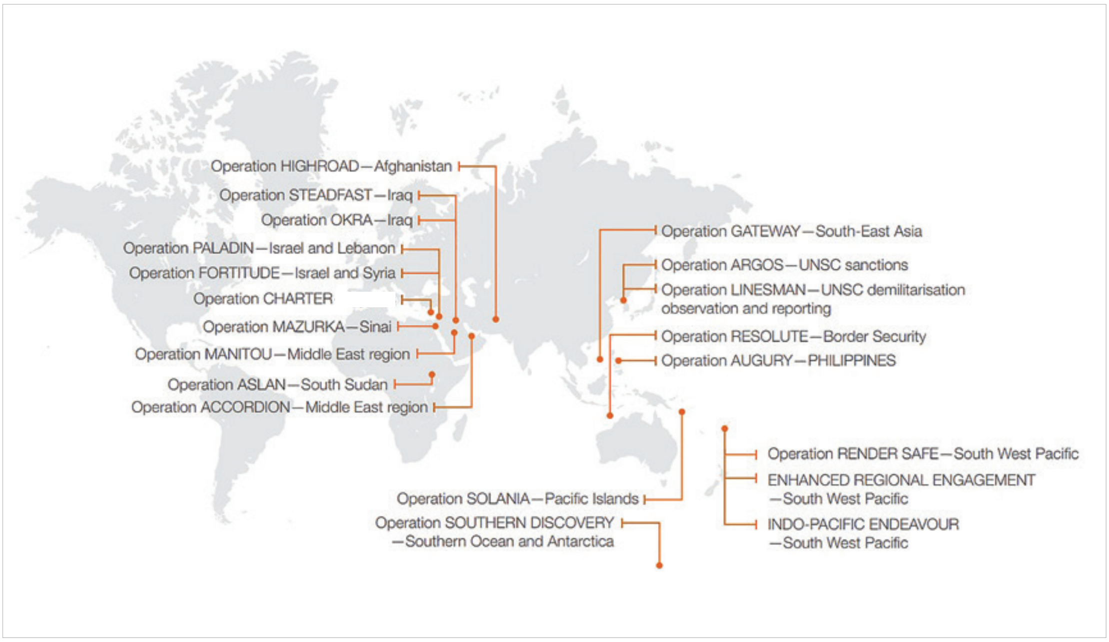

Figure 4: Australia Defence Force operations during 2018-2019
Source: Department of Defence annual report 2018-2019

crastinate in addressing its challenges is starting to negatively affect its partnerships, especially with the Indo-Pacific region, threatened by the already rising sea level and calling for action for climate change. This impacts commercial and military cooperation and influences export and import trends as well as Australia's energy security. The ADF's capacity to ensure national integrity would greatly benefit from a “greener” Australian policy. It would limit the need for the ADF to intervene in climate change included natural disasters, while also limiting their negative political, social and financial consequences.

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Hydrogen as Fuel: Production and Costs

A closer look to highly regulated market situations

by **Dr. Jutta Lauf**

ABSTRACT

Hydrogen may play an important role in the efforts to reduce the burning of fossil fuels for energy production. The biggest energy consuming sectors are electricity generation, transportation and heating. Transformation of the electricity generation sector seems to be the easiest goal to achieve while the replacement of fossil fuels with CO_2-neutral or CO_2-poor fuels is far more difficult. The coupling of energy consuming sectors is discussed as one of the solutions. The usage of surplus electricity to produce fuels, heat and/or chemical base materials appears to be very promising. This article provides an overview over H_2-electrolyser technologies, their input factors and costs.

The profitable operation of an electrolyser plant currently appears only possible above a threshold of three to four thousand full-load hours (FLH) per year. The electric energy generated by wind and solar plants in Germany is not sufficient for profitable hydrogen production. Consequently, only using surplus energy from these sources is even less profitable. To reach profitability, four technical solutions are have been suggested which are aiming to increase the FLH: (1) Usage of batteries. (2) Usage of 100 % of the electricity produced by wind/solar plants. (3) Import of power from stable renewable sources. (4) Construction of solar/wind powered electrolyser plants in regions with higher FLH and import of the produced H_2. Financial solutions are also possible either by subsidies on the investment costs until at least five thousand FLH per year are reached or by usage of non-renewable power sources for a limited amount of years without losing the status of "green" hydrogen.

INTRODUCTION

Hydrogen (H_2) is very versatile in its usage and

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may become an important part in efforts to reduce fossil fuel burning for energy production and help mitigating global warming. Hydrogen can be used for heating or as fuel in the transport and mobility sector. It also is an important base material in the chemical industry. Under normal conditions, hydrogen is a gas which burns without producing carbon dioxide (CO_2) emissions and – depending on the technology – without nitrogen oxide (NO_x) emissions.

Global warming is affecting all parts of society, as the discussions about a "Green new deal" in the USA recently demonstrated (US Congress 2019). NATO and the military sector are affected in at least three ways: First, causes for and regions of conflict will shift away from securing fossil carbon production sites and transport routes to e.g. water and social unrest related topics resulting in more refugee and rescue missions. Second, the costs for maintenance of military bases will increase, especially for Navy bases due to rising sea water levels (Reinardt & Toffel 2017). Third, as an integral part of democratic societies, NATO military will become increasingly involved in efforts to reduce emission of CO_2 due to the combustion of fossil fuels.

The three biggest energy consuming sectors are electricity generation, transportation and heating. It is generally acknowledged that the transformation of the electricity generation sector to a carbon free electricity production is technologically the easiest goal to be achieved (Arlt 2018). This is true due to several reasons: (1) Produced electricity can be supplied directly to the transmission networks. (2) Electricity production in close proximity to demand location is at least partly possible e.g. solar panels on rooftops. (3) The existing transmission network infrastructure can be used and only short distances have to be built anew. (4) Efficiency losses due to the conversion into other energy forms do not occur. (5) Highly fluctuating sources e.g. wind and solar as well as sources without fluctuations and with a certain buffering capacity like biogas plants and hydroelectric dams are available to cancel out variations in supply and delivery.

The replacement of fossil fuels with CO_2-neutral or CO_2-poor fuels in the transportation sector is far more difficult (Arlt 2018). Most efficient is the direct use of electricity by electric motors with an efficiency factor of 69%. (All efficiency factors in this chapter are given with respect to the electricity input at the production site (frontier economics 2020). However, the main obstacle for application is the resulting low range in cars and trucks due to the weight of the electric batteries for energy storage. Nonetheless, batteries are currently used in special applications such as military drones (Mayor-Hilsem & Zimmermann 2019). The transformation of electricity to H_2 and its usage in fuel cells leads to an efficiency factor of 26% (in cars) and is e.g. used in the SilentCamp and the Class 212A/Todaro-Class submarines (Mayor-Hilsem & Zimmermann 2019). The lowest efficiency factor of 13 % in cars results from using electricity to generate liquid carbon based fuels via H_2 by electrolysis and burning the synfuel in conventional internal combustion engines (frontier economics 2020).

The coupling of energy consuming sectors is widely discussed as one of the solutions to reduce greenhouse gas (GHG) emissions of which CO_2 is the most common one. With respect to the reduction of CO_2-emissions, the use of surplus electricity to produce fuels or heat seems to be very promising since CO_2-emissions in electricity production and in fuel usage/heat production are avoided.

The present article provides an overview of the so called "electrolyser" technologies for commercial hydrogen production by electrolysis. We will look at the costs as well as the possible sources for powering electrolyser plants with renewable electricity sources. Especially the economic potential of the usage of "surplus electricity" from renewable energy sources will be investigated. We choose Germany as a case study because it has on the one hand large renewable wind and solar energy production capacities and on the other hand a strictly regulated energy market.

3 COMPONENTS OF ELECTROLYSER SYSTEMS

3.1 ELECTROLYSER TECHNOLOGIES

Chemical reactions during electrolysis

All chemical bonds contain energy and the more complex a chemical substance is, the more energy is stored in it. The most common description of this energy content is the inferior heating value (net caloric value H_i) which is normally expressed in kiloWatthours [kWh]. In chemistry however, the energy unit Joule is used and expressed in kilojoule [kJ]. The conversion factor is 1 kWh = 3.6 x 103 kJ. The H_i of the natural gas methane (CH_4) is approx. 10 kWh/m³ while the H_i of hydrogen (H_2) is 3 kWh/m³ (Reitmair 2013). We use the energy of these gases by burning them and transforming this energy into thermal energy (for heating) or mechanical energy (for movement). The combustion of fuels creates chemical components which contain less energy. In the case of a complete combustion of these gases H_2O and/or CO_2 are formed.

Electrolyser technologies convert H_2O and electric energy into hydrogen and oxygen gas. Chemical bonds can be broken via the input of either chemical energy (chemolysis), electrical energy (electrolyse) or thermal energy (thermolysis). The bonds between hydrogen and oxygen in water are quite strong: The input of 4.5 kWh (16.2 MJ) of energy (commonly termed "power") is needed to produce one m³ of H_2 and 0.5 m³ of O_2 at the classical setting and at standard conditions of 1013hPa pressure, 0% humidity and 0°C (Holleman et al. 1985).

The net chemical reaction of all types of water electrolysis is:

(1)

$$286.02\,\text{kJ}\ (0.08\,\text{Wh}) + H_2O\ (\text{liquid}) \rightarrow H_2 + \frac{1}{2} O_2$$

For this reaction direct current is applied to a flask of water. To increase the conductibility, an acid or base may be added. The flask is separated by a diaphragm barrier which is permeable for electrons but not for H_2 and O_2. With this setting the gases are separated and the formation of an explosive oxhydrogen gas is avoided. The net chemical reaction (1) can be separated into a cathodic and an anodic reaction.

Cathodic reaction:
The H^+-ion, driven by the electric field, moves to the cathode, where it takes up an electron and H_2 is formed.

(2)

$$2\,H^+ + 2\,e^- \longrightarrow H_2$$

Anodic reaction:
The OH^--ion, driven by the electric field, moves to the anode, where it releases an electron and O_2 is formed.

(3)

$$4\,OH^- \longrightarrow O_2 + 2\,H_2O + 2e^-$$

The complete reaction is shown in formula (1).

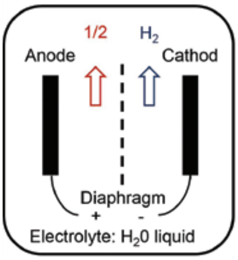

Figure 1: Setting of the original apparatus for the electrolysis of water (Holleman et al. 1985). Chemical compounds in red: oxygen related species. Compounds in blue: hydrogen related species. Liquid water serves as electrolyte. The anode is the positive, the cathode is the negative electric pole. The diaphragm is permeable for electrons but separates the electric poles. (Modified after Pichlmaier et al. 2020).

Electrolysis techniques

Several techniques and different settings have been described (Holleman et al. 1985 b). Three techniques (Figure 2) are in use commercially or at the brink of use (Smolinka et al. 2020). In alkaline electrolysis (AEL) 20–40% potassium hydroxide (KOH) at ambient air temperature is used as the electrolyte. The diaphragm used is permeable for electrons and OH$^-$-ions. In proton exchange membrane electrolysers (PEM or PEMEL) pure water is used as electrolyte at ambient air temperature. The diaphragm used is permeable for electrons and H$^+$-ions. In contrast, high temperature electrolysers (HTEL) use water vapour as electrolyte at temperatures between 100 and 900°C. Since a significant part of the energy required to break the chemical bonds of water is applied in the form of heat, high efficiency factors are obtained with respect to the electricity required. The diaphragm used in HTELs is a solid oxide, which allows O^{2-}-ions to pass.

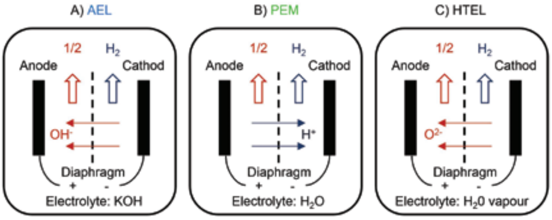

Figure 2: Setup and main chemical reactions of three types of commercially used electrolysers. The anode is the positive electric pole, the cathode is the negative electric pole. Chemical compounds in red: oxygen related species. Compounds in blue: hydrogen related species. A) AEL: The electrolyte is a 20–40 % potassium hydroxide solution (KOH), the diaphragm is permeable for electrons and OH$^-$-ions. B) PEM: The electrolyte is pure water, the diaphragm is permeable for electrodes and H$^+$-ions. C) HTEL: Water vapour is used as electrolyte. The diaphragm is permeable for O^{2-}-ions. Modified after (Pichlmaier et al. 2020).

KPI	AEL	PEM	HTEL
Technical parameters			
Efficiency factor [%]	66	63	81
Power consumption [kWh/Nm^3] *	4.6	4.8	3.7
Working pressure [bar] *	18	30	4
Working temperature [^{o}C]	50 - 100	20 – 100	500 – 900
Offset time after 48 h of standstill [min] *	55	15	600
Offset time until 48 h of standstill [min] *	17	5	20
Aeric electric current [A/cm^2] *	0.4	1.8	0.8
Durability of stack [h] *	60 000	40 000	15 000
Financial parameters			
CAPEX [€/KW] *	1 450	900	2 250
CAPEX [€/Nm^3/h] * (including efficiency factor electrolyser)	4 000	7 000	8 800
OPEX fix [€/a/kW] *	13	18	32
Raw material availability	Uncritical	Partially critical	Critical
Future potentials until 2050			
Usage	ALE and PEM comparable	ALE and PEM comparable Slight advantages in decentralised plants	Industrial settings with available industrial waste heat

Table 1: Mean technical and financial key performance indicators (KPI's) and possible future usages of the commercially available electrolyse technologies AEL, PEM and HTEL (Smolinka et al. 2020). KPI's with approximate values are indicated by an asterisk (*).

Technical parameters and production costs of electrolysis

The technical parameters and production costs of different electrolysis procedures vary considerably and determine the applicability. The main characteristics of the three most common commercial technologies are shown in Table 1.

The key factor for the further development of electrolyser technologies and its related costs is the upscaling of the hydrogen demand. Germany for example is subsidising this process since 2006 (Bonhoff 2016). Assuming this scenario, a survey of leading companies producing two thirds of the world's electrolyser production in 2017 (Smolinka et al. 2020) shows the possible developments of the industry and its technologies for 2020 (Figure 3).

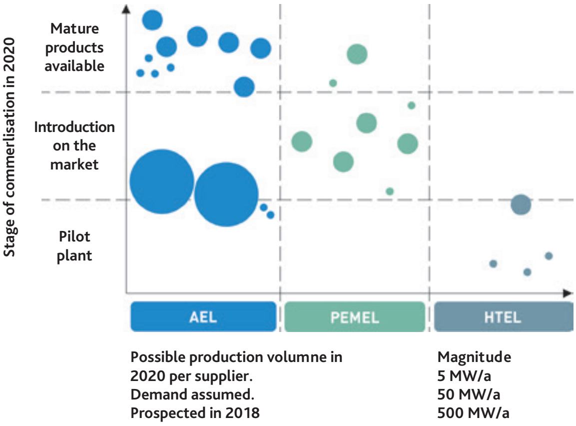

Figure 3: Stage of development for AEL (blue), PEM / PEMEL (green) and HTEL (grey) electrolyser technologies as reported in a survey which included 2/3 of the world leading electrolyser producers for 2020 on the basis of 2017. The scenarios are set in an upscaling market with rising demand of electrolysers. The size of the symbols is a measure for the peak electric power of the electrolyser. Modified after Smolinka et al. (2020).

AEL is the electrolyser technology mostly used in commercial settings. It is also the most robust technology with a long development history of several decades (Hydrochenik 2020). More than 15 suppliers worldwide are available who commercially build plant sizes from 5 – 500 MW. No critical raw materials are needed for the production of this type of electrolyser.

PEM technology has been under development for about three decades. Its efficiency rate is the lowest of the three technologies. Efficiency is predicted to rise with further technical improvements. PEM is best suited for highly fluctuating power supplies as the offset times are low.

AEL and PEM are comparable in almost all other technical KPI's except for durability. Productions costs are also comparable.

HTEL electrolysers are on the brink of entering the market and are the most expensive of the described technologies. Pilot plants built in Germany are supported by government funding (Sunfire GmbH 2020). HTEL has the highest efficiency rates with respect to power input because it uses heat as additional energy source. It is best suited in industrial areas with a supply of waste heat and a demand of H_2. However, off-set times after standstill are long, therefore a constant power supply for HTEL is crucial. Only a few suppliers are currently available worldwide.

The Hydrogen Strategy of the German Government („Wasserstoffstrategie"):

Germany initiated a long term "Program for Innovation for Hydrogen- and Fuel Cell Technologies 2006–2016 (NIP)" at the beginning of this century (Bonhoff 2016). The follow up "Government Program Hydrogen- and Fuel Cell Technology 2016–2026 - from Introduction on the Market to Competitive Products" aims at the upscaling of markets for hydrogen related technologies. The goal is to become a spearhead in this sector, creating jobs and reducing the costs for these technologies. These aims are means to reach the CO_2-reduction targets for Germany. In June of 2020 the government announced subsidies of 310 x 10^6 € in 2020–2023 for research and development projects for the production, storage, transport and distribution of hydrogen (BMBF-Internetredaktion 2020). On an international basis, Australia, China, Japan and South Korea are also working intensely on hydrogen related topics (Hille 2019).

3.2 POWER PROVISION AND SUPPLY USING THE EXAMPLE OF GERMANY

This chapter discusses the conditions of the electricity supply from renewable sources for running electrolysers, using Germany as an example. With its government energy transition plan ("Energiewende") Germany attempts a true energy revolution by subsidising and boosting the market share of renewable sources such as wind, solar and water plants for the production of electric power. Simultaneously, it attempts to phase out fossil and nuclear energy. However, wind and solar electricity production is highly volatile i.e. variable during the day and it shows a pronounced seasonality. Mean wind electricity production peaks in spring while mean solar electricity production peaks in autumn. In December, the dark doldrums with almost no wind and no sunshine result in the lowest electricity production during the year (Figure 4). This situation may occur for up to two weeks with a probability of one in every 2-3 years (Sinn 2017; uniper 2017a). Consequently, such volatile electricity production requires intermediate storage capacity as a buffer for providing a stable and predictable electricity supply to the consumer. However, the geological and topographic options for affordable temporal energy storage by building new pumped storage hydropower stations in Germany are almost exhausted (Sinn 2017) and other forms of temporal electric energy storage are still very expensive.

Energy transition (Energiewende), Renewable Energy Law (Erneuerbare-Energien-Gesetz 2017, EEG), Federal Network Agency (Bundesnetzagentur, BNetzA):

The energy transition in Germany was initiated in 1998 by the former Red-Green coalition under Chancellor Gerhard Schröder. The aim was the increase in electricity production from renewable sources, e.g. solar, wind, water, biomass and biogas etc. (Koenig et al. 2013). This could only become a reality, when the former regional electricity providing monopolists were split up. These companies held electricity production, transmission networks, distribution networks, energy distribution and consumption measuring in one hand. The Renewable Energy Law in its current version from 2017 was created in 2000 (EEG 2020) with the aim to enable all producers of electricity (e.g. large commercial offshore wind farms and small e.g. private rooftop solar plants) to feed electricity into the network and to allow all customers to select a national electricity provider other than the former regional monopolist. To ensure the right to use the electricity network for all electricity producers a regulation authority, the "Federal Network Agency BNetzA" was created. Nowadays the EEG is mostly known for its regulations and privileges given for electricity produced from renewable sources.

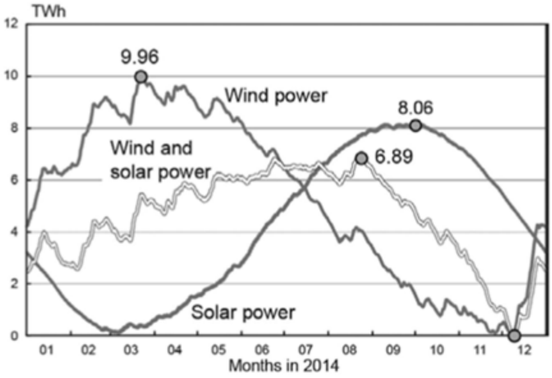

Figure 4: Seasonal electricity production in 2014. Solid grey line: electricity production by wind plants. Solid grey line: electricity production by solar plants. Open white line: electricity production by wind and solar plants subtracted by a virtual consumption of the average daily German consumption as stored in a pumped storage hydro power station (Sinn 2017). The effect of dark doldrums in December can clearly be seen.

While in theory 100% of the German electricity demand could be met by the capacity of all renewable production sources, buffering strategies are needed because of temporal mismatches in electricity supply and demand. At night the demand exceeds what wind and hydroelectric plants are able to supply while the supply from solar and wind plants on bright windy winter weekends may exceed the demand. In such a carbon dioxide reduced electricity production scenario 60 - 70 GW of power in highly flexible gas powered electrical plants using methane or hydrogen are needed to stabilise the system (uniper 2017). Currently, buffering in Germany is achieved by maintaining a back-up set of conventional power plants which is very expensive as it involves double fixed costs (see below). Germany is phasing out nuclear and coal powered plants in the coming years, so the back-up plants usually use natural gas which is a more expensive but cleaner fuel than coal or oil. As a consequence, one kWh of electric power cost 29.69 €-cent for German end customers (first half of 2016), while a French end customer had to pay 16.85 €-cent per kWh only (Sinn 2017).

In order to buffer discrepancies between renewable power production and demand, technological solutions for the storage of excess electricity (when supply is higher than demand) are needed. Electric energy can be stored in batteries, but the capacity required to buffer the power demand of an entire country is currently not achievable. Electricity can be used instantly for heating purposes in district heating grids (power-to-heat) for bridging the gap between energy consuming sectors (sector coupling). This buffering method is widely used in Denmark (Plenz 2016) where about 45% of its needed electricity was produced by wind-solar sources in 2014 (Sinn 2017).

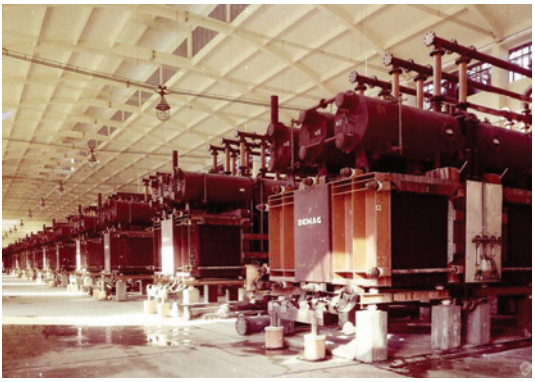

Figure 5: Array of electrolysers in the Aswan hydroelectric dam, Egypt (Hydrochenik 2020). These electrolysers were installed in 1960 and were mainly used for providing hydrogen for nitrogen based fertilizer production.

Electric energy can also be stored as H_2 using electrolysers. As early as 1960 electrolysers were installed at the Aswan dam in Egypt (Figure 5) with a capacity to produce 40 000 m^3 of H2 per hour under standard conditions (Hydrochenik 2020). Hydrogen is needed in large quantities for industrial processes e.g. in the production of fertilisers using the Haber-Bosch-process (Holleman 1985a).

Hydrogen and carbon can be further synthesized to methane or liquid fuels, such as synthetic diesel (frontier economics 2020). However, these storage compounds are not able to re-convert the stored energy into electric power at any acceptable costs. Electricity storage using pumped hydropower plants is only possible for a small amount of the electricity needed in the European Union, as the topographic and geologic preconditions are not present. The production of H^2 using surplus power from renewable energy production is often suggested as an option for regions outside the global Sun Bel while areas within the Sun Belt may use other storage technologies. The Andasol solar thermal power plant in southern Spain for example is able to bridge a gap of ca. 7.5 hours of darkness under full-load operation because surplus solar energy is accumulated as heat in a liquefied sodium nitrate/potassium nitrate salt mixture at a minimum temperature of 240°C. The energy can be recovered in a heat exchanger to produce steam for running a turbine (Wikipedia 2020).

In accordance with the German EEG regulations, renewable electricity production plants are entitled to several privileges within the first twenty years of production. One is financial compensation for electricity which cannot be supplied to the transmission network due to low or non-existing distribution capacities. Similar issues exist within the United Kingdom, where wind turbines in Scotland have to be temporarily shut down and owners compensated during surplus power production (ingenieur.de 2014). Due to the obligatory compensation payments, the amount of surplus power from renewable sources is well documented by the German Grid Agency BNetzA and the amount of surplus power from 2009 to 2019 is shown in Figure 6 (Bundesnetzagentur, Bundeskartellamt 2020). About 95% of these 5.4 GWh are produced in the northern part of Germany encompassing Schleswig-Holstein, Mecklenburg- Western Pomerania, Lower Saxony and Brandenburg (Ostermann et al. 2020). The amount of surplus power is expected to rise constantly, as Germany aims to further increase power production from renewable energies (Sinn 2017).

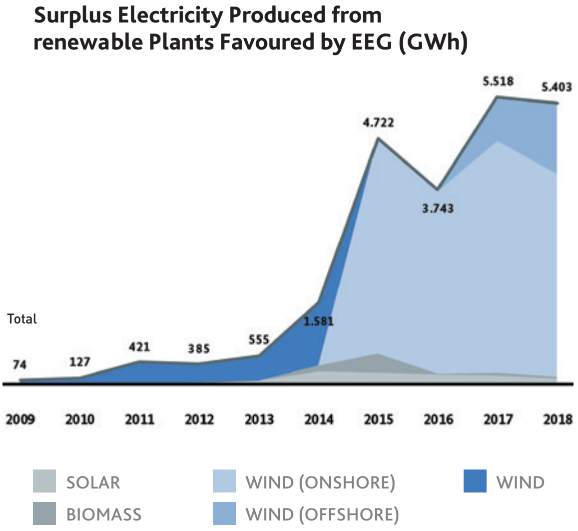
Surplus Electricity Produced from renewable Plants Favoured by EEG (GWh)

Figure 6: Surplus electricity production in Germany from renewable sources between 2009 and 2019 according to its source of production (Bundesnetzagentur, Bundeskartellamt 2020). Light grey: solar plants. Dark grey: biomass plants. Light blue: onshore wind plants (since 2015). Dark blue: total of onshore and offshore wind plants (2009 to 2014). Medium blue: offshore wind plants (since 2015).

4 FINANCIAL COST ASPECTS OF H_2 GENERATED FROM RENEWABLE POWER

In the following chapter, the cost aspects of using electrolyser technology are discussed in the context of using surplus power production from renewable sources.

Economic law of mass production

Costs for H_2 production from renewable power sources follow the general economic laws of production: Costs in companies are typically split into capital expenses (capex) and operative expenses (opex). Typical capex's are the funds needed for acquiring assets e.g. electrolysers. Opex's are further divided: Either in terms of dependency of the output into fixed and proportional expenditures or in terms of the duration of the contracts into fixed and variable expenditures (see Table 2). In the literature, it is often not clearly indicated which definition of costs is being used.

In this article the respective definition for opex is always stated explicitly. Payroll costs in production units are most critical in terms of dependency of the output (fixed/proportional) or the duration of the contract (fixed/variable). In economies with mandatory employment protection (like Germany) they are proportional in terms of the output, but fixed in terms of the duration of the employment contract. In economies without employment protection (like in the US), they are proportional in terms of output and variable in terms of duration of the contracts. Overhead payroll costs are always fixed costs.

Example	Dependency on output	Duration of contract
	Dependant	**Timeframe**
Acquiring of an electrolyser	No	Long term
Housing of the plant	No	Long term
Rent for a building	No	Long term
Employees overhead units	No	Long Term
Employees production units	Yes	Long term
Electricity	Yes	Short term
Network usage fee	Yes	Short term

Table 2: Examples of capex, opex and their assignment to fixed, proportional or variable costs with respect to operating an electrolyser plant in an economy with employment protection.

Cost curves relate the expenses to the output. Depending on the economy in which the plant is operating, payroll costs from employees in production units are fixed or proportional. They are useful tools in economics as they highlight the general relationships between costs and output (Wikipedia UK 2020). Figure 7 shows the relation of average fixed costs (AFC), average proportional costs (APC) and the average total costs (AC) in relation to the total output. As a general rule AFC are reduced with every additional unit produced. This phenomenon is called "economy of scale" and is the underlying principle of cost reduction in mass production. APC do rise from a certain output onwards, as for example, labour cost are rising for additional work shifts at night and on weekends. The minimum costs of production occur at the minimum of the Average Cost curve.

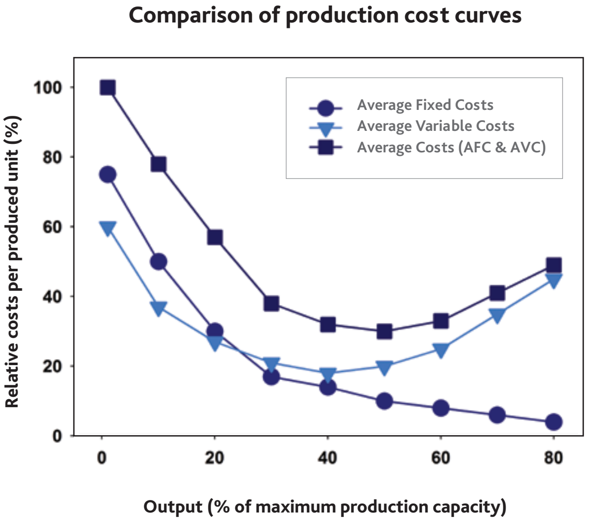

Figure 7: Dependency of costs per unit on total output. APC is the Average Proportional Cost and AFC the Average Fixed Cost. AC is the Average Cost, which is the total of APC and AFC. Payroll costs in production units are defined as proportional costs (Wikipedia UK 2020). All values in the graph are normalized to % based on the highest value of AC at zero output.

Current costs of hydrogen production using Germany as a reference

A calculation of the H_2 cost curve using renewable power sources in Germany is shown in Figure 8. The FLH are a measure for the output. In the case of hydrogen production via electrolyses they are directly proportional to the output. The costs of the three commercially available technologies in 2017 are used and weighted according to the market share using data from 2017 (Smolinka et al. 2020). In the specific situation of H_2 production by electrolysis from electricity produced by renewable energy plants according to German EEG (EEG 2020), three main cost drivers (Figure 8) have to be accounted for:

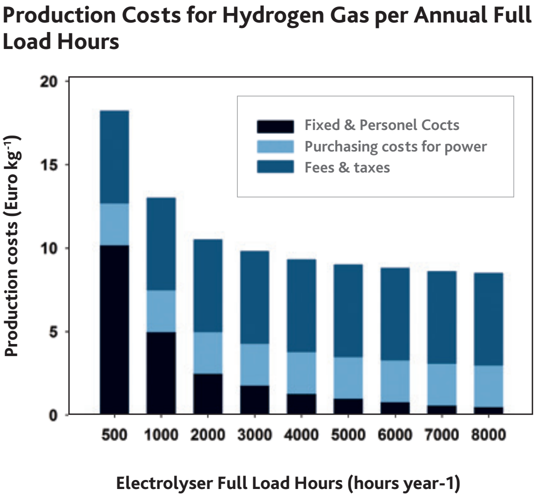

Figure 8: Calculated cost curve of operating electrolysers for the three commercially available technologies of energy production in Germany (based on the market shares in 2017) in dependence of the FLH (Smolinka et al. 2020). Dark grey: Fees and taxes according to German laws. Light grey: Electricity purchasing costs. Black: Fixed and personnel costs.

(1) Fees and Taxes: According to the EEG, fees and taxes for the usage of the transmission networks, the EEG-compensation (a fee for financing of the energy transition in Germany), electricity tax and other fees must be paid. These costs are proportional to the amount of electricity procured and do not vary on the basis of the total amount of H_2 produced.

(2) Procurement costs: They are given as 15.40 €-cent/kWh. These are the conditions for industrial contracts within the range of 16 x 10^4 and 60 x 10^6 kWh per year. Globally the total costs from wind/solar plants are decreasing constantly and are even now lower than the total productions costs from nuclear or fossil power plants (IRENA 2019; uniper 2017a). In Germany they are less than 6 €-cent/kWh and still falling due to the regulations of the §§ 22 ff. of the EEG. Procurement costs are proportional to the output with no depreciation with rising output per FLH.

For (1) and (2) the total of fees, taxes and electricity procurement cost are constant across the entire range of the output/FLH (ca. 8 €/kg H_2).

(3) Other costs: All costs which are not fees, taxes or electricity procurement costs are fixed costs in this context. They contain for example the capital costs for acquisition and housing of the electrolysers. Maintenance costs are calculated as a fixed percentage of the installed capacity of the electrolyser. Employee costs are fixed, because labour contracts are long term and electrolysers do work fully automated. The fixed costs do vary from approx. 10.2 €/kg H_2 at 500 FLH to 0.5 €/kg H_2. This means that depending on the FLH, the percentage of the fixed costs related to the variable costs vary from 6% (8000 FLH) to 128% (500 FLH). Therefore a minimum of 3000 to 4000 FLH a year are needed in order to benefit from the economies of scale. With each added unit of output the cost effects are getting smaller. FLH of > 8000 are considered a continuous operation (hours per year = 8760) since the remaining time span is normally required for plant maintenance.

The determining cost factors show that the total production costs are mostly driven by the fixed costs of the plant and therefore directly depend on the amount of the FLH of the plant: The more FLH the electrolysers are running each year, the better the cost/benefit ratio.

5 SUPPLY AND DEMAND OF ELECTRICITY FROM RENEWABLE SOURCES

Approximately 5.4 GWh of surplus electricity were theoretically available in Germany in 2018. The main sources (Figure 6) were wind and solar plants (Bundesnetzagentur, Bundeskartellamt 2020). The peak power supplied from solar plants was 29 GW and remained relatively constant between 2012 and 2018. The term "power" in this article always means "performance" in watt [W]. The peak power supplied from wind plants has doubled from 24 GW in 2012 to 50 GW in 2018. The increase of the combined peak power supplied followed the increase in the number of wind power (see Figure 9). The core area for wind power plants is Northern Germany while solar power plants are mainly located in Southern Germany. At the moment, the usage of electricity from both types of plants in the same H_2-production site would not be possible due to the existing technical capacity limitations of the transmission networks (Bundesnetzagentur, Bundeskartellamt 2020).

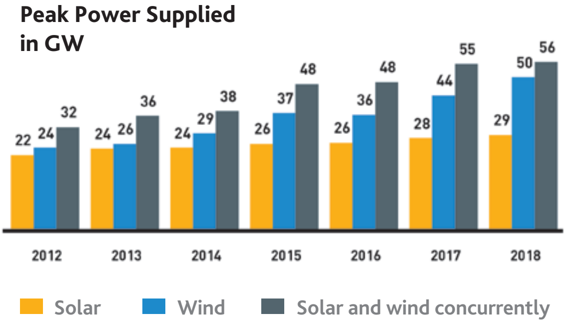

Figure 9: Peak power in GW supplied by solar and wind power plants in Germany between 2012 and 2018. Yellow: solar power plants. Blue: wind power plants. Grey: Total of solar and wind power plants. Modified after Bundesnetzagentur, Bundeskartellamt (2020).

Production by solar powered electrolyser plants is normally limited to a maximum of 12 hours a day during summer and about 8 hours a day during winter. Cloud coverage and fog further reduce the operating time. Wind power is even more volatile as shown in Figure 11 (Bundesnetzagentur, Bundeskartellamt 2020). Power peaks resulting from storms normally do not last more than 2-3 days. Estimates of the combined wind & solar FLH in Germany vary between 2750 and 4400 h per year (Table 3). The volatility of the power supply increases dramatically when solely "surplus power" is used for H_2 production. Although about 5.4 GWh of surplus energy in Germany is currently available, the usage for H_2 generation is difficult due to the start-up times of the electrolysers (Table 1) and the peak power variability of the power plants.

Considering all limitations mentioned above, the concept of only using surplus energy from wind turbines and solar plants for H_2 production with electrolysers is economically not profitable. Both, scientists and operators of pilot electrolyser plants do agree that electrolysers should be best operated with a maximum of 8000 FLH per year (frontier economics 2020; Sinn 2017) or at least with 3000 – 4000 hours per year (Perner et al. 2018) to reduce costs to the lowest possible level. Only a few companies do work on the basis of surplus electricity supply only. One example is the test plant of uniper (Figure 10) which was established in 2012 in Falkenhagen, Northern Germany (Plenz 2016; uniper 2017b). The usage of surplus power seems to be a promising path in terms of CO_2 reduction but certainly not in terms of cost reduction.

Figure 10: The Power-to-Gas Plant Falkenhagen in Brandenburg, Germany is operated by Uniper SE since 2012. Uniper was outsourced in 2015/2016 from the e.on AG, one of the former regional monopolists for electric power generation in Germany. The two containers on the right hand side of the picture hold the electrolysers. The left hand side shows the methanation unit for conversion of carbon dioxide into methane (uniper 2017a).

Peak Power Supply from Wind Plants 2018 in GW

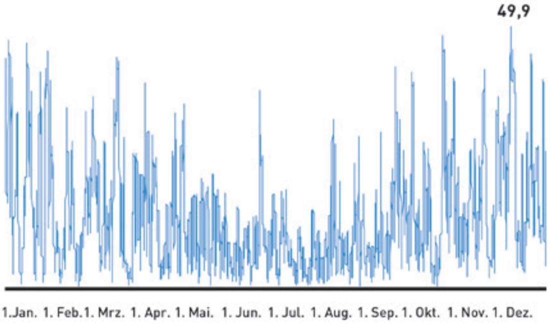

Figure 11: Peak electric power [GW] supplied by wind power plants in Germany in 2018. Modified after Bundesnetzagentur, Bundeskartellamt (2020).

6 CONCLUSIONS

Current profitability

The profitable operation of an electrolyser plant is currently only possible above a threshold of 3000–4000 FLH per year. Using the example of Germany, even offshore wind parks located along the North Sea and Baltic Sea and land based wind parks in Northern Germany are not able to deliver sufficient surplus energy to allow this amount of FLH operation. The same applies to solar power plants which are mostly located in the southern part of Germany. Currently, the electric energy generated by wind and solar power plants in Germany is not sufficient for a profitable hydrogen production. Consequently, using only the surplus energy from renewable sources is even less profitable.

Future options

To reach a technological implementation or even profitability for electrolyser plants, four technical solutions are suggested:

(1) Usage of batteries for buffering the supply volatility in order to increase the FLH. This method is expensive and will only cover time scales of hours, rather than days. It is a small scale solution: In 2017 Australia built a wind powered battery buffer of 120 MWh capacity with the aim to stabilise the electric power supply of 30 000 household during the summer months (der SPIEGEL 2017).

(2) Usage of 100% of the electricity produced by those wind/solar plants which do no longer benefit from the privileges of the German EEG because they are more than twenty years old. Such plants are sometimes difficult to re-power and therefore the owners of old turbines are looking for new business models. Re-powering means the usage of the same place for a new, bigger and more effective wind turbine which will benefit again for twenty years from EEG privileges. The proposed measure will reduce the volatility of the supply, but it will not erase it.

(3) Import of electric power from more stable renewable sources (e.g. hydroelectric, geothermal) at least during times with no domestic supply. For example, cooperation with Norway's hydroelectric power dam operators is already practised and could be enlarged. In this scenario Norway would supply electricity from hydro dams during low wind/solar power generation to Germany (Sinn 2017). In the beginning of the upscaling of the H_2 production such a scenario seems possible, as only a small amount of the surplus electricity in Germany would be needed for the electrolysers. Iceland has huge potentials for additional geothermal electricity production which is currently unused because the domestic energy demand is saturated. The technology itself is proven and runs in nearly permanent operation (> 8000 FLH). The construction of an 1100km long electric power transmission sea cable from Iceland to Scotland was discussed several times in the past. However, this project has not yet been realised due to the currently low global energy prices (ingenieur.de 2014).

(4) Construction of solar/wind powered electrolyser plants in regions with higher FLH of the plants and import of the produced H_2 (Perner et al. 2018; Sinn 2017). The estimated possible FLH of renewable electricity plants in different regions of the northern hemisphere are listed in Table 3. Even in regions such as North Africa and

Region	Technology	FLH [h] Scenarios
	Photovoltaic (single axis tracking)	2100 – 2500
	Wind onshore	2000 – 3400
	Photovoltaic (single axis tracking) + wind onshore	3485 – 5015
	Photovoltaic (single axis tracking)	2200 – 2600
	Wind onshore	2400 – 2500
	Photovoltaic (single axis tracking) + wind onshore	3910 – 4335
Iceland(*)	Geothermal energy + big hydroelectric power dam	8000
Norway(**)	Big hydroelectric power dam	8000
North/Baltic Sea Germany(*)	Wind offshore	3500 – 4400
North/Baltic Sea Germany(***)	Wind offshore	< 3000
Germany(****)	Wind on-/offshore	2750

Table 3: Estimated Full Load Hours (FLH) in different regions of the earth for different power production technologies. Sources: (*) Perner et al. 2018; (**) Sinn 2017; (***) Smolinka et al. 2020; (****) uniper 2017 d.

the Middle East which are located in the global sun belt, FLH of >4000 are not guaranteed and can only be achieved by a combination of wind and solar plants. Due to the double investment for both technologies, fixed costs will rise significantly. Both regions are politically not stable and pose risks to the supply chain. Also, the means for transportation of large amounts of H_2 are not yet established. This option would also not address the problem of the available surplus power in Germany and therefore has a low potential for realisation.

Besides the four technical solutions for reducing the production costs presented above, two financial solutions seem to be possible as well:

(6) Governments could provide subsidies on the investment costs as long as it is not possible to procure power from renewable sources for at least 5000 FLH per year (uniper 2017c).

(7) Governments could provide temporary incentives to electrolyser plant operators by allowing the usage of fossil or nuclear power sources without denying the privileged tax status of producing "green" H_2 (uniper 2017c).

In conclusion, hydrogen generated from renewable electricity certainly is an environmentally clean option which will help to reduce the use of fossil fuels and mitigate the negative effects of global climate change. Hydrogen should be an important part of a future energy mix and is also a chemical base material for chemical syntheses.

This paper has reviewed both, the current processes and technologies available for using electrolysers in the production of hydrogen and the costs for installation and operation of electrolyser plants. While several proven electrolyser technologies exist, the main obstacle is the availability of constant power sources to run electrolyser plants on a large scale and under full load for a sufficient time yearly to be profitable. Neither surplus electric power generated by solar parks nor by wind parks provides sufficient and stable energy needed at a large enough scale to be economically feasible.

While several short and long term technological and fiscal solutions are available for reducing the costs of H_2 production from renewable power sources, the realisation of hydrogen production for fuel on a large scale appears not to be imminent. This is due to significant and mainly financial obstacles. A conversion from a fossil, carbon based energy system to a hydrogen based system requires both a very large H_2 production capacity and a stable power supply. Establishing such a capacity will continue to be a challenge for the coming years.

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Replacing NATO F-34: Technologies and economic aspects of using secondary carbon sources for Power-to-Fuel production

by **Dr. Jutta Lauf**

ABSTRACT

The burning of fossil carbon based fuels – of which NATO F-34 is one - contributes significantly to global warming, ground-level ozone building and health hazards. Several NATO members actively strive to reduce the negative environmental impacts of their military activities while ensuring energy security for their forces. High priorities have the substitution of fossil fuels and the reduction of primary carbon sources for fuel production. Power-to-Liquid technologies can use synthetic gas to produce a vast array of organic components, which can be further processed to synthetic fuels of great purity. Synthetic gas is a mixture of hydrogen and carbon monoxide. Combining hydrogen derived from electrolysers powered by electricity from renewable sources with carbon monoxide derived from non-fossil carbon dioxide sources can make a contribution to reduce environmental and health hazards.

Hydrogen production from electrolysers is a well-established technology on industrial scale. Carbon dioxide capture from point sources is established, but not widespread. Retrofitting of existing plants is possible when emitted flue gases are treated. Retrofitting is more difficult when the carbon dioxide accumulates in early productions steps. A wide array of possible carbon dioxide point sources from industrial processes with high concentrations and purity is described. In

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contrast, carbon dioxide capture from ambient air is in early development stages and not a mature technology yet. Finally, the technologies for the production of synthetic fuels are well known.

The main cost drivers of Power to Fuel are the costs of electricity since electrolysis and carbon dioxide capture technologies have high energy demands. Availability of cheap electricity supply from renewable sources is a key factor for reducing the costs. The costs decrease with the maturity of the production technology used and with the yearly running time of the installation. Comparisons between e.g. geothermal/hydro power in Iceland and solar/wind farms in the global Sunbelt show, that production costs in Iceland are the lowest. This reflects the mature technology and the full use of production capacity. However, currently even the lowest Power to Liquid production technologies and production sites are at least twice as expensive as fossil-based fuels.

The article gives an overview on carbon dioxide capture technologies from point sources and ambient air as well as cost estimates of several combinations of Power to Liquid (PtL) technologies and production locations.

INTRODUCTION

In 1998 NATO agreed to use F-34 (NATO Code) as the main liquid fuel (NATO 1997) for military aviation, ground based tactical vehicles and generators. F-34 is a kerosene and therefore fossil carbon based liquid fuel known internationally also as J-8 in military aviation. It is chemically very similar to the civil aviation fuel type A-147. The chemical properties are described in the NATO Logistics Handbook (NATO 1997) as well as in data sheets of industrial suppliers (Shell 2007). F-34 fuel is currently widely used for aviation within NATO forces and can be easily transformed in the field into diesel fuel for trucks and generators by using some additives. Up to date F-34 is almost exclusively produced from crude oil which is a “primary” fossil source, indicating that the carbon comes directly from mineral oil or gas extraction. In operation NATO forces equipment inevitably releases carbon dioxide (CO_2), nitrogen oxides (NO_x), particulate matters (PM) and unburned volatile organic components (VOC’s) during operation of their equipment causing environmental pollution. Also, CO_2 and NOx exhausts contribute to atmospheric warming (IPCC 2019) and in consequence to climate changes while NOx, PM and VOC’s do have substantial ground-level ozone (O_3) building potentials harming human health (Baird 1997; Reinhardt & Toffel 2017).

NATO forces are an integral part of democratic societies and have to adhere to environmental standards set by their governments for protecting the health and wellbeing of their population. Consequently, NATO members actively strive to reduce the negative environmental impacts of their military activities while maintaining combat readiness and ensuring energy security for their forces. High priorities have the substitution of fossil fuels used by NATO forces with more environmentally friendly, cleaner fuels and the reduction of primary carbon sources for fuel production. Technological options to achieve these goals were investigated as far back as 2007 (Kotsiopoulos et al. 2007).

The most pressing environmental problem for our societies as well as for our armed forces are the currently increasing global temperature with all its negative consequences like rising sea levels melting of the permafrost areas and changing weather patterns with more droughts and severe storms. Stabilizing the mean global temperatures at 2°C above the preindustrial values is one of the main goals of the international community. The most important greenhouse gas (GHG) responsible for atmospheric warming is CO_2 originating from burning of fossil fuels and industrial processes (IPCC 2019). Not setting it free, or at least reusing it for fuel production from so called “secondary carbon sources” like the atmosphere or industry and converting it by means of renewable energy into fuel would be a major achievement in combatting global warming.

This article provides an overview of available power-to-liquid technologies and the steps involved to produce liquid fuels for replacing fossil carbon based F-34 and diesel for propulsion and transportation purposes. We will look at technologies for producing liquid fuels from CO_2 and electricity as well as technologies for capturing CO_2 from air streams. Furthermore, this article identifies the most promising places to do so with respect of costs, geographic regions and promising secondary CO_2-sources.

Figure 1: Fuel truck of the French Army Corps d' Essence in a field camp in Niger loaded with NATO F-34 fuel. The fossil carbon based F-34 is currently the standard liquid fuel for military aviation and also the basis of truck diesel in NATO forces (Photo: Zimmermann 2019).

1. POWER-TO-LIQUID

The use of electricity from renewable sources and non-fossil CO_2 is called Power-to-X (PtX) technology while Power-to-gas (PtG) summarizes technologies for producing gaseous components which contain hydrogen (H_2) from electrolyser technologies (Lauf 2020), liquefied ammonia (NH_3) and methane (CH_4) as secondary products. Power-to-liquid (PtL) technologies are used to produce carbon-based liquid fuels for the transportation sector, mainly for usage in jet engines or internal combustion engines ("Diesel and Otto type engines"). For PtL two main commercial processes are in use: (a) Liquefaction of gas from a PtG process, mainly using methane CH_4. Since liquids are easier to handle in transportation and storage they are preferred over gases. The additional energy needed for liquefaction generally outweighs the advantages of liquids. Liquids have a higher energy density compared to gases and require less safety measures as well as less storage space than gases. (b) Synthesis of liquid components on the basis of synthesis gas (syngas). These technologies often result in a mixture of different components, depending on the conditions of the reaction and the catalyser used, and need further refinement processes (Wikipedia 2020). The term Power-to-fuel (PtF) summarizes PtL and PtG technologies.

The main production steps, inputs, uses and engine types for PtF products are shown in Figure 2 (Perner et al. 2018; Sterner 2019). Electricity from renewable power sources mainly originates from solar, wind or hydropower plants (1). Electric energy can be used for charging the batteries of electric engines (7) or for hydrogen (H_2) production (2) (Mayor-Hilsem & Zimmermann 2019). Hydrogen can be used directly in fuel cells (6) which drive electric engines (7) or for producing syngas which may be used for methanol synthesis with high yields of pure methanol (4, 5) (Beyer & Walter 1988; Holleman et al. 1985). Methanol can be used in fuel cells (6) providing power for electric engines (7) or it can be added to the products of Fischer-Tropsch-reactions (4) and processed to fuels (5). Feeding syngas into Fischer-Tropsch-reactors results in a mixture of short-chained, oxygen free, saturated and unsaturated aliphatic hydrocarbons (Beyer & Walter 1988; Holleman et al. 1985). Depending on the conditions in the reactor (temperature, catalyzer) low boiling fractions (gases) or middle boiling fractions (petrochemicals) and waxes are formed (Beyer & Walter 1988; Pöhlmann 2017). Petrochemical fractions can be processed in the same ways as the analogous fraction from fossil carbon sources. Each conversion step from (1) to (7) results in a new product and inevitably in a loss of free (i.e. usable) energy.

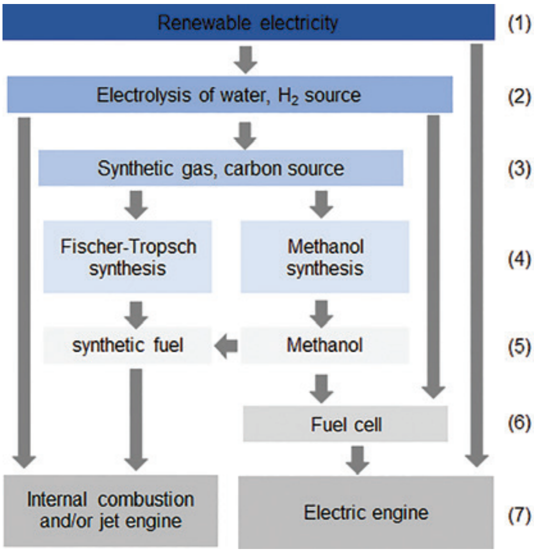

Figure 2: Schematic of the most common power-to-fuel (PtF) production pathways and the usage of the products for mobility at different stages. (1) Electricity production from renewable sources. (2) Electrolysis of water, production of hydrogen (H_2). (3) Production of synthetic gas (syngas) with H_2 and CO_2 from non-fossil sources. (4) Reactors for the synthesis of organic compounds. (5) Main product of the chemical reactions in (4). (6) Fuel cell for electricity production. (7) Engine technologies useable for different types of fuels. Electricity from the producing plants can be used directly in electric engines. H_2 can be used in fuels cells, which power electric engines or directly in internal combustion engines. Modified after (Perner et al. 2018; Sterner 2019).

Several fuels types for use in different types of engine technologies can be obtained from PtF processes (Figure 2). In this article we focus on liquid fuels for internal combustion engines and jet engines. As mentioned before, whether or not a PtF process is CO_2-neutral i.e. whether it adds primary fossil CO_2 to the atmosphere or not, is defined by the carbon source of the syngas used.

Second law of thermodynamics and total degree of efficiency

According to the second law of thermodynamics, each physical or chemical process results in free (i.e. usable) energy losses. Free energy is the amount of energy available to perform work. This concept is known as “entropy”. Each energy transformation process inevitably leads to substantial losses in free energy (Perner et al. 2018; IEA 2019). The least efficient processes transform chemical energy into kinetic energy e.g. combustion of fuels in internal combustion engines (Atkins et al 1990). All efficiency rates in this chapter are calculated with respect to the electricity produced in an electricity producing plant. With respect to PtX in cars, the most efficient transformation is the direct use of electricity from a battery with an electric motor which results in a conversion efficiency of 69%. The usage of electricity to produce H_2 and its subsequent use in a fuel cell has an efficiency of 26%. The lowest efficiency of 13% has the synthesis of liquid fuels for use in conventional internal combustion engines (Perner et al. 2018) (See Figure 3). The possible use of intermediate energy forms is shown in Figure 2.

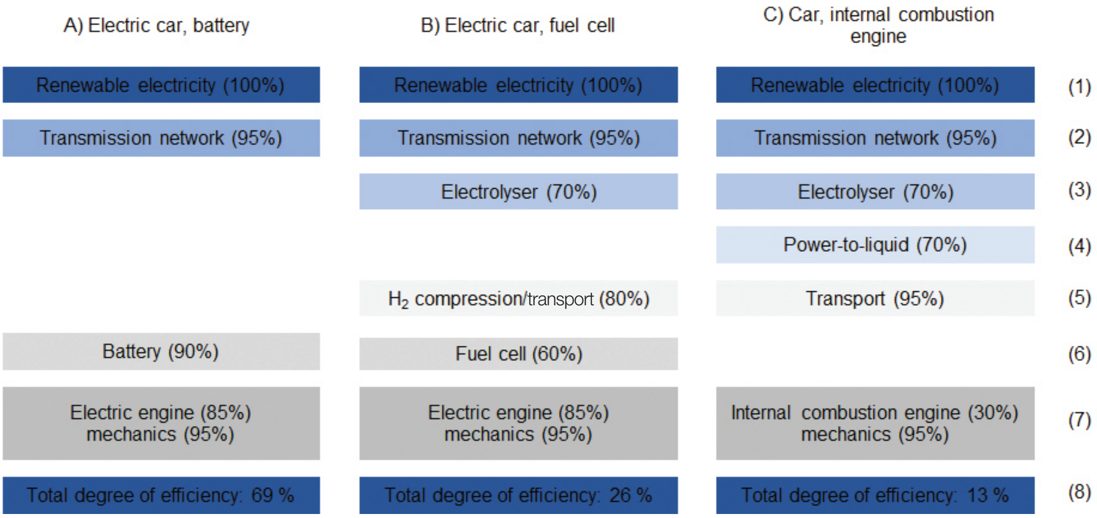

Figure 3: Total degrees of efficiencies for cars powered by (A) an electric engine and battery, (B) an electric engine and fuel cell and (C) an internal combustion engine. Each thermodynamic process is coupled with an energy loss in terms of energy able to perform work. (1) Electricity produced in the plant is given as 100%. (2) Transmission of electricity in networks. (3) Electrolysers producing H_2. (4) PtL processes. (5) Transport and transport related processes. (6) Electricity production and provisioning. (7) Engine technology and losses due to mechanics. (8) Total degree of efficiency on the basis of the electricity produced in the plant (1). All degrees of efficiencies are given as percentage of usable free energy relative to the initial energy content. Modified after (Perner et al. 2018).

2. SYNGAS IN POWER-TO-FUEL PROCESSES

Syngas is the key to all industrial technologies for producing liquid fuels, either in PtL or in conventional processes. Since the early 20th century it is used as a chemical base material in industrial processes. Syngas is predominantly produced from fossil natural gas or by thermal cracking of coal (Beyer & Walter 1988; Holleman et al. 1985). It contains of a mixture of carbon monoxide (CO) and H_2 and is used as hydrogen and/or as a carbon source (see equation 1).

$$206.2\ \mathrm{kJ} + CH_4 + H_2O \rightleftharpoons CO + 3\,H_2 \qquad (1)$$

Syngas can also be produced by the reverse water-gas shift (RWGS) reaction, using CO_2 and H_2 in fuel cells. RWGS is not yet a mature technology but a few demonstration plants already exist worldwide and research and development efforts intensified in the past years (IEA 2019; Pekridis et al. 2007; Wenzel et al. 2018).

$$37.0\ \mathrm{kJ} + H_2 + CO_2 \rightleftharpoons CO + H_2O \qquad (2)$$

The RWGS technology is crucial for CO_2-poor or CO_2-neutral PtL production because secondary carbon sources (carbon from previously emitted CO_2) can be used instead of fossil sources such as natural gas, coal or oil. Each CO_2 molecule can be even used several times if cascade use is applied. The necessary technologies for capturing already emitted CO_2 for

PtL processes will be described in the following chapter.

3. CO_2 CAPTURE TECHNOLOGIES FROM SECONDARY CARBON SOURCES AND FURTHER PROCESSING

Emissions and concentrations of CO_2 are monitored and controlled in a wide range of environments due to its toxicity to humans (German Federal Government 2013). Many countries e.g. Germany define a maximum of 5000ppm or 0.5% of CO_2 in the atmosphere as the mean daily exposure allowed at human workplaces (Bundesanstalt für Arbeitsschutz und Arbeitsmedizin 2020). This threshold value is only about 12 times higher than the actual ambient air concentration (Bereiter et al. 2015). Therefore, CO_2 is not only a problematic greenhouse gas but also potentially toxic for workers handling it as well as for consumers and citizens living in close proximity to CO_2 handling plants

Industry is one of the main producers of carbon emissions (mostly flue gases) next to transportation and heating, Flue gases originate from industrial high temperature combustion processes e.g. from blast furnaces in the iron and steel sector while waste gases originate from small scale processes e.g. internal combustion engines in cars or biological processes in biogas plants. Both, flue and waste gases vary greatly in chemical composition and their concentration in the gas mixture. For capturing CO_2 for PtL from such emitted gases, its concentration in the flue or waste gas is important. The higher the concentration, the simpler the technology applied and the lower the production costs (see Table 2).

The actual global ambient air concentration of CO_2 varies around 405ppm or 0.04% (Bereiter et al. 2015). In contrast, flue gases may contain up to 30% CO_2 and waste gases even up to almost 100% CO_2, which makes both valuable CO_2 sources (IEA 2019). Several techniques and technologies for CO_2-capture from such high concentration point sources as well as from ambient air have been introduced. Some of them are mature, others are in a pilot or demonstration phase (Cuellar-Franca & Azapagic 2015). With respect to the politically demanded mitigation of global warming, CO_2 capture from both, point sources and from ambient air must be considered. CO_2-capture from large industrial point sources is attractive but not 100% efficient. To capture the CO_2 emissions from a multitude of small emitters such as private and public transportation and heating or agriculture is impractical. The third option, CO_2-capture from ambient air is called direct air capture (DAC). Several DAC technologies exist at an early commercial stage (Fasihi et al. 2019). All carbon capture technologies require significant energy input which lowers the efficiency rate of the main PtL process (IEA 2017). An overview of the available carbon capture options is presented in Figure 4.

3.1 CO_2-CAPTURE FROM POINT SOURCES

Several technologies and three principal separation techniques exist for capturing CO_2 from point source flue gas or waste gas. For choosing the best technique and technology, the technical details of the plant, the toxic components in the flue/waste gas which needed treatment as well as possible nearby uses of the captured CO_2 need to be considered. Some CO_2 capturing technologies are used in several separation techniques as the chemical or physical principals are the same (IEA 2017; Cuellar-Franca & Azapagic 2015). Typically, CO_2 capture rates from flue/waste gas point sources are within the range of 50-94% (Fasihi et al. 2019).

Post-conversion capture

Post-conversion capture, in power plants also known as post-combustion capture (IEA 2017), involves the separation of CO_2 from flue/waste gas streams after the conversion of the carbon source to CO_2. This technique is used in natural gas and coal power plants, during the production of ethylene oxide, in the iron or steel production, in the cement industry and during biogas sweetening (a technical term for the removal of acid gaseous components or their precursors which cause corrosion, e.g. CO_2 and H_2S). As shown in Figure 4 various technologies are available, but most commonly used is the adsorption by chemical solvents or sometimes by solid materials (often called filters, which they aren't in a chemical sense). Some techniques require heat for the regeneration of the solvent, therefore they are best suited for plants with a potential for recoverable heat coming either from the main production process or from nearby providers. Post-conversion capture techniques represent the most mature technologies and are in use since 1990. Retrofitting of existing plants for post-conversion CO_2 capture is an add-on technology and can be easily done (Shimekit & Mukhtar 2012; IEA 2017; Cuellar-Franca & Azapagic 2015).

Pre-conversion capture

Pre-conversion capture, also known as syngas/hydrogen capture (IEA 2017) refers to capturing CO_2 which was generated as an undesired co-product of an intermediate reaction during a conversion process. It is most common in steam methane reforming (SMR) when only the hydrogen is needed (e.g. for ammonia production) and chemical and physical adsorption technologies are in use. Retrofitting of existing plants is difficult as it requires drastic changes in the power supply and the main industrial process itself (IEA 2017; Cuellar-Franca & Azapagic 2015).

Oxy-fuel combustion capture

As the name suggest, oxy-fuel combustion can only be applied to processes involving combustion processes such as power generation in fossil-fuelled plants or in the iron and steel and the cement industry. Since pure oxygen (O_2) is used for the combustion process and nitrogen from ambient air is absent, no toxic combustion products like NOx occur. The CO_2-concentration in the resulting flue gas is highly enriched. Pure oxygen is an expensive feedstuff and the production via liquefaction of air is an energy intensive process in which CO_2 may be released depending on the energy source (Holleman et al. 1985). Retrofitting of existing plants is difficult as it requires drastic changes in the power supply setup and the industrial process itself (IEA 2017; Cuellar-Franca & Azapagic 2015).

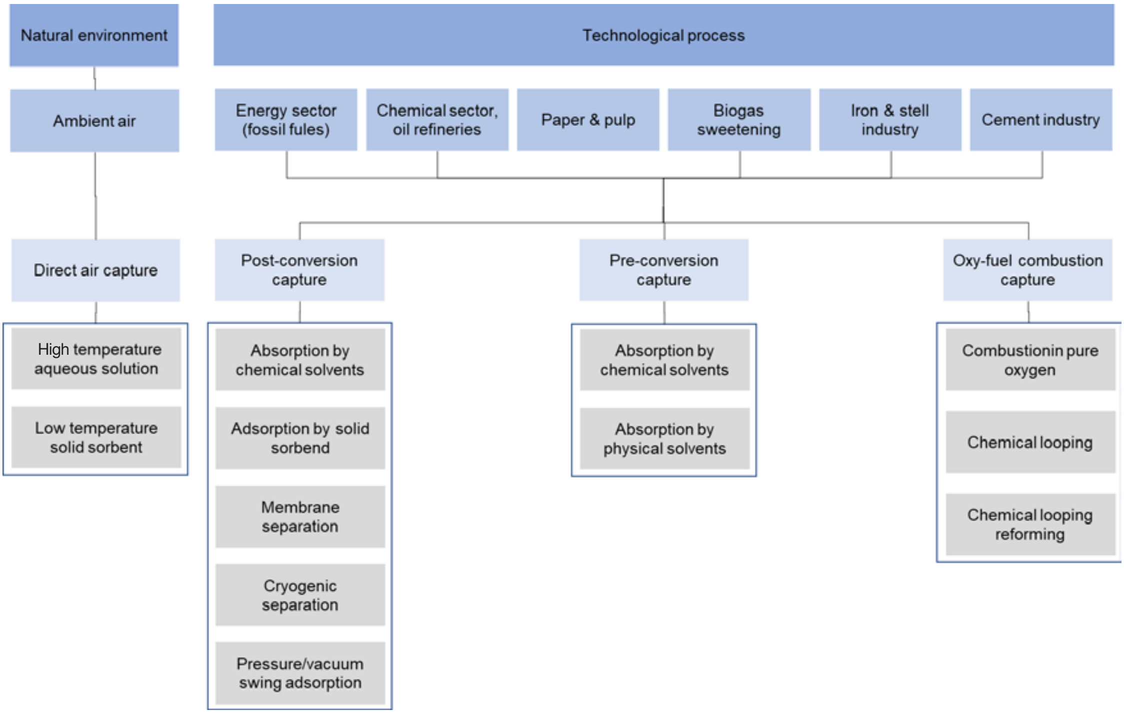

Figure 4: Overview of available CO_2-removal (carbon capture) techniques from ambient air (top left) or from products of technological processes like waste gases or flue gases (top centre and right). Modified after (Fasihi et al. 2019; Cuellar-Franca & Azapagic 2015).

3.2 CO_2-CAPTURE FROM AMBIENT AIR

Direct air capture is a new technique with very few existing plants in industrial production (Butler 2019). Two main technologies are discussed and tried: (a) high temperature aqueous solution (HT) and (b) low temperature solid sorbent (LT) technology. HT technologies use chemical reactions to absorb CO_2 while LT technologies use physical adsorption. Both technologies are analogue to pre- and post-conversion technologies for point sources (Fasihi et al. 2019). Plants for DAC can be built virtually anywhere, but the required area for such installations is considerable. For DAC plants to operate without noticeable depletion of the ambient CO_2 concentration in the vicinity, about 25km² of area per one Megaton of CO_2 capture per year are needed. Therefore, such plants are more likely to be built in rural or remote areas. Model calculations show that CO_2-depletion in ambient air caused by DAC plants should not be problematic for adjacent vegetation or the efficiency of DAC plants. Both technologies have a considerable energy demand for moving air through the capture units by fans. When operated with electricity obtained from fossil fuels, the CO_2-capture efficiency is considerably decreased. Optimal scenarios use energy from renewable sources. Depending on the technologies used, considerable amounts of (a) water, which could be provided by desalinations plants or (b) low-grade heat are needed. Cheap and environmentally friendly produced heat could be provided as waste heat from nearby plants or by heat pumps (Perner et al. 2018; Fasihi et al. 2019).

Region	Process	CO_2 uptake ($t\ CO_2\ ha^{-1}\ year^{-1}$)
Temperate forests [1]	Photosynthesis	23
Tropical rain forests [1]	Photosynthesis	29
Croplands (Agriculture) [1]	Photosynthesis	16
Sugarcane plantation (Maximum yield) [1,3]	Photosynthesis	433
Ocean surface, global average [1,2]	Solution in water	9
Terrestrial surface, global average [1,2]	Photosynthesis	15
Direct air capture (DAC) plants [1,2,4]	Physical/chemical process	approx. 400

Table 1: Annual CO_2 fixation capacities (tons per hectare) for natural terrestrial vegetation, oceans, and industrial (DAC) systems. Uptake rates for vegetation indicate net primary production (NPP) expressed as carbon equivalents (CO_2) fixed by photosynthetic uptake; for ocean surfaces it is the two-way gross exchange of CO_2 between the atmosphere and ocean surface and for DAC the uptake capacity of a plant with a 25km² footprint

[1] Bogdan 1977; Prentice et al. 2018. [2] Terrestrial global surface is 151.2 x 10^6 km², ocean surface 361.9 x 10^6 km². [3] Bogdan (1977). [4] Fasihi et al. (2019)

3.3 FURTHER PROCESSING

Depending on its further uses the captured CO_2 has to be purified. The captured gas has to be dried and toxic and/or corrosive components like H_2S or radon have to be removed below the threshold values given by local legislation. Highest purity grades (>99% CO_2) are required for medical (e.g. endoscopy) and foodstuff (e.g. sparkling beverages) applications. Lower purity grades are acceptable for cooling purposes, welding or for fire extinguishers. Even lower grades can be used in carbon storage projects. Depending on its use and scale of demand, CO_2 is handled and delivered in three states of aggregation. For cooling purposes, it is used as a pre-cooled (below –78.5°C) solid substance known as dry ice. For all other uses, the scale of the demand determinates the state during transport. Small scale consumers use pressurized cylinders or tanks where the CO_2 is kept in liquid phase. It expands into a gas during the release from the vessel. Large scale consumers use pipelines where CO_2 is transported as a gas. Several thousand km of CO_2-pipelines in various countries are already in use (Air Liquide 2016; Shimekit & Muhktar 2012; IEA GHG 2014).

4. SECONDARY CARBON SOURCES

Since the onset of the industrial revolution fossil fuels are the primary energy source for mobility, transport, electricity production and heating. Fossil carbon also serves as raw material for the industry, services, the agricultural sector, government and private households. All carbon releasing or emitting processes and their waste and by-products are valuable point sources of secondary carbon. An overview of major point sources is given in the following chapters (Table 2).

4.1 CO_2-CAPTURE FROM FOSSIL SOURCES

Considerable amounts of CO_2 are released during the production of base chemicals for the chemical industry via the synthesis from syngas (Beyer & Walter 1988; Holleman et al. 1985) and the subsequent stages of production. Syngas contains of a mixture of carbon monoxide (CO) and H_2 and can be used as hydrogen and/or as a carbon source (see equation 1). The bulk of the annual global production is generated by gasification of coal, oil and natural gas. Several pathways of CO_2 emissions are possible: (a) As a waste product and/or as a by-product in the syngas production or the following processes which produce base chemicals. The multitude of these processes and products is termed “chemicals and petrochemicals” and “coal to chemicals” or “gasification” (Table 2). (b) During the syngas production when H_2 is needed e.g. for petrochemical processes or NH_3 production (Holleman et al. 1985). In this case CO_2 is a waste product. NH_3 is a base chemical for organic and inorganic synthesis. Processed to ammonium (NH_{4+}) it is used in fertilizer production. Oxidized to nitric acid (HNO_3) and added to glycerine the explosive nitro-glycerine is formed (Beyer & Walter 1988; Holleman et al. 1985). When NH_3 is further processed to urea and when done at the same plant CO_2 emissions do not occur because the CO_2 originating from the syngas is used as the carbon source.

Ethylene oxide is a chemical base material used in a multitude of organic syntheses. Most of the products are then base materials themselves. About 80% of pure ethylene oxide is formed by the oxidation of ethylene at approx. 250°C and at pressures between 1 – 2MPa using silver as catalyst. The rest of 20% CO_2 is formed as waste gas. Ethylene oxide is a precursor in the production of the toxic mustard gas known as Yperite or LOST (Beyer & Walter 1988) and often not freely tradable to foreign countries, depending on local laws.

Dry natural gas in “pipeline” quality is required for many industrial and private uses. Natural gas from wells typically is a mixture of methane and several other, sometimes toxic or radioactive components which are gaseous, liquid or even solid. It may contain inorganic gases like CO_2, hydrogen sulphide (H_2S) and radon, organic gases like ethane or propane as well as mercury, water and organic liquids such as hexane. Some of these components are of economic value and are further processed or sold while CO_2 is separated from the raw gas either by chemical absorption in amines or by membrane technologies.

The smelting and reduction of iron ore during iron and steel production can be performed with coal or with electricity. Electricity is used in countries with no natural coal deposits or abundant and cheap electricity supply. Coal fired blast furnace processes are the main technology. The production of one ton of iron consumes among other things about one ton of coke and releases seven tons of hot blast furnace gas. Furnace gas contains about 25–30% CO, 10–16% CO_2, 1–5% H_2, 0–3% CH_4 and other substances (Holleman et al. 1985). The European Union is presently funding a research project which captures CO_2 and H_2 from a steel production site in Sweden to produce methanol which is used as fuel in a ferry commuting between Gothenburg in Sweden and Kiel in Germany (INEA 2020). In Iceland methanol is produced from CO_2 and electricity, both coming from geothermal sources (Figure 5) (Carbon Recycling International 2020).

Figure 5: View of the Carbon Recycling International (CRI) plant in Iceland. Electricity is generated from geothermal sources and the carbon dioxide is captured from geothermal sources as well. Both raw materials are synthesized into methanol, which can be used as fuel (brand name "Vulcanol") in internal combustion engines in fuel cells and as chemical base material (Carbon Recycling International 2020).

Cement contains 58–66% of calcium hydroxide ($Ca(OH)_2$) and is obtained by burning limestone ($CaCO_3$) at 900–1000°C. The heat is normally provided from fossil fuels. When burning limestone CO_2 is released during the chemical transformation process (Holleman et al. 1985). The scale of global cement production is enormous: if the global cement industry would be concentrated in one single country it would be the third largest CO_2 emitter worldwide (BBC Business Daily 2019).

Electricity and heat production from fossil fuels are major CO_2 emitters. Electricity from fossil sources is normally produced at an industrial scale. Therefore point sources can be easily accessed to provide CO_2 from the waste gas. In contrast, heat production occurs in small and local units and their "decarbonisation" is a huge challenge, best tackled by the installation of district heating systems or heat pumps running with electricity from renewable sources. District heating systems can be supplemented with waste heat from industrial sources or surplus electricity from fossil or renewable sources which becomes transformed to heat (Plenz 2016).

Electricity consumption of aluminium smelters with fused-salt electrolysis is very high and is accompanied by the emissions resulting from the electricity production. An additional CO_2 source is the anodic reaction of the aluminium reduction process, in which oxygen is formed. The anode is made of coal and thus the oxygen and carbon react to CO_2 (Holleman et al. 1985).

4.2 CO_2-CAPTURE FROM RENEWABLE OR BIOGENIC SOURCES

In Europe bioethanol is mainly produced from grain and to a lesser degree from sugar beets via alcoholic fermentation. With mono-saccharides as substrate each molecule of ethanol produced releases one molecule of CO_2. The CO_2 gas is about 1.5 times heavier than ambient air and accumulates above the fermentation substrate, thus further increasing the fermentation rate. It can easily be recovered in high rates and purity from the fermentation waste gas (Kaltschmitt et al. 2016).

Biogas is produced by bacteria from biomass like corn, from food industry waste, manure or sewage and sludge etc. Biogas is a by-product and contains a water vapour saturated mixture of 45-65 vol% CH_4 and 35-55 vol% CO_2. The composition of the gas is mainly influenced by the substrate used and the degree of oxidation in the bioreactor. On-site use of biogas requires purification from water and H_2S. It then can be used

Process	Total global emission (Gt_{CO2} year $^{-1}$)	Percentage of CO_2 in gas emitted (%)	Capture cost (US$ tCO_2^{-1})
Fossil bases sources			
Coal to chemicals (gasification) Chemicals and petrochemicals	1.20[1] 1.08[3]	98-100[2]	15-25[2]
Ethylene oxide	n.n.	98-100[2]	25-35[2]
Natural gas processing	n.n.	96-100[2]	15-25[2]
Ammonia	n.n.	98-100[2]	25-35[2]
Hydrogen	n.n.	30-100[2]	15-60[2]
Iron and steel	2.08[1] 2.32[3]	21-27[2]	60-100[2]
Cement	2.18[1] 2.24[3]	15-30[2]	60-120[2]
Electricity and heat	15.01[3]	n.n.	n.n.
Aluminium	0.33[1] 0.25[3]	n.n.	n.n.
Renewable/biogenic based sources			
Bioethanol		98-100[2]	25-30[2]
Biogas plants		35-55[4]	n.n.
Paper and pulp	0.22[1] 0.25[3]	n.n.	n.n.
Atmospheric sources			
Direct air capture	n.n.	0.4[1,5]	10-200[2] 11-395[6] 100[7]

Table 2: Sources of CO_2-emissions, total global emission, CO_2 content in the waste gas and costs of carbon capture for several highly CO_2-emitting processes. Costs are mostly calculated based on models or small prototypes than on long term averaged costs of running plants.
[1] IEA (2020). [2] IEA (2019). [3] IEA (2017). [4] Kaltschmitt et al. (2016). [5] Bereiter et al. (2015). [6] Fasihi et al. (2019). [7] Butler (2019).

in combined heat and power plants. Following further cleaning it can be fed into the natural gas grid (Kaltschmitt et al. 2016).

Paper production is a very energy intensive process. When used paper is processed, printing ink, additives and admixtures have to be removed by floatation techniques (de-inking). The waste of this process is toxic and is often incinerated. When wood or e.g. straw is used as raw material, the cellulose for the paper production process has to be extracted. This is normally done by boiling the raw material for several hours with added chemicals. Finally, the paper pulp is formed into sheets and actively dried which requires substantial energy input (Blechschmid 2013).

5. COST OF POWER-TO-LIQUID DERIVED FUELS

Crucial to the wider use of alternative liquid fuels are their production cost. Fossil fuels prices are currently at a long term low (BBC World Service 2015; British Petroleum 2020) and difficult to compete with. Transparency of the total production costs and their specific drivers at all production stages is important. The production costs for PtL are subdivided according to the main production steps (Table 3). The specific efficiency rates for each stage of production differ according to the author. The four stages of production of diesel equivalent fuel from PtL processes are shown in Table 3.

The starting point for PtL fuel production is the generation of the electric energy needed. This corresponds to stages (1) and (2) in Table 3C. The next step of the production is the electrolysis of water for H_2 generation corresponding to stage (3) in Figure 3C. The third stage contains the costs of CO_2 capture, syngas production and the Fischer-Tropsch synthesis. These are summarized into costs of PtL at stage (4) in Figure 3C. The last stage is the transport and distribution of the synthetic fuel corresponding to level (5) in Figure 3C. All calculations discussed in this article were done under the following three preconditions (if not mentioned otherwise): (a) DAC is used to provide CO_2, (b) electricity plants, DAC and PtL are in close proximity to each other and large networks for delivering power and CO_2 are therefore not needed, and (c) transportation is only needed for the finished fuel product (Perner et al. 2018; IEA 2019).

Stage of production	Production stage as shown in Figure 3 C	Efficiency based on step before (%)	Total efficiency (%)	Main cost driver
Electricity production Transmission network	1 2	100 95	95	CAPEX, FLH
Electrolyser	3	70	67	OPEX
CO_2-capture, Syngas, Fischer-Tropsch	4	70	47	OPEX
Transportation	5	95	44	OPEX

Table 3: Main stages of production of diesel equivalent fuel from PtL processes (Perner et al. 2018). For each stage of production, the efficiency is given based on the respective upstream step (third column). Electricity production is defined as 100% efficiency. Total efficiency related to electricity production is given in the fourth column. The main cost driver of the total costs is given in the last column. FLH = full load hours. CAPEX = capital costs. OPEX = operational costs.

With respect to PtL processes, all technologies discussed in this paper are not yet in a mature state. The only exception to this is the production of electricity from geothermal plants and from large hydropower dams (IRENA 2018). Significant cost reduction potentials are predicted for the realization of these not yet mature technologies according to the established theory of the “learning curve” in economic science (Kost & Schlegl 2018; Perner et al. 2018; IRENA 2018). Specific technologic designs will reduce the capital costs (CAPEX) as well as the operating costs (OPEX) for each additional production unit established (Wikipedia UK 2020). As soon as a plant is operative, the absolute amount of CAPEX is defined and can only be changed by a change in technology or an upgraded version of the same technology. In this situation the costs per unit produced (kWh, H_2, fuel, transported fuel with respect to the chosen steps of production) directly dependent on the full load hours (FLH) of the installation and the amount of years the plant is in service. The FLH are a measure of the degree of capacity utilization: The higher the

FLH, the lower the CAPEX per unit and therefore the total costs per unit (economy of scales). The more CAPEX intensive a technology, the more important are high FLH to reduce costs. Eight thousand FLH annually (out of 8760 hours total per year) are considered a continuous working mode. Electrolysers, PtL-plants, transport facilities and electricity production from geothermal plants and in some cases even hydro plants can technically be run in a continuous working mode.

Continuous electricity production from solar and wind as renewable sources cannot run in a continuous mode without having a large energy storage option. OPEX of electricity producing solar and wind plants are low and basically defined by the maintenance costs of the plants. OPEX for fossil and nuclear plants also contain fuel costs. OPEX in planning and building of the plants and the necessary machinery may vary due to costs for employees, raw materials and intellectual property rights. It is important to recognize, that the total costs per unit of the upstream production step is always part of the OPEX of the downstream production step. The main input required for PtL processes is electric energy for the electrolysis of water and for DAC. Therefore the costs of electricity matter most and are discussed in greater detail below (Perner et al. 2018; IEA 2019).

5.1 COSTS OF ELECTRICITY AND THE INFLUENCE OF CAPACITY UTILIZATION

The leveled costs of electricity (LCOE) are generally used to compare production cost of different technologies. They contain CAPEX, OPEX, weighted average cost of capital (WAAC) which are the interest rate for the planned investment and the produced kWh in the respective period of time. Costs for CO_2-certificates are not included in the results shown below (Kost & Schlegl 2018; PowerTech VGB 2015; IRENA 2018).

Obviously, FLH do affect the total cost most profoundly (Kost & Schlegl 2018; Perner et al. 2018; IRENA 2018) (see Table 4). With respect to security of the electricity supply, geothermal plants can potentially work as close to a continuous mode as technically possible (>8000 h per year) and must be shut down for maintenance work only. Potential FLH are comparable to fossil fuel and nuclear power plants running at full capacity. Second in reliable electricity production and first in terms of its possible storage capacities for electricity production are hydropower plants and pumped hydropower plants (Figure 6). Solar plants and wind farms normally do not reach more than 4400 FLH (Kost & Schlegl 2018; Perner et al. 2018) depending on the location. Combined solar and wind farms in the Global Sunbelt (see Figure 7) may reach up to 5000 FLH (Perner et al. 2018). Plants with FLH lower than the above mentioned numbers indicate an in-

Figure 6: Pumped storage hydropower station "Hohenwarte II" in Thuringia, Germany which is owned by the Swedish company Vattenfall GmbH. The upper reservoir is filled with pumped water from the lower reservoir and river power plant during times of surplus electricity production. The water from the upper reservoir powers on demand the eight turbines in the machine hall, the height of drop is 304 meter (Flickr 2020; Vattenfall 2020).

sufficient use of their capacity. In Germany the currently low FLH of fossil fuel plants show the negative economic consequences of a fast transition from fossil and nuclear plants to renewable electricity sources because the fossil and nuclear power plants are mainly used for providing energy security in periods of insufficient supply from renewable sources (Sinn 2017; Lauf 2020).

THE GLOBAL SUNBELT

The term Global Sunbelt refers to the regions between 35 degrees of northern and southern latitude. In this region the annual global solar irradiance at the land and ocean surfaces is highest on earth with the best conditions for solar power plants (Hauff et al. 2020). Accounting for approximately 80% of the world's population, 148 out of 201 countries belong partly or completely to this region. NATO-members with at least some state territory in the Global Sunbelt are Greece, Italy, Portugal, Spain, Turkey, the United States of America and Malta which is a Euro-Atlantic Partnership Council (EAPC) member. NATO partners situated in the Global Sunbelt are Afghanistan, Australia, Colombia, Iraq, Japan, the Republic of Korea and Pakistan.

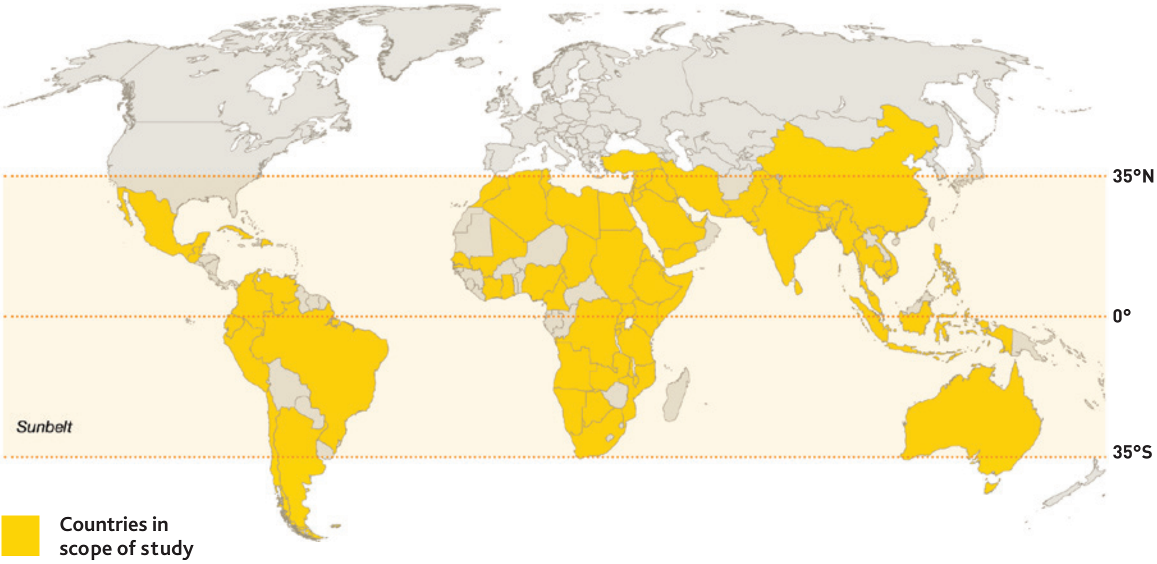

Figure 7: The region between 35 degrees of northern and southern latitude is referred to as the Global Sunbelt. Countries marked in yellow are included into a study by Hauff et al. (2020). Countries within the Global Sunbelt and marked in grey are not included in the detailed analysis of the European Photovoltaic Industry Association.

The levelled costs of electricity for several power plant technologies from two different studies looking at power plants commissioned in 2018 (Table 3) show similar trends (Table 4): The IRENA-Study (IRENA 2018) calculates worldwide average LCOE with 5th-95th percentile values and shows that LCOE vary greatly with respect to the size of the plant. The Fraunhofer-ISE-Study (Kost & Schlegl 2018) lists minimal and maximal LCOE for plants in Germany. Nuclear power plants under construction in 2015 incur LCOE of 3.6-8.4 €-cent 2015/kWh, without considering the cost of radioactive waste disposal (PowerTech VGB 2015). Globally the cheapest newly build renewable power plants (hydropower, bioenergy and offshore wind parks) show lower average LOCE than fossil fuel power plants built in 2018. Considerable further reductions in costs are predicted in the years and decades to come, with higher cost reduction effects for renewable tech-

Electricity source	LCOE IRENA-Study 5th-95th percentile (\$-ct$_{2018}$ kWh^{-1})[1]	LCOE Fraunhofer-ISE Study[2]	
		Performance	Min-max costs (€-ct$_{2018}$ kWh^{-1})
Solar, small (private households)	10.9 - 27.2	950 - 1300 kWh m^{-2} year^{-1}	7.23 - 11.54
Solar, medium (industrial)			4.95 - 8.46
Solar, large (solar parks)			3.71 - 6.75
Wind, onshore	4.4 - 10.0	1800 - 3200 FLH	3.99 - 8.23
Wind, offshore	10.2 - 19.8	3200 - 4500 FLH	7.49 - 13.79
Biogas		5000 - 7000 FLH	10.14 - 14.74
Bioenergy (direct combustion and gasification)	4.8 - 24.3	n.n.	n.n.
Hydro	3.0 - 13.6	No new plants in Germany in 2018	
Geothermal	6.0 - 14.3		
Lignite fired power plants	5.6 - 17.5	6450 - 7450 FLH	4.59 - 7.98
Coal fired power plants		5350 - 6350 FLH	6.27 - 9.96
Gas and steam power plants		3000 - 4000 FLH	7.78 - 9.96
Gas fired power plants		500 - 2000 FLH	11.03 - 21.94

Table 4: The leveled costs of electricity (LCOE) of renewable and fossil fuel electricity producing plants commissioned in 2018 according to two major studies by IRENA (2018) and Fraunhofer ISE (Kost & Schlegl 2018). The electricity source is given in the first column and the second column shows the 5th-95th percentile of global average LCOE for plants commissioned in 2018. Columns 3 and 4 refer to the LCOE of plants commissioned in 2018 in Germany with column 3 showing the performance range with respect to the local solar radiation or the FLH and column 4 showing the LCOE.
[1] Shell (2007). [2] Kost & Schlegl (2018).

nologies compared with fossil and nuclear power plants (Kost & Schlegl 2018; Perner et al. 2018; IRENA 2018). In terms of production costs and energy supply security hydropower plants are the best choice. Nevertheless, many countries do not build new hydro dams because of the negative environmental impacts and social issues (Sinn 2017).

5.2 TOTAL COSTS OF SYNTHETIC FUEL PRODUCTION

The large German AGORA study (Perner et al. 2018) on the costs of synthetic fuel production quantified the potential minimum and maximum total costs of synthetic fuel production. Several renewable electricity sources and DAC as the source of CO$_2$ in different places of the world were considered. Also the respective variation of FLH and the transport costs for delivery of the fuel to the German border (without fees and taxes) was taken into account (Table 5). The resulting fuel costs vary with the CAPEX of the chosen technology for electricity production and the assumed FLH. The cheapest production is possible in Iceland with mature, low cost electricity production using geothermal energy and hydro plants in a continuous production mode. This is also in accordance with the production costs of geothermal plants commissioned in 2018 (see Table 4) (IRENA 2018). The highest fuel costs result from offshore wind parks located in the North Sea and Baltic Sea due to the high building and network costs in terms of connection to the mainland grid and relatively low FLH. The costs of fuel from solar plants in North Africa and the Middle East do not vary greatly. Increasing the FLH of these

Location/technology	FLH of electricity production (h)	Agora-Study (€-ct_{2017} kWh_{PtL}^{-1})	
		Minimum costs	Maximum costs
North Africa / solar	2100-2500	16.52	19.29
Middle East / solar	2200-2600	16.10	18.71
North Africa solar / onshore wind	3485-5015	16.65	22.67
Middle-East solar / onshore wind	3910-4335	18.21	21.29
Island geothermal / hydro	8000-8000	11.25	11.73
North-, Baltic Sea / offshore wind	3500-4400	21.93	33.17
Premium fossil gasoline	n.a.	4.66	

Table 5: Minimum and maximum total costs and FLH of renewable plant site locations with favorable conditions for energy production. Fuel costs are compared with the price of premium gasoline fuel as projected for 2017-2020. KWh_{PtL} refers to the energy content in kWh of the fuel produced (Perner et al. 2018).

plants by installing nearby wind plants could improve the FLH but increases the electricity costs since additional CAPEX are needed for installation of wind parks. The range of minimum and maximum costs of solar and combined solar and wind plants in North Africa and the Middle East do not vary greatly. For all renewable power generation technologies, even in if installed in the most suitable locations, the resulting fuel costs would be currently at least twice as high as the projected costs for premium fossil gasoline fuel (given prices for the year 2020).

Stage of production	Island geothermal/hydro plants (8000 FLH) (€-ct_{2017} kWh_{PtL}^{-1})	North- and Baltic Sea offshore wind plants (4000 FLH) (€-ct_{2017} kWh_{PtL}^{-1})
Electricity production, Transmission network	5.091	17.179
Electrolyser	1.858	3.716
CO_2-capture, syngas, Fischer-Tropsch	4.556	5.173
Transportation	0.014	0.000
Total costs	**11.520**	**26.468**
Price for premium gasoline	4.66	4.66

Table 6: Total minimum costs for synthetic fuel production including transport to the German border with respect to the stages of production and in dependence of the degree of capacity utilization for the year 2020. Costs are given without costs for distribution, fees and taxes and compared with the price of premium fossil gasoline (2017-2020). KWh_{PtL} refers to the kWh of the fuel produced (Perner et al. 2018).

For the Iceland scenario with lowest total fuel costs and the North Sea and Baltic Sea scenario with the highest total fuel costs a detailed overview for the production stages (see Table 3) are shown in Table 6. The Island scenario shows the lowest electricity costs but involves long transportation routes for the fuel produced in order to reach Germany. The North Sea and Baltic Sea scenario involves high electricity costs at an expected lower than 50% capacity use but no further costs for transportation. This difference is explained by the H_2 production costs. The lower amount of FLH in the North- and Baltic Sea scenario results in approximately twice the amount of productions costs related to this step of production (Perner et al. 2018). This fact is in close accordance with the fact that the total efficiency rate based on the electricity input is 67% (Table 3).

A study by the International Energy Agency (IEA 2016) calculated the minimum and maximum costs of synthetic fuel production according to the stages of production (c.f. Figure 3C). Costs of all technologies are grouped into CAPEX, OPEX, electricity and CO_2. Cost for electricity supply were calculated for averaged renewable sources with 3000 FLH. The costs for CO_2 supply are divided into a low cost version with CO_2 from a bioethanol plant and a high cost version with DAC. Calculations for the near future until 2030 and the longer term after 2030 are shown in Table 7. In the near future total costs are driven by the cost for electricity production and CO_2 supply by DAC. The production costs for electricity and DAC are expected to drop in the future by approx. one third due to learning curve effects. However they will remain the dominant cost factor.
The total costs for synthetic fuels in the Agora study (Perner et al. 2018) and the IEA (2017) study are in the same order of magnitude while the reference cost of fossil fuel may vary quite substantially in the future.

Table 7: Near (2030) and long term (>2030) minimum costs of synthetic fuel production without transport, fees and taxes as calculated from worldwide projects with different technologies for power and CO_2 production (IEA 2017). Fossil diesel price is calculated based on 75 US Dollar per barrel of crude.

CONCLUSIONS

The production technologies for synthetic fuels (synfuel) are well established (Pöhlmann 2017;

	Unit	Near term (2030)	Long term (>2030)	Cost reduction (%)
FLH electricity production	[h year^{-1}]	3000	3000	n.a.
CAPEX	[$-ct$_{2017}$ kWh$_{PtL}^{-1}$]	6.83	4.55	33
OPEX		1.82	1.38	24
Electricity costs		10.92	4.55	58
CO_2 feedstock costs – low		0.91	0.91	0
CO_2 feedstock costs – high		10.47	1.82	83
Total costs – low		**20.48**	**11.39**	**11**
Total cost – high		**30.95**	**22.78**	**44**
Diesel price (fossil)	[$-ct kWh^{-1}]	4.81	4.81	n.a.

Table 7: Near (2030) and long term (>2030) minimum costs of synthetic fuel production without transport, fees and taxes as calculated from worldwide projects with different technologies for power and CO_2 production (IEA 2017). Fossil diesel price is calculated based on 75 US Dollar per barrel of crude.

Perner et al. 2018; Lauf 2020). Synfuels provide environmentally cleaner fuel emissions. If H_2, reused CO_2 and electricity from renewable sources are used for synfuel production, these fuels will not contribute to the increase of CO_2 concentration in the atmosphere and help combatting climate warming. However, the production costs of synfuels are currently not at all competitive compared to the much lower price for fossil fuels. In addition the technologies for H_2 production, CO_2 capture and fuel production are currently not yet in a mature state. However, significant cost reductions are predicted for future large scale applications (Kost & Schlegl 2018; Perner et al. 2018; Fasihi et al. 2019; IRENA 2018). Since the production processes of synfuels are very electricity intensive, the availability of cheap and secure renewable electricity sources are the prerequisite for making PtL competitive with fossil energy.

Since 2018 newly build renewable electricity plants can produce cheaper electricity than newly build fossil or nuclear power plants. However, this does not take into account that solar and wind power plants suffer from an inherent non-continuous power generation and therefore require additional intermediate storage options. Predictions on costs of energy storage do suggest that the trend in cost reductions for renewable technologies will continue in the coming years and decades. A report issued in 2010 predicted for the year 2020 a drop for LCOE of PV onto the range of 5–12 €-cent which fits the actual prices reached in 2018 (Hauff et al. 2020). The technology and therefore the power source and the location of the PtL plants are the main determinants for the production costs. The most influential parameter is the degree of technical capacity utilization, also expressed as full load hours (FLH). In this respect geothermal and hydropower plants are the most favourable energy providers for PtL technologies. Because power production is the key parameter for determining the total costs of synthetic fuels, it seems favourable to concentrate all stages of production in the proximity of electricity plants. Industrial point sources of CO_2 provide very concentrated carbon but typically do not provide enough CO_2 for large scale PtL production or are not in proximity to low cost renewable energy. Therefore, ambient air is most likely to be used as carbon source in combination with direct air capture technology because DAC plants can be located next to renewable energy producers.

As DAC is a highly energy intensive and a space requiring process it is likely to be installed in remote rural areas. Innovative combinations of electricity-, H_2- and CO_2 production plants may offer interesting alternatives: The best option would be to have geothermal or hydropower electricity production near large scale high concentration CO_2 emitters, but these settings are extremely rare on a global scale. The second best solution would have CO_2 pipelines running from CO_2 emitters to the electricity plants. CO_2 pipelines are an established technology but they add additional costs to the final product (IEA GHG 2014). A third option would be to combine solar and wind plants in the Global Sunbelt. However, such a setup faces the same problems of obtaining sufficient and low cost CO_2 supplies as do geothermal and hydropower plants (Perner et al. 2018; IEA 2017). Since industrial processes with their high CO_2 concentrations and often impure waste gases are much cheaper carbon sources than DAC (Kaltschmitt 2016; Bereiter et al. 2015; Butler 2019; Fasihi et al. 2019; IEA GHG 2014; IEA 2020), innovative measures are needed to link CO_2 emitters in industrial areas, PtL plants and renewable electricity power plant.

For the next years, synthetic fuels will remain significantly more expensive than fossil fuels (Perner et al. 2018; IEA 2017) but may become more competitive due to the predicted reductions in costs and the politically driven implementation of ever more expensive CO_2 certificates. Nonetheless the costs are predictable and the supply lines secure when established by politically and economically stable countries. The establishment of renewable energy plants with DAC in vulnerable regions or in “failed states” belonging to the Global Sunbelt would not contribute to our energy security. In contrast to fossil oil prices, synthetic fuel production costs are comparably stable because their input costs are predictable. The main cost drivers are CAPEX for the renewable energy plants, electrolysers, Fischer-Tropsch plants and CO_2 capture technologies. OPEX are reduced mostly to maintenance, as the renewable energy and CO_2 comes for free. Pure water for running the electrolysers may be expensive but can be achieved by desalination of sea water.

In 2015 the OPEC predicted an oil price of 70 $ per barrel for 2020 (BBC World Service 2015) which fits the actual price in January 2020 quite well. The year 2020 has already seen oil price spikes in the wake of airstrikes to oil refineries in January (BBC World Service 2020a) as well as negative oil prices in the aftermath of disagreements over supply rates between oil producing states by the mid of April. The corona pandemic induced worldwide lockdowns and further decreased the demand for oil (BBC 2020 b). On an economic basis the world oil price defines which oil sources are exploited. Shale oil production in the USA and Canada for example is much more expensive than oil production from wells in the Middle East. The international oil price also influences or even dominates national budgets of many oil exporting nations like Russia, the UAE or Venezuela. In these countries the crude oil price determines in consequence the level of social benefits provided by the government to its citizens and therefore social and political stability.

For the near future and considering costs and benefits on all levels, it appears to be a prudent strategy for NATO nations and partners to establish a balanced and diversified portfolio of investments in Power to Liquid technologies at home and in politically stable regions. This will improve energy security, ensure own technological competence and leadership for promising technologies and secure a basic fuel supply for countries with small or no fossil fuel reserves. PtL investments in some volatile regions on the other hand may also contribute to stabilize NATO's partners and vulnerable neighbours.

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