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Content

Editorial

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The clean energy transition is without a doubt one of the greatest challenges of the 21st century. The reasons for that are myriad, complex and sometimes overlapping. There are significant challenges associated with some of the new and innovative energy technologies that could help to decarbonise hard-to-abate sectors. And, due to a number of reasons, even some of the more established technologies have flaws that often are easily overlooked.

In addition to these technological problems, in some countries historical path dependencies can hinder the clean energy transition from gaining momentum. Or, alternatively, traditional energy security issues may at times divert some of the attention that could otherwise be spent on making the energy systems greener.

This issue of Energy Highlights will tackle some of these challenges head on.

In their contribution, Dr. Jutta Lauf, Wsewolod Rusow and Dr. Reiner Zimmermann examine the utility of nitrogen-based fuels. They argue that these fuels have significant advantages over carbon-based fuels because they do not emit greenhouse gases or any other hazardous compounds during combustion. While the authors agree that it may take a while before nitrogen-based fuels can become adopted on a wider scale, they are confident that in the near future these fuels could play a meaningful role in the global decarbonisation effort.

Meanwhile, in his piece Thomas Troszak examines the environmental impact of solar photovoltaics (PV) production. More specifically, the author introduces the readers to the many types of fossil fuels that are used in PV production and notes how some other environmentally hazardous inputs are required before the delivery of a solar PV array can take place.

In the third article, Camille Fourmeau, Nicolas Mazzucchi and Dr. Reiner Zimmermann analyse Australia's energy transition challenges and its implications for the country's military. The authors place particular emphasis on the difficulties Canberra faces while trying to reconcile its current dependency on fossil fuels, the negative implications of climate change and the urgent need to expand investments in renewable sources of energy.

Finally, Justinas Juozaitis explains why it is important for the Baltic States to disconnect their power systems from the Soviet-era BRELL power grid and to synchronize with the Continental European Network. The author not only provides a comprehensive account of the historical development of the BRELL grid, highlights the synchronization significance for Baltic energy security, but also points out how Russia and Belarus have been pursuing various strategies to deter the Baltics from leaving the BRELL grid.

In the end, we hope that these articles would provide you, the readers, not only with a better grasp of the clean energy transition challenges that many governments face, but would also inspire you to be part of the change.

Nitrogen based propellants as substitute for carbon containing fuels

by **Dr. Jutta Lauf, Wsewolod Rusow and Dr. Reiner Zimmermann**

1. ABSTRACT

Nitrogen based fuels have several advantages over carbon-based fuels. No greenhouse gases (GHG) or health compromising compounds are emitted during the combustion and the subsequent waste gas treatment of most nitrogen bases fuels. When nitrogen based fuels are produced with power from renewable sources, no GHG are emitted during the production process either. All nitrogen based fuels originate from ammonia (NH_3), which is produced via the Haber-Bosch-Process. Ammonia combustion engines have been developed and tested as prototypes for several decades. In recent years the interest mainly for use in naval propulsion systems has grown. Marketable fuels cells using ammonia are now commercially available, as well as fuel cells using hydrogen which was stripped from the ammonia. Hydrazine is a commonly used rocket propellant but is not used in civil environments due to its high toxicity. Ammonium nitrate and urea engines are fringe applications which were currently tested in laboratory environments. Production of nitrogen based fuels by using renewable power sources would be most economically feasible with energy produced in the global Sunbelt. Since the necessary Haber-Bosch technology is mature and plants are existing in all major agricultural countries, the upscaling of ammonia production seems easily possible. The prime advantage of nitrogen based fuels are both, the intrinsic lack of carbon as well as the technological maturity of their production, transport and storage. As the various propulsion engines and the combustion technologies reach technical maturity, nitrogen based fuels will certainly become attractive for a decarbonizing world.

2. INTRODUCTION

Nitrogen based fuels are well known since several decades but rarely used for transportation purposes. Their inherent environmental advantage is the absence of any carbon dioxide (CO_2) emissions during combustion. Therefore, they may contribute significantly to the internationally demanded decarbonisation of the transport sector. However, easy access to fossil carbon-based gas (methane) and liquid fuels (derived from crude oil) during the past decades as well as their cheapness, low safety risks and established processing infrastructure made them the almost exclusive propulsion energy for transportation purposes. Crude oil is easily refined to e. g. kerosene,

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diesel, or gasoline. In the next decade the need to move away from fossil carbon-based energy may favour – at least in part - nitrogen as fuel in the transportation sector due to its ecologic advantages, the technological practicability and the relatively moderate changes needed to existing infrastructure for production and logistics.

As early as 1943, during the fossil fuel shortages in WW II, a retrofitted bus engine was propelled by ammonia (NH_3) in Belgium (Kroch 1945) (Figure 1). In the 1950ies an Austrian inventor redesigned a motor bike to run on hydrazine (N_2H_4) in a fuel cell (Figure 2). Hydrazine in combination with other fuels was used during WW II as a propellant for the German A4 rocket and the rocket engine driven German Me-163 interceptor airplane (Ziegler 1976). Hydrazine is still common in the Titan and Ariane rockets as well as in satellites and space ships (Haidn 2008). However hydrazine is not widely used because of its high toxicity (Table 1) (Bundesanstalt für Arbeitsschutz und Arbeitsmedizin 1991). Nitrous oxide (N_2O) injection in piston driven engines was used by high performance airplanes during WWII as an additional power booster.

Non-fossil originated carbon-based fuels (often called "synthetic carbon fuels") are very expensive in production and are currently used for niche applications only. Even after the global oil price shocks in 1973 and 1979/80, which were caused by geo-political disruptions (BP 2020), no serious actions were taken to reduce the dependency from fossil carbon fuels in the transportation or heating sectors on a global scale and only the nuclear power generation sector gained importance since the end of the 1970ies, mainly in technologically advanced countries (Roser 2020).

Figure 1: Retrofitted bus with an ammonia driven internal combustion engine in 1943 during WWII in Belgium (Kroch 1945).

Even today most attempts to reduce or minimise the usage of carbon-based fossil fuels are not price driven. In fact, global oil prices have reached a relatively stable minimum caused by the increased application of fracking techniques in North America, political discord of the oil producing countries about production quantities and the current economic slow-down due to the SARS-CoV-2 pandemic (BP 2020; BBC 09.06.2020). Current attempts to reduce the usage of fossil fuels and to replace them with carbon free fuels are due to mounting concerns regarding the negative environmental consequences of rising global temperatures which are caused by the increasing atmospheric concentration of CO_2 and other greenhouse gases. The increasing global temperatures cause rising sea levels, more severe droughts, raging wildfires and the melting of permafrost areas. The resulting natural disasters, economic disruptions, social unrest and mass migrations will result in more refugee and rescue missions for the military forces (Reinhardt and Toffel 2017; Fourmeau and Zimmerman 2020).

The present article will provide an overview of the chemical production processes of nitrogen-based fuels using power from renewable energy sources as well as cover the safety issues of nitrogen fuels in comparison with carbon-based fuels. Also, propulsion technologies for nitrogen based fuels and possible global NH3 production capacities will be discussed.

3. NITROGEN BASED FUELS IN POWER-TO-FUEL PROCESSES

Power–to-fuel (PtF) is an umbrella term for processes using electricity from renewable sources for the production of gaseous or liquid fuels. Liquid fuels are the most attractive and cost-effective approach for storing and delivering energy for large scale applications. They are unmatched in terms of transportability and energy density

(Andersson and Grönkvist 2019) compared with gaseous fuels (Table 1).

Liquid fuels come with higher production costs compared to gaseous fuels because more steps are required to produce them. Due to the second law of thermodynamics each energy conversion process – of which chemical synthesis is one - results in a loss of energy available to perform work (free energy). This fact leads with each additional step of synthesis to substantial losses in the useable fuel energy content (Atkins et al. 1990; Perner et al. 2018). Consequently, the number of production or energy conversion steps should always be kept as low as possible.

A selection of production pathways for nitrogen-based fuels is presented in Figure 2 . All processes start with the production of electricity from renewable sources (1). Electricity can be directly used in electric engines via battery storage. Electricity driven electrolysers produce hydrogen (H_2), from water, which is the first possible chemical storage (Holleman et al. 1985). H_2 is a nontoxic gas under normal conditions, but handling is difficult due to its flammable and explosive properties (Table 1) (Bundesanstalt für Arbeitsschutz und Arbeitsmedizin 2020). The volumetric and gravimetric energy density of H2 in compressed or liquefied form is high but it requires a significant amount of energy and safety precautions to reach these states (Table 1) (Andersson and Grönkvist 2019). H_2 is also a valuable base chemical, leading to further applications in fuel syntheses.

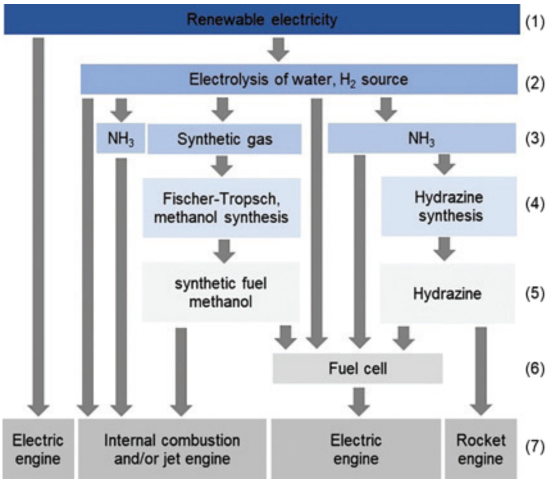


Figure 2: Schematic of power- to-X (PtX) production pathways and the usage of the products for mobility.

(1) Electricity production from renewable sources. Electricity can be used directly in electric engines. (2) Electrolysis of water and production of hydrogen (H_2). (3) Synthetic gas (syngas) or ammonia (NH_3) can be produced with H_2. Syngas requires a CO_2 source from fossil or non-fossil sources. NH_3 requires nitrogen (N_2) from ambient air. (4) Reactors for the synthesis of organic compounds (synthetic fuels or methanol) or hydrazine. (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, NH_3 and hydrazine can be either used in fuels cells, which power electric engines or in internal combustion and rocket engines. Modified after (Sterner 2019; Perner et al. 2018; Grinberg Dana et al. 2016).

NH_3 produced by the Haber-Bosch process (Holleman et al. 1985) is the first of several possible nitrogen based fuels (3). Nitrogen (N_2) is needed as a base component (Formula 1) and normally extracted from ambient air. NH_3 can be used as a base chemical for further synthesis (4), in fuel cells (6) or in internal combustion or jet engines (7). Hydrazine and its methyl derivatives are used as long term storable rocket fuels (Haidn 2008). Because hydrazine is extremely toxic (Bundesanstalt für Arbeitsschutz und Arbeitsmedizin 1991) (Table 1), its usage is only allowed in environments where no substitutes are possible, e.g. in military and space technologies. Fuels which are based on nitrates (NO_3-) - including aqueous solutions of urea, ammonium nitrate and their mixtures - are currently tested in laboratory environments (Grinberg Dana et al. 2016).

Carbon based fuels (often simply called synthetic fuels) derived from the Fischer-Tropsch process or methanol from methanol synthesis can be obtained via the production of synthetic gas (syngas) (Holleman et al. 1985). These chemical processes require CO_2 as the carbon source. Non fossil CO_2 sources (secondary carbon sources) as well as their production costs were discussed in (Lauf 2020b). Methanol can be used in fuel cells and methanol or synthetic fuels can also be used in internal combustion and jet engines.

Ammonia and hydrazine are generally more toxic than conventional fossil or synthetic fuels (Table 1). Many countries define maximum workplace air concentrations for mean daily exposure to humans (e.g for Germany: Bundesanstalt für Arbeitsschutz und Arbeitsmedizin 1991; Bundesanstalt für Arbeitsschutz und Arbeitsmedizin 2020). Hydrogen as the first fuel generated from electricity is not toxic but extremely inflammable and explosive. It is odourless and can only be detected by elaborate technical devices. NH_3 is also toxic but self-alarming due its pungent smell. The limit of detection (LOD) by the human nose is about 4 times lower than the allowed workplace air concentration (Assumpção et al. 2014). The unpleasant smell of NH_3 normally forces humans to leave a contaminated area before health risks occur. However, if suddenly exposed to high concentrations, the human nose can no longer detect it. Hydrazine is the most toxic and inflammable of the fuels discussed. Ammonia is 200 times less toxic than hydrazine and not inflammable. The smell of hydrazine is similar to that of NH3, but less intense. Ammonium nitrate is not toxic but explosive in solid state while urea is neither toxic nor inflammable.

The carbon-based methanol and diesel fuels are less toxic than NH_3 but inflammable. A maximum workplace air concentration for diesel is not given, as it is a mixture of many components. The most toxic component is benzene. Synthetic diesel may differ from its fossil counterpart, as the Fischer-Tropsch synthesis can be managed to result in less toxic by-products.

The so-called inferior heating values or net ca-

	Maximum workplace air concentration [ppm]	Inflammable and/or explosive	Energy content, H_i [kWh/kg]
Hydrogen (g) (H_2)	- (1)	Yes (3)	33,3 (6)
Ammonia (g) (NH_3)	20 (1)	No (3)	5,2 (6)
Hydrazine (l) (N2H_4)	0.1 (2)	Yes (3)	5,5 (6)
Urea (s) (H_2NCONH_2)	- (1)	No (3, 4)	2,6 (6)
Ammonium nitrate (NH_4NO_3)			
- Solid	- (1)	Yes (5)	-
- Aqueous solution	- (1)	No (5)	-
Methanol (l) (CH_3OH)	100 (1)	Yes (4)	6,3 (6)
Ethanol (l) (CH_3-CH_2OH)	200 (1)	Yes (4)	7,5 (6)
Diesel fuel (l) (analogue to F-34)	- (1)	Yes (1)	11,8 (7)
Carbon dioxide (g) (CO_2)	5 000 (1)	No	-

Table 1: Maximum workplace air concentrations in parts per million [ppm], flammability and energy density for selected alternative fuels as well as for ethanol and carbon dioxide. State of aggregation at ambient air temperature and pressure: g = gaseous, l = liquid, s = solid). Energy content expressed as the so called inferior heating value (net caloric value, Hi) Citations: (1) (Bundesanstalt für Arbeitsschutz und Arbeitsmedizin 2020); (2) (Bundesanstalt für Arbeitsschutz und Arbeitsmedizin 1991); (3) (Holleman et al. 1985); (4) (Beyer and Walter 1988); (5) (Grinberg Dana et al. 2016); (6) (Beilicke 2010); (7) (Reitmair 2013).

loric value Hi of a selection of fuels (referenced to weight) are shown in Table 1. H_2 shows the highest Hi value. The nitrogen-based fuels NH_3 and N_2H_4 as well as methanol and ethanol show inferior heating values within the same order of magnitude. Hi is rising with the increasing number of chemical bonds of the respective compound. The energy content of diesel fuel is highest, as it contains much more chemical bonds. From the perspective of Hi values, diesel appears to be the most promising fuel to produce. However, the Hi does not reflect the amount of energy needed – or, in other words, the amount of free energy lost - to produce these components from steps (3) to (5) in Figure 2. If the energy content of the product and the energy needed for its synthesis are accounted for, H_2 is the best fuel to use and NH_3 is the second best.

FLUCTUATING POWER SUPPLY FROM RENEWABLE PLANTS AND STORAGE OF ELECTRIC ENERGY

Electricity is difficult to store on a large scale. It has to be provided "on time" to enable efficient and effective processes in all sectors of society. Most providers ensure this flexibility by providing excess production capacity in plants with inherent ultralow response times (e.g. gas powered plants). Power from renewable sources usually can't be managed in this way as it has to be produced when e.g. the wind blows or the sun shines. Therefore, the key enablers for the shift to renewable energy sources are efficient means of storing renewable electricity for times when it is not generated and distributing the stored energy effectively over large distances. Hydro powered dams and biogas plants are the only renewable energy producing technologies which are adjustable to fluctuating electricity demands. However, they are not available on a scale needed for many industrial processes.

Three forms of storage are considered in this article: a) batteries, b) physical storage and c) chemical storage. This scheme is not the conventional classification of physics and chemistry. Energy in batteries is stored due to electrochemical processes. Physical storage in this article means gravitational, kinetic and thermal energy. Chemical storage means the synthesis of new compounds where the energy is stored in chemical bonds.

Large scale electrochemical storage in batteries is not yet economic and affordable, although a pilot project in Australia shows promising results in levelling fluctuations and peaks in the electricity demand during the summer months for a community of 30 000 households (DER SPIEGEL 2017). Physical storage using pumped hydro power stations is a mature technology but limited by topographic conditions. Environmental and social problems invoked in building them are paramount and have led to an almost complete construction freeze during the past decades in the western world (Sinn 2017; Bundesministerium der Justiz und für Verbraucherschutz 2020). Chemical storage of electricity is currently intensely studied. It is the preferred storage solution because the energy carrier can be directly retransformed into electricity by fuel cells, internal combustion engines, jet engines etc or used as fuel for mobility.

The focus of the following sections is on the production steps of nitrogen based fuels from renewable electric power, in comparison with carbon bases fuels.

4. INDUSTRIAL SCALE PRODUCTION OF NITROGEN-BASED FUELS

AMMONIA

Ammonia is a poisonous (Table 1), colourless and lighter-than-air gas with a characteristic pungent smell. Its synthesis (artificial nitrogen fixation) from atmospheric nitrogen (N_2) and hydrogen (H_2) was invented before WWI by the German scientists Fritz Haber and Carl Bosch. The so called Haber-Bosch process was implemented at an industrial scale during WWI (Holleman et al. 1985) and provided the German Empire with nitrate (NO_3-) which could not be obtain from the mines in Chile as they were controlled by the Allied forces. Nitrate was needed for the production of explosives like nitroglycerine and dynamite. Since more than 100 years the Haber-Bosch process remains virtually unchanged and this mature technology provides NH_3 at low costs. Nowadays about 70 % of the global ammonia production of about 11,3 * 10^9 t in 2014 is used for fertilizer production (Ritchie and Roser 2020).

The chemical reaction is performed using catalysators at >10 MPa pressure and temperatures between 400 – 500 °C (Holleman et al. 1985).

$$91.8\ \text{kJ} + 3\ H_2 + N_2 \rightleftarrows 2\ NH_3 \qquad (1)$$

Currently about 90% of the hydrogen needed for the process is obtained via synthetic gas by steam gas reformation of fossil resources (typically gas or coal) which releases huge amounts of CO_2 (Holleman et al. 1985).

$$206.2\ \text{kJ} + CH_4 + H_2O \rightleftarrows CO + 3\ H_2 \qquad (2)$$

Hydrogen can also be obtained by the expensive process of electrolysis of water (Holleman et al. 1985) which requires large amounts of electric energy (Lauf 2020a).

$$286.02\ \text{kJ} + H_2O\ (\text{liquid}) \longrightarrow H_2 + \tfrac{1}{2}\ O_2 \qquad (3)$$

Industrial sized Haber-Bosch plants have their own on-site N_2 supply, which is obtained from ambient air (78% N_2, 21% O_2 and other gases). In steam gas reforming plants, the ambient air is used in the clean-up of the synthetic gas (Formula 1) resulting in a pure N_2 gas. In electrolyser plants, pure N_2 gas can be generated either by cryogenic distillation of liquified air or by membrane filtered compressed ambient air. The latter is less expensive and delivers lower, but sufficient, N_2 purity grades. (Holleman et al. 1985; thyssenkrupp Industrial Solutions AG 2020)

HYDRAZINE

Hydrazine is a toxic and carcinogenic oily liquid. Its smell resembles that of NH_3. For safety reasons it is mostly used in the form of hydrazine hydrate which is unstable and even as in aqueous solution dangerous to handle. At industrial scale three pathways for hydrazine (N_2H_4) are in common use which all use NH_3 as base chemical. The most common pathway is the two step Raschig synthesis in which the sodium salt of hypochloric acid (NaClO) is used as oxidant for NH_3 (Holleman et al. 1985).

$$NH_3 + ClO^- \longrightarrow NH_2Cl + OH^- \qquad (4)$$

$$NH_2Cl + NH_3 + OH^- \longrightarrow N_2H_4 + Cl^- + OH^- \qquad (5)$$

AMMONIUM NITRATE

Ammonium nitrate (NH_4NO_3) is globally produced in large quantities as a raw material for most common nitrogen fertilizers. It is produced in two steps: Nitric acid (HNO_3) production from NH_3 and subsequently NH_4NO_3 production from nitric acid. Both steps are often performed at the same industrial site. The production and handling of NH_4NO_3 involves mature technologies.

Ammonia as a gas (g) from the Haber-Bosch process is oxidised with oxygen (g) in the presence of platinum/rhodium catalysts in solid state (s) to nitric acid (HNO_3) which is dissolved in the water formed during the reaction and which results in an aqueous solution (aq). This process is called Ostwald process.

$$2\ NH_3\ (g) + 4\ O_2\ (g) + H_2O\ (l) \longrightarrow 2\ HNO_3\ (aq) + 3\ H_2O\ (g) + 740\ \text{kJ} \qquad (6)$$

Ammonium nitrate is produced by the acid-base reaction of NH_3 in aqueous solution and HNO_3 in aqueous solution. The dissolved salt is then dried and handled in solid state.

$$NH_3 + HNO_3 \longrightarrow NH_4NO_3 \qquad (7)$$

Ammonium nitrate is explosive and therefore widely used in mining and quarrying. As fertilizer it is mixed with lime (calcium carbonate, $CaCO_3$) and oil to prevent its explosive properties (Holleman et al. 1985). However, several catastrophic accidents have occurred ever since the Haber-Bosch- and Ostwald processes were first estab-

Figure 3: Aerial photo of the BASF Oppenau/Ludwigshafen (Germany) production plant after the devastating explosion of 400 tonnes of ammonium sulphate nitrate in 1921 causing 559 fatalities (Abelshauser 2003). The crater in the foreground indicates the location of the storage area where the explosion happened.

lished in Germany on an industrial scale. In 1921 at the BASF Oppenau/Ludwigshafen manufacturing plant in Germany approx. 400 tonnes of stored ammonium sulphate nitrate exploded and killed 559 persons, mostly workers of the plant (Figure 3) (Abelshauser 2003). The most recent explosion occurred in 2020 in Beirut (Lebanon), when approx. 2750 tonnes of stored ammonium nitrate exploded in a warehouse at the harbour (BBC 05.08.2020).

UREA

Pure urea is a non-toxic and non-explosive crystalline solid which easily dissolves in water or alcohols. It is used as fertilizer in agriculture and for the reduction of NOx in power plants and combustion engines. Sold under the trademark "AdBlue" it contains one third of urea mixed with water. Other applications are as a pharmaceutical for the treatment of skin diseases. The production of urea at an industrial scale became possible after the Haber-Bosch process was established. Carl Bosch and Wilhelm Meiser established an urea production site in 1922 (Holleman et al. 1985).

For urea production NH_3 and CO_2 are mixed at temperatures of 170 – 220 °C and at pressures between 12.5 – 25.0 * 10^6 Pa (125 – 220 bar). The reaction is in equilibrium and can be pushed towards the desired urea product by adding NH_3 in excess (Holleman et al. 1985).

$$2\,NH_3 + CO_2 \rightleftarrows H_2NCONH_2 + H_2O \tag{8}$$

5. WASTE GAS PROPERTIES AND APPLICATIONS OF NITROGEN-BASED FUELS

The composition of waste gases are defined by the energy conversion technology used. Waste gases from fuel cells contain only the products of a complete combustion with no side products. In the case of carbon-based fuels these are carbon dioxide (CO_2) and water (H_2O) in the case of ammonia- and nitrate-based fuels these are N_2 and H_2O. The waste gases of urea contain CO_2, N2 and H_2O.

Fossil fuels do contain varying amounts of sulphur. The maximum sulphur concentration of fuels is often regulated by local laws. Sulphur burns into a mixture of sulphur oxides (SOx). In carbon-based fuels volatile organic compounds (VOC's) and particulate matter (PM) are formed during incomplete combustion. Depending on the combustion temperature, the nitrogen (N_2) and oxygen (O_2) from the air form a mixture of nitrogen oxides (NO_x). This process occurs for both, carbon- and nitrogen-based fuels and sparked an intense environmental debate over the future use of diesel engines. In nitrogen based fuels nitrous oxide (N_2O) and NOx may form as products of an incomplete fuel combustion.(Baird 1995; Holleman et al. 1985; Pavlos and Rahat 2020)

AMMONIA

The complete combustion of ammonia under laboratory conditions is shown in Formula 9. No greenhouse gases (CO_2, N_2O, NOx) and no toxic components (NOx, SOx, VOC's and PM) are released to the atmosphere (Holleman et al. 1985).

$$4\,NH_3 + 3\,O_2 \longrightarrow 2\,N_2 + 6\,H_2O + 1\,267\ \text{kJ} \tag{9}$$

A selection of ready to use solutions as well as development projects in early and advanced stages with emphasis on NATO members and partners is given below. Intensive research and development work in this field is also done by the Peoples Republic of China, the Republic of Korea and Japan.

Ammonia in NH_3-fuel cells

Fuel cells provide optimal combustion conditions with no secondary reactions. However, NH_3-fuel cells are not yet a mature technology and research and development efforts are being undertaken on a global scale (Assumpção et al. 2014; Cinti et al. 2016; Holleman et al. 1985).Currently a pilot project which is partly financed by the EU Horizon 2020 SHIPFC program is upscaling a 100 kW NH_3-fuel cell to a 2 000 kW version. It will be installed the long haul vessel "Viking Energy", allowing emission free sailing for 3 000 hours annually. The system should be operative on the vessel by the end of 2023. The NH_3 needed will be produced by electrolysis.(SHIPFC 2020)

Ammonia in H_2-fuel cells

Ammonia is also useable in H_2-fuel cells. The NH_3 is catalytically split into N_2 and H_2. The N_2 is released directly into the air while the H_2 is fed into the fuel cell. No secondary products are formed. Such H_2-fuel cells systems powered by NH_3 can be purchased for private sector applications (GENCELL, Israel). They provide uninterruptable power supply (UPS) for critical infrastructure i. e. hospitals or main power supply for remote communities or remote telecommunications infrastructure(GENCELL WORLDWILD 2020).

Ammonia in internal combustion engines

A Canadian inventor showed the feasibility of diesel engines retrofitted in commercially available cars and trucks to run on pure NH_3, as well as standard carbon-based fuels mixed with NH_3. Prototype cars and trucks are operating (Vezina 2020). Ammonia is also tested under laboratory conditions as sole fuel in internal combustion engines in the shipping sector by the Finnish shipping company Wärtsilä. Results are not available yet, but first tests seem promising (Figure 4 a) (Wärtsilä Helsinki Campus 2020). The German engineering company MAN has already developed a NH_3 driven internal combustion engine and is currently building cooperations with shipyard companies for its implementation (Figure 4 b). (MAN Energy Solutions 2019)

While NH_3 as fuel shows no CO_2, PM, VOC's or SOx emissions, other emissions from unburnt NH_3, N_2O and NOx are significant. Therefore post treatment technologies for cleaning these exhaust gases are needed. Mature technologies like selective catalytic reduction, SCRare available (MAN Energy Solutions 2019; Pavlos and Rahat 2020).

Ammonia and diesel in dual fuel internal combustion engines

In recent years the diesel engine has received a great deal of scrutiny with respect to NOx and PM emissions. Emission treatment systems (i. e. AdBlue injection) are now widely available to

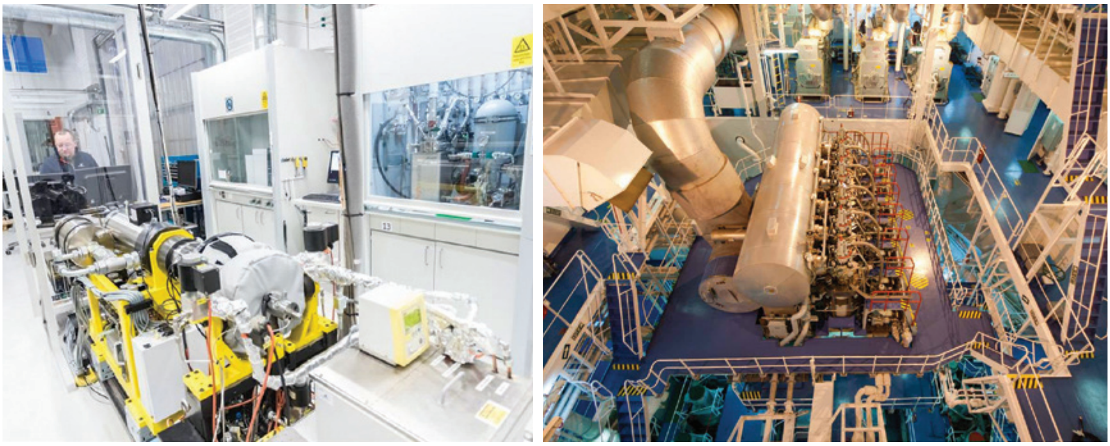


Figure 4: A)Test engine for using NH3 as fuel in an internal combustion engine in a laboratory at the Wärtsilä Helsinki Campus of the Wärtsilä Corporation (Finland) (Wärtsilä Helsinki Campus 2020). B) Engine test room at MAN Energy Solutions (The Maritime Executive 2020)

minimise these emissions and became standard in many truck engines. With respect to the decarbonisation of the economy, dual fuels of NH_3 and lower auto-ignition temperature fuels like diesel fuels are in early testing phases. Preliminary results show that conventional diesel engines can use NH_3/diesel mixtures but produce high amounts of NH_3 and NOx emissions. Adjustments on the injection system may reduce the emissions, but the implementation of an after-treatment system is required to meet emission standards.(Pavlos and Rahat 2020)

Ammonia in new settings

Ammonia as carrier for H_2 is a versatile agent for innovative energy solutions. The decomposition of NH_3 into N_2 and H_2 is a well-known process (see above, NH_3 in H_2 fuel cells). The H_2 gained may be used either in pure H_2 combustion engines or in dual fuel (H_2/diesel) combustion engines (Wang et al. 2013).

HYDRAZINE

As early as in May of 1944 the German Luftwaffe put a rocket engine powered interceptor aircraft into active service. The Messerschmitt Me-163 “Komet” used a volatile fuel mixture of T-Stoff (80% hydrogen peroxide and 20% water) and C-Stoff (hydrazine hydrate, methyl alcohol and water), which provided a maximum thrust of 1 500 kp (3 300 lb.). The airplane set the speed record for its time at 1 170 km/h or 700 mph. A surviving airplane is on display in at the Smithsonian's Boeing Aviation Hangar at the Steven F. Udvar-Hazy Center in Chantilly, VA (USA) (National Air and Space Museum 2021). The first operational military use of hydrazine as rocket propellant was in the German A4 ballistic long range artillery rockets (also known as V-2) which were launched in late 1944. The same A4 type rocket started successfully from the deck of a US aircraft carrier in 1947 initiating the era of seaborne rocket launches. (Zaloga 2003).

Hydrazine (pure or in mixture with e. g. dimethyl hydrazine) is a very commonly used liquid rocket fuel. It ignites as a hypergolic fuel (self-igniting fuel mixture) if brought in contact with an oxidizer like dinitrogen tetroxide ($NO_2 \rightleftarrows N_2O_4$) thus requiring no external ignition devices or chemicals. Hydrazine based liquid fuels are e. g. Aerozin 50 used in the USA built Titan rockets and UH 25 used in the European Ariane rocket. It is estimated that currently about 500 satellites in orbit use hydrazine based small control rockets for position and orbit control. In the NASA Space Shuttles missions, the high toxicity of hydrazine required careful pre-launch and post-touchdown checks for N_2H_4 leaks by teams wearing protective gear and self-contained breathing equipment (Jenkins 2016).

Many naval forces currently use hydrazine in their submarine rescue systems for emergency surfacing by rapid displacement of the ballast tank water upon injection. The RESUS (REscue system for SUbmarineS) uses hydrazine which catalytically decomposes in the ballast tanks and creates buoyance. (ArianeGroup 2020)

NITRATE AND UREA-BASED FUELS

Nitrate-based fuels burn under optimal laboratory conditions without releasing CO_2, VOC, PM or NOx. Urea-based fuels do not release NOx under optimal laboratory conditions but always release CO_2. (Grinberg Dana et al. 2014; Grinberg Dana et al. 2016). Whether this can be also achieved in service engines has not been tested yet. A fuel infrastructure is not existing but ammonium nitrate could be transported as non-toxic substance in solid state or in aqueous solutions. The solid state – when handled properly – is also non-explosive. However, accidents occur on a regular basis (c.f. Fig 3).

6. AMMONIA COMBUSTION IN INTERNAL COMBUSTION ENGINES FROM AN ENGINEERING POINT OF VIEW

If the question is the feasibility of using ammonia in internal combustion engines there is only one simple answer: yes, an internal combustion engine can be driven with either ammonia or its mixtures. This answer remains valid for Compression-Ignition Engines (CIE) and Spark-Ignition Engines (SIE) likewise. A gas turbine can be “fired” with ammonia blends as well. This has been proven several times through basic research, feasibility studies, experiments and prototypes.

Nevertheless, the challenge is not to offer a new propulsion technology to the public or markets, it rather is to suggest a new propulsion technology which can replace the existing technology.

In the following, the focus is more on feasibility and less on economic competition, which is discussed separately. While it is not very difficult to replace passenger cars after a couple of years of service it is more difficult to modify a fleet of hundreds of container freighters where the life cycle of the asset is 25 years and more. The logical solution is a dual use technology that provides a sufficient transition period for the new technology with a minimum of drawbacks on the overall performance. A dual use technology in this context means that either one or the other fuel is used for combustion. No mixtures of fuels are used.

COMPRESSION-IGNITION ENGINES (CIE)

Ammonia is flammable, but the ignition temperature is higher than for petroleum-based fuels. Thus, it is not possible to use ammonia as a sole fuel in a CI-engine due to the high compression ratios needed for ignition/combustion (Pearsall and Garabedian 1967; Brohi 2014). Very high compression ratios as much as 35:1 are needed for ammonia as fuel in CI-engines (Kong and Reiter 2011). Therefore, the use of a pilot fuel is required in order to achieve and maintain a certain ignition temperature and compression ratio. Very common and useful pilot fuels are diesel or Dimethyl Ether (DME) – a synthetic substitute for diesel fuel. Fuels with higher cetane numbers show generally better ignition characteristics with ammonia (Pearsall and Garabedian 1967). An ammonia content up to 95% was feasible with only 5% diesel fuel when used in a John Deere engine. However, the optimal mixture is 40% diesel with 60% ammonia since a diesel amount larger than that would limit the ammonia´s flammability (Reiter and S.-C. Kong 2008). Due to the DME chemical characteristics it can be mixed directly with liquid ammonia and injected into a CI engine. Researchers at the Iowa State University (USA) demonstrated this in 2013 when they successfully used it in an off-the-shelf diesel engine.

The original setup used for the exploration of highly advanced liquid ammonia direct injection was designed very similar to a diesel direct injection system. A fuel combination of ammonia and DME was directly injected into the engine, using

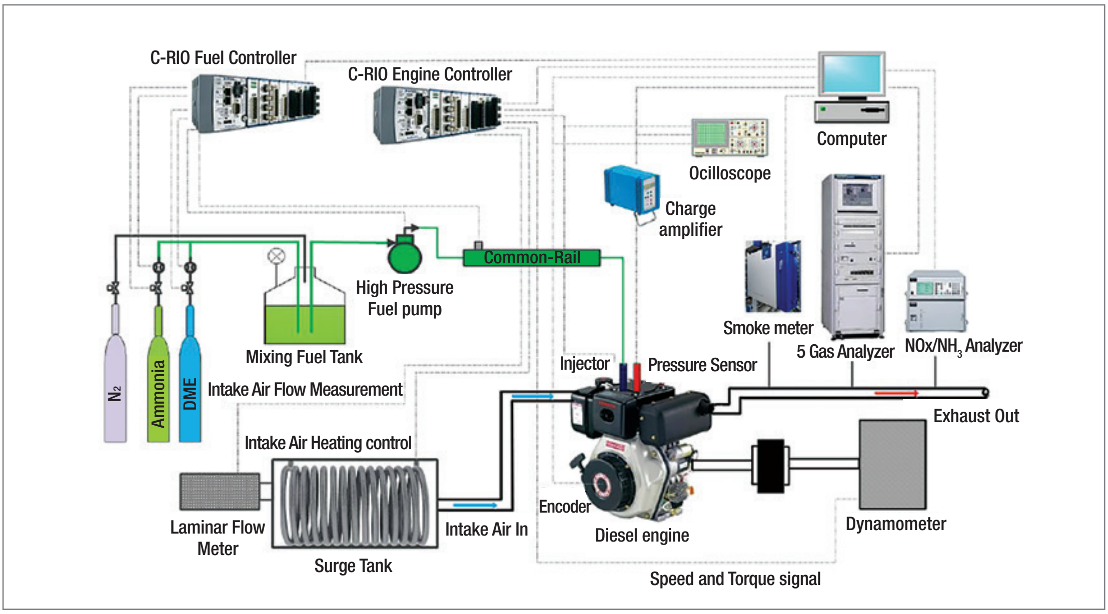


Figure 5: Schematic of an experimental apparatus for highly advanced liquid ammonia direct injection testing (Zacharakis-Jutz 2013).

conventional to slightly early diesel injection timings. However, it was observed that conventional injection timing or even earlier injection timing was insufficient to achieve more than 40% ammonia content in fuel. Thus, in an attempt to increase the operating range and maximum percent of ammonia in the fuel, highly advanced injection timing was used. Such highly advanced injection timing transforms conventional diesel combustion into a homogeneous charge compression ignition (HCCI) combustion. The highly advanced injection allows the heat loss due to the vaporization of the ammonia to be mitigated over a longer time period thus reducing its negative effects (Zacharakis-Jutz 2013).

The technical retrofitting efforts will have to include additional fuel installations (tank, mixing tank, pumps, and valves), inject assembly upgrade, engine management software (compression ignition timings) and extensive exhaust treatment system. The implementation of CI engine technology is feasible and requires moderate retrofitting only. A significant drawback, however, is the unstable performance at alternating loads. The use of pilot fuels for NH_3 engines is a double fuel technology. Therefore, these engines do not avoid CO_2 emissions completely but rather reduce them substantially.

SPARK-IGNITION ENGINES (SIE)

The use of ammonia as sole fuel for SE-engines is possible but requires significant changes to the ignition hardware. For instance, ammonia as sole fuel has been patented by Toyota where they suggest that several plasma jet igniters arranged inside the combustion chamber or plural spark plugs that ignite the ammonia at several points will facilitate ammonia combustion (EP 2378105 A; EP 2 378 094 A1). Those changes are not trivial and would probably require the redesign of the entire cylinder head. As of now, there is no single fuel asset on the market which would be at the serial production level or even close to that. More promising are double-fuel applications. Hydrogen dissociates at 400 °C and can be used as a combustion promoter for ammonia as fuel. A hydrogen content of 3-5% weight basis is the minimum amount of hydrogen required as combustion promoter (Starkman and Samuelsen 1967). For comparison: Using gasoline as a combustion promoter requires a compression ratio of 10:1 for optimal operation with a gasoline content of 30% (Grannell et al. 2008).

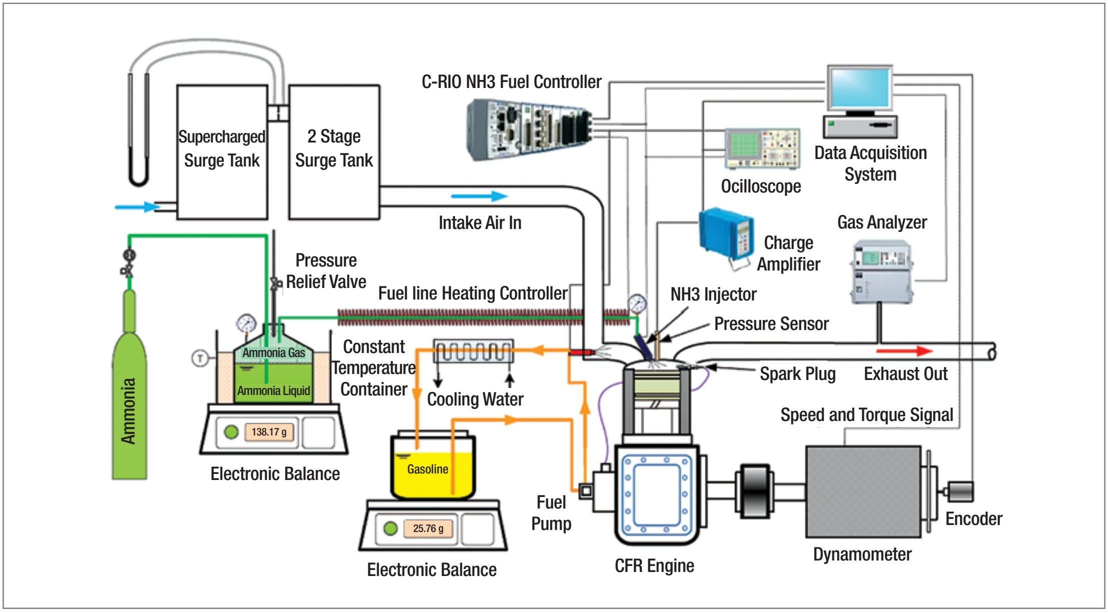


Figure 6: Schematic of an experimental setup for testing gaseous ammonia direct injection (Zacharakis-Jutz 2013).

Figure 7: Ammonia storage facility in Japan (Harding 2020).

Researchers from Iowa State University (USA) conducted a trial with a Cooperative Fuel research (CFR) Engine and had to overcome significant upgrade challenges while adjusting the injection assembly for the gaseous ammonia usage.

Furthermore, they (Zacharakis-Jutz 2013) assessed that the required changes and add-ons for the ammonia injection such as an ammonia vaporizing unit, an ammonia gas preheating and ammonia direct injection system, are not suitable for small-scale engines. With respect to retrofitting efforts, the statements made about CI engines apply as well: The subsystems to be modified are injection assembly, engine management and exhaust after treatment. In the case of SI engines the injection assemblies are more complex and voluminous.

NH_3 AS A FUEL OF THE FUTURE

As of today, it is not easy to say how the future for ammonia as a fuel for combustion engines may look like. From an engineering perspective, the answer is positive. All the challenges and setbacks described above are manageable issues and all these issues can be solved with state-of-the-art technologies. All required technologies are available and the only thing to do is to find applications where the advantages of ammonia combustion dominate over the existing disadvantages.

Based on the research discussed above, it is obvious that when using ammonia a volumetric enlargement of equipment is unavoidable: larger tanks with additional equipment, the usage of pilot fuels and comprehensive exhaust after-treatment subsystems. This automatically reduces the number of possible applications. The large space demand paired with a limited response time to fast changing load demands indicates that two common applications are likely: In stationary power generation facilities and as naval propulsion systems. Both applications could provide a significant contribution towards global GHG emission reduction if implemented at a large scale.

While the usage of ammonia for power generation may sound like fiction for the European audience, it does play an essential role in Asian (Japan, Korea, China) future energy strategies (Figure 7) (Harding 2020). Japan for instance is strongly heading towards ammonia usage in the near future. Green ammonia is supposed to be generated by renewables (though imports are needed) and used in gas turbines for power generation. Japanese industries conducted successful tests and are now able to engage 100% ammonia driven turbines (without any pilot fuels). Within the near future, ammonia will cover at least 1% of the country's electricity demand.

In general, NH_3 represents a very economic storage option for renewable power. It is also much easier to handle than storing electric power in secondary cells or hydrogen. Another promising application is in the maritime sector. The future of naval propulsion systems is on the brink of undergoing significant changes. Political and public demands result in national and international environmental regulations and expect the industry to provide solutions. Ammonia is one of several mature solutions to address these challenges and will compete with LNG, LPG, hydrogen, biofuels and synfuels. From many points of view ammonia is a strong competitor and makes especially sense if being implemented with a strategic approach and not in a case-by-case scenario. Several research activities provided prove of concept for ammonia technologies but did not go beyond laboratory and test environments yet. The next step could be the presentation of a fully functioning device as a minimum viable product being able to serve the market requirements.

The project performed by Wärtsilä Corporation with the support of the Norwegian Government (see chapter 5) might deliver such a device. The project successfully passed the laboratory trials in Finland in 2020 and was then moved to Norway for further development. A maritime vessel with ammonia propulsion is expected to sail in 2023. If successful, that vessel would be much more than just a working prototype. It will be able to provide information on the necessary depth and the volume of retrofitting naval engines for use of ammonia. Besides that, the vessel will allow both, to formulate the ammonia supply infrastructure requirements and to evaluate the economic framework conditions of using ammonia as fuel.

Today, it is difficult to predict whether ammonia will win the competition for the fuel of the future or will end up in scientific libraries as a “missed chance”. What is sure, however, is that if ammonia propulsion will reach the market, it is going to be first in the maritime sector.

7. CONCLUSIONS AND OUTLOOK

Electricity production from renewable sources is well established. From 2018 on it became cheaper on the international energy market than electricity produced by fossil power plants (Kost et al. 2018; The International Renewable Energy Agency 2019). Decarbonising the economy demands both, energy storage options for time periods when renewable energy sources are not available and production of carbon neutral or no-carbon fuels for mobility and e.g. heating. Large scale storage of electricity in batteries is currently not economic. Physical storage in pumped hydropower stations is possible if certain geological and topographic conditions are met, but public acceptance is low. Flywheel storage technology is not yet widely established but appears promising. Chemical energy storage in newly synthesised compounds seems an interesting pathway.

According to the second law of thermodynamics, each conversion is ultimately coupled with losses in free energy (Atkins et al. 1990). Therefore, the number of production steps for fuels should always be kept to a minimum. Hydrogen is the first fuel product of the electrolysis of water and shows the least loss of free energy (Holleman et al. 1985). Hydrogen can be used as a fuel in (a) fuel cells – as currently tested in pilot projects in public transportation buses (Waterstofnet 2020) and trains (VDI 2018), (b) blended into natural gas pipelines for heating purposes (Atlantic Council 2020; Sadler 2016) or (c) used as pure H2 as an chemical basic material (Gasunie Waterstof Services B.V. 2020). In The Netherlands, a consortium of the Gasunie pipeline operator, Groningen harbour and Shell Netherland built a wind farm to power electrolysers for H_2 production. The project was started at the beginning of 2020 (N.V. Nederlandse Gasunie 27.02.2020). In all those technologies mentioned, the final product of the incineration process is H_2O. The disadvantages of using H_2 are its highly inflammable and explosive properties as well as its low energy density as gas. Thus, before transport and storage, a liquefaction or pressurisation is necessary which is expensive and energy consuming (Table 1).

Hydrogen can be further on processed to ammonia which is mostly known as a precursor for nitrogen fertiliser production (nitrates and urea), but is also used as fuel since many decades. NH_3 may also serve as a chemical storage substance for H_2. Catalytic dissociation of ammonia produces N_2 and H_2. The hydrogen can then be used in all applications mentioned in the paragraph above. NH_3 is easier and safer to handle and to transport than H_2. Applications supplying power in remote areas are already established (GENCELL WORLDWILD 2020). Since additional transformation steps cause further energy losses, direct uses of ammonia should be preferred. The most promising short term NH_3 applications are in marine vessels. Both, ammonia driven fuel cells (SHIPFC 2020) and internal combustion engines (Wärtsilä Helsinki Campus 2020) are on the brink of their first real life tests. Both technologies will provide CO_2- and SOx- emission free mobility. However, such internal combustion engines need selective catalytic reduction (SCR) treatment systems) because the NH_3, N_2O and NOx emissions are high. These treatment systems are mature and well established technologies in ships, as they are already used with carbon based fuels for reducing NOx emissions (MAN Energy Solutions 2019). These combined technologies would have a huge positive impact on decreasing the pollution with SOx, PM and heavy metals in harbours and coastal regions since the fuels currently used in most large ships are waste products from the crude oil refining processes and are highly enriched in substances hazardous to health. The concentrations permitted for these hazardous substances in shipping fuels are currently much higher than for land based mobility fuels (Umweltbundesamt - UBA) - but this may change soon.

Zhao et.al. (2019) estimated the costs for different non-fossil fuels from source-to tank in cars. He compared several hydrogen-, nitrogen and carbon-based fuels produced from renewable electricity, H_2 from electrolysis, methanol and Fischer-Tropsch syntheses. On the source to tank basis, NH_3 as a fuel is superior to H_2 and methanol. The efficiency of the NH_3 fuel cells, however, has to be improved to sustain the cost advantage of NH_3.(Zhao et al. 2019)

Ammonia is toxic but self-alarming to humans due to its pungent smell and it is neither inflammable nor explosive. Ammonia is widely used as a cooling agent in the food industry, in sporting arenas and in emission treatment systems in ships. NH_3 production, transportation and distribution by ships and trucks is common practise. Safety routines are well established during maintenance and repair works (Bundesministerium für Umwelt, Naturschutz und nukleare Sicherheit 2018; MAN Energy Solutions 2019). The practical obstacles for large scale NH_3 usage seem smaller than for H_2 usage.

Ammonia is one of the most commonly produced commodities on a global scale. In 2014 approx. 113 x 10^6 tonnes of NH3 were produced globally. Production, transportation and distribution capacities are available on all continents (Figure 8) (Ritchie and Roser 2020). Countries with large agricultural and industrial sectors show high levels of production.

Using NH_3 as fuel would require a significant upscal-

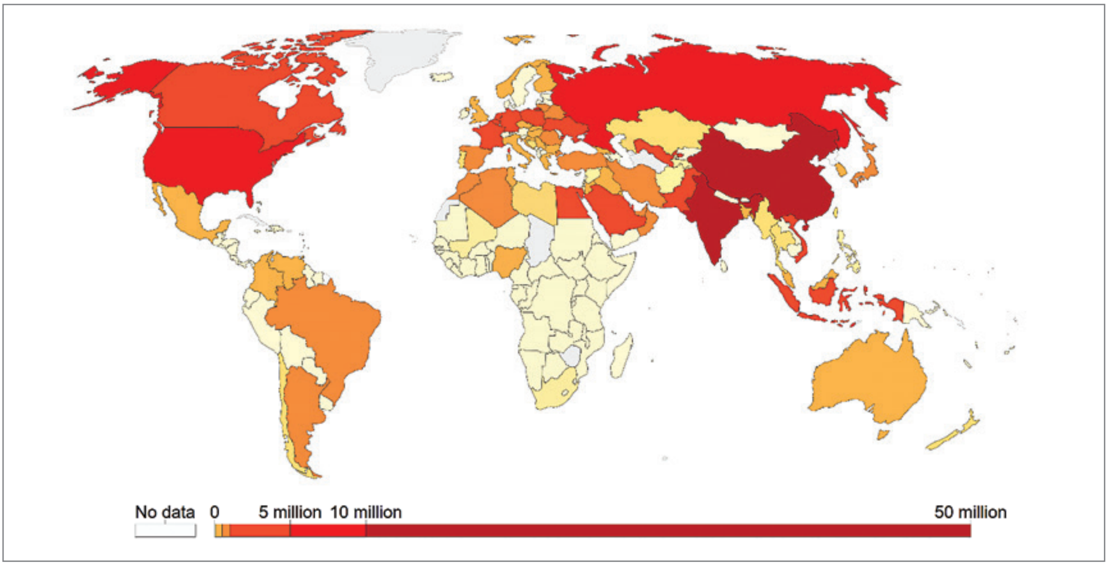
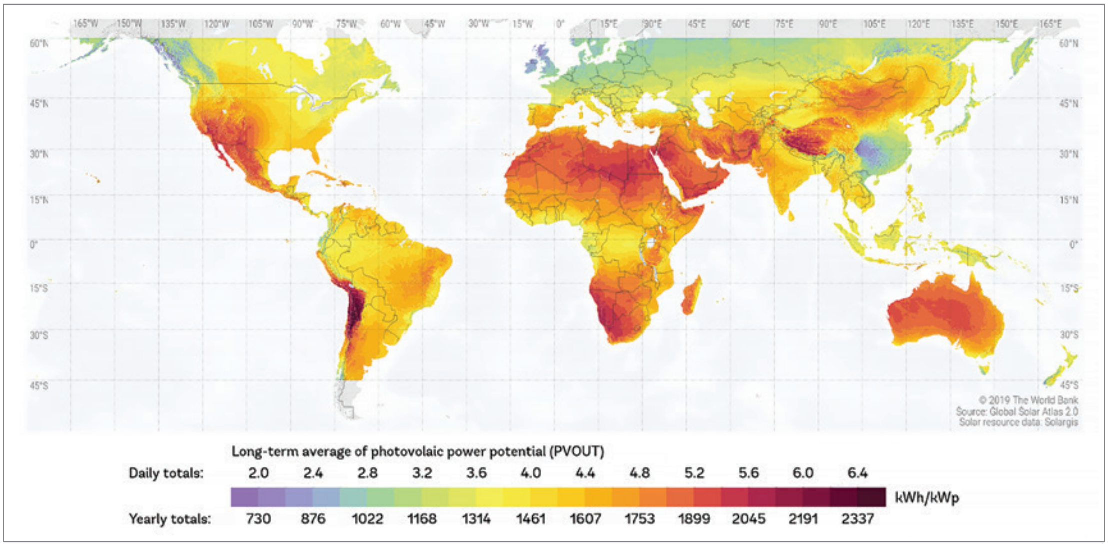


Figure 8: Global nitrogen fertilizer production in 2014. Global production in 2014 was 113.31 * 10^6 tonnes (Ritchie and Roser 2020).



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Source: Global Solar Atlas 2.0
Solar resource data: Solargis

Figure 9: Global map of photovoltaic power potential(THE WORLD BANK, 1818 H Street, NW Washington, DC 20433 USA 2020).

ing of the production capacities. Under the given conditions this seems a manageable task and various CO_2-free or low CO_2- routes are thinkable. On a larger scale, additional plants for ammonia production would be needed. If powered with renewable electricity for the electrolysis of water, the overall CO_2 emission could be substantially reduced. Many of the countries with a large NH_3 production output are located in the global Sunbelt (Figure 9) between 35th degrees of northern and southern latitude, where global yearly irradiation is the highest. These regions are very well suited for solar electricity production. The German plant manufacturer Thyssen-Krupp already offers small scale Ammonia production plants with H_2 obtained by electrolysis of water with electricity gained from renewable sources (thyssenkrupp Industrial Solutions AG 2020). Upscaling of these plants is surely possible. MAN Energy Solutions (Denmark), the producer of two-stroke NH_3 internal combustion engines for ships, proposes the production of NH_3 fuel in plants in the Australian deserts, powered by electricity from solar parks (MAN Energy Solutions 2019).

Hydrazine is highly toxic and applications for the general public are unlikely. It is currently used as a fuel in space travel and military applications only. Nitrate and urea based fuels are in early laboratory testing phases. Whether these fuel-technologies will reach marketability is not yet conceivable.

In the future we will surely experience intensified research and development for using fuels on a nitrogen basis. The prime advantages of nitrogen based fuels are both, the intrinsic lack of carbon – with exception of urea - as well as the technological maturity of their production, transport and storage. As the various propulsion engine and combustion technologies reach technical maturity, nitrogen based fuels will certainly become attractive fuels for a decarbonizing world.

For the next years it appears to be a prudent diversification strategy for NATO nations and partners to establish a balanced strategy of investments in Power to Liquid technologies at home and in politically stable regions and to include nitrogen fuel research in their portfolio. This will ensure own technological competence and leadership for promising technologies.

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The hidden costs of solar photovoltaic power

by **Thomas A. Troszak**

INTRODUCTION

Despite many optimistic predictions, solar photovoltaic (solar PV) power still represents only a small fraction of the global electricity supply as of 2020. More than two decades of near-exponential growth and investment in solar PV development have taken place, yet the amount of fossil fuels being burned for power is still increasing. [1] This apparent paradox has been attributed to a variety of economic or political issues, but a critically important factor may be missing from the discussion.

All modern technologies are dependent upon the supply of fossil fuels and fossil energy that made them possible. Similarly, every step in the production of solar PV requires an input of fossil fuels - as raw materials, as carbon reductants for silicon smelting, for process heat and power, for transportation, and for balance of system components. Regardless of any intentions, no quantity of banknotes or any number of mandates can yield a single watt of power unless a significant expenditure of raw materials and fossil energy takes place as well.

Therefore, the author of this article invites all interested parties including environmentalists, consumers and policy makers to consider the wider environmental impact, and the great debt of resources that actually must be paid before a PV system can be installed at any utility, workplace, or home. If we wish to recognize the hidden costs of this highly engineered industrial technology, we must first examine the non-renewable reality of the PV manufacturing process itself. To be even more realistic, we must also consider the additional consequences resulting from the fossil-fuel-powered global supply chains that are necessary for the mining, production, and implementation of PV power systems.

Moreover, as the power output of solar PV is intermittent, highly variable, and largely unpredictable, it is not equivalent to conventional power in availability, capacity, or dependability. As a result, a number of other fossil-based industrial technologies must be deployed alongside PV in order that it may be integrated into existing power grids at all. When viewed on this broader scale, the development of the solar PV industry may be held responsible for a number of other, indirect expenditures of fossil fuels that have not been fully accounted for in previous evaluations of solar PV alone.

This article introduces readers to the many types of fossil fuels that are used in PV production, and notes some of the other fossil energy inputs that

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[1] "...despite the huge policy push encouraging a switch away from coal and the rapid expansion of renewable energy in recent years, there has been no improvement in the mix of fuels feeding the global power sector over the past 20 years. Astonishingly, the share of coal in 2017 was exactly the same as in 1998. The share of non-fossil fuels was actually lower, as growth in renewables has failed to compensate for the decline in nuclear energy." Statistical Review of World Energy, 67th Edition, June 2018 https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2018-full-report.pdf

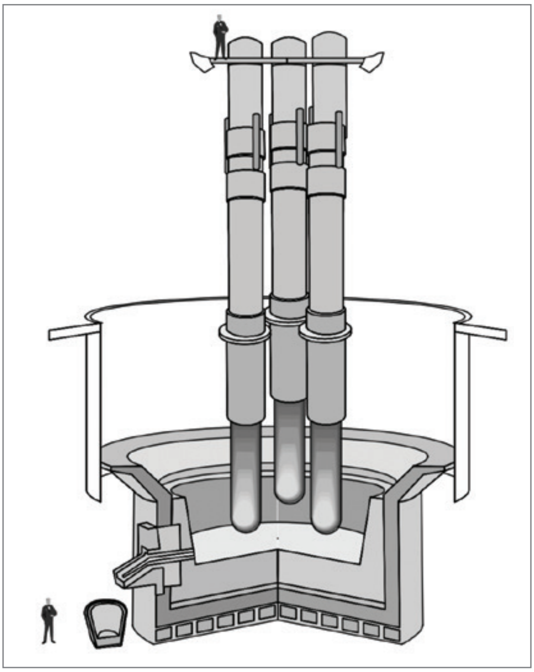

Figure 1. Diagram of a silicon smelter showing the three giant carbon electrodes that provide arc temperatures > 3,000ºF for smelting quartz into "metallurgical grade" silicon (mg-Si) using carbon as a reductant. ©2003 (John Wiley and Sons, Ltd.)

are necessary before the delivery of a solar PV array can take place. We also highlight several environmental impacts and other issues that may have been excluded from previous analyses.

1. AN OVERVIEW OF SILICON-BASED PV MANUFACTURING (AS OF 2020):

Most commercial solar PV modules use photovoltaic cells (solar cells) made from highly purified silicon (Si). [1] Since the early 1900s, semi-metallic silicon has been reduced from quartz by the use of fossil carbon in submerged-arc furnaces powered by megawatts of electricity. [2][3][4][5][6] See Figure 1

As we can see by this emissions permit from the New York State Department of Environmental Conservation (valid through the year 2021) - virtually nothing about the silicon smelting process has changed in more than a century:

"Globe Metallurgical produces high purity silicon metal...Reactants consisting of coal, charcoal, petroleum coke, or other forms of coke, wood chips, and quartz are mixed and added at the top of each furnace...The submerged electric arc process is a reduction smelting operation...At high temperatures in the reaction zone, the carbon sources react with silicon dioxide and oxygen to form carbon monoxide and reduce the ore to the base metal silicon... The facility is a major source of emissions of sulfur dioxide, carbon monoxide, hydrogen chloride and nitrogen oxides" [2]

The subsequent production of polysilicon, crystalline silicon, silicon wafers, and the assembly of PV modules also require a continuous supply of electrical power, fossil fuels, and dozens of other non-renewable mineral resources. [1-24] However, even if 100% carbon free energy were available for all these processes, the ongoing production of PV is still heavily dependent on a supply of elemental carbon, which comes primarily from fossil fuels. [1-19]

2. WHY IS CARBON NEEDED FOR SOLAR PV PRODUCTION?

Elemental silicon (Si) cannot be found by itself anywhere in nature. It must be extracted from the mineral quartz (SiO_2) using carbon (C) and heat (from an electric arc) in the "carbothermic" (carbon + heat) reduction process called smelting ($Si0_2 + 2C = Si + 2CO$).

Several commercially available solid fuels are typically used as carbon reductant sources in silicon smelting. The smelting plant requires ~20 MWh of electricity and releases up to 5 - 6 tons (t) of CO_2 (and CO) for every ton of metallurgical grade (mg-Si) silicon that is smelted from ore. [6] Thus, the first step of commercial solar PV production is gathering, transporting, and burning millions of tons of coal, coke and petroleum coke - along with charcoal and wood chips made from hardwood trees to smelt >97% pure mg-Si from quartz ore (silica rocks). [21-25]

Even more fossil fuels are burned later, to generate heat and electricity for the subsequent polysilicon, ingot, wafer, cell, and module production steps. As a result of all these processes, the solar PV industry generates megatons of CO and CO_2 annually. [1-20] However, as shown in Figure 3, some of the most authoritative and frequently-

Figure 2. In the silicon smelter, three 1-meter diameter carbon electrodes penetrate the surface of the charge of coal, coke, woodchips, and quartz rock. Each electrode is 10-20 meters tall.

cited descriptions of solar module production omit the raw materials, fossil fuels, and burnt trees from their PV supply chain. This obscures the inherent necessity of fossil fuels as raw materials for PV manufacturing, and sidesteps the potential for social or political conflict that could result from disclosing the significant amount of deforestation that is necessary for solar PV production to take place. [21-25]

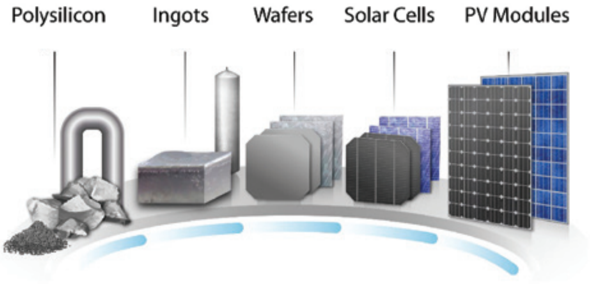

Figure 3. This NREL supply chain schematic omits all of the coal, trees, quartz, and other raw materials needed for smelting metallurgical silicon from ore. (Source: National Renewable Energy Laboratory, 2018) [44]

3. RAW MATERIALS NEEDED FOR METALLURGICAL-GRADE SILICON

Raw materials for one ton (t) MG-Si (Kato, et. al) [13]
Quartz 2.4 t (ton)
Coal 550 kg
Oil coke 200 kg
Charcoal 600 kg
Wood chip 300 kg.

Raw materials for one ton (t) MG-Si (Globe) [1]
Quartz 2.8 t
Coal 1.4 t
Wood chips 2.4 t.

For 110,000 tpy (tons per year) MG-Si (Thorsil) [6]
Quartz 310,000 tpy
Coal, coke and anodes 195,000 tpy
Wood 185,000 tpy
Total 380,000 tpy.

When estimating the CO_2 emissions from the silicon smelting process, several previous authors "by joint agreement"[22] excluded the CO_2 emissions from all non-fossil carbon sources (charcoal, wood chips), from power generation, and the transportation of raw material. [22] This illustrates an important issue. The validity of any estimate depends on where the study boundaries are drawn. If the range of inputs is too narrow, the overall environmental impact of a real-world industry may not be adequately documented. Over time, the assumptions inherent in one study may propagate into all the subsequent literature, resulting in conclusions that are incomplete, and therefore unrealistic.

4. SOURCES OF CARBON FOR SOLAR SILICON SMELTING

Coal - Is a dense, rock-like fuel extracted from mines. The low ash coal used directly in silicon smelters is mostly the "Blue Gem" from Cerrajón, Columbia, Kentucky, USA, or Venezuela. It must be washed before smelter use; the byproduct is then sold as fuel. [6][8][10][15-18] See Figure 4.

Metallurgical Coke (metcoke) - is a tough, cinder-like solid fuel made by coking previously-mined coal in large slot ovens - to drive out most of the volatile tars, etc. to the atmosphere as smoke, flame, carbon monoxide, carbon dioxide, sulfur dioxide, other gasses, and water vapor. The coking process is nearly identical to the process used for making charcoal from wood (see wood charcoal production). Restricting the air supply to a large mass of burning coal allows about 40% of the coal to burn off - leaving behind a solid residue (coke) with a higher carbon content per ton that the original coal. It takes about 1.3-1.6 t of coal to make a ton of metcoke. Metcoke looks like porous, silvery grey coal. [19][20[21]

Petroleum Coke (Petcoke) - is a solid fuel in the form of dense, pellet-like granules, which are a carbon-rich byproduct of crude oil refineries. Millions of tons of petcoke are also made directly from raw bitumen (tar). Due to its low market price and high carbon content, petcoke made in American refineries from "Canadian Tar Sands" has already been exported from the U.S. to silicon manufacturers in China by the millions of tons. In addition, the full extent of CO_2 emissions resulting from petcoke is not well documented. [23] “Because it is considered a refinery byproduct, petcoke emissions are not included in most assessments of the climate impact of tar sands.” [22]

Figure 4 The Cerrejón open-pit mine in Columbia supplies “Blue Gem” coal, a primary source of carbon for solar silicon smelters around the world.

Figure 5. Beehive charcoal kilns in Brazil. Many trees must be burned, as the traditional process requires up to ten tons of hardwood to make one ton of wood charcoal.

Wood Charcoal - Many hardwood trees must be burned to make wood charcoal. In the traditional process, wood is stacked into "beehive ovens," ignited, then mostly smothered with earth or clay to prevent the wood from burning completely to ash. See Figure 5.

By weight, up to ~90% of the wood harvested is lost to the atmosphere as CO, CO_2, smoke, and heat, so as much as ten tons of raw wood must be burned to produce a single ton of wood charcoal. [28][33] A few silicon producers claim to use dedicated "charcoal plantations," but such plantations are limited in scope, so they can only supply a fraction of the overall demand for carbon in silicon production. [29-31]

The rest of the carbon supply for silicon production has to come from imported coal or coke, or the cutting and burning of "virgin" rainforest. [30][35][36] In Brazil, it is estimated that as of 2015, more than a third of the country's charcoal supply is still produced illegally from protected species. [30] Brazil is also a charcoal exporter to silicon producers in several other countries, including the United States. [30-34] Silicon smelters around the world use charcoal from many sources, so solar silicon may be smelted with charcoal made directly from rainforest trees that were not grown on plantations. [30][35][36]

Hardwood Chips (also called Metchips) - Matchbox-sized fragments of shredded hardwood must be mixed into the silicon smelter pot for several reasons - to allow the reactive gasses to circulate, so the liquid silicon that forms can settle to the bottom for tapping, and to allow the resulting CO (and other gasses) to escape the smelter charge safely. [24] No silicon smelter can function without this moist, low-impurity bulking agent added to the charge as up to ~60% of the mixture. Thus, perpetual deforestation is an inherent component of solar PV production. [1][10][11][24-32]

As these biological CO_2 emissions have been omitted from the CO_2 balance of solar PV production, their negative environmental effects may have not been adequately quantified. [27] However, the negative effects of deforestation can extend far beyond the mere emissions of CO_2 to include land erosion, topsoil depletion, natural habitat destruction, possible species extinction, and many other issues. [34]

5. SOURCES OF SILICON ORE (SIO_2) FOR SOLAR SILICON SMELTING AND CRUCIBLE PRODUCTION.

Quartz (silica, silicon dioxide, SiO_2) - even if it were sufficiently pure, ordinary silica sand won't work in any silicon smelter because the particle size is much too fine. Instead, specially selected deposits of high-purity quartz (HPQ) are mined and graded into "lumpy" (fist-sized) gravel for solar silicon smelting applications. Worldwide, solar and electronic grade deposits of HPQ are somewhat scarce, and highly valued. [37][38][39]

Another issue for PV is the requirement for even higher grades of *ultra* high-purity quartz with contamination levels lower than 0.003% (99.998% SiO_2). These grades are necessary for the production of the high temperature quartz crucibles consumed in Czochralski (Cz) process single-crystal silicon ingot pullers, which are also used to produce electronic grade wafers for integrated circuit (IC) production.

See section 7. Crystal growing (ingot production). Virtually the entire global supply of crucible grade quartz is sourced from a single mining region in Spruce Pine, North Carolina, USA. [38] Which means that virtually the entire global production of all silicon-based semiconductors, computers, electronics, and solar PV is also dependent on the annual productivity of a single mineral deposit in the Earth's crust. This is a topic of critical strategic importance, which has not been previously addressed in PV literature. Other (very minor) sources of crucible-grade quartz exist, but it is uncertain if their production could be scaled up to provide more than a few percent of the current global demand for Cz crucibles, or how long the supply would last. [36-39]

6. POLYSILICON PRODUCTION.

Metallurgical grade silicon (mg-Si) from the smelter is only about 97-99% pure, so it must undergo two more energy-intensive purification steps, before it can be made into wafers for solar cells (or electronics). First, the Siemens Process converts metallurgical silicon from the smelter into polycrystalline silicon (called polysilicon) by means of a high-temperature Continuous Vapor Deposition (CVD) method. This works a bit like growing rock candy on a string submerged in a jar of sugar water. But in this case, the polysilicon crystals are grown on thin, hyper-pure silicon 'strings' called filaments – which are mounted vertically inside a pressurized-gas filled bell-jar type reactor. As a mixture of silicon gas (made from the mg-Si) and hydrogen gas is pumped through the reactor vessel, some of the silicon gas molecules cling to the electrically pre-heated silicon filaments, which slowly fatten into "rods" of 99.9999% pure (or better) polysilicon. When pre-heated to around 1100°C, the silicon filaments/rods growing beneath the reactor cover can catch about 20% of the silicon atoms that pass through the reactor in gaseous form. [1] See figure 5.

Figure 5. Polysilicon rods grown in a CVD reactor. In this photo the CVD process is complete, the "bell jar" reactor dome has been removed, and the rods are ready for harvest.

Each batch of polysilicon rods takes several days to grow, and a continuous, 24/7 supply of electricity to each reactor is essential to prevent a costly run abort. So all polysilicon refineries depend on highly reliable conventional power plants, and usually have two separate, incoming high-voltage supply feeds. [41][42] A polysilicon plant consumes anywhere from ~1.6 - 6t of mg-Si and requires at least 175 MWh (or more) of additional electricity per ton of polysilicon produced. [15][42] After the rods are removed from the reactor, they are sawed into sections - or broken into chunks by hand (or by thermal fracturing) in a clean room environment. A single polysilicon plant (20,000t/year capacity) can draw 400 megawatts of electricity, enough power for about 300,000 homes. [42]

7. CRYSTAL GROWING (INGOT PRODUCTION)

For making single-crystal solar cells (also called mono PV) the PV industry uses the Czochralski (Cz) process to further purify the polysilicon, and align the silicon molecules into a single-crystal form with specific semiconductor properties. [43][46]

First, polysilicon chunks are melted (by induction) within a rotating, ultra-pure quartz crucible, and surrounded by an inert gas atmosphere (usually argon). Rare earth doping metals are added to the melt in minute quantities to provide the specific semiconductor properties desired in the finished cells. Then a small seed crystal of pure silicon is lowered into the molten polysilicon. As the crucible slowly turns, a new crystal of silicon begins to form on the tip of the seed. As the new, single crystal is slowly drawn from the liquid, it continues to grow into a tall cylindrical ingot (or "boule") - leaving most of the non-silicon impurities behind in the 5-10% of pot scrap remaining in the bottom of the crucible. This process requires several days, and uninterrupted power. [40] After slow cooling, the ingot's unusable crown and tail are cut off (about 10%), the cylindrical center section is then ground down, the four “chords” (long sides) are sawn off (about 25%) - leaving a nearly rectangular “brick” so the solar wafers will be almost square after slicing. [44][45] See figure 6

For multi-crystalline cells (also called multi PV), chunk polysilicon is melted in rectangular quartz molds under inert gas, and then cooled very carefully to encourage "directional solidification" into a rectangular ingot of multi-crystalline silicon. The quartz mold is then broken away, and the rectangular ingot is trimmed all over to remove the unusable external portions. Then the remaining core is sliced vertically into a cluster of ‘bricks.’ [44]

8. WAFER SAWING.

Then, like a loaf of bread, the crystalline silicon bricks are sliced with wire saws into thin wafers, which will later be processed into cells. About half of each brick is lost as sawdust in the wafer slicing process, and this can't be recovered. Therefore, after all of the energy and materials that have gone into making each brick, much of the incoming polysilicon does not ever become finished wafers. See Figure 6

Some of the heads, tails, chords, and trimmings may be etched in acid to remove contamination and re-melted again later if the purity of the scrap is sufficient to justify the expense - otherwise they are discarded as waste. Depending on the particular combination of processes used,

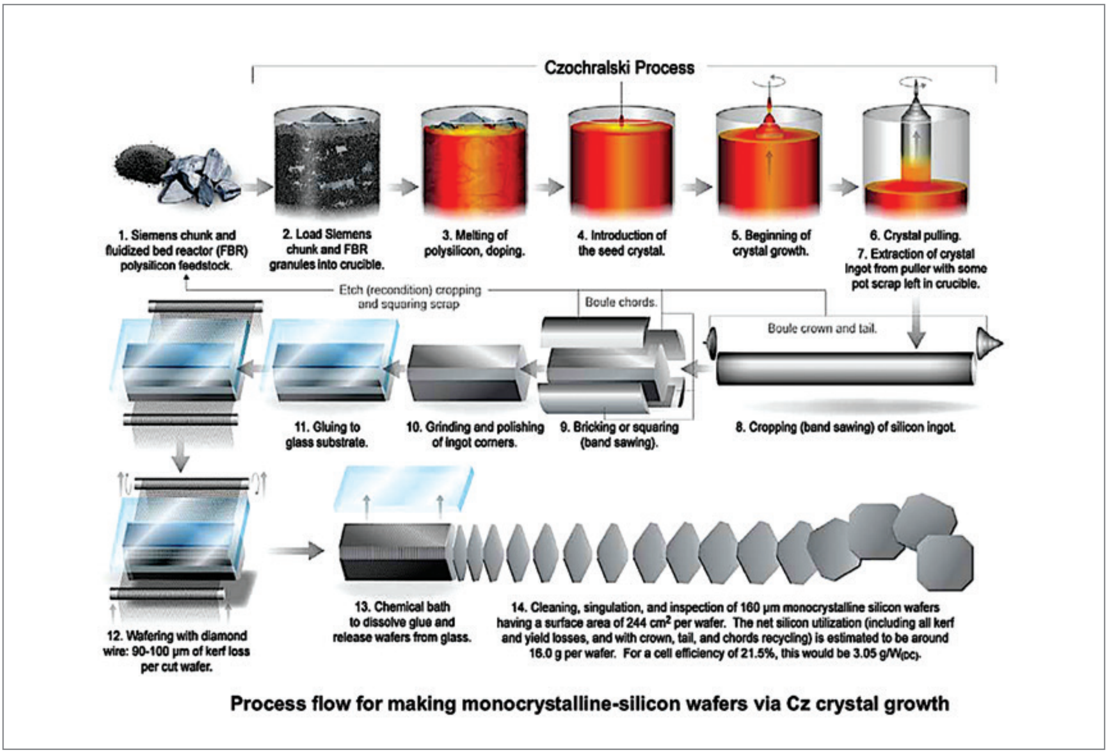

Figure 6. Cz Ingot-wafer process. Source NREL 2018 [45]

the ingot/wafer process can require an additional ~350 MWh of energy per MWp of modules. [45]

9. CELL AND MODULE PRODUCTION.

Once the wafers are sliced, they are made into photovoltaic "cells" by adding layers of other materials and components in a series of additional production steps. The amount of power needed for these processes varies depending on the type of cell. Then the finished cells are wired into strings of cells, and permanently encapsulated into weatherproof modules.

Beside silicon wafers, solar PV modules also require many other energy-intensive materials: glass, aluminum for the structural frame (if used), copper, silver, plastic - along with rare earth metals, acids, gases, and dozens of other materials that are needed for processing the polysilicon into cells and modules. [16] Additional electricity is needed to power the module assembly process, about 113 MWh/MWp of modules assembled. [45] A supply of natural gas is used to provide heat in the cell and module processes. The amount of additional primary energy needed for process heat is roughly equal to the primary energy needed for electricity. [45]

10. BALANCE OF SYSTEM COMPONENTS.

Once the modules are assembled and delivered, a commercial PV array usually needs some empty land, or a rooftop, steel or aluminum support framing and concrete foundations to position it securely toward the sun, and external wiring to connect the array to the existing power grid (through DC/AC inverters and transformers) - or directly to battery banks. Of course, it takes a lot of fossil energy and non-renewable resources to make steel, aluminum, concrete, DC/AC inverters, copper wiring, and all of these other "balance of system" components. In many cases, these can require as much (or more) "up-front" resources and energy to make as the modules. [40]

11. TRANSPORTATION.

Throughout the solar PV manufacturing process all of the raw materials, intermediate stages, and finished products must be shipped to and from more than a dozen countries around the world in large barges, container ships, trains, or trucks - all powered by non-renewable oil. [51]

12. POWER FOR PV PRODUCTION.

Worldwide, only a few silicon smelters, like those in Norway, are powered primarily by hydro-electricity. [6] In fact, most new PV plants are connected to dedicated coal-fired power plants.

From a 2020 polysilicon market analysis: "*...the electricity for the new factories comes from coal-fired power plants. The polysilicon produced – and the solar panels made out of it – thus leave a large carbon footprint.*" [3]

From a July 2020 industry report: "*...a new polysilicon plant...in northwestern China...started production in October 2018...By obtaining electricity from a nearby coal-fired power plant at a very low tariff...*" [4]

From a 2017 investor's guide: "*...Photovoltaics is one of the rapidly growing renewable energy sources in the world...ironically...all this is driven by the low LCOE of coal-fired plants in China.*" [5]

Or as a 2018 proposal for PV manufacturing in India states: "*...Government could also provide a dedicated power plant facility to supply reliable and low-tariff power similar to China...A dedicated coal power plant is established in the vicinity of [the new] polysilicon plant*" [6]

From the Poly Plant Project: "*...Upon completion of the polysilicon plant, Shansheng New Energy will be a vertically integrated PV company with its own coal and quartz mines, coal-fired power generation plant...*" [11]

As the majority of smelters, polysilicon refineries, ingot growers, cell and module factories are running on grids powered mostly by fossil fuels, the additional quantity of coal, coke, or gas that is being burned to deliver power 24/7 to the PV factories may be greater than the amount needed as the carbon reductant used in smelting silicon from ore. So to be realistic, all of this must also be added to the "fossil fuel bill" for PV production and deployment. [40]

13. PV MANUFACTURING INFRASTRUCTURE

A considerable up-front investment of fossil fuels and other nonrenewable mineral resources are required to construct and maintain the PV production facilities themselves. [40] Additional fossil resources must also be consumed on an ongoing basis for repair, maintenance, and eventual replacement of all the production equipment over time. [47] However, all of this embodied energy and all of those fossil fuels have been excluded from the previous "life cycle analysis" (LCA) and 'energy payback time' (EPBT) energy analysis of solar PV products by definition. [48] Therefore, these hidden costs of fossil resource depletion, fossil energy and emissions, and the environmental pollution resulting from the growth in PV manufacturing infrastructure have not even been considered in most previous analyses.

14. GRID INTEGRATION OF PV POWER SYSTEMS

PV arrays can only produce power during daytime hours, and in clear weather. So, if PV is added to an existing power grid, 100% of conventional generation capacity must still be maintained for use at night, and during long periods of poor weather. In addition, the introduction of intermittent power sources into existing grids generally increases the cycling costs and CO_2 emissions of existing fossil thermal generation plants. The inherent variability of PV output due to daily weather changes may also require that "quick start" or "spinning reserve" gas turbines be added to the grid in equal measure with PV as backup to prevent grid collapse. [52]

In addition, if any power from PV arrays is desired after sunset, some means of converting PV electricity into some other form of energy for later use must be provided. At present, Li batteries are the most common form of energy "storage". However, previous studies have shown that the energy-intensive manufacture of Li batteries adds an excessive burden of embodied energy onto PV systems that are already operating at a net energy deficit. Thus, when Li batteries are added to any PV power system, the overall net energy return of the system becomes negative, as *"PV technologies [CIGS and sc-Si] cannot 'afford' any storage while still supplying an energy surplus to society… since they are already operating at a deficit."* [47]

Further, actual tests of three operational grid-scale EES storage systems were conducted, including the largest utility-scale Li battery installation in Europe as of 2015. The study found that *"The round trip efficiencies for the [Li-ion] EES systems have been calculated…between 41% and 69% where parasitic loads are included,"* Therefore on average, nearly half of the electricity supplied to the three grid-scale Li batteries was not returned to the grid as usable power. [50]

15. DISPOSAL OF PV POWER SYSTEMS AT THE END OF SERVICE LIFE

Due to the many complex and irreversible material transformations taking place during production, the expired components of PV power systems cannot be wholly recycled. While commercial-scale reclamation streams may exist for the external glass, aluminum, copper or steel components, millions of fully encapsulated PV cell assemblies, DC/AC inverters, charge controllers, etc., constitute an ever-growing accumulation of non-recyclable "electronic waste" at the end of their typical service life:

"Lu Fang, secretary general of the photovoltaics decision in the China Renewable Energy Society, wrote...By 2050 these waste [PV] panels would add up to 20 million tonnes, or 2,000 times the weight of the Eiffel Tower"

"Tian Min, general manager of Nanjing Fangrun Materials, a recycling company in Jiangsu province that collects retired solar panels, said the solar power industry was a ticking time bomb. "It will explode with full force in two or three decades and wreck the environment, if the estimate is correct" [53]

16. CONCLUSIONS

Other than the continual deforestation necessary to provide the wood chips and charcoal used in PV manufacturing, no part of any PV power systems are self-reproducing in nature. Thus, the public perception of PV power as a source of “renewable energy” must be re-examined for validity. Like any other modern technology, every aspect of the development of solar PV requires an input of fossil fuels and power. Thus, government or institutional policies promoting PV power as a "carbon-free" substitute for fossil fuels must be reconsidered. Overall, the merit of further fossil-fuel expenditures into utility-scale, grid-connected PV systems can certainly be called into question. [40][47][50]

When all of the hidden costs of solar PV are taken into consideration, it becomes more evident that the technology that was intended to reduce CO_2 emissions may turn out to be less beneficial for the environment as a whole than is commonly assumed. [19][40][47] It is certain that from this point onward, such intentions need to be more fully thought out, the previous assumptions tested, the potential consequences evaluated, and before determining the way ahead.

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What to expect from an energy transition for Australia's energy security and its Defence Force?

by **Camille Fourmeau, Nicolas Mazzucchi and Dr. Reiner Zimmermann**

ABSTRACT

Now that most countries are taking energy transition more seriously, Defence forces must also adapt their energy use accordingly. In Australia, where the energy future is still undefined while moving constantly between clean energy initiatives and renewed interest in coal, the energy transition remains to be developed. Australia will gain in developing an energy plan which will pave the way to energy transition considering the forecasted decrease of demand for coal in favour of renewable energy sources. This will imply for Australia the necessity to regain control of strategic elements of its energy network and production. It also means to keep the upper hand in energy exports and to maintain full control on its energy transition process. In prevision, the Australian Defence Forces are already preparing themselves to reduce their energy use and to design new equipment powered with a greater share of renewable energy.

INTRODUCTION

In the 2021 Climate Change Performance Index[1] [13] [16], looking at national climate action across the categories of emissions, renewable energy, energy use and policy, Australia ranked 54th among 61 countries evaluated. The country received *extremely low* ratings in the Energy Use category and ranked at the bottom of low performers in both, the GHG Emissions and the Renewable Energy categories. Concerning climate policy, Australia is placed among the worst with unclear and environmentally unfriendly measures. Yet, Australia with its energy production system being the most polluting sector of the country, will have no choice but to walk the path of energy transition. The country is still powered principally by an aging coal industry and is making slow progress in clean energy efforts despite its high potential. Moreover, with no true will to begin an energy transition, Australia faces an uncertain energy future. This lack of planning is fragilizing the energy system which is already suffering from energy reliability issues causing blackout events in one of the richest countries with respect to energy resources. In this paper we will take a closer look to the Australian mineral and renewable industries, revealing Australia's

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[1] It is an independent monitoring tool of countries' climate protection performance. It aims to enhance transparency in international climate politics and enables the comparability of climate protection efforts and progress made by individual countries. The ranking results are defined by a country's aggregated performance in 14 indicators within the four categories "GHG Emissions", "Renewable Energy" and "Energy Use", as well as on "Climate Policy", in a globally unique policy section of the index. It is prepared by a group of think tanks comprising the NewClimate Institute, the Climate Action Network and Germanwatch.

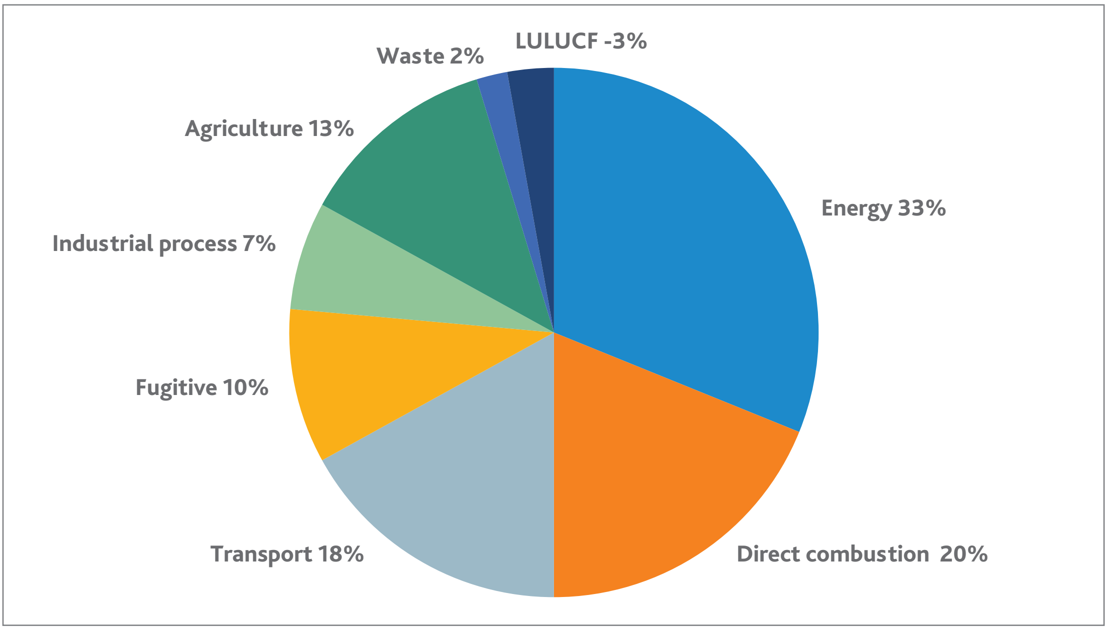

Figure 1: Major sectors contributing to greenhouse gases emissions in Australia / Source: Data from government and Climate Council for the year 2020 [5] [7] [27]

ambiguous position on climate change, economy, and energy choices. We will then focus on energy security issues brought by the indecisive position of Australia on energy, as well as study the impacts on the Australian Defence Forces' (ADF) choices of energy use. Finally, we will question and discuss the state of Australia's energy transition.

AUSTRALIA'S ENERGY CHOICES

Eight sectors are responsible for the majority of Australia's greenhouse gas emissions: energy, transportation, direct combustion[2], agriculture, fugitive emissions (gases leaked or vented from fossil fuel extraction and use), industrial processes, waste, land use, land use change and forestry (LULUCF) (see Figure 1). Among these sectors, energy (production) is the largest emitter of greenhouse gas. Australia's reduction scheme uses a pro-rata emissions reduction target of 26-28% by 2030 for each economic sector. According to the Climate Council [12], it will be more cost-effective for Australia to concentrate its efforts on sectors allowing a lower reduction cost. Such is the case of the energy sector where options to reduce electricity sector emissions are readily available and cost-effective, giving Australia's high potential in renewable energy and storage technologies. Moreover, Australia has an important renewable energy potential which is, per capita, superior to any other developed country [33]. Yet coal remains a massively used source of energy, representing 44.3% of Australia's energy mix.

To date Australia's energy needs have been largely met by fossil fuels [14]. Australia's abundant and low-cost coal resources are used to generate three-quarters of domestic electricity and underpin some of the cheapest electricity in the world. In 2019, with 70% of its coal exported predominantly to Eastern Asia, Australia became the world's largest coal exporter with a dominance in the global market for high-quality coking coal used to make steel [18]. Even though coal production has been slowing down in the past few years due to the rising use of gas and renewable energies, production has soared back in 2017, going against international agreements to move toward a zero-carbon future [25].

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[2] Produced from burning fuels for energy used directly either in the form of heat, steam, or pressure. This includes emissions from energy production, mining, manufacturing, commercial and residential buildings (mainly from heating), agriculture, forestry, fishing, and the military.

Australia's renewable capacity has surged rapidly over the past decade, a growth helped by an extraordinary fall in the cost of equipment for solar and wind energy production as well as for technologies to store renewable energy in order to balance demand and supply. By 2017, production from renewable sources other than hydro had more than tripled from 2007 levels, providing 10% of the electricity demand. In 2019, the share of renewable sources in electricity generation came up to 24%, overachieving the government's Renewable Energy Target (RET) [14]. But recently, the government declared that it will not extend the target and investments in new renewable energy capacity were slowing down. After more than a decade of unstoppable growth, 2019 saw a 50% downturn in new large-scale renewable energy investment commitments [29].

In addition, to compensate times of low renewable energy productivity, gas turbines were chosen to adjust for energy needs. Natural gas provides notable advantages in electricity generation, heating, and transport as it yields relatively less greenhouse gas emissions per energy output than other non-renewable forms of energy (except for nuclear) and can make use of already existing equipment. LNG exports make up about 2.5% of the Australian GDP and are shipped to Japan, China, and South Korea. But the climate effects of LNG exports are mixed. Australia claims that gas export is helping to bring down global emissions, especially in developing countries that are moving away from coal. Even though natural gas emits only about half the quantity of greenhouse gases during combustion as coal, gas leakage is important and offsets much of the difference[3]. Indeed, the projected increasing emissions in the energy subsector are mainly driven by the growth in LNG production [4].

In Australia, along with hydropower and storage, gas power generation will continue to play a part in managing the output variability of wind and solar power plants. Factors that could impact gas generation and gas supply could be unexpected shifts in the timing of building new transmission lines, renewable energy generation, or energy storage developments. Alan Simon Finkel, Australia's Chief Scientist[4] who helped prepare and release the National Hydrogen Strategy in late 2019, believes that Australia will need to rely on gas generation to support renewables for the next 10 to 20 years and potentially for up to 30 years, but tipped that hydrogen might be the way forward. He points out that hydrogen carries more energy than natural gas, is carbon-free and the burning of it does not contribute to climate change if produced through electrolysis using solar and wind energy. However, hydrogen may also be produced by using fossil fuels like coal and gas, thus leading to a high climate impact.

The importance of coal in Australia's energy mix and the still weak role of renewable energies poses two questions: First about the current state of energy transition in Australia and second about energy security. Coal power infrastructure has been ageing and it has been 10 years since a new coal power plant was commissioned. Also, about 75% of coal-fired power stations in Australia are currently operating beyond their life design. Using intensively an ageing coal fleet without having a real energy transition plan will mean more carbon leakage and unreduced GHG emissions. This may lead ultimately to climate warming and a greater energy demand for air conditioning in Australia with the risk of summer blackouts and heavy consequences when Australia will have no choice but to turn to new sources of energy.

WHICH OBSTACLES: AN ENERGY SECURITY ISSUE

Before heading for an energy transition, Australia will have to build a reliable and secure energy system as well as to design an energy transition plan. Despite being the 10th richest country in natural resources, Australia has suffered from blackouts in the South, the most densely populated region, following extreme weather events

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[3] The biggest source of LNG fugitive emissions is from gas venting and gas flaring. Venting is in the intentional release of gas (including carbon dioxide and methane) usually from routine operations. Flaring is the burning of excess gasses that cannot be recovered or reused during plant operations and is important in managing the pressure, flow, and composition of the gas in production and processing.

[4] The Office of the Chief Scientist (OCS) is part of the Department of Industry, Innovation and Science. Its primary responsibilities are to enable growth and productivity for globally competitive industries.

[21]. The blackouts revealed several issues in Australia's energy system. First, that energy capacities lacked risk and mitigation planning and second, that national energy thinking was affected by inconsistent political decisions and disconnected energy management which depends on private companies.

The Australian energy system is not efficiently designed to respond to an energy shortage. It has no energy storage, no back up plan and little consideration of the impact of climate change. Natural events are not seen as a direct threat to the energy grid. Yet, due to climate change, they have become more frequent and severe presenting a considerable risk to the energy infrastructure. These external factors combined with a non-existent global energy framework showed the precarity of Australia's energy security status on a national level.

Australia will have to focus on three axes: energy storage, transmission and policy [31]. With the increasing share of renewable energy that an energy transition will bring, supply flexibility is now as important as stability. When Australia's energy grid was powered mostly by coal, vast amounts of excess electricity were produced because generators could not be easily turned on or off. Now Australia is moving toward a nonlinear energy mix due to the fluctuating characteristic of renewable sources [20].

The diversity of renewable energy sources and of their location can be exploited as an asset if coupled with a smart and integrated energy grid [6] which is able to source the renewable energy in relation to the demand, and provide storage of energy generated by renewable sources when not needed. The adaptation of the electricity and power distribution grid could also facilitate the achievement of a low-carbon economy. This will require sensors, smart meters, and digital relays to provide energy savings, and for identifying control faults. Aside from using renewable energy's full potential and managing the flow of electricity through storage and smart mechanism, the transmission system needs to be improved because renewable energy production is often located in remote areas. For example, solar energy is maximised in the interior and in the northern part of the continent which are the least populated regions of Australia. An enhanced energy transmission system will therefore increase connectivity between consumers and such renewable energy supplies.

The Australian Renewable Energy Agency[5] (ARENA) [11], is providing more and more funding for transmission networks to review the opportunities and challenges presented by connecting large-scale renewable generators to the National Electricity Market NEM [26]. Investment in transmission will help to build a more interconnected electric highway that allows diverse resources to be shared across the system. Interconnected transmission will be necessary not only to secure greater geographic diversity of weather dependent resources but also to manage the risk of anticipated but uncontrollable climate effects such as bushfires, droughts, and long heat periods. An interconnected grid can provide the flexibility, security, and economic efficiency associated with a power system designed to take maximum advantage of existing resources, integrate variable renewable energy, and support efficient competitive alternatives for consumers.

AUSTRALIA'S ENERGY DEPENDENCE ON FOREIGN DECISIONS

Despite Australia's rich share of energy resources, other aspects of energy security are also at risk due to the increasing level of foreign ownership of Australia's energy infrastructure. The potential of foreign governments to influence Australia's critical energy supplies is non negligible and exposes Australia to manipulation, sabotage, espionage and coercion in addition to cyber manipulation.

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[5] ARENA is an independent agency of the Australian federal government, with the objective of increasing supply and competitiveness of Australian renewable energy sources.

[6] Power generators, which produce energy to sell to the wholesale electricity market / Distributors, who design, construct and maintain the network of "poles and wires" / Transmitters, which transport power from generators to the distribution system via the high-voltage transmission network / Retailers, who purchase power from the wholesale electricity market to sell to retail customers.

There are four parts to Australia's electricity market: generation, transmission, distribution, and retail[6]. Of Australia's eight states and territories, only three governments retain full ownership of all elements of their electricity networks: Western Australia, Tasmania and the Northern Territory. For the rest of the country, the retail energy markets in southern and eastern Australia are dominated by three private players: AGL Energy, Origin Energy and EnergyAustralia. Of these three companies none is only Australian owned. AGL Energy and Origin Energy are both partly Australian owned, whereas EnergyAustralia is a full subsidiary of the Hong Kong-based energy company China Light and Power (CLP) Group.

Looking more closely at energy company ownership in Australia, we find a dominance of Chinese ownership of critical energy infrastructure. The Chinese Government-owned State Grid Corporate[7] and Hong Kong-listed Cheung Kong Infrastructure Power Assets (CKI) already own significant shares of the privatised state power distributors. When it comes to gas, Chinese and Hong Kong companies have a stake in 99% of the transmission and distribution network in Victoria, 100% in NSW and the ACT, as well as 86% in South Australia, 78% in Queensland, 74% in the Northern Territory and 62% in Western Australia. China is duplicating in Australia the very same strategy like in Europe, where Chinese state-owned companies already acquired large parts of electricity and gas transmission and distribution networks in Greece, Italy, Luxemburg, Portugal and other European countries.

Foreign ownership is also a problem for mining industries specialized in metals like lithium, copper, and nickel. These companies play a critical role in the energy transition processes. A 2016 Treasury paper on Foreign Investment in Australia stated that less than 10% of mining projects are solely owned by Australian companies, while over 90% have some level of foreign ownership[8]. Chinese investment in minerals is specifically directed to lithium, a resource sought after in the electric batteries industry [23].

The foreign control over Australia's energy needs is amplified by Australia's great dependence on petroleum and crude oil imports [34]. Unlike electricity or gas where the source energy is produced in Australia, less than 10% of liquid fossil fuels are produced in the country. Moreover, Australia's fuel security is precarious and does not meet the internationally mandated 90-day stockpile requested by the IEA. This makes Australia the only IEA member that fails to meet its stockholding obligations [10]. Moreover, on an economy-based thinking, the number of refineries has also decrease from seven to four in 2015 as refined fuels became cheaper to import making Australia largely dependent on market forces. Before releasing a review of Australia's Liquid Fuel Security in April 2019, fuel supply was not addressed as an energy security problem by the Government and the Oil Industry. Yet, any serious disruption of such resource supplies will have negative consequences for food supplies, medication stocks, and military capabilities.

The importance of both, foreign export ownership and investment in the energy sector, makes Australia's highly dependent on external decisions. Without full control over crucial energy and strategic metal supplies for the energy transition, Australia's renewable energy plan and energy security projects might be slowed down. Energy security is fundamental to both civilian and military. Without energy security and without resilient supply chains, basic national needs cannot be fulfilled, and Defence Forces are unable to operate. It rather puts national defence capacities at the mercy of foreign nation's decisions to deal with harvested energy and may end in cutting supplies at their will [22]. This potential threat elevates Australia's energy security issues to the national security level.

[7] The State Grid Corporation of China (SGCC), commonly known as the State Grid, is the state-owned electric utility monopoly of China [10]. It is the largest utility company in the world, and as of 2019, the world's fifth largest company overall by revenue. The Area served include China, Philippines, Australia, Brazil, Italy, Portugal, and Greece.

[8] Foreign investment accounts for 86% share of ownership of major mining projects, including 26% from the US and 27% from the UK. Nowadays, there are 625 companies in the Metals Mining industry listed on the Australian Stock Exchange (ASX) from which can be found Australia's leading mining industries except Hancock Prospecting a privately owned Australian company leading in iron ore.

TOWARD A "GREEN" DEFENCE?

Energy is a critical and essential input to all Defence activities. Reliable supplies of energy are needed to fuel aircraft, ships, and other military vehicles, to transport and house personnel and to power offices, computer centres and laboratories. ADF's energy requirements are significant, its energy use represents close to 0.42% of Australia's total energy consumption and over 70% of the energy used by the Australian Government as a whole. Thus, energy transition is a matter taken seriously by the ADF. In its Defence Environmental Strategy [19], the Australian Department of Defence claims that it will become "a leader in sustainable environmental management to support the ADF capability to defend Australia and its national interests".

The ADF has the responsibility to manage its energy use, supply and security to continuously support operations and maintain its ability to defend Australia and its interests. Improving energy performance is compulsory for two reasons: First, to make economies to invest in other crucial military activities. Indeed, in 2011-12, from its total government funding of AUD 24.2 billion, Defence's annual spending on energy exceeded AUD 607 million (AUD 483m for fuel and AUD 124m for electricity) and this share has increased. The Defence's Strategic Reform Program (SRP) has implemented cost reduction targets in energy to improve efficiency and enable reinvestment of funds in other strategically important areas. Second, to minimize the impacts of operations on the environment[9] [9].

The ADF faces a number of challenges in implementing a consistent and reliable energy transition. To cite but a few there are the problems of the extent and diversity of the ADF Estate in terms of location and speciality, the ADF's ageing infrastructures, the activity and operation intensity and the ADF's budget.

Indeed, Defence Estates are located in different parts of Australia, near different types of resources and with diverse energy needs depending on the military activity held. A standardised approach to energy management is therefore difficult to implement. In response, the ADF is planning to take advantage of the diversity of viable energy resources available at Defence sites (e.g. land, wind, sun, waste and geothermal heat) and to switch to renewable energy generation. In the case of ageing infrastructure, plans for new equipment and facilities using renewable energy sources are developed. But for Defence's frequency of activity and funding, uncertainties remain as they depend on Government decision, as well as on natural and external political threats. For now energy security is the predominant concern and safeguard capabilities will depend on the budget and resources allocated by the Government.

One of the energy solutions commonly used by ADF bases is solar energy. In 2018, the Australian Air Force installed a solar and battery storage microgrid system at a facility in the Northern Territory. The Department of Defence subsequently installed a 1.2MW solar array at the Australian Defence Satellite Communications Station near Geraldton, Western Australia, as well as 12.5MW of solar arrays split between two facilities, the Robertson Barracks in the Northern Territory and the RAAF base in Darwin. In July 2020 a program to upgrade the Headquarters Joint Operations Command[10] (HQJOC), announced a solar installation with a capacity of 1.9MW to power Australia's defence operations headquarters located outside Canberra, following the trend of other defence facilities already supplied by an on-site solar energy installation.

ENSURE THE MOBILITY AND THE INDEPENDENCE OF THE AUSTRALIAN DEFENCE FORCE

Fuel consumption represents a large proportion of total ADF's energy use. The Department of Defence relies on petroleum for approximately 77%

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[9] In this regard, Defence has released a Defence Estate Energy Policy under the Defence Environmental Strategic Plan (DESP) in charge of implementing Australia's Defence Environmental Policy. The policy describes Defence's commitments, objectives and targets related to energy on the Defence Estate that must be met over the period 2014- 2019. The Defence Estate Energy Strategy includes initiatives under four themes: Improving the efficiency of existing assets and equipment/ Providing efficient new infrastructure and equipment/ Using energy from renewable and alternative sources/ Driving energy saving behaviour.

[10] The HQJOC, houses Australia's most senior defence leadership, and is where Australia's international defence operations are coordinated.

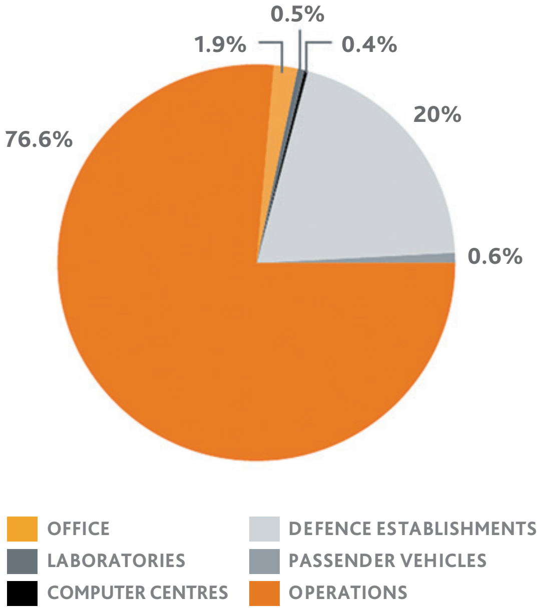

Figure 2: Defence Energy use by End-use Category (2012-2013) / Source: Defence Estate Energy Strategy, Department of Defence

of its energy needs (see Figure 2). Thus, research and partnerships are developed to explore the possibility of using alternative fuels and sources of energy to reduce Australia's dependency on oil imports and coal power. The Strategic Logistics Branch works closely with the Defence Science and Technology Organisation (DSTO) to coordinate research into alternative fuels and energy. Ongoing projects study the feasibility, costs, energy security and interoperability benefits of using biofuels for operational requirements. Biofuels is also a matter of interest in other military forces such as the United-States. This common interest has led to a partnership between the two Defence agencies. In 2013, the Royal Australian Navy has signed an agreement with the US Navy which is now on the way to achieve the permission to use a 50/50 blended biofuel for its equipment. Through this partnership the Australian and US Navies are co-operating on research into alternative fuels for the naval fleet[11].

With the need to address the 2050 zero emissions target, looking for alternatives to fossil fuels is a primary concern of the ADF. In the civil sector electric vehicles are seen as the future for mobility considering the encouraging results of research and development in battery technology. But this does not address all mobility needs of the ADF which include long-range, long endurance air, surface, and undersea vehicles. The current step in shipping is to shift from the present low sulphur fuels to liquefied natural gas (LNG) by that halving emissions by 2050, a target set by the United Nations International Maritime Organisation. LNG causes lower carbon emissions for the same energy output compared with diesel oil fuel. However, that alone will not suffice to meet the zero-emissions goal. Instead, various forms of hybrid propulsion are being developed to make further reductions possible, mostly using some form of battery storage to supplement conventional internal combustion engines.

To decide in which fuel to invest in the future, the ADF must focus on the needs of their land, air, and sea (surface and underwater) operations. The Defence Science and Technology Group (DSTG) must evaluate alternatives to fossil fuels for all vehicles employed in ADF operations and prioritize investments in emerging new technologies for ADF early adoption. Air mobility may use electric energy but most likely with a limited performance and range. A more likely way ahead for military aircraft is the use of synthetic fuels[12]. Surface mobility for land vehicles using hydrogen is already under development and will most likely be adopted for ADF land vehicles and for naval vessels not designed for high performance or long-range independent operations. For high-performance naval vessels, and especially submarines, nuclear propulsion will be the preferred choice and is being investigated by the Submarine Institute of Australia through its Nuclear Seminar series[13] [28].

Yet, an important part of the ADF equipment is not really under Australia's control, because major industries providing military equipment are foreign

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[11] Since 2013, the Royal Australian Navy (RAN) has maintained interoperability with the US Navy (USN) to benefit from alternative naval fuel to meet its Great Green Fleet energy initiative, which outlines the USN's commitment to source 50% of fuel from renewable sources by 2020.

[12] Synthetic fuels are usable in much the same way as current fossil oil-based diesel and aviation fuels. The difference is they are manufactured and consumed by chemical processes in which the carbon content is added to create the fuel and then recovered in combustion to return through the cycle again.

owned. For Australia's Defence in order to obtain full control over their energy transition process, the Defence industry must solve three problems: The high level of imports, the low level of production and the existing control by foreign entities. The Australian defence industry's exports are greatly outweighed by the scale of imports of military goods and services to Australia[14]. Between 2001 and 2016, the total value of defence exports from Australia (using the Stockholm International Peace Research Institute SIPRI methodology, the world's leading authority on global military spending), represented only 6.8% of the total value of defence imports to Australia. In 2019, figures from the SIPRI showed that Australia has become the world's second largest weapons importer but has dropped to 25th in the export rankings [8]. In the July 2020 Force Structure Plan [36] and Defence Strategic update [35] a highlight was put on the Australian Defence industry, outlining the Government's commitment to a program of future investment and opportunity for its defence industry.

WHAT WILL PUSH TRANSITION IN AUSTRALIA

Australia's poor commitment to climate change mitigation has tarnished the country's international reputation. In September 2019 Australia was denied from speaking at the United Nations climate summit in New York. More recently, the country has been held responsible for the weak outcome of the COP25 and criticised for stopping its contribution to the Green Climate Fund [15]. Moreover, despite Australia's claim of being on track to meet its 2030 target, the country's own 2020 emission projections reveal the contrary [5]. While climate talks are not making significant moves, investors are directing investments toward a renewable energy transition as the value of clean energy companies is soaring[15]. Thus, Australia will have no choice but to take the path of energy transition.

In the political debate the transition costs have been considered too high to take action. Yet, there is nowadays a growing emphasis on the potential opportunities and gains from embracing the energy transition. A study[16] of the Australian-German Energy Transition Hub, published in September 2019, has examined the economic opportunities of decarbonisation over the coming decades [32], a view shared by several other papers and reports [17] [1]. According to the report, embracing low-carbon opportunities could lead to a clean electricity system and could meet 100% of Australia's electricity requirements by the 2030s, with high degrees of security and reliability. They also detailed how Australia could become a net exporter of clean energy through green hydrogen, green steel and aluminium produced from green electricity and become an energy "superpower" in a carbon-constrained world. Moreover, the major importers are moving slowly away from coal, which will mean that Australian coal export will depend on the rate at which the largest importers are able to transition away from using fossil fuels to generate energy to cheaper renewable sources.

In the future, for other countries to import large volumes of low-emission products from Australia, the country will have to comply and be seen as delivering on emissions reduction targets consistent with the Paris objectives. Else, Australia will lose important markets because many countries are getting more and more interested in low-emissions products. However taking the example of the European Union, some countries already apply restrictions on imports of high-carbon products. Consequently,

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[13] Nuclear propulsion is in wide use for submarines and high-performance, long-endurance ships including aircraft carriers. Australia has the resources to produce nuclear energy but did not developed the industry for ethical reason. There are many issues to be resolved for nuclear propulsion for the ADF, including repeal of legislative prohibitions on nuclear power and on adding value to Australian mined uranium to create nuclear fuel or to reprocess spent fuel and consign residual radioactive waste to approved geologically stable repositories.

[14] The United States, Spain and France were the major exporters of weapons to Australia during the last five years. F-35 combat aircraft and P-8A Poseidon anti-submarine warfare (ASW) aircraft received from the US and warships from Spain accounted for more than 80% of Australia's imports between 2014 and 2018.

[15] In the end of 2019, Goldman Sachs announced it had ruled out direct finance for new or expanding thermal coal mines and coal-fired power plant projects worldwide, and has committed to phase out financing for significant thermal coal mining companies that do not have a diversification strategy.

[16] The researchers examined six scenarios for the Australian economy ranging from the status quo – which considered only Australia's existing climate and energy policies – to a "leadership and export" scenario, which assumed deep decarbonisation across sectors including electricity, transport and industry. Under the latter, renewable would produce 200% of Australia's domestic electricity demand and supply a large export market. There would also be widespread electrification of transport, buildings, heat, and industrial processes. But the researchers note that achieving this would require the world to move to a zero-carbon energy system.

the import of zero-emissions products would follow assessments that the exporter is making acceptable contributions to the global mitigation effort.

There is also a certain urgency to the need for transition. With the projected decline of coal industries [3], an unplanned energy transition will place increasing pressure on major coal-using regions in Australia. If done right, the coal industry decline could be compensated for by an increasing demand in other mining branches. The development of renewable energy will require specific materials, and this presents inter alia, an opportunity for the extraction of e.g. nickel and copper, both strategic materials in energy transition technologies and batteries. Thus, with the prospect of an Australia with abundant low-cost electricity, the country could also grow into a major global producer of minerals needed in the post-carbon world, such as lithium, titanium, vanadium, nickel, cobalt and copper [30].

CONCLUSIONS

Australia is a country full of contradictions. Despite being greatly exposed to climate change, few state policies exist to mitigate its negative effects. Regardless of the country's large options for generating renewable energy, coal and gas are still favoured for electricity generation and exportation while reports describe how Australia could become a 100% renewable country and a leader in green exports. Australia's measures for the energy transition are still uncertain, weakening the already fragile energy system [15]. This raises energy security issues already at stake, considering Australia's strong dependency on fossil fuel imports and on decisions from foreign ownership in the mining and energy industry. At this level, energy security in Australia is not just about energy supply reliability for consumers but a question of national security. In this complicated equation between climate change, energy and policies, Australia's Defence Forces must find an equilibrium to align their national and international duties with the protection of Australia's national interests. In response to the climate challenge, the ADF is now working on both, mitigation plans for reducing greenhouse gas emissions and adaptation, and on designing equipment to operate under more variable environmental conditions while keeping in mind energy security and cost effectiveness.

The Australian Defence Forces' energy use and supply depends on the national energy system. Today, the ADF is on its way to acquire suitable defence capacities alimented by renewable energy resources. Yet, just like the national energy system, the energy distribution networks within the forces are fragmented and are in need of a central management. As the need for energy security will push Australia to implement its 5th generation[17] energy capability so it will be the case of the defence sector. The 5th Generation promises more integrated technologies, efficiency and amplified capabilities which will enhance the sustainability and capabilities of the ADF and provide safety to a more resilient Australian Nation [2].

The ADF has developed several plans in view of a renewable powered Australia, considering energy transition planning, energy storage, connectivity, transmission, and reliability. Energy independence is an important factor for any defence force and energy security holds a central part in the Defence road map including solutions to reduce the need for imported fuels. The impact of climate change on the ADF's performance capabilities is also an increasingly discussed matter and presented in front of the government as a key issue, mainly as a threat for defence cooperation, activities and infrastructure.

The impacts of climate change in Australia will be complex and to some degree uncertain, but all analyses agree on how much Australia will lose if the country does not act now. Well planned mitigation and adaptation measures combined with global cooperation can reduce the ultimate extent of climate change and its impacts. Yet, the federal Australian government continues to reject a 2050 target of net zero emissions and has chosen a gas-led economy recovery in response to the COVID-19 pandemic, also supporting the coal industry [24]. In this context, the Australian Defence Forces as the safeguard of national security could play an

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[17] By following the construction of generations capability from the energy sector we can speak of biomass as Australia's 1st Generation, coal as its 2nd, oil and gas as its 3rd and nuclear and renewables as the 4th. Acquiring a 5th Generation in the energy platform will mean achieving a generation capability which will include energy security assessment and an integrated energy network.

important role in pushing the Australian government back onto the track for an energy transition towards renewable energy and tip the balance toward climate change mitigation.

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The Synchronization of the Baltic States': Geopolitical Implications on the Baltic Sea Region and Beyond

by **Justinas Juozaitis**

INTRODUCTION

The Baltic States remain the last countries within the Euroatlantic space whose electricity grids continue to operate synchronously with the Russian Integrated Power System/Unified Power System (IPS/UPS). On 28 June 2018, after a long marathon of multilateral negotiations and decades of prior discussions, Lithuania, Latvia, and Estonia had finally agreed to synchronize their power systems with the Continental European Network (CEN) through Poland. With European Union allocating €323 million in January 2019[1] and additional €720 million in October 2020[2] for synchronizing Lithuanian, Latvian and Estonian power systems, the Baltic flagship energy project gains momentum.

Given the joint Baltic and Polish political commitment reinforced by financial aid and political support from the European Union, Russia's capabilities in opposing the Baltic withdrawal from the IPS/UPS are diminishing rapidly. Nevertheless, there should be no room for complacency. The Kremlin is interested in maintaining electricity trade with Lithuania, Latvia and Estonia after their synchronization with CEN that goes directly against the principles outlined in Political Roadmap on the synchronization of Baltic States.[3] With the launch of Ostrovets nuclear power plant (NPP) in early November 2020, Belarus also wants to gain access to the Baltic energy markets that Lithuania, Latvia and Estonia collectively denied just two months before the operational start of its NPP.

In here, one should note that both Belarus and Russia have specific cards to play in achieving their aims. For example, Russia has a competitive edge in the Baltic electricity market as the country does not follow the EU's environmental policies. Free of environmental regulations, Russia can apply pressure on the Baltic States by positioning the withdrawal from electricity trade with the 3rd countries as an economically irrational decision. Russia's experience in framing negative opinion towards strategic energy projects in the neighbouring states is plentiful.

Moreover, Russia is moving faster with its preparations for the desynchronization of the Baltic States from IPS/UPS than they are doing so themselves. Russian authorities have already narrowed the BRELL[4] ring by building additional transmission lines along its borders with the Baltic States and Belarus. The Kremlin has also installed reinforcements in other parts of its circular transmission system to increase the electricity transfer capacity between North-Western and Central

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regions of IPS/UPS. Most importantly, Russia has doubled Kaliningrad's generation capacities, diversified its natural gas supply (primary fuel in electricity generation) and successfully tested its capabilities to operate in an isolated mode twice. The Baltic States are lagging as critical infrastructural projects enabling their synchronization with CEN will only be completed during 2022 – 2025. To make matters worse, the Baltic States' capabilities to operate their power systems in isolation from IPS/UPS remains untested.

Having completed the first unit of Ostrovets NPP, Belarus will also try all means at its disposal to persuade the Baltic States to open its markets for electricity trade in the short term and long term perspectives. In here, Minsk will strive to offer cheap electricity for the Baltic market even if the proposed price will be lower than its nuclear generation costs. Since the majority of expenditures (90 %) on the construction of Ostrovets NPP are financed by the Russian loan that Belarus will start paying back in April 2023,[5] Minsk has room for manoeuvre in offering electricity price that temporarily does not fully incorporate capital costs.

Given the following processes, the paper studies geopolitical implications on the Baltic States' synchronization with CEN with a specific emphasis given on the Russian and Belarusian behaviour. First, the study exposes the interconnection between tectonic geopolitical shifts and the establishment, development and disintegration of synchronous interstate power networks. Second, it introduces Russian response to the synchronization of the Baltic States, its current objectives and means to achieve them. Third, it discusses Belarusian prospects in gaining access to the Baltic electricity market. The paper concludes that the Baltic States should strive to move quickly not only in proceeding with the synchronization but also in increasing their readiness to operate in an isolated mode and to establish an emergency synchronous interconnection with Poland if needed. With researchers and policymakers mostly focusing on the classical themes of Russian energy geopolitics, i.e. natural gas and oil, the paper hopes to shed more light on another important object of study – the geopolitics of synchronous interconnections.

SYNCHRONIZATION AND GEOPOLITICS

To recognize the geopolitical implications associated with Lithuanian, Latvian and Estonian withdrawal from the IPS/UPS, one first needs to grasp the strategic significance of synchronous power grids operating beyond national borders. An interstate synchronous power system, therefore, should not be understood merely as national power grids functioning together under the same frequency and management principles or as a system sharing standard regulations. One should also perceive such a system as a geopolitical bond between countries either trusting each other enough to enter into an interdependent relationship in the strategic power sector or being forced to do so by finding themselves under the sphere of influence from a foreign power. Even if economic, infrastructural, technological, managerial and legal factors have a role to play in explaining the emergence, development and disintegration of interstate synchronous networks, European history shows that these processes cannot be fully understood without analyzing geopolitics.

During the Cold War, the emergence of interstate synchronous power systems in Europe was influenced by the great power rivalry. It is not a coincidence that today one finds three major interstate synchronous areas in Europe as they were created by countries that shared a similar strategic environment. For example, West Germany, France, Italy and the Benelux countries not only have signed the Treaty Establishing the European Coal and Steel Community in 1951 but, together with Austria and Switzerland, they have also established the Union for Coordination of Production and Transmission of Electricity (UCPTE) that is now known as Continental European Network.[6] Seven years later, their power grids began operating synchronously, and most of these countries were NATO members (Austria and Switzerland excluded).[7] The first significant enlargement of the CEN occurred in 1987 when three NATO members and contemporary newcomers to the European Union – Portugal, Spain, and Greece – together with Albania and Yugoslavia synchronized their power grids with CEN. In here, one should note that the West had previously supported the development of asynchronous interconnections with Yugoslavia 'to lure Yugoslavia further away from the socialist block',[8] thus further highlighting the importance of geopolitics as opposed to contradicting the argument.

A similar process took place behind the Iron Curtain. During 1957 – 1960, the power systems of German Democratic Republic, Poland, Hungary and Czechoslovakia were interconnected, paving the way for the establishment of the Мир (Mir) synchronous area in 1962 – a predecessor of IPS/UPS. During the same year, these Central Eastern European countries were synchronized with the Soviet Union, while Romania and Bulgaria joined the synchronous operation shortly afterwards.[9] At first, Moscow permitted the dispatch centre in Prague to manage the synchronous area outside the Soviet Union on a day-to-day basis. In contrast, a similar dispatch in Moscow was more focused on the core Soviet territory, even though it was hierarchically superior to the one in Prague. The control centre in Moscow, however, became more involved in regulating the system frequency in the Central Eastern European countries since the 1970s, thus centralizing Kremlin's control over the common synchronous area within its sphere of influence.[10]

Northern European countries have also synchronized their power grids into a separate system. In 1963, the transmission system operators (TSOs) of Denmark, Finland, Iceland, Norway and Sweden founded NORDEL leading to a creation of a synchronous power grid interconnecting Finland, Sweden, Norway and a small portion of Danish territory.[11] The interconnectivity between the Nordic, Eastern and Western synchronous areas remained negligent throughout the Cold War as the period sought the construction of high-voltage interstate power lines only on the Czechoslovakian – Austrian, Finnish – Russian and Bulgarian – Greek borders. Hence, not only the Iron Curtain existed in Europe during the Cold War, but the 'Electric Curtain' was present as well.[12]

As the international system started to reshuffle after the collapse of the Soviet Union, changes in geopolitical alignment translated to the transformation of the Western and Eastern synchronous areas. In 1995, Poland, Hungary, Czech Republic and Slovakia joined the CEN, while Romania and Bulgaria followed their footsteps in 2004. With Romania and Bulgaria also came the resynchronization of Bosnia and Herzegovina, Croatia, Greece, Macedonia, Montenegro and Serbia that were temporarily disconnected from CEN because of the Yugoslav Wars.[13] Notably, Turkey had also synchronized its power grid with CEN in 2015. Most of the countries mentioned above either belonged to the Euroatlantic space via memberships in NATO or the EU or had aspirations of joining it by the time they have synchronized their power grids with CEN. Others eventually expressed their willingness to join either both organizations or one of them.

These developments happened against the Russian will. Russia wanted to maintain the synchronous operation with its former subjects and reorganized Mir into IPS/UPS in February 1992 through the newly established Commonwealth of Independent States (CIS). As of a consequence, CIS countries became the core participants within the IPS/UPS. The Central Eastern European states, however, were not optimistic about continuing their synchronous operation within IPS/UPS due to economic (export possibilities to Western Europe), technical (reserve capacities, emergency support and frequency stabilization) and geopolitical (membership aspirations in NATO and the EU) reasons.[14] Highlighting the last point, Poland, Czech Republic, Slovakia and Hungary established a separate CENTREL synchronous area in November 1992 as opposed to continuing to operate within the IPS/UPS until their synchronization with CEN.[15]

Despite the Euroatlantic aspirations, the Baltic States had many obstacles in their way for synchronizing their power systems with CEN during the 90s. Having no cross-border power lines with Poland and the Nordics and dealing with political instability and a bumpy economic transition from the centrally planned economy to a free market, the Baltic States were forced to remain in IPS/UPS. As of a consequence, the Baltic TSOs signed the so-called BRELL agreement in 2001, formalizing their synchronous operation within the Russian power system.

For the Baltic States, desynchronization from the IPS/UPS is first and foremost a strategic matter. Having the first-hand experiences of Russian energy geopolitics and dealing with its revisionist and expansionist policies, Lithuania, Latvia and Estonia aim to loosen its ties with Russia and enjoy the full benefits of European integration in a rules-based synchronous area. Synchronization will end a central Russian oversight on the Baltic power grids that gives the Kremlin a very detailed and up-to-date picture on the situation of Lithuanian, Latvian and Estonian power systems. It will also help the Baltic States to enforce their boycott on Belarusian electricity. The Baltic States plan to stop the electricity trade with the so-called third countries (Russia and Belarus) after their synchronization with CEN is finished, thus preventing the electricity generated in Ostrovets NPP from entering Lithuanian, Latvian and Estonian markets. This capability is crucial as the current political consensus among Lithuania, Latvia and Estonia still lacks proper implementation mechanisms and paves the way for interstate disagreements and political friction.

The synchronization also brings economic and infrastructural benefits. As mentioned before, synchronization comes together with significant financial support from the European Union that continues to be an essential asset for growing three small Baltic economies and their industry. During the next five years, the Baltic States, together with Poland, will use more than one billion euros of EU's funding for the development of their power grids not only allowing for smooth synchronization with CEN but also improving the reliability and interconnectivity of their power networks. Implementing synchronization project will allow making reinforcements to internal Lithuanian, Latvian and Estonian power lines, strengthening interconnectivity among them and significantly enlarging joint transmission capacity with Poland through interconnections with Lithuania (from 600 MW currently to 2700 MW once LitPol link begins synchronous operation (2000 MW), and high-voltage direct current (HVDC) interconnection Harmony link (700 MW) starts working). After synchronization, therefore, the Baltic States will find themselves not only firmly integrated to the Western geopolitical space but also having modern, secure and reliable power grids.

Sharing national security concerns with the Baltic States regarding the reliance on Russia, Ukraine (together with Moldova) is also set to withdraw from the IPS/UPS. In June 2017, Ukrenergo and Moldelectrica signed agreements with the European Network of Transmission System Operators for Electricity (ENTSO-E) to synchronize Ukrainian and Moldavian power systems with CEN.[16] For Ukraine, the need to synchronize its power grid with CEN stems from strategic concerns (reliance on its rival – Russia) and enhanced economic opportunities (expanding electricity export to Western Europe from 5 TWh to 18–20 TWh).[17]

All in all, the synchronization will eventually end a geopolitical anomaly – Baltic States' reliance on Russia (a primary threat to their national security) to maintain the stable functioning of their power systems. IPS/UPS will continue to contract beyond the former borders of the Soviet Union following the macro geopolitical processes – the shrinkage of the Russian sphere of influence. It is a strategic loss for Russia as Lithuanian, Latvian and Estonian synchronous operation in the BRELL ring remains the last significant Russian advantage in their energy systems, allowing the Kremlin to exert influence and creating potential to undertake various malevolent activities.[18]

RUSSIAN APPROACH TO THE BALTIC SYNCHRONIZATION

Looking from the Russian perspective, the synchronization of the Baltic States with CEN is disadvantageous due to three reasons that eventually became apparent during different stages of the project development. As illustrated in the last chapter, Baltic withdrawal from the IPS/UPS removes their dependence on Russia that contradicts with Kremlin's strategic interest of maintaining influence in its close neighbourhood. Second, the shrinkage of IPS/UPS forces Russia to choose between investments in Kaliningrad's autonomy and its dependence on Lithuanian and the EU. And finally, the synchronization is set to deny Russia's access to the Baltic electricity market that reduces their reliance on its electricity supply and removes a valuable market segment.

Even if the Kremlin consistently perceived the Baltic synchronization as disadvantageous, its responses changed over time. When Lithuanian, Latvian and Estonian prime ministers declared the synchronization with CEN a mutual strategic priority in 2007, Russian authorities did not believe that such an undertaking was possible and started developing nuclear projects in Kaliningrad and Belarus. As the relations with the European Union deteriorated following Russian military aggression against Ukraine, the synchronization of Baltic States received more attention from Brussels with the opening prospects of significant European financial contribution. Reacting to the changing strategic realities, Russian leadership eventually became more active in opposing the Baltic synchronization. Even if the future perspectives of successful Baltic synchronization were far from being certain by that point of time, Russia decided not to take any chances and started upgrading its power system with a specific emphasis given to upgrading Kaliningrad's power grid.

Russia ultimately failed in preventing the synchronization from moving forward. Still, the decision to invest in its power grid was beneficial from a strategic point of view. By the time Lithuania, Latvia and Estonia agreed to synchronize their power systems through Poland as opposed to doing so through Finland, Russia was already mostly finished upgrading its power system. Most importantly, Russia showcased Kaliningrad's capabilities to operate in an isolated mode in May 2019, when the Baltic States were only starting to build the necessary infrastructure for synchronizing their power systems with CEN and will continue to do so in the mid-term perspective.

Having a chronological advantage over the Baltic States allows Russia pursuing two broad policy options. First, to desynchronize the Baltic States from the IPS/UPS prematurely either by upholding the six-month warning outlined in the BRELL Agreement or doing so unexpectedly. Second, to use all available tools in persuading the Baltic States and the EU to maintain electricity trade with Russia after its neighbours start operating synchronously with CEN. The paper argues that keeping electricity export routes open will be the main Russian focus in the years to come. That does not knock-out its capabilities, however, to use its chronological advantage as political leverage until the Baltic States either prepare for operating their power grids in an isolated mode for a prolonged time, or they are ready for emergency synchronization with Poland. In the following sections, the paper outlines this case by discussing Russian diplomacy and internal policies towards the Baltic States' synchronization with CEN, presents the importance of maintaining electricity with the Baltic States once their synchronization is complete and discusses Russia's possible instruments in doing so.

VOCAL OPPOSITION AND SILENT PREPARATION

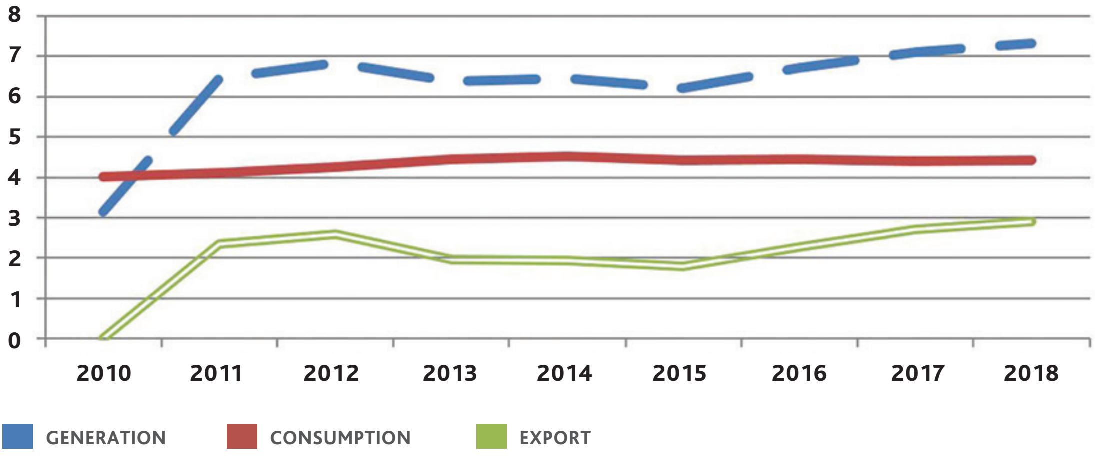
The Russian approach to the Baltic synchronization was twofold. On the diplomatic level, Russia opposed synchronization by framing it as a costly and unnecessary project that causes a plethora of problems for Russia. Even the Russian President Vladimir Putin denounced the Baltic synchronization project on several occasions while giving interviews to the European and the US media outlets.[19] Despite such a diplomatic façade, Russia behaved as if Lithuanian, Latvian and Estonian desynchronization from the IPS/UPS is only a matter of time and started upgrading its power system in 2014 – 2015 to prepare for the upcoming break-up in advance.

Russia's preparations were twofold as the Kremlin started reinforcing its transmission grid in the mainland and preparing Kaliningrad to operate in an isolated mode. Starting from the former, it is worth mentioning that Russia has 'narrowed' the BRELL ring by building two additional 330 kV transmission lines: 271 km long Novosokolniki – Talashkino[20] and 150 km long Pskov – Luzhskaya[21] along the borders of the Baltic States and Belarus. In preparation for the Baltic withdrawal from the IPS/UPS, Russia has also implemented many other infrastructure projects, including the construction of a 450 km long 750 kV transmission line Belozerskaya – Leningradskaya. These upgrades have increased the electricity throughput between the North-West and the Central part of the IPS/UPS by 50 %, thus compensating for the upcoming loss of the transmission capacity associated with the Baltic power lines.[22] To understand the significance of the latter, one needs to briefly overview the history of Kaliningrad's power system and changing Russian perceptions towards its future development.

Following the initial assumption that the synchronization of Lithuanian, Latvia and Estonia with CEN is a strategic utopia, Russia made plans for Kaliningrad's infrastructural integration as opposed to thinking about its remote operations. Reacting to talks between the Baltic States and Poland about the construction of a regional nuclear power project – Visaginas NPP – that was supposed to replace Ignalina NPP already scheduled for closure at the end of 2009, Russia decided to construct a directly competing nuclear power plant in Kaliningrad – Baltic NPP. By doing so, Russia not only tried to oppose Visaginas NPP but also attempted to exploit the emerging interconnectivity between the Baltic States, Sweden (NordBalt), Finland (Estlink 2) and Poland (LitPol link) power grids to its benefit (exporting electricity generated in the Baltic NPP to additional markets).[23] Together with the construction of Baltic NPP, came Russian proposals for building power lines to interconnect Kaliningrad with Poland and Germany and to enhance its transmission capacity with Lithuania.[24] After failing to reach agreements with the countries mentioned before, Russia had no other options but to freeze the construction of Baltic NPP in 2013 and to rethink its strategy for the Kaliningrad region.

By the time Rosatom has frozen the construction of Baltic NPP, Russia has substantially improved Kaliningrad's generation capacities. Until 2005, Kaliningrad's internal generation could cover less than 10 % of its electricity needs, but the region compensated its shortages by electricity transfers from continental Russia through Lithuanian power lines. Kaliningrad had decreased its electricity generation gap in October 2005, when Russia constructed the first block of Kaliningradskaya central heating and power plant (CHPP)-2 (450 MW). After building its second unit (also 450 MW) in December 2010, Kaliningrad became a surplus region that started exporting its excess electricity to Lithuania (please see the graph below).[25]

1 Graph. Dynamics of power generation, consumption and export in Kaliningrad, 2010 – 2018.



Source. Lohse, et. al.[26]

Even if Kaliningrad acquired more than sufficient indigenous generation capacities to satisfy its power demand, the region was yet not capable of operating in an isolated mode for an extended time. For example, in August 2012, Russia disconnected Kaliningrad from the IPS/UPS, running its power grid twice for 10 minutes in isolation from the rest of the synchronous area. To a certain extent, the media described this experiment as a success, showing that Kaliningrad's power system can function independently from the BRELL ring. Still, such a conclusion was not entirely correct. Russian authorities had conducted this isolated system test during the summer night, when the electricity demand was low, as opposed to doing it during the working hours and under the freezing conditions when the demand is considerably higher.[27] The short time span has not allowed accessing how the power system reacts to demand fluctuations during peak hours. Moreover, by the time of testing Kaliningradskya CHPP-2 had no indigenous back-up capacities that would have left Kaliningrad with no tools to mitigate any unforeseen incidents in the power supply chain if the region operated in isolation for a prolonged period.

One year later, real events validated the argument made above. On 8 August 2013, at approximately 9 pm, a malfunction in the high-voltage power line linking of Kaliningradskaya CHPP-2 with the power grid caused a blackout in Kaliningrad, affecting roughly 1/3 of the region's population. After 45 minutes, the authorities restored the system by electricity flows from Lithuania.[28] Since the continuous isolated operation was not possible and constructing additional power lines between Kaliningrad and the neighbouring countries was out of the question, the Kremlin had to develop a new vision for its strategically important exclave.

According to the Joint Research Centre, the Baltic withdrawal from IPS/UPS left Russia with three general options for Kaliningrad's power system: *European integration, negotiation* and *autonomy*. European integration foresees joint synchronization of Lithuania, Latvia, Estonia and Kaliningrad with CEN. *Negotiation* envisages diplomatic dialogue between Lithuania and Russia for constructing an additional power line interconnecting Kaliningrad with IPS/UPS through Lithuanian territory. *Autonomy* calls for making Kaliningrad capable of functioning independently from IPS/UPS.[29]

Each policy option established a different kind of balance between economics and national security. From the economic point of view, synchronizing Kaliningrad and the Baltic States was the most cost-effective option as it allowed avoiding substantial investments into its power grid. It also offered the best conditions for maintaining electricity trade between Kaliningrad and the Baltic States. Following this logic, Rosatoms' program director Sergey Boyarkin even stated at the 9th CEE Energy Forum in Warsaw that 'Electricity transmission systems of Lithuania and Russia's Kaliningrad region cannot operate one without the other, hence the Kaliningrad region will seek to become part of ENTSO-E together with Lithuania, which has decided to synchronize its electricity transmission grids with the continental European system'.[30] From the political point of view, however, European integration seemed controversial (especially after Russian military intervention in Ukraine in 2014) because it would have subjected Kaliningrad's power system to EU's regulations, thus strengthening its dependence on the European Union and Lithuania.

Once again, the economics favoured the negotiation scenario, but national security considerations argued on the contrary. Joint Research Centre estimated that establishing a direct interconnection between Kaliningrad and Belarus through Lithuanian territory would cost €28 million and additional €150 million would have to be spent on the back-to-back (BtB) converter on Lithuanian – Kaliningrad border for electricity trade.[31] This scenario would have transformed the interdependent relationship between the Baltic States' and Kaliningrad's power systems to the one of dependence when the latter is depending on the former.[32]

The third option was the most expensive but offered the highest degree of autonomy and security for Kaliningrad. According to JRC's estimates, establishing an autonomous power system in Kaliningrad would require investing €378 million in a flexible power generation capacity (450 MW) and €150 million – to a BtB converter on Kaliningrad – Lithuanian border for exchanging power reserves. Additional investments in Kaliningrad's transmission network were also necessary, but the price was not significant compared to the costs mentioned above.[33]

In the end, Russia has chosen to create an autonomous power system in Kaliningrad, but went well beyond JRC's vision, installing larger generation capacity and diversifying Kaliningrad's natural gas supply routes at the same time. In October 2015, the Government of Russia had ordered to build three gas-fired and one coal-fired power plants (1000 MW generation capacity in total) in Kaliningrad. A joint venture of Rosneftgaz and Inter RAO, Kaliningrad Generation, started implementing these projects in 2016.[34] In 2018, Russia finished building two natural gas-fired TPPs: Talakhovskaya (161 MW)[35] and Mayakovskaya (157 MW).[36] One year later, Russia completed its flagship generation project – a natural gas-fired Pregolskaya TPP (454 MW).[37] At the moment of writing, it is also close to finishing a coal-fired Primorskaya TPP (195 MW).[38] In total, these power plants add additional 967 MW generation capacities to Kaliningrad, thus increasing it by more than twofold (please see table 1).

Table 1. Electricity generation capacity in Kaliningrad by unit and fuel

No	Generation Unit	Location	Fuel Type	Installed Capacity
1.	Kaliningradskaya CHPP-2	Kaliningrad	Natural gas	900 MW
2.	Pregolskaya TPP	Kaliningrad	Natural gas	454 MW
3.	Primorskaya TPP	Svetly	Coal	195 MW
4.	Talakhovskaya TPP	Sovetsk	Natural gas	161 MW
5.	Mayakovskaya TPP	Gusev	Natural gas	157 MW
6.	CHPP-10	Sovetsk	Natural gas	24 MW
7.	Gusevskya TPP	Gusev	Natural gas	8,5 MW
8.	Ushakovskaya wind farm	Ushakovo	Wind	5,1 MW
	Total			1905 MW

Source. The Governor of the Kaliningrad Region [39] *and Inter Rao* [40]

Together with upgrades in the transmission network, investments into generation capacities have fulfilled their strategic purpose – making Kaliningrad independent from the IPS/UPS as two isolated power system tests have shown. In May, Russia successfully operated Kaliningrad's power system in isolation from IPS/UPS for 72 hours. Russia conducted the test during the timespan that included regular working days, thus accounting for fluctuations in electricity demand.[41] On 19 September 2020, Russia has performed another isolated power system test in Kaliningrad that lasted eight hours, using all of the newly built gas-fired power plants for regulating the frequency.[42]

In addition to building new gas-fired generation units, Russia diversified Kaliningrad's natural gas supply and expanded its storage facility. In December 2017, Russia built two underground natural gas reservoirs that expanded Kaliningrad's natural gas storage capacity to 174 million cubic meters and plan to increase the storage capacity further to 800 million cubic meters by 2024.[43] Despite having a natural gas transit contract with Lithuania until 2025 involving a "take or pay" clause,[44] Russia inaugurated a floating storage regasification unit FSRU Marshal Vasilevskiy in January 2019 as an alternative to natural gas transit through the Lithuanian pipeline system.[45] This ship is capable of storing 174,000 cubic meters of liquefied natural gas (LNG) that is equivalent to 100 million cubic meters of natural gas. With the annual natural gas consumption in Kaliningrad hovering around 2.5 billion cubic meters, the combined underground and LNG storage capacity can supply the region approximately for a month depending on the daily demand intensity (less during the winter, more – during the summer). This number will increase to three months after the underground storage reaches full capacity allowing to utilize Marshal Vasilevskiy for commercial operations and to sail it back to Kaliningrad when needed.[46] On top of that, Russia is also building Portovaya LNG plant in the Leningrad region that will provide LNG for Kaliningrad if required.[47] After multiple delays, Russia should finish the plant next year.[48]

Energy security, however, came with the price-tag. Russia has invested 37.2 billion roubles (412 million euros) in strengthening the ties between the North-West and the Central regions of the IPS/UPS.[49] Besides, Russia spent approximately 1.3 billion euros for the construction of additional generation capacities in Kaliningrad[50] and 800 million euros on the Marshal Vasilevskiy FSRU.[51] Even though Russia moved quicker than Lithuania, Latvia and Estonia, its investments in Kaliningrad alone (2.1 billion euros) have substantially exceeded the estimated costs of the whole Baltic synchronization project (1.5 billion euros).[52]

It means that by the end of 2020, Kaliningrad finds itself in an ambiguous position. Additional generation capacities lived up to the expectations[53] as two consecutive tests have shown that Kaliningrad is capable of operating autonomously. Looking from the economic perspective, Russian investments in Kaliningrad's energy security were enormous. It is important to note here that Russia decided to make substantial investments in Kaliningrad's energy system not because the European Union and the Baltic States forced the Moscow to make them, but because Russian leadership chose to do so. The Baltic States, European Commission and Poland maintain that they will guarantee system services for Kaliningrad's power system if they are proven necessary to the functioning of the system.[54] At the same time, JRC's had more cost-effective suggestions for the development of the Kaliningrad's power system, and even its proposal for its autonomy was significantly cheaper than the actual Russian project.

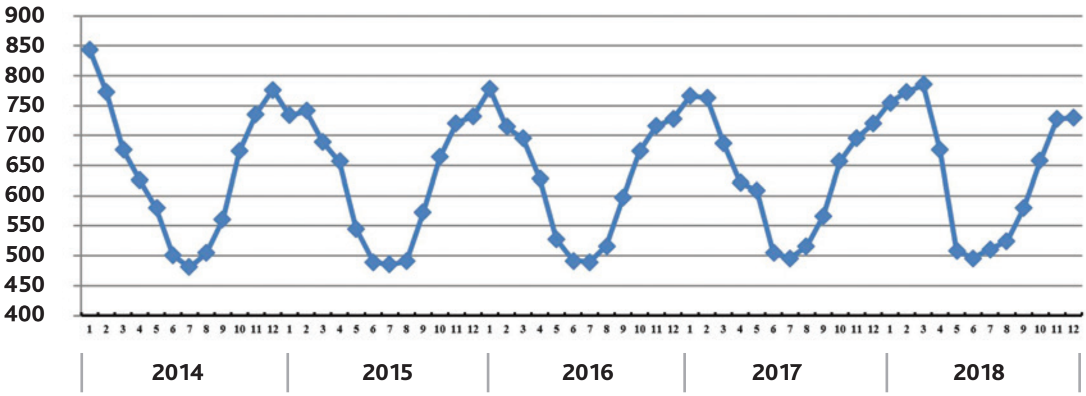
KEEPING ELECTRICITY TRADING ROUTES OPEN

Given the following discussion, one can reasonably make a case that investments in Kaliningrad's strategic energy infrastructure will be one of the drivers in steering Kremlin's policy towards persuading the Baltic States and the EU to maintain trade between Russia and the Baltic States. Even though Kaliningrad is important, but it is not the only factor explaining why Russia continues to be interested in maintaining electricity trade with the Baltic States. In here, one should also consider the usual suspects. First, maintaining electricity trade with the Baltic States is a rather large and profitable business. Second, keeping electricity trade helps to maintain a degree of Baltic dependence from Russia. In this section, the paper analyses all three factors simultaneously.

Starting from Kaliningrad, Russia cannot find much use for the majority of its power generation capacities for most of the time. The data shows that Kaliningrad's peak demand (heavily influenced by the weather conditions) can reach between 700 and 800 MW during the winter months, between 600 and 700 MW during spring and autumn and only around 500 MW during the summer. It means that during spring and autumn, Kaliningrad will never utilize more than approximately 37 % of its generation capacity to cover the peak electricity demand. During the summer, this number will decrease to around 25 %. During the winter, it can increase to roughly 40 %. For most of the time, however, the load will be significantly smaller as the percentages mentioned above only indicate the maximum demand and does not deal with daily averages (please see graph 2).

Currently, Russia can mitigate the generation surplus to a certain extent by exporting electricity to the Baltic States (600 MW capacity for trading purposes is available on Lithuanian – Kaliningrad border). In 2019 alone, Kaliningrad exported 2,623 TWh of electricity to Lithuania, a number that constitutes more than half of its annual electricity demand. Due to this reason, Russia continues to be interested in exporting Kaliningrad's surplus electricity to the Baltic States after they synchronize with CEN.[56]

2 Graph. Monthly peak demand in Kaliningrad, 2014 – 2018.



Source. The Governor of the Kaliningrad Region.[55]

Maintaining electricity trade is also important for Russia because of the volume and financial gain that this operation brings. In 2019, Russia exported 6,377 TWh of electricity to Lithuania (3,754 TWh indirectly through Lithuanian – Belarusian interconnections and 2,623 TWh directly through Kaliningrad),[57] making it the second most important export market for Russia (please see the second table).[58] Russian electricity export to Lithuania constitutes about 1/3 of its total electricity exports (19,338 TWh). In 2019, Inter RAO's revenue from electricity trading in Lithuania amounted to 20.5 billion roubles (226 million euros) also constituting a significant portion of its total revenue (77 billion roubles – 770 million euros) from electricity trading.[59]

The last point concerns the energy independence of the Baltic States. In general, Russia aims to maintain a foothold in the Lithuanian, Latvian

2 Table. Russian electricity exports by country and year

Indicator	**2019**	**+/-**	**2018**	**2017**	**2016**	**2015**	**2014**
Export, billion kWh	**19.338**	**+15.7%**	**16.711**	**+15.7%**	**17.002**	**17.492**	**14.044**
Finland	7.023	+1.7%	6.903	+1.7%	5.2816	3.383	2.995
China	3.099	-0.3%	3.109	-0.3%	3.320	3.299	3.376
Lithuania	6.286	+42.4%	4.415	+42.4%	3.019	2.995	3.216
Belarus	0.031	-3.7%	0.049	-3.7%	3.181	2.815	1.425
Kazakhstan	1.437	+6.7%	1.347	+6.7%	1.164	1.542	1.644
Georgia	0.525	+154%	0.206	+154%	0.369	0.511	0.607
Mongolia	0.372	-10.5%	0.416	-10.5%	0.3	0.284	0.39
Azerbaijan	0.091	+19.3%	0.076	+19.3%	0.0596	0.055	0.053
Other	0.474	149%	0.19	149%	0.2716	2.608	0.318

Source. Inter RAO[60]

and Estonian energy systems. Having a strong presence in the Baltic electricity import structure, Russia can indirectly influence electricity generation patterns in Lithuanian, Latvia and Estonia. It is easier for Russia to compete with the indigenous power generation in the Baltic energy market as the country does not have to follow EU's environmental regulations. As a case in point, EU CO2 emission dues constituted 50% of the overall cost the electricity generated from the fossil fuels in Estonia in 2018, making it uncompetitive with Russian electricity.[61] Russia's competitive edge also makes it harder to justify building new generation units in the Baltic States and creates possibilities for shaping a negative public attitude towards strategic Lithuanian, Latvian and Estonian energy projects.

Given the following reasons, it seems natural that the Kremlin will safeguard its electricity trading routes between Russia and the Baltic States. To a certain extent, Russia is already starting to oppose Lithuanian, Latvian and Estonian regulations. The Baltic TSOs have recently prepared a new methodology for electricity trade with the third countries to better prepare for preventing the Belarusian electricity from entering their market after the launch of Ostrovets NPP. The revisions of the methodology also influence the Baltic electricity trade with Russia. The methodology relocates trading with continental Russia from the Lithuanian – Belarusian power lines (1300 MW capacity) to the Latvian – Russian interconnection reducing the trading capacity to approximately 600 MW.[62] So far, the methodology reduces the maximum trading capacity on Latvian – Russian border by 38 %, but the discussions are underway to lower it even further. For example, the National Energy Regulatory Council of the Republic of Lithuania[63] and Eesti Energia suggest that the capacity should be decreased by 72 %,[64] thus potentially reducing it to 266 MW.[65]

Responding to the new methodology drafted by the Baltic TSOs, Russian energy minister Alexander Novak called upon Lithuanian energy minister Žygimantas Vaičiūnas to revise the regulations regarding the electricity trade with third countries in October 2020. He requests to remove the 38 % reduction.[66] Lithuanian counterpart, however, replied that such Russian position shows that the Baltic States are working in the right direction and is not planning to make concessions. Inter RAO Lithuania have also joined the Russian official by asking not to reduce the trading capacity on the Latvian – Russian border.[67] If Russia opposes the slight reduction of the trading capacity now, it will continue to push for keeping the electricity trading routes open after the Baltic States will join CEN. The question remains, however, how can Russia persuade the Baltic States and the EU to change their mind?

INSTRUMENTS OLD AND NEW

In making its case for the electricity trade, Russia will likely proceed in the following fashion. First, it will try to persuade the general public and the critical decision-makers in the Baltic States that removing electricity trade with the third countries is a wrong decision from an economic point of view. Second, it will try to use the diplomatic instruments by making the case that removing electricity trade will be disadvantageous to Russia and especially to the Kaliningrad region. The third tool is geopolitical blackmail that stems from Russia's chronological advantage in preparing for the desynchronization of the Baltic States from the IPS/UPS.

Framing negative public opinion towards strategic Baltic energy projects has a longstanding tradition in Russian energy geopolitics towards Lithuania, Latvia and Estonia. From the construction of LNG terminal Independence to the implementation of the Visaginas NPP project, Russia was consistent in trying to discredit the need for such projects and aiming to prevent their construction by proposing itself as an alternative. In doing so, Russia framed its energy supply as economically beneficial to the Baltic end consumers, while denouncing potential energy infrastructure upgrades in Lithuania, Latvia and Estonia as economically detrimental and irrational. Given its competitive edge in the Baltic electricity market, Russia will continue using such tactics by trying to persuade the general public in the three Baltic countries that maintaining electricity trade with the third countries serves their interests. As the Lithuanian security services point out, Russia will utilize all available tools at its disposal to frame a negative public opinion regarding the projects that increase the energy independence of the Baltic States from Russia.[68]

The effectiveness of such framing largely depends on three factors. First, the general economic situation in the Baltic States as the extent of damage caused by the COVID-19 will only be exact in the years to come. The worse is the economy in the Baltic States; the easier it is for Russia to spread its message across. Second, the extent and the quality of the information provided by the Lithuanian, Latvian and Estonian authorities explaining why it is necessary to discontinue the electricity trade with the third countries. As the Lithuanian Energy Security Research Centre (ESRC) points out, the more consistent and frequent is the communication regarding energy policy, the more support from the society the governments can muster.[69] Third, it is the political unity among the Baltic States. In principle, it is enough to persuade one Baltic country to establish asynchronous interconnections with Russia to maintain electricity trade after they will join CEN.

Russia will also continue to lobby Brussels in an attempt to safeguard its electricity trade with the Baltic States as the political sensitivity surrounding Lithuanian, Latvian and Estonian withdrawal from the IPS/UPS mostly stems from the Kaliningrad question.[70] Even after Russia showed that Kaliningrad could function independently from the rest of IPS/UPS, ENTSO-E still follows closely how the Baltic synchronization project will impact Kaliningrad's power system. In the August draft version of the 2020 Regional Investment Plan Baltic Sea, ENTSO-E claims that 'one of the most serious challenge standing in the way of the synchronization project development is the unclear solutions regarding the operation and status of the Kaliningrad electrical enclave. This issue will require a lot of political willpower and might influence the technical outcomes and schedule of the synchronization process'.[71] It remains to be seen, however, what specific arguments advocating for the extension of electricity trade with the Baltic States Russia will bring to the table having in mind two successful independent operations' tests in Kaliningrad.

The final Russian tool is geopolitical blackmail – threatening the Baltic States with premature desynchronization. Given the infrastructural upgrades in the North-Western and Central parts of IPS/UPS and Kaliningrad, Russia can disconnect its Baltic neighbours and to do so in compliance with the procedures outlined in the BRELL agreement. The document binds its signatories (the Baltic, Russian and Belarusian TSOs) to inform about the intention to withdraw from the Agreement six months in advance and to coordinate the steps of withdrawal. The remaining parties cannot prevent the withdrawing party from discontinuing the agreement, and they cannot demand any compensation from the withdrawing party.[72]

Russia can use its chronological advantage in another course of action – unexpected desynchronization of the Baltic States from the IPS/UPS. In doing so, Russia can choose to maximize the damage and to desynchronize the Baltic States when their largest generation units or major interconnections are undergoing scheduled maintenance, or they are not working due to other reasons. If pursued, such an action could lead to a blackout in Lithuania, Latvia and Estonia that would cause socio-economic damage of majestic proportions. For example, Elering maintains that a three-day blackout in the Baltics would cost €2.3 billion[73] not to mention other national security issues it would cause.

It is not to say, however, that Russian decision to desynchronize the Baltic States prematurely will not have high political and economic costs for the Kremlin. Nor it is to argue that Russian attempt to desynchronize the Baltic States before 2025 is likely. Premature desynchronization would cause political resonance that would hurt the prospects of implementing other strategic energy projects abroad, especially in the EU. Even if Kaliningrad is capable of functioning as an isolated power system, its stand-alone operation will cost more.[74] It is only to say that Russia can exploit its infrastructural readiness in advancing its case for electricity trade, depending on the underlying geopolitical and economic circumstances.

THE OSTROVETS' FACTOR

Belarus shares Russia's interest in maintaining electricity trade with the Baltic States that mostly emanates from the recent launch of the first unit of Ostrovets NPP and the undergoing construction of the second one (installed generation capacity in each reactor is 1200 MW). In here, it is essential to note that Belarusian electricity production exceeds its demand since 2018 even without launching Ostrovets NPP. Initially, Belarus exported its surplus electricity generation to Lithuania and Ukraine and planned to expand its foothold in these markets once Ostrovets NPP is fully operational. Despite such ambitions, Ukraine has decided to halt its electricity imports from Belarus in 2020 due to fallen electricity demand during the COVID-19 pandemic. Lithuania, on the other hand, enforced its law banning electricity trade with Belarus after Ostrovets NPP became operational, while Latvia and Estonia eventually made a respective political commitment.

With Lithuanian, Latvian, Estonian and Ukrainian markets closed for the time being, the future outlook does not look promising for Belarus either. On the one hand, the upcoming shrinkage of the IPS/UPS will not allow Belarus to circumvent the Baltic ban on its electricity by camouflaging it as Russian in the future. On the other hand, a similar process is taking place on Belarus' southern border. Moldova and Ukraine will synchronize with CEN by 2023 putting the southern export route in permanent jeopardy. Current interconnections on Belarusian – Ukrainian border (Chernobyl NPP – Mozyr and Chernihiv – Gomel)[75] allows maintaining 900 MW trading capacity. Still, they will cease to function after Ukraine's synchronization with CEN unless Belarus and Ukraine agree to construct converter stations, thus maintaining their functionality.

Even in the absence of trade restrictions, electricity produced in Ostrovets NPP can hardly compete with the market prices in the Baltic States that were rarely higher than 5 euro cents/kWh over the last five years. Russian and Belarusian experts have estimated that the electricity produced by Ostrovets NPP should cost 7.7 euro cents/kWh to break even.[76] Such a price would be sufficient to cover the capital costs, operating, maintenance and nuclear fuel during the lifetime of a nuclear power plant. In such a setting, Belarus could only sell its generation surplus to the Baltic States for a price that is significantly below the estimated generation costs, thus failing to make a profit.

One can make the case, however, that the actual generation cost will be somewhat cheaper. Belarus have recently managed to lower the capital costs of Ostrovets NPP (the main component of the total cost structure for the nuclear generation) by renegotiating the terms of Russia loan. The original agreement between Russia and Belarus regarding the 10 billion US dollar loan for Ostrovets NPP established two separate interests' rates. One half of the loan had a fixed annual interest rate of 5.23% while the other half had a fixed annual interest rate of 1.83% plus a six month USD LIBOR interest rate. Under the conditions of the agreement, Belarus had to start repaying the loan in April 2021 and to return it in full by 2036. On 14 July this year, however, Russian and Belarusian prime ministers have renegotiated the terms. First, the parties agreed to change the interest rate to 3.3 % for the entire loan. Second, Belarus persuaded Russia to postpone the start of the repayment until April 2023.[77]

Given the current political and economic circumstances, Belarus has one card to play in advancing its electricity exports to the Baltic States that mostly stems from the distribution of expenditures between Russia (9/10) and Belarus (1/10) in building Ostrovets NPP and the loan repayment schedule. Since the majority of spending on Ostrovets NPP are so far Russian and Belarus will start repaying its loan only in April 2023, Belarus can temporarily offer an electricity price that mostly does not account for its capital costs. To put this argument in perspective, one should remember the case of Ignalina NPP. During its operations, the Lithuanian NPP generated electricity for slightly cheaper than 2 euro cents/kWh.[78] The price was so low because the capital costs were absent as the Soviet Union built the NPP. Similarly, the Belarusian authorities will be capable of temporarily operating the first unit of Ostrovets NPP with negligent capital expenditures that allow baiting the Baltic States to rethink their trade restrictions. It is clear, however, that Belarus will not be able to sustain such a price for a long time.

Another widely discussed possibility for the Belarusian electricity to enter the Baltic market is to camouflage it as Russian with Inter RAO working as an intermediary for its sales.[79] Even though such a tactic is possible in principle, it faces several limitations. With the shrinkage of the trading capacity between the Baltic States and Russia due to the new trading methodology that relocates the trade on the Latvian – Russian border, Russia should prioritize its own electricity exports as opposed to worrying about the Belarusian energy producers. In here, it is crucial to consider that both continental Russia and Kaliningrad has generation surpluses. At the same time, the trading ban on Belarusian electricity does not change Minsk's obligations to repay the loan.

On the other hand, Inter RAO Lithuania became quite vocal in making the case that the company is not going to be involved in any electricity trading schemes with Belarus as it views Ostrovets NPP as a competitor. The company also considers the risks of losing a trading license because of smuggling Belarusian electricity.[80] Belarusian and Russian prime ministers Mikhail Mishustin and Roman Golovchenko discussed the issue of Ostrovets NPP in September 2020.[81] Still, it remains unclear wherever Russia will help Belarus to circumvent the Baltic electricity ban as it should prioritize its interests, leaving Belarus alone in its attempts to persuade the Baltics in opening the electricity trade.

DISCUSSING THE BALTIC RESPONSE

Having outlined the interests of the Lithuanian, Latvian and Estonian neighbours, it is time to consider how they can best protect the synchronization project from foreign meddling. The most immediate assignment for the Baltic States is countering Russian capabilities to use geopolitical blackmail. In doing so, the Baltic States must better prepare to operate their power systems independently from IPS/UPS, test their readiness and do to it as quickly as possible.

Initially, the Baltic States were supposed to perform an isolated system test in June 2019. Despite the previously agreed date, Latvian and Estonian TSOs decided to delay the testing as were there some doubts regarding its success (the official reason for postponement – similar test in Kaliningrad that took place a few weeks earlier).[82] The trial would have allowed to scrutinizing the weaknesses and strengths of the Baltic power systems in practice. The failure to perform the joint test means that the Baltic States have accumulated limited field experience in maintaining their power networks independent of Russia.

The Baltic States, Belarus and Kaliningrad tested their joint ability to operate independently from the IPS/UPS in April 2002. At that time, however, Baltic States' energy systems were different from the contemporary ones, and they conducted the test together with third countries and their territories.[83] Lithuania and Estonia have also gathered some experience on the national level. Estonia has separated sections of its power grid in November 2006 and April 2009,[84] while Lithuania conducted similar tests in May 2019 and August 2020.

For example, just a week before Russia tested Kaliningrad's power system, Lithuanian TSO Litgrid created a couple of energy islands in the national power grid by desynchronizing them from the IPS/UPS. During the test, Lithuanian generator units maintained the system frequency in the selected islands with the assistance of converter stations on HVDC lines LitPol link and NordBalt. After the trial, Lithuania successfully reconnected the artificial energy islands with IPS/UPS.[85] Lithuania repeated a similar test one year later. The results of Lithuanian tests are promising, but they were during the weekends, thus sparing the dispatch from dealing with the full magnitude of challenges. Moreover, they cannot serve as a replacement to the joint isolated system test of the Baltic States that will involve disconnecting all power lines interconnecting them with Russia (including Kaliningrad) and Belarus.

Recent Plan of Measures for Strengthening the Independence and Reliability of the Electricity System of the Republic of Lithuania provides a blueprint on how the Baltic States can nullify Russia's political pressures. The document calls for strengthening the joint emergency preparedness by taking a couple of essential steps. First, making multilateral political agreements with Finland and Sweden regarding their assistance in case of an emergency in the power system. Second, preparing for emergency synchronization with Poland. Third, conducting an isolated system test not later than 2023 as opposed to just barely making the deadline in 2025.[86]

By setting these goals, Lithuania aims to lead by an example. Lithuanian Government seeks to be ready for synchronous emergency operation with the Polish energy system in the first half of 2021 as the necessary upgrades for the LitPol link interconnection are underway. Until the end of the same year, Lithuania plans to test its capabilities to work synchronously with Poland. In parallel, Lithuania will work towards strengthening its capabilities to work in an isolated mode individually by blowing the dust of its older power generation capacities and investing in electricity storage. For this purpose, Vilnius will restore the capabilities of 7th and 8th units of the Lithuanian power plant in Elektrėnai (600 MW total generation capacity) and the first unit of the 3rd Vilnius power plant (180 MW). Both power plants can use heavy oil and natural gas for electricity generation. Besides, Lithuania will integrate a battery system capable of storing 200 MWh of electricity. By the end of 2022, these measures should lead to Lithuania conducting a national isolated power system test.[87]

Not having to worry about premature desynchronization, the Baltic States can better defend its interests. As far as the electricity trade is concerned, the Baltic States are capable of decreasing Russian presence in their electricity market and to better prevent the 'smuggling' of Belarusian electricity. For one thing, the Baltic States can gradually lower the trading capacity between Latvian and Russian border and the discussions are already underway. Lithuania, Latvia and Estonia can also proceed in implementing the long-discussed infrastructure tax on the electricity imported from the third countries that are not subject to EU's environmental regulations. The combination of these measures allows for achieving three results. First, further reduction of trading capacity on Latvian and Russian border makes it much harder for Belarusian electricity 'contraband' to enter the Baltic market. Smaller trading capacity forces the Kremlin to choose between exporting national electricity surplus and helping Belarus to sell its electricity by disguising it as Russian. In here, one can make a reasonable argument that such a bottleneck would result in Russia choosing the former. Second, reducing trading capacity smoothens the Baltic transition to the total elimination of electricity trade with Belarus and Russia by 2025. Third, the proposed infrastructure tax on Russia will mitigate is a competitive advantage and create fairer conditions in the electricity market.

Last but not least, the Baltic States should learn from the experience (Visaginas NPP, LNG terminal, unconventional hydrocarbons, etc.) and develop a coherent public information strategy that clearly explains why specific decisions in relation with the synchronization project are necessary. Naturally, they should emphasize the electricity trading questions, emergency preparedness and Ostrovets NPP. Suppose the Lithuanian, Latvian and Estonian governments will not devote sufficient resources for public relations. In that case, their societies will seek alternative information sources and Russia and Belarus will be more than happy to provide them and thus take the initiative in organizing the public debate in a manner that serves their interests.

Hence, just as Russia and Belarus have specific tools in advancing their national interests, the Baltic States have the necessary instruments to counter their pressure. In here, emergency preparedness, electricity trade regulations, and consistent public communication are vital in protecting the synchronization from foreign meddling.

CONCLUSION

The paper shows that the Baltic States are consistently getting closer to achieving a historic feat – synchronizing their power systems with the Continental European Network. What not so long ago seemed as a distant political ambition now resemble a coherent energy project. With the European Union and Poland supporting the Baltic plug to the European energy system, the project continues to gain momentum.

Russian and Belarus, however, will continue to put pressure on the Baltic States to keep the electricity trade open. In advancing such an interest, Russia will combine diplomatic means with misinformation and threats, while Belarus will argue that importing electricity from Ostrovets NPP is beneficial for the Baltic States.

The Baltic States, however, are capable of responding to the threats posed by Belarus and Russia if it proceeds in four steps. First, the Baltic States need to boost emergency preparedness that mitigates Russian capabilities to desynchronize them prematurely. Second, the Baltic governments should consider further decreasing trading capacity on the Latvian – Russian border as this would make Belarusian electricity smuggling much harder and provide a transition period to full decoupling in 2025. Third, to introduce the long-debated electricity infrastructure tax to make the competition between the Baltic and Russian power generation fairer. Finally, the Baltic States should not neglect public communication and explain the particularities of the synchronization to their citizens.

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