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Beyond the era of fossil fuels

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Editorial

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The latest NATO Declaration from Brussels in July 2018 reinstated the importance of energy security in the common security of NATO. The need for stable and reliable energy supply, the diversification of routes, suppliers and energy resources, and the interconnectivity of energy networks, were highlighted as critical importance.

Energy systems across NATO nations are in the process of transformation quite unseen since the industrial revolution. Promising results from Italy, where renewable energy capacity has grown from a mere 1.7 GW in 2000 to 34.5 GW in 2017 (and is expected to grow to 63.4 GW in 2030!), from the UK, where wind already creates on an optimal day a third of the electricity used in the Great Britain electricity system, or from Germany, where renewable energy sources have overtaken coal as the most important power source, show that we are on a steady path toward an era beyond the fossil fuels.

Transforming energy systems requires not only production capacity, but also distribution, demand-side flexibility, and energy storage. With companies such as Veolia in France, who focus on the commercial-based recycling of solar panels, we can hopefully cut some of the import dependency of monopolistically produced rare earth minerals and materials that the renewable energy industry requires. The recent successful implementation of Tesla big battery in Hornsdale, Australia, shows that technology developments are happening faster than most people can even imagine.

In a post-fossil fuel era, research and development is required on various different means of energy production. NATO partners across the globe, such as Japan, are ambitious in pioneering as a "hydrogen society". The vision in Tokyo is that hydrogen can be a decisive response to the country´s energy and climate challenges. One of the articles in this Operational Highlights provides an overview of hydrogen as part of a resilient energy strategy for NATO defence.

This monumental change is also visible within NATO militaries. Promising examples from the US military bases in Mississippi, California, and Massachusetts show the integration of solar and wind-powered micro grids to support the bases and provide them energy independency and security.

In the military sphere, NATO ENSEC COE has had a continuous positive input in enhancing renewable energy applications in the military. The fourth Innovative Energy Solutions for Military Applications (IESMA2018) held in Vilnius gathered a new record number of participants from various NATO and Partner nations, who showcased the numerous ways NATO and its members are already deploying renewable energy sources and storage options in the operational theatres. Especially the strong support from industry has convinced us that there is a huge potential for innovative energy solutions for military in the future.

But as a NATO Energy Security Centre of Excellence, we also carry our responsibility in monitoring and analysing regional and global developments in our field. As promising as the future looks, NATO nations need to stay awake and vigilant. This edition of Operational Highlights is set to help succeeding in exactly that – three of the articles play the devil's advocate in looking at the different risk factors our transforming energy system might bring forth.

We introduce a methodology of different risks that academia has identified as future risk factors, and then ask various country representatives to assess their countries' preparedness against these threats. We also have a closer look at the renewable energy infrastructure vulnerabilities, especially those related to cyber-threats. Lastly, we provide an overview of the recent R&D done on hydrogen fuel cells in the military domain – an area of development we are sure will gain more popularity in the coming years.

Changing security aspects for future energy systems:

Renewable energy and possible risks at the local, regional, and global levels

by Ms Julia Vainio

RENEWABLES WILL CHANGE THE ENERGY SECURITY LANDSCAPE IN THE FUTURE

In the energy domain, the increase in the use of of Renewable Energy Sources (RES) is usually portrayed as the ultimate goal for nations to strive towards. They provide means of diversification and energy independency for nations.

However, in the last few years, discussion has risen on the possible threats that might emerge alongside the expansion of renewables in the global energy sector. These changes do not happen radically or overnight. They develop over time as energy sectors gradually change from the phasing out of fossil fuels to the phasing in of renewable technologies.

The evolution of energy sectors in incorporating renewables varies already considerably among nations, and the trend is only set to continue. Energy production from RES is estimated to increase globally by two and a half times the current amount by 2040, based on the two degrees Celsius target of limiting the rise in global temperature [1]. NATO Alliance and Partner Nations are in the forefront of deploying RES in their power production. Developments in the energy sector will also change the geography of energy production, as more importance is put on optimizing the production of RES in the countries where that energy is consumed [2].

This article focuses specifically on the electricity production side of renewable energy utilization.

By renewable energy, we adhere to the International Energy Agency's (IEA) definition of RES:

"Energy derived from natural processes (e.g. sunlight and wind) that are replenished at a faster rate than they are consumed. Solar, wind,

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geothermal, hydro, and some forms of biomass are common sources of renewable energy." [3]

This review article has two main functions. First, to increase awareness about a set of possible threats to nations and regions that the academic literature, as well as various recently published policy papers, have identified. It comprises different threats to nations and regions associated with the increase of RES on a general scale.

Second, it also identifies new threats and ways in which these threats could be categorized. The methodology can act as a future reference point for extended country or region specific analyses.

The topic is divided into different dimensions; risk factors on the local, regional and global scale. The factors are further categorized as being either economic and political risk factors, technical risk factors, or environmental risk factors.

The categorisation follows loosely the themes presented in the most recent NATO Allied Command Transformation Strategic Foresight Analysis report [4], where the characteristics of the future of warfare were classified into the following chapters; political, human, technology, economics or resources, and environment. The purpose of this article is not to act against implementing new energy sources and technologies, but to prepare NATO Alliance and Partner Nations for the future.

CATEGORISATION OF IDENTIFIED RISKS; LOCAL, REGIONAL AND GLOBAL RISKS

Some of the identified risks have overlapping qualities and they can be categorized into several different categories. For the purposes of clarity, we have categorised each risk only once and assigned it to the category where its risk profile could be seen as most notable.

Local risks

Local level energy systems can be imagined as those means of power production that serve a certain group of end-users near the production site. A wind power park producing electricity for a near-by village is an example of a local level energy system.

Regional risks

A regional level energy system could be an offshore windfarm or a hydropower station that produces electricity for the national transmission grid, which then distributes it on a regional basis.

Global risks

Even though global energy systems are most often understood as involving fossil fuel driven markets, electricity produced by using RES can have global risks as well. Power units producing renewable energy are significantly more metal intensive than power units producing energy from fossil fuels, and the raw materials required to produce these power units are often highly concentrated on certain geographic regions and countries [5] [6]. As demand for these materials grows, it might create new political capital for those countries that have them. For example, the European Commission has identified raw materials as critical assets for the European Union in terms of the supply risks and their economic importance. [7]

CATEGORISATION OF IDENTIFIED RISKS: ECONOMIC AND POLITICAL, TECHNOLOGICAL, AND ENVIRONMENTAL RISKS

Economic and political risks

Economic and political risks mainly deal with questions on policy decisions with regards to energy strategies: how is the system able to adapt to new small scale producers and local grids; what will the reduced security of demand mean to traditional energy exporters, and how are different nations able to finance the investment heavy energy sector transformation.

In most NATO nations, significant renewable energy investments are done in a market environment where the investor is expecting a certain Return of Investment (ROI) for their product. Along with several other variables, such as market competition and the current regulatory environment, this expected ROI plays a part in determining what sort of power generating assets to build and where. Just like with fossil fuel power generating units, and with renewable units such as hydropower plants, Photovoltaic (PV) cells, and wind turbines, there is a constant trade-off between the best possible geographical location, the best possible building materials, and the ROI wanted from the project. This might mean that the investor or company is more willing to cut costs on the mechanics or grid connections of wind turbines, or neglect the security measures of industrial control systems of these power-producing units in order to increase their expected short-term profit from the project.

Technological risks

Identified technological risks focus on base-load issues; what happens when more RES with intermittent power producing capabilities are introduced into the electricity system; the adequacy of storage capacities; long distances between producing power units and markets, and on technological uncertainty.

In order to maintain grid reliability, the European Network of Transmission System Operators for Electricity (ENTSO-E) has estimated that the increase of RES in Europe by 2030 will require around 150 billion euros in investments to grid infrastructure alone [8]. To elaborate on the issue, Germany has spent an estimated 189 billion euros since 2000 on its energy transition known as the 'Energiewende' that is set to transfer its energy sector [9]. The heavy investments needed for the transformation of energy systems can create further divergence and inequality between neighbouring nations or regions, as one country or region might have the resources and political will to advance the transformation of their energy system, whereas the other might not.

Especially in NATO and EU countries, most of the hydropower capacity available is already in use. This would mean that most of the growth would have to come from other RES, such as wind, solar, and biofuels. As wind and solar power provide the greatest potential for the required growth, the electrification of the energy system is a likely future outcome. [10] This would essentially require sectors like transportation to switch from carbon-based fuels to electric vehicles and means of transportation.

Environmental risks

Identified environmental risks include possible negative public perception towards increasing the land-area to allow more RES such as wind turbines to be constructed or biomass plantations to be grown; or environmental regulations that might prohibit the building of additional grid infrastructure or mining sites required to mine rare earth minerals.

Another future risk factor will be the recycling rate of renewable energy supplies. Traditional fossil fuel plants such as coal fired turbine plants might have a lifetime of around 40 years, whereas nuclear power plants can be utilised for 60 years on average [11]. The average technical lifespan of a hydropower plant varies from 40–150 years with easily replaceable mechanical or electrical parts requiring maintenance anywhere from 15–70 years [12]. At the same time, an average lifespan of a wind turbine is around 25 years. Given the high number of rare earth minerals and other critical materials needed to produce wind turbines and PV cells, the life cycle assessments and recycling rates of these units need to be given top priority.

METHODOLOGY TO ASSESS SECURITY RISKS IN THE FUTURE

Table 1 compiles a list of risk factors in relation to the future of renewables. The risk factors have been analysed according to recommendations made within the academic literature. The table presents the risks in three categories in columns (economic and political, technological, environmental), mapped against categories in three different rows (local, regional, global). This article does not differentiate between the geographical scopes of the referenced academic research or policy papers. Some of the identified risk factors might not be relevant for all NATO nations.

Risk factors / Geographical scope	Economic and political risk factors	Technological risk factors	Environmental risk factors
Local	• Lobbying both for and against renewables – the risk of uninformed policy decisions [13] • Corruption – the risk of uninformed policy decisions • Social unrest where large scale biomass plantations might substitute small-scale farming [14]	• Lower grid reliability [15] • Base-load issues • Compromised cyber security of individual electricity producing units	• Environmental regulations prohibiting new grids, building sites or mining • NIMBY[2] people
Regional	• Subsidization of RES might lead to market distortions or creation of a new market that disrupts the current system [16] • The level of resilience of the interconnected system to large-scale terrorist attacks or sabotage	• Inadequate storage capacity [17] • RES usually located elsewhere to where the need or consumption is • Potential targets for terrorist groups [18] • Cyber-attacks on the grid or power producing units	• Threats to biodiversity [19]
Global	• Investment heavy sector – resources for Research and Development (R&D) needed, which might produce more winners and losers [20] • Weakened security of demand for fossil-fuel based energy exporters [21] • Scarcity of critical resources [22] • Limited supply chain of critical resources • Violations of intellectual property rights [23]	• Technological uncertainty [24]	• Environmental risk factors related to non-energy resources, such as mining of rare earth minerals • Need for an increased recycle rate of RES

Table 1 Energy-generated threats that could arise from the implementation of RES to electricity systems divided by risk factors and geographical scope. Inspiration from the work of Bengt Johansson [18]. The list is not exhaustive.

[2] "Not In My Backyard" people, often describes a group of people who in principal support a certain decision as long as it does not have any consequences in their lives.

CONCLUSIONS

In the future, the energy systems of NATO Alliance and Partner Nations will go through significant changes. The societies will adapt to more low-carbon based economies that will have global as well as local level consequences. These consequences can be both positive and negative.

Changes towards more RES based energy systems have several positive benefits and there is significant political will behind them. However, the security environment will continue to evolve as new risk factors and threats follow from the systemic changes in how we produce and use energy. In order to better adapt to the changing energy environment, NATO Alliance and Partner Nations must understand these changes.

In today's world, energy - and especially electricity - pertains in every aspect of society. Understanding the interdependencies of risk factors associated with RES and being aware of how they might affect individual NATO nations or the Alliance as a whole will enable NATO to better prepare itself against future operational challenges.

REFERENCES

[1] Semkin, Nikita, Lyyra, Satu, and Olli Sipilä. "Global energy sector transitions will have an impact on geopolitics." Prime Minister's Office, Policy Brief: Government plan for analysis 14/2017. September 11, 2017. https://tietokayttoon.fi/julkaisu?pubid=21501

[2] Stang, Gerald. "Shaping the future of energy." European Union Institute for Security Studies. July 2016. https://www.iss.europa.eu/sites/default/files/EUISSFiles/Brief_24_Energy.pdf

[3] International Energy Agency website. "Renewable Energy." https://www.iea.org/about/glossary/

[4] NATO Allied Command Transformation. Strategic Foresight Analysis report. (2017). http://www.act.nato.int/images/stories/media/doclibrary/171004_sfa_2017_report_hr.pdf

[5] Kleijn, René, van der Voet, Ester, Kramer, Gert Jan, van Oers, Lauran, and Coen van der Giesen. "Metal requirements of low-carbon power generation." Energy: 36 (2011):5640–5648.

[6] Semkin, Nikita, Lyyra, Satu, and Olli Sipilä. "Global energy sector transitions will have an impact on geopolitics." Prime Minister's Office, Policy Brief: Government plan for analysis 14/2017. September 11, 2017. https://tietokayttoon.fi/julkaisu?pubid=21501

O´Sullivan, Meghan, Overland, Indra, and David Sandalow. Working paper: the Geopolitics of Renewable Energy. Center on Global Energy Policy, Columbia University and the Geopolitics of Energy Project, Harvard Kennedy School. June 2017. https://www.hks.harvard.edu/publications/geopolitics-renewable-energy

Johansson, Bengt. "Security aspects of future renewable energy systems – a short overview." Energy 61, (2013): 598–605.

[7] European Commission, DG Enterprise and Industry. "Report on critical raw materials for the EU: Report of the Ad hoc Working Group on defining critical raw materials." November 08, 2013. https://ec.europa.eu/growth/tools-databases/eip-raw-materials/en/community/document/critical-raw-materials-eu-report-ad-hoc-working-group-defining-critical-raw

[8] The European Network of Transmission System Operators for Electricity (ENTSO-E). "Ten Year Network Development Plan Executive Report". 2016. https://tyndp.entsoe.eu/

[9] Reed, Stanley. "Germany's shift to green power stalls, despite huge investments." The New York Times, 7.10.2017. https://www.nytimes.com/2017/10/07/business/energy-environment/german-renewable-energy.html

[10] Davidsson, Simon. Doctoral thesis: "Natural resources and sustainable energy.

Growth rates and resource flows for low-carbon systems." Digital Comprehensive Summaries of Upspsala Dissertations from the Faculty of Science and Technology. 2016. Uppsala: Acta Universitatis Upsaliensis.

[11] Semkin, Nikita, Lyyra, Satu, and Olli Sipilä. "Global energy sector transitions will have an impact on geopolitics." Prime Minister's Office, Policy Brief: Government plan for analysis 14/2017. September 11, 2017. https://tietokayttoon.fi/julkaisu?pubid=21501

[12] Karin Flury, and Rolf Frischknecht. "Life Cycle Inventories of Hydroelectric Power Generation." Öko-Institute e.V. 2012. http://esu-services.ch/

[13] Paltsev, Sergey. "The complicated geopolitics of renewable energy." Bulletin of the atomic scientists, 72:6. (2016): 390–395.

[14] Van den Horst, Dan, and Saskia Vermeylen. "Spatial scale and social impacts of biofuel production." Biomass and Bioenergy, 6:35 (June 2011):2435–2444.

[15] Paltsev, Sergey. "The complicated geopolitics of renewable energy." Bulletin of the atomic scientists, 72:6. (2016): 390–395.

[16] O´Sullivan, Meghan, Overland, Indra, and David Sandalow. Working paper: the Geopolitics of Renewable Energy. Center on Global Energy Policy, Columbia University and the Geopolitics of Energy Project, Harvard Kennedy School. June 2017. https://www.hks.harvard.edu/publications/geopolitics-renewable-energy

Paltsev, Sergey. "The complicated geopolitics of renewable energy." Bulletin of the atomic scientists, 72:6. (2016): 390–395.

[17] Paltsev, Sergey. "The complicated geopolitics of renewable energy." Bulletin of the atomic scientists, 72:6. (2016): 390–395.

[18] Johansson, Bengt. "A broadened typology on energy and security" Energy, 53, (2013):199–205.

[19] Johansson, Bengt. "A broadened typology on energy and security" Energy, 53, (2013):199–205.

Johansson, Bengt. "Security aspects of future renewable energy systems – a short overview." Energy 61, (2013): 598–605.

[20] Stang, Gerald. "Shaping the future of energy." European Union Institute for Security Studies. July 2016. https://www.iss.europa.eu/sites/default/files/EUISSFiles/Brief_24_Energy.pdf

Semkin, Nikita, Lyyra, Satu, and Olli Sipilä. "Global energy sector transitions will have an impact on geopolitics." Prime Minister's Office, Policy Brief: Government plan for analysis 14/2017. September 11, 2017. https://tietokayttoon.fi/julkaisu?pubid=21501

Paltsev, Sergey. "The complicated geopolitics of renewable energy." Bulletin of the atomic scientists, 72:6. (2016): 390–395.

[21] Semkin, Nikita, Lyyra, Satu, and Olli Sipilä. "Global energy sector transitions will have an impact on geopolitics." Prime Minister's Office, Policy Brief: Government plan for analysis 14/2017. September 11, 2017. https://tietokayttoon.fi/julkaisu?pubid=21501

[22] O´Sullivan, Meghan, Overland, Indra, and David Sandalow. Working paper: the Geopolitics of Renewable Energy. Center on Global Energy Policy, Columbia University and the Geopolitics of Energy Project, Harvard Kennedy School. June 2017. https://www.hks.harvard.edu/publications/geopolitics-renewable-energy

Paltsev, Sergey. "The complicated geopolitics of renewable energy." Bulletin of the atomic scientists, 72:6. (2016): 390–395.

Johansson, Bengt. "Security aspects of future renewable energy systems – a short overview." Energy 61, (2013): 598–605.

Risk factors of energy sector transitions – views from the Nordic-Baltic countries

by Ms Julia Vainio

ABSTRACT

This article sets out to discover the extent of how energy Subject Matter Experts (SMEs) in Nordic-Baltic countries perceive any emerging threats stemming from energy system transformations turning them from fossil fuel consuming to renewable energy dependent countries. Through interviews conducted with energy SMEs in Estonia, Finland, Latvia, Lithuania, Norway, and Sweden, it became clear that attitudes and preparedness for new types of risks were dependent on the energy mix of each country. Most identified local risks were either technical or market-related in their nature, whereas the political and economic risks were identified more often on the regional and global level. All the people interviewed considered the increase of use of Renewable Energy Sources (RES) in electricity production as more of a positive course of evolution than a negative one.

METHODOLOGY

A total of 15 experts in 14 different occasions were interviewed for this article. A majority of the interviewed SMEs, six people, work in various levels of policy planning and implementation in the civil sector. Four people work in the academic sector, three people in non-profit organizations, and both transmission system operators and the private sector are represented by one person interviewed from each. It is noteworthy that several of the SMEs have worked extensively in the field of energy in various different roles.

The majority of the interviewees were either recommended by the Ministries of Employment, Energy, Foreign Affairs, or Defence (or the equivalent of each Ministry), or selected based on their academic merit and relevance to the topic. At least one civil servant working in the field of energy from each nation is represented. Of the 15 people interviewed, three

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people were from Sweden, three from Finland and three from Estonia, and two people were from each of Norway, Latvia, and Lithuania. An anonymized list of the interviewees can be found at the end of the article. The interviewees are referred to by their personal identification numbers in the footnotes.

The method used to conduct the interviews was a pre-structured format of four questions, and the qualitative interviews were either carried out over the phone or in person. The interviewees were provided with the draft version of the article *"Changing security aspects for future energy systems: Renewable energy and possible risks at the local, regional, and global levels"*. The pre-structured interview questions included both questions about the interviewee's professional opinion on the risks to the energy security of the country they reside in, as well as questions on how the country they reside in has prepared for any emerging threats from the increase of RES in their energy mix. The questions included a local, regional and global aspect to the issue.

- **Question 1:** "Are you aware whether your country has identified risks to their energy security that stem from renewable energy sources? If yes, what are these risks? If no, why not?"

- **Question 2:** "In your opinion, what are the main concerns of your country with the increase of renewable energy sources to its energy mix?"

- **Question 3:** "In your opinion, does your country believe that regional insecurities will increase because of energy system transformations?"

- **Question 4:** "In your opinion, does your country believe that global insecurities will increase because of energy system transformations?"

Many of the SMEs approached the emerging security threats in a two-fold manner: they discussed both the threats that the increase of use of renewables might bring to different sectors in society, as well as the possible threats that might delay the implementation of RES.

NORDIC-BALTIC STATES DIFFER IN THEIR ELECTRICITY PRODUCTION SOURCES

In presenting country-specific energy system details, we have relied on the comprehensive work done by the Nordic Energy Research, Nordic Council of Ministers and International Energy Agency organisations [1]. Despite the geographical proximity, the energy generation portfolios vary from country to country. There is a close co-ordination of power supply in the Nordic power market, where Nord Pool power exchange covers Denmark, Estonia, Finland, Latvia, Lithuania, Norway, and Sweden. Regional interconnectors among the Nordic-Baltic countries provide for increased security of supply, lower the system costs, and facilitate the integration of renewables.

In terms of electricity generation and consumption, Norway is entirely reliant on one source of energy for generation. Over 95% of the country's production is from hydropower plants and pumps. Norway is also an active exporter of electricity and it is set to increase the amount of interconnectors to neighbouring countries in the future. (Figure 1.) In 2015, 97.9% of Norwegian electricity and heat output came from hydro, geothermal, solar, wind, biofuel or waste sources. [2] Norwegians, by far, are at the top of the leader board of the nations examined in terms of the use of RES to produce electricity.

Nuclear power plays a large role in electricity and heat production in both Finland and Sweden. Where in Sweden the political discussion has circled around the possibility of phasing out nuclear power plants, Finland has a fifth nuclear reactor under construction and a sixth one is in the planning phase. In 2017, Sweden produced nearly as much electricity from hydropower plants as it did from nuclear power plants. Wind power production

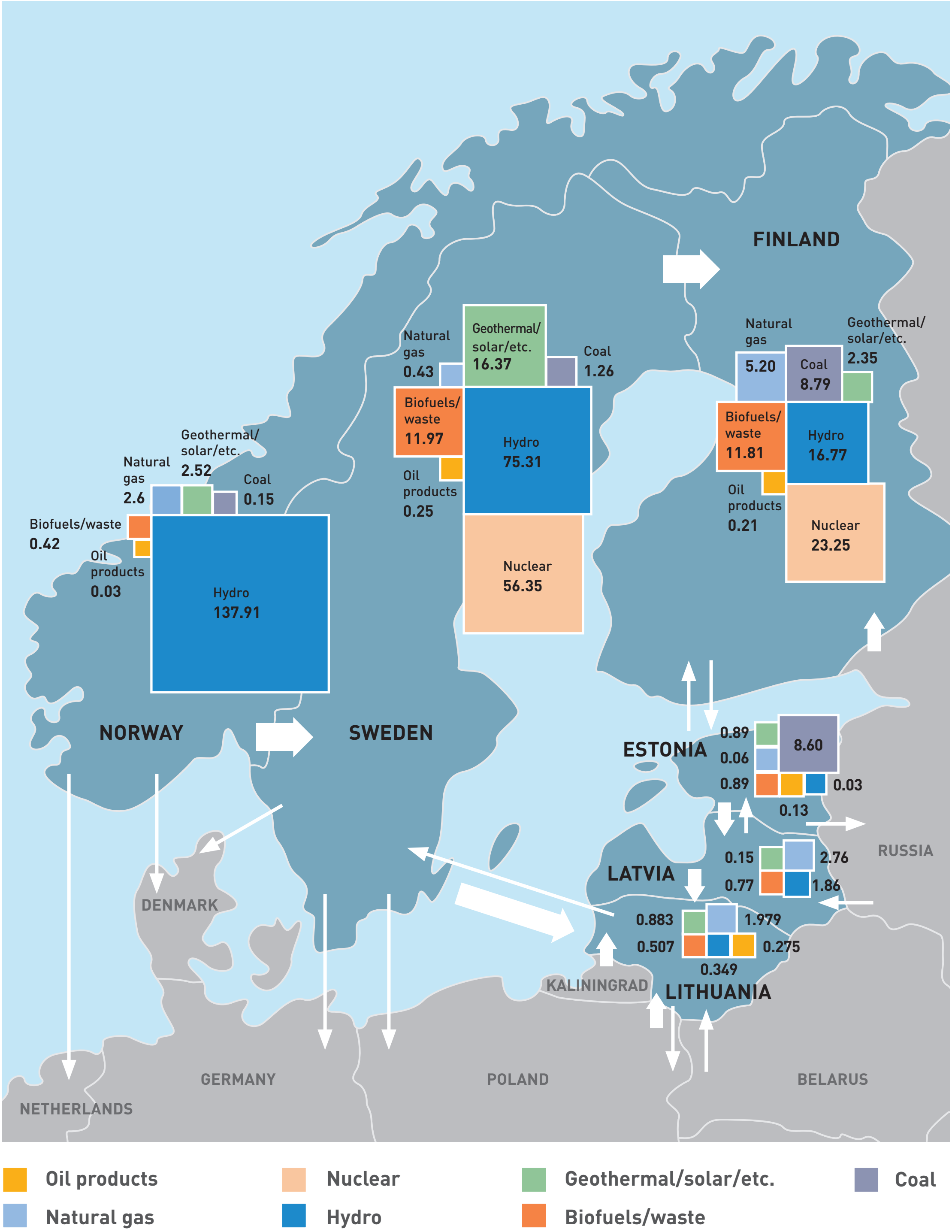

Figure 1 Electricity output from different energy sources in Estonia, Finland, Latvia, Lithuania, Norway and Sweden in 2016 (TWh). The arrows show the main bilateral electricity trades in the region (the thickness of the arrow demonstrates the amount of electricity that flows through the interconnections). Data: IEA World Energy Balances 2017, Nordic Energy Research, Litgrid. Figure design by Rasa Ulevičiūtė

in Sweden is the largest among Nordic-Baltic states. (Figure 1.) In 2015, 57.2% of Swedish electricity and heat output came from hydro, geothermal, solar, wind, biofuel or waste sources. [3] In other words, Sweden already produces more than half of their electricity using RES.

Like in Norway, Latvia's indigenous electricity production relies on large hydropower plants. The three largest plants formed around a third of Latvia's electricity production in 2015. The annual variation in hydropower generation is relatively high (±30% between 2012 and 2015), which leaves Latvia to utilize natural gas, biomass, and biogas to cover the rest of the electricity generation demand. [4] In 2015, 50.3% of Latvian electricity and heat output came from hydro, geothermal, solar, wind, biofuel or waste sources. [5]

In 2017, in addition to nuclear power, thermal power plants that commonly use biomass, peat, and coal provided for most of the electricity needs for Finland. (Figure 1.) In 2015, 45.2% of Finnish electricity and heat output came from hydro, geothermal, solar, wind, biofuel or waste sources. [6]

Much like Finland in the Baltic Sea Region, Lithuania is more dependent than its Baltic neighbours on electricity imports. This situation has been prevalent ever since the shutdown of the Ignalina nuclear power plant in 2009. Most of Lithuania's electricity production capacity is gas generation based. The country has also hydropower that can be used to balance short-term variability in the power system. [7] In 2015, 40.8% of Lithuanian electricity and heat output came from hydro, geothermal, solar, wind, biofuel or waste sources. [8]

A significant part of electricity generation in Estonia is based on oil shale. These allow the country relative electricity independence. However, the oil shale infrastructure is old and faces significant modernization procedures in order to comply with the new air quality targets set by the European Union for 2026. It is likely that Estonia will begin a large-scale phase out of oil shale-based power plants and will in the future focus on the refining of oil shale. [9] In 2015, 15.7% of Estonian electricity and heat output came from geothermal, solar, wind, biofuel or waste sources. [10]Current data puts Estonia at the bottom of the leader board of the nations examined in terms of the use of RES to produce electricity.

GEOGRAPHICAL DIFFERENCES IN ENERGY SYSTEMS CREATE DIVERSE RISKS

All interviewees approached the issue of increasing use of RES as an essentially positive step for the energy security of the Baltic Sea Region. The projected RES-led world system was described by one interviewee as *"a more boring place to live in"*, where global energy security risks will decrease as energy sources become more diversified and decentralized[2].

However, there was a wide consensus that energy system transformations bring forth new threats and vulnerabilities, as well as new opportunities. One interviewee was worried about the public's inadequate understanding of energy system knowledge and how this might create *"unrealistic assumptions on the success of renewable energy transformation compared to the real share of renewable energy production on a global scale"*[3].

THE COLLISION OF NATURAL SECURITY INTERESTS AND WIND FARMS

The impact of wind farms on national security has raised concern at least in Estonia, Finland, Lithuania and Sweden, and several of the interviewees raised the issue.

The Estonian Ministry of Defence has declined nearly a dozen wind farm projects from being developed in the East Viru area. If built, the projected parks would disturb the operation of the air surveillance radar in Kellavere, which detects aircrafts approaching from Russian airspace. The Ministry of Defence has also prohibited wind parks in the Lüganuse municipality based on national security interests [11]. In south-east Finland, more than 200 wind energy projects have been declined due to the suspected disruptions to military radars if built [12].

In Lithuania, the wind farms in the Šilutė and Tauragė districts of western Lithuania have been identified as impacting the ability of the armed forces' air surveillance radars to detect and track air targets [13]. Defence interests in protecting low-flying zones for the Swedish Air Force have led the previous Swedish Government to curb the possible wind power production sites for commercial purposes. [14]

POLITICAL AND ECONOMIC THREATS WERE THE MOST COMMONLY IDENTIFIED RISK FACTORS

Each interview was analysed in terms of content and the answers were categorised according to three themes: *political or economic* risk factors; *technological* risk factors; or *environmental* risk factors. Even though there was a lot of diversity among the answers, some themes appeared consistently throughout the interviews. This article includes those risk factors that were mentioned by three or more interviewees.

The first question required the expert to evaluate the different threats stemming from the use of RES that their respected country had identified to date. The most occurring identified threats were

- System stability[4]
- Intermittency issues[5]

Both of these threats are technological risk factors.

Power system stability is the ability of a power system to return to its normal state after a disturbance. Disturbances to the system can vary between sudden changes of load (such as the result of a particularly windy day across the Baltic Sea Region), line-to-line faults, malfunctioning or improper operation of equipment, and so on.

Intermittency forms a part of the system stability. RES like wind and solar are considered as intermittent generation technologies, where the supply of energy into the electricity grid is dependent on the availability of their primary energy source. The production of electricity from RES does not necessarily follow the demand curve, and in systems with high input of intermittent sources of energy, there is a risk of inadequate production of electricity. Storage options, interconnectivity to other energy systems, and compensation from other sources of electricity are considered as options to increase the system stability and reduce intermittency issues.

The second question required the expert to assess their main concerns for their country related to the increase of the use of RES in their country's energy mix. The most occurring identified threats were:

- "Not in my backyard!"[6]
- Bad policy-making[7]
- Price for consumers[8]
- BRELL[9]

Political and market related risks dominated the answers to the second question. In addition, issues such as: wind volatility; different support mechanisms for the markets; the EU and green energy development measures; and conflicts with radars and radio signalling were mentioned.

There seemed to be some spill-over effect of electricity sector security concerns, as several interviewees from the Baltic States mentioned the desynchronization of the Baltic

[2] Interviewee number 8
[3] Interviewee number 6
[4] Interviewee number 5, 11, 13
[5] Interviewee number 4, 10, 11, 12
[6] Interviewee number 3, 7, 10, 11
[7] Interviewee number 3, 6, 7, 12
[8] Interviewee number 4, 7, 13
[9] Interviewee number 5, 7, 13, 14

States from the BRELL[10] network as a security risk that also has relevance to the transformation of energy systems. The vulnerabilities related to the increase of the use of RES and synchronization to the Central-European network were also mentioned as regional concerns, not only as national level concerns. The increase of the use of RES does not have an immediate causality with synchronization issues, but both are part of a larger, more comprehensive security landscape.

Concern over the high cost of RES for consumers was also more pronounced among the interviewees from the Baltic States. The main concern was whether the increase of the use of RES would financially strain the end-consumers and thus lead to decreased popularity of RES production.

The interviewees often mentioned not only risks that were enhanced due to the increase of the use of RES, but also risks that might prohibit the extension of the use of RES in their respected countries. One of the latter risks included a negative public perception regarding Renewable Energy (RE) infrastructure. Dr. Mazzuchi successfully demonstrates in the article *Renewable Energy Infrastructure: Physical and Cyber Vulnerabilities Assessment* [15] that due to the distributed nature of these facilities, they require more surface space to provide for the same power generation that a more energy intensive power plant might need. In addition, the technical requirements of intermittent power generation require significant investments in the grid maintenance and extension. In relation to these requirements, the public opinion of "Not In My Backyard" (NIMBY) was identified by several interviewees as problematic for the increase in the use of RES.

Political decision-making has a large influence on the energy system transformation. Both private and public investing decisions on different forms of power production require stable, long-term policy planning. However, when embarking on something new, it is not always clear which decisions and results are the most optimal for each country and region in the long-term. Uninformed policy decisions, bad policy-making and external pressure from lobbying groups were identified as serious risks related to the increase in the use of RES. Manipulation of policymakers from the incumbent industry, or an unsuccessful RE subsidy scheme that enables companies to take advantage of the system, were mentioned as examples of risks.

The third question required the interviewees to assess those threats that their respected country might identify as a regional threat in the energy system transformation. The most commonly identified threats were:

- Cyber threats for the transmission network[11]
- Renewables' tax for large customers[12]
- Subsidies and market distortions[13]

Close to half of the respondents mentioned growing cyber vulnerability as a risk factor due to the increased complexity of the energy system, and, in some cases, because of the inadequate system security of RE power production. Case examples have shown how wind turbines are often physically accessible for intruders, which consequently allows the intruder to place rogue devices on the Industrial Control Systems (ICS). This, in turn, might allow the intruder to penetrate the network and cause large-scale damage [16]. However, many of the interviewees felt that there is already increased awareness of hybrid and cyber threats that has also affected in the way operators and actors operate in the field of energy.

The other two identified risk factors ('renewables' tax for large customers', and 'subsidies and market distortions') were categorized as

[10] Belarus-Russia-Estonia-Latvia-Lithuania Integrated/Unified Power System network
[11] Interviewee number 2, 6, 7, 8, 9, 12, 13
[12] Interviewee number 4, 6, 7
[13] Interviewee number 5, 6, 7, 13

political or economic risk factors. There was a consensus among the Baltic States interviewees that increased renewables' taxes and state subsidies not only distort fair market competition, but they might also act as a hindrance for attracting large, energy intensive industries to the countries in question. One of the interviewees referred to unfair market interactions, where state-subsidized fossil fuel energy producers from third party countries (i.e. outside the European Union) could gain access to the European Union's internal electricity market[14]. This would enable the third country producer to unfairly subsidize its product, offering lower prices than the local production and thus distorting the European Union's markets.

The fourth question required the interviewees to look beyond the Baltic Sea Region and focus more on the global shifts that might be expected from the increase in the use of RES. Risks related to the political and economic environment were among the most commonly identified risks. The most frequently identified threats were:

- The escape of the energy intensive industry[15]
- The supply chain and geopolitics of rare earth minerals[16]
- Russia as a resource state[17]

With the increase of zero-marginal cost production of renewable energy, one of the commonly identified threats was the escape of the energy intensive industry to more southern countries where solar power could be harnessed more efficiently than in the north.

The concentration of mining and supply routes of earth minerals critical for the RE industry to one major supplier, China, was seen as a future risk factor. Mineral commodities used in solar power systems such as gallium, germanium, and indium are all mainly produced by China. [17] Even though recycling of the minerals was identified as a possible solution to this vulnerability, the process of recycling alone does not seem to be enough to cover the increasing demand for the materials. The process of recycling will often result in certain impurities (required in the process of recycling) being left in the recycled materials. These impurities narrow the suitable applications for the recycled material in the future [18].

If we are set to reach the targets of the Paris Agreement[18], the world needs to decrease its consumption of carbon dioxide emitting sources of energy. This would mean vast reduction in the consumption of coal, oil, and gas, which would have a significant impact on countries dependent on fossil fuel exports. For countries with an abundance of fossil fuels, such as Russia, oil and gas taxes represent a major share of the country's budget revenue. It is estimated that during times of high oil prices, the revenue obtained from oil and gas taxation accounts for half of the federal budget of Russia; even during times of low prices of oil, the proportion remained high at 40% of the federal budget revenue. [19] Several of the interviewees identified this loss of future revenue as a threat to global stability. Unless countries wealthy in fossil fuels, such as Russia, manage to transform their energy systems in synergy with the rest, they could face internal disruptions or behave aggressively in the markets to maintain their dominant player position. However, the RE transition is not considered to be "rapid enough to surprise exporters of fossil fuels", as one interviewee suggested[19].

RENEWABLE ENERGY SOURCES ARE NOT CONSIDERED AS RISK FACTORS TO NATIONAL SECURITY

NATO and EU countries around the Baltic Sea Region are highly developed in their use of RES as a source of power production. The

[14] Interviewee number 6
[15] Interviewee number 1, 2, 6
[16] Interviewee number 1, 4, 11
[17] Interviewee number 1, 2, 5, 12
[18] The central aim of the Paris Agreement is to strengthen the global response to the threat of climate change by keeping a global temperature rise this century well below 2 degrees Celsius above pre-industrial levels and to pursue efforts to limit the temperature increase even further to 1.5 degrees Celsius.
[19] Interviewee number 14

effects and vulnerabilities of these sources have been studied to varying degrees, but identification of any risk factors have yet to appear in most national energy development strategies.

The distinction between risk factors caused by the increase in use of RES or risk factors as a result of the increase in the use of RES proved to be hard to distinguish for many of the interviewees. National energy strategies are more fixed on analysing the reasons that might prohibit or delay the building of RES power plants, rather than analysing the effects that increased use of RES have on energy systems.

Based on the interviews conducted for this article, it is clear that even though the uses of RES have unique geopolitical risks, they are considered more as an *enabler of security* rather than as an *enabler of insecurity* in Estonia, Finland, Latvia, Lithuania, Norway, and Sweden. Most of the technical risks identified were very practical in nature, and some, like radar disturbances from the presence of wind parks, are already being addressed. Political and economic risk factors were largely related to national legislation and taxation.

The main lessons learned for NATO Nations and Partnership for Peace countries should be:

1. There is a need for extended awareness on the increased importance of energy system interconnectivity in Europe.

2. The gradually changing nature of what is considered as critical energy infrastructure. Physical interconnections and large-scale offshore and onshore wind power parks will become as important as fossil fuel or nuclear power plants that are traditionally considered as critical energy infrastructure.

3. The geopolitical changes in neighbouring countries. As the interdependency of oil producers and oil consumers will decrease, oil producing states need to find new markets or disrupt the energy transformation to their benefit.

The trend of increased electrification of societies will only continue in the future, and as one of the interviewees put it: "The best energy mix is a well-balanced energy mix."[20].

REFERENCES

[1] This work is partially based on the Nordic Energy Technology Perspectives 2016 report developed by the International Energy Agency in collaboration with Nordic Research institutions and Nordic Energy Research – an intergovernmental organisation under the Nordic Council of Ministers, © OECD/IEA 2016 but the resulting work has been prepared by NATO ENSEC COE and does not necessarily reflect the views of the International Energy Agency".

"This work is partially based on the Baltic Energy Technology Scenarios 2018 report funded by the Nordic Council of Ministers. This is an adaptation of an original work by the Nordic Council of Ministers. Responsibility for the views and opinions expressed in the adaptation rests solely with its author(s). The views and opinions in this adaptation have not been approved by the Nordic Council of Ministers."

[2] IEA (2018), "World energy balances", IEA World Energy Statistics and Balances (database), https://doi.org/10.1787/data-00512-en

[3] IEA (2018), "World energy balances", IEA World Energy Statistics and Balances (database), https://doi.org/10.1787/data-00512-en

[4]] Lindroos, Tomi J., Antti Lehtilä, Tiina Koljonen, Anders Kofoed-Wiuff, János Hethey, Nina Dupont, and Aisma Vītiņa. Baltic Energy Technology Scenarios. Denmark: Rosendahls, 2018.

[20] Interviewee number 7

[5] IEA (2018), "World energy balances", IEA World Energy Statistics and Balances (database), https://doi.org/10.1787/data-00512-en

[6] IEA (2018), "World energy balances", IEA World Energy Statistics and Balances (database), https://doi.org/10.1787/data-00512-en

[7] Lindroos, Tomi J., Antti Lehtilä, Tiina Koljonen, Anders Kofoed-Wiuff, János Hethey, Nina Dupont, and Aisma Vītiņa. Baltic Energy Technology Scenarios. Denmark: Rosendahls, 2018.

[8] IEA (2018), "World energy balances", IEA World Energy Statistics and Balances (database), https://doi.org/10.1787/data-00512-en
[9]]

[9] Lindroos, Tomi J., Antti Lehtilä, Tiina Koljonen, Anders Kofoed-Wiuff, János Hethey, Nina Dupont, and Aisma Vītiņa. Baltic Energy Technology Scenarios. Denmark: Rosendahls, 2018.

[10] IEA (2018), "World energy balances", IEA World Energy Statistics and Balances (database), https://doi.org/10.1787/data-00512-en

[11] Ruuda, Lennart. "Wind farm developers claim compensation from the state." Postimees, July 3, 2017. https://news.postimees.ee/4166109/wind-farm-developers-claim-compensation-from-the-state

[12] YLE News. "Firms struggle to cope with Finnish military's wind turbine ban." August 29, 2018. https://yle.fi/uutiset/osasto/news/firms_struggle_to_cope_with_finnish_militarys_wind_turbine_ban/10374540

[13] Army Technology. "ELTA Systems to supply air surveillance radars to Lithuania." April 4, 2018. https://www.army-technology.com/news/elta-systems-supply-air-surveillance-radars-lithuania/

[14] Karagiannopoulos, Lefteris. "In Sweden, wind farms and warplanes battle for airspace." Reuters, 18.04.2018. https://www.reuters.com/article/us-sweden-windpower-military/in-sweden-wind-farms-and-warplanes-battle-for-airspace-idUSKBN1HP1CK

[15] Mazzuchi, Nicholas. "Renewable Energy Infrastructure: Physical and Cyber Vulnerabilities Assessment". Operational Highlights 12: Beyond the Era of Fossil Fuels. NATO ENSEC COE: Vilnius.

[16] Staggs, Jason. Adventures in Attacking Wind Farm Control Network, Presentation at black hat USA 2017. Presentation slides: https://www.blackhat.com/docs/us-17/wednesday/us-17-Staggs-Adventures-In-Attacking-Wind-Farm-Control-Networks.pdf

[17] Schulz, K.J., DeYoung, J.H., Jr., Seal, R.R., II, and Bradley, D.C. Critical mineral resources of the United States—Economic and environmental geology and prospects for future supply: U.S. Geological Survey Professional Paper 1802, eds. 2017.. DOI: http://doi.org/10.3133/pp1802, link: https://pubs.er.usgs.gov/publication/pp1802

John D. Jorgenson. Selenium and Tellurium. USGS Mineral Resources Program, 2002. Link: https://minerals.usgs.gov/minerals/pubs/commodity/selenium/selemyb02.pdf

[18] EASAC policy report. Priorities for critical materials for a circular economy. November 29, 2016. ISBN: 978-3-8047-3679-5. Link: https://www.easac.eu/fileadmin/PDF_s/reports_statements/Circular_Economy/EASAC_Critical_Materials_web_corrected_Jan_2017.pdf

[19] Simola, Heli and Laura Solanko. "Overview of Russia's oil and gas sector." Bank of Finland, BOFIT No. 5:31, 2017. https://helda.helsinki.fi/bof/bitstream/handle/123456789/14701/bpb0517.pdf?sequence=1

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3. Director of Taastuvaenergia, Estonia

4. Senior Expert, Ministry of Economic Affairs and Communications, Estonia

5. Deputy state secretary for energy at Ministry of Economics, Latvia

6. Lecturer at Vilnius Institute of International Relations and Political Science, former Vice-Minister of Energy, Lithuania

7. Board member of AST - Augstsprieguma tīkls, Latvia

8. Research Professor and Head of the Center for Energy Research at the Norwegian Institute of International Affairs (NUPI), Norway

9. Policy Director in the Energy and Climate Section, Norwegian Ministry of Foreign Affairs, Norway

10. Research Director and Deputy Director, Stockholm Environment Institute, Sweden

11. Expert, Swedish Energy Agency, Sweden

12. Affiliate Professor of Renewable Energy, Co-Director of Energy Area of Advance, Chalmers University, Sweden

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A Review of Fuel Cells and Their Military Applications

By Mr Damien Mayor-Hilsem, and Dr. Reiner Zimmermann, NATO ENSEC COE

NATO'S INTERESTS IN FUEL CELLS

Increased energy consumption of NATO nations has led to research and development efforts into replacing fossil fuel based sources of energy. Among the prospective candidates are fuel cells, which present the advantages of high energy density (power to weight ratio), high energy efficiency, no recharge time compared to batteries, and are silent usage. As an example of its high energy density, the combustion of 1kg of hydrogen, a main chemical component used by fuel cells, releases three times more energy than 1kg of oil and only emits water [1].

For NATO, the search for alternatives to fossil fuels has been on the agenda since 2012 by the successive declarations of the Chicago summit (2012), the Wales summit (2014) and the Warsaw summit (2016). On the policy level, the Green Defence Framework approved in February 2014 has a key role. Through its three pillars; operational effectiveness, environmental protection and energy efficiency, it aims to face logistical challenges, to decrease the risks for soldiers protecting fuel convoys and to reduce NATO's environmental footprint [2].

The question of energy consumption for armed forces will be a crucial issue for the years to come. In 2016, the United States military alone used 85.7 million barrels of fuel for a total cost of 8.7 billion dollars [3]. Therefore, turning toward electricity powered military capacities rather than those powered by fossil fuels is an area worthy of exploration. In 2017, Donald Sando, deputy of the US Manoeuvre Centre of Excellence, declared that in 10 years from now some US army units will be replaced by all-electrical ones [4].

In this scheme, fuel cells appear as an interesting lead for NATO's needs as there is increasing interest for these applications from various states, and the defence industry. Fuel cells are devices that produce electricity through a chemical reaction of two or more types of fuel. Contrary to batteries, they produce energy as long as fuel flows through them. Therefore, like engines running on

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gasoline, they do not need time to recharge. Fuel cells would, for example, allow cars to run for longer and on electricity. They appear in two NATO policy papers from 2014. In the *"Petroleum Committee Vision on future fuels"* fuel cells are dubbed as a possible long-term option for NATO [5], and in the *"Policy on power generation for deployed infrastructure"* as a "potential way of reducing liquid fuel consumption" [6].

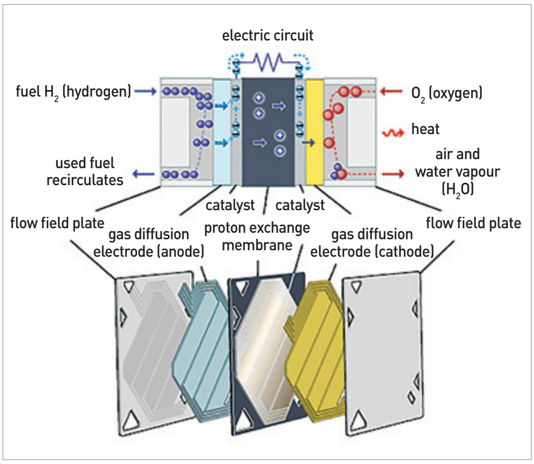
Yet, fuel cells remain costly and complex, which has to be taken into consideration when it comes to applying them in the field of military applications. Canada, France, Germany, Spain, and the USA are among the NATO members currently developing hydrogen powered, fuel cell-based, military capabilities.

This article gives a wide but non-exhaustive overview of various fields related to the military applications of the Proton Exchange Membrane Fuel Cell (PEMFC) among NATO members. The article will serve as an introduction to the many uses of PEMFC technology and its potential operational use. It presents case examples from past, present and future projects lead either by the public or the private sector.

DIFFERENT FUEL CELL TECHNOLOGIES AND THE QUESTION OF HYDROGEN

The expression "fuel cell" covers a range of different types of cells, which are classified according to the electrolyte they use. Indeed, a fuel cell is composed of an electrolyte between two electrodes, of which one is an anode provided with fuel, and the other is a cathode provided with air [7]. In the case of PEMFC, hydrogen is split between the electrons, which follow an external circuit and produce electricity. The protons, which go through the electrolyte and mix with electrons and oxygen in the cathode, produce water and heat (see Picture 1).

Other features have been used to help categorise fuel cells. These include specifications like the fuel they can use or reform, their operating temperatures, their weight/size, their materials, their emissions, or their electrical efficiency[2]. The types of fuel cells available are [8] [9]:



Picture 1 Diagram of a Proton Exchange Membrane Fuel Cell [37].

- **Alkaline Fuel Cells (AFC):** Using an aqueous potassium hydroxide or an alkaline membrane as electrolyte, AFCs benefit from high performance, thanks to the high rate of the electro-chemical reaction. They can operate from a temperature of 100 degrees Celsius and are also cheaper to produce than other fuel cells, as a wider range of materials can be utilised. However, the AFCs are vulnerable to carbon dioxide which is in the fuel, reformed to obtain the hydrogen, or in the air, as they are subject to carbonate formation which reduces the performance and the durability of the cell. Recirculating liquid electrolyte can partially solve this problem but it might also create others (wettability, corrosion, pressure etc.). These types of cells are very similar to the PEMFCs.

- **Proton Exchange Membrane / Polymer Electrolyte Membrane Fuel Cells (PEMFC):** Considering their weight and volume compared to other fuel cells, PEMFCs deliver an important power density and their electrical

[2] Based on Lower Heating Value (LHV), which is the net heat production during combustion.

efficiency can reach 60% when fed directly with pure hydrogen and 40% when using a fuel reformer. The electrolyte of PEMFC is perfluorosulfonic acid which is a water-based, acidic polymer membrane. Contrary to Solid Oxide Fuel Cells or Molten Carbonate Fuel Cells, they are use hydrogen and oxygen and only emit water, heat and electricity. PEMFCs are also quick to start as the operating temperature is around 100/120 degrees Celsius. Because of these advantages they are currently the main research focus especially for vehicle applications. However, they require expensive materials to be produced and are also sensitive to carbon dioxide from reformed fuel, limiting their possible use.

- **Direct Methanol Fuel Cells (DMFC):** Despite using the same electrolyte as the PEMFC, DMFCs have the ability to directly supply their anode with pure methanol and not hydrogen, unlike other fuel cells. As a consequence, they release carbon dioxide when operating.

- **Phosphoric Acid Fuel Cells (PAFC):** PAFC's electrolyte is a liquid phosphoric acid. They were the first types of fuel cells to reach the stage of commercial use, for stationary power generation or large vehicles. Contrary to AFCs, the PAFCs can endure carbon dioxide or other fuel impurities. However, they are more expensive as they require more platinum catalyst, are sensitive to sulphur and are the least efficient of all the fuel cells when generating electricity. Their electrical efficiency performance rate is between 37% and 42%, which is slightly higher than combustion generators, which generally perform at 33% efficiency. Finally, they also use hydrogen to fuel their anode and their operating temperature is higher than AFCs, from 150 degrees Celsius to 200 degrees Celsius.

- **Molten Carbonate Fuel Cells (MCFC):** With a higher electrical efficiency rate than PAFCs, these type of cells can used in non-precious metals much like with the AFCs. The electrolyte here is molten carbonate salt, which often comprises lithium carbonate, potassium carbonate and, or, sodium carbonate. MCFCs operate at high temperature, from 600 degrees Celsius to 700 degrees Celsius, which allows direct extraction of hydrogen from fuels inside the cell, but which also implies a longer kick-off time. As such, a fuel like methane or light hydrocarbon based fuels can be used. However, issues related to corrosion and breakdown are present. These cells have another difference; the anode is fuelled with syngas, a mix of hydrogen and carbon monoxide, and the cathode by both oxygen and carbon dioxide. As such, contrary to fuel cells that are using hydrogen and air, this type of fuel cell is emitting carbon dioxide. [10]

- **Solid Oxide Fuel Cells (SOFC):** With an operating temperature comprised between 500 degrees Celsius to 1000 degrees Celsius, SOFCs require the highest operating temperatures of all fuel cells. This allows the cells to operate without a reformer, nor the need to use precious metals for the catalyst. SOFCs are also very resistant to sulphur and carbon dioxide, which allows the use of natural gas, biogas or coal-based gas as fuel. Using a non-porous ceramic compound electrolyte, these cells have an important electricity efficiency of 60%. Yet, SOFCs suffer the same issues as MCFCs in relation to heat and carbon dioxide emission. As a consequence, they take longer to start up and are less likely to be used for mobile applications as their use is more cumbersome.

A common feature to of all these fuel cells, except for the DMFCs, is the use of pure hydrogen or hydrogen from reformed fuel to supply their anode. Developments related to hydrogen technologies are just as crucial for the future of fuel cells as the improvement of their own technologies. Indeed, hydrogen is a very simple chemical element that can be turned into an energy conveyor, can be stored, and can be found all around the world in significant quantities.

Yet, hydrogen does not exist in a pure state in nature and its extraction from primary resources like oil, gas or water (mainly by steam reforming, electrolysis or gasification) requires significant amounts of energy that can release greenhouse- or noxious gases. As a consequence, the pollution emitted by the production of hydrogen relies on whether or not renewable energy sources have been used in the extraction operation and from which resource it has been extracted from.

Today, hydrogen is mainly extracted from natural gas in a process that emits a significantly large amount of greenhouse gases [11]; fuel cells that do not use pure hydrogen as a main fuel are also more polluting. For example, in the field of inland navigation, fuel cells using reformers to use hydrogen from gasoline are almost as polluting as classic combustion engines, while those using hydrogen from methane are almost six times less polluting than classic engines, but still release more greenhouse gases than pure hydrogen based fuels [12].

Another issue is the question of storage. Hydrogen can be stored in 3 different ways:

- **Gaseous state storage:** at low pressure, it is a cheap and already common way of storing hydrogen for static use, for example. However, it requires considerable amounts of storage space and becomes more expensive and difficult to apply to mobile use.

- **Liquid state storage:** mainly used for high specification technology like in the space industry. Leaking is a major drawback of liquid state storage, which has yet to be resolved. The storage tanks should stock the hydrogen at a temperature minus 253 degrees Celsius, but they irremediably absorb heat, making the hydrogen evaporate.

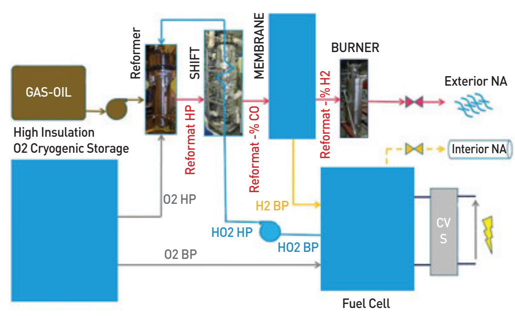
- **Metal hydrides storage:** hydrides are materials that can absorb or reject hydrogen depending on the temperature. It's the most efficient way to store hydrogen in terms of volume but to the cost of weight [13].

Fuel cells require bigger tanks to run longer, and as such they require a lot of space. These storage issues explain why pure hydrogen is not necessarily commonly used and why the industry prefers to use reformers extracting it from fuels, especially when it comes to submarine applications. In addition, hydrogen is also highly flammable, which poses a threat for soldiers in operations that could use or wear hydrogen powered fuel cells. Reinforcements and improvements in hydrogen storage technologies are essential for more frequent military use. Methanol, used for DMFCs, is flammable as well but, most of all, very toxic and has a smaller power density. However, as methanol is a liquid, it can be stocked and transported the same way as other liquid fuels, such as gasoline [14].

APPLICATIONS FOR MILITARY SUBMARINES: CASE EXAMPLES FROM FRANCE, GERMANY, AND SPAIN

Submarines are the main military field of application for fuel cells, as fuel cells provide crucial advantages in submarine warfare, stealth, and autonomy. Indeed, combined with Air Independent Propulsion (AIP), an anaerobic engine technology that allows submarines to stay submerged for longer, they can become virtually silent compared to diesel powered models and even compared to nuclear submarines [15]. Fuel Cell and AIP technologies avoid releasing too much gas or

FC-2G
Second-generation fuel cell AIP operating principle



Picture 2 Diagram of Naval Group Proton Exchange Membrane Fuel Cell [38] (Diagram from Naval Group (previously called the DCNS) via Mer et Marine)

heat and let the submarine avoid resurfacing too often.

In this sector, Germany both appears as a pioneer and as a leader through ThyssenKrupp Marine Systems GmbH (TKMS), which produces the submarine class 212A with a first model launched in March 2002. This submarine project is in cooperation with the Italian Navy, who built their own 212A under licence at the naval shipyard of Fincantieri under the designation of Todaro-Class submarine [16]. The 212A is equipped with a fuel cell system based on the SINAVY PEM Fuel cell technology, in development since 1985 by Siemens, but adapted for submarine use by Howaldtswerke Deutsche Werft AG (HDW), a company that is part of the TKMS group. This fuel cell unit uses oxygen and hydrogen directly stored on board as fuel.

In Spain, the publicly owned shipbuilding company Navantia launched in 2004 a construction programme for a new submarine for the Spanish navy, the S-80 Plus class (or Isaac Peral class) [17]. The S-80 is equipped with an AIP engine and uses fuel cells. The Spanish government ordered four submarines for a total original cost of 1.8 billion euros. The first delivery was scheduled for 2013 [18]. The fuel cells are provided by American company UTC power (since purchased by ClearEdge Power) and are supplied by a bioethanol processor manufactured by the Spanish company Abengoa [19]. However, because of the succession of miscalculations and technical problems (not related to AIP or fuel cells) none of the submarines have been delivered yet, with delays predicted to last until 2022 for the launch of the first S-80 and until 2027 for the fourth submarine. The current cost is now estimated to be up to 3.7 billion euros [20].

During 2016, the French company Naval Group (previously known as DCNS) unveiled their SMX 3.0, a submarine concept ship aiming to show what their vessels will look like in 2025. The model is equipped with an AIP Fuel Cell Second Generation (FC2G) (Picture 2)[21]. The FC2G is a modular submarine system that can be adapted to any vessel with a diameter of at least six meters. The FC2G is equipped with a fuel cell using a reformer to extract hydrogen from diesel fuel at high pressure and temperature [22].

APPLICATIONS FOR MILITARY LAND VEHICLES: CASE EXAMPLES FROM THE UNITED STATES

Of all NATO nations, the US army has researched the application of fuel cells for land vehicles most extensively. Already in 2010, a test lead by the US Army Tank Automotive Research, Development and Engineering Centre (TARDEC) aimed to include fuel cells in the M1 Abrams, the United States main battle tank, as a means to power and support more on-board electrical devices [23]. However, early tests do not seem to have been conclusive, as fuel cells have not yet been implemented to the M1 Abrams units.

More recently, General Motors and TARDEC revealed a Chevrolet Colorado ZH2 model, which is a hydrogen fuel cell powered off-road vehicle (picture 3) [24]. The Colorado ZH2, which has started its tests in field conditions by the US Army in Fort Carlson, Colorado, is based on a civilian vehicle but it is modified to suit military use. The main benefit of a hydrogen powered vehicle is increased stealth as the Chevrolet ZH2 is almost completely silent and emits a very low heat signature. These features could be an important advantage on the field, especially for Special Forces' operations. However, the model also suffers from drawbacks as hydrogen is highly flammable and the range capacity of the engine appears to be inconsistent [25]. This vehicle is mostly presented as a life-size test to define whether fuel cells are suitable for military needs and if it is worth researching further into projects that are more ambitious [26].

The Chevrolet ZH2 is not the only project developed by General Motors. The company also presented its Silent Utility Rover Universal Superstructure (SURUS) during the As-

Picture 3 Dr. Paul Rogers, director of the U.S. Army TARDEC, addresses the gathering as General Motors hands over keys to the Chevrolet Colorado ZH2 on Monday, April 10, 2017, in Milford, Michigan. The U.S. Army will test the Colorado ZH2 in extreme field conditions to determine the viability of hydrogen-powered vehicles on military missions. (Photo by Jeffrey Sauger, General Motors Media Center.)

sociation of U.S. Army's annual meeting of 2017. It is hydrogen powered four-wheel drive transportation platform that can be adapted to various needs [27]. The SURUS has been conceived for a dual military and commercial use but can overcome operational transport challenges related to terrain, soldier's safety, varying loads, or different vehicle ranges. The fuel tanks in the SURUS let the platform operate to a maximum range of around 640 kilometres.[28]

MILITARY APPLICATIONS FOR UNMANNED VEHICLES: CASE EXAMPLES FROM CANADA AND THE UNITED STATES

Drones appear as a very promising field of fuel cells development. They would enable military drones to be stealthier and would let them acquire much better range capacities compared to drones using batteries.

In Canada, Ballard Power Systems, an enterprise that specialises in fuel cells solutions, has developed a full hydrogen powered fuel cell propulsion for Unmanned Aerial Vehicles (UAVs). They have trialled this technology on their drone platform ScanEagle [29]. ScanEagle is a drone that can have dual use in both the civilian and military sectors. Another Canadian enterprise called EnergyOr Technologies Inc. started delivering the H2QUAD 1000, a fuel cell powered multirotor UAV destined for operational use, to the French armed forces in 2017 [30].

On the US side, few projects can also be cited, such as the Ion Tiger Fuel Cell Powered UAV, developed by the US Naval Research Laboratory with the aim of increasing battlefield surveillance and communication capabilities. It has proved its long-range endurance through various tests. The UAV uses liquid hydrogen as fuel [31]. General Motors and the US Navy Office of Naval Research also declared in 2016 that they were working on an Unmanned Undersea Vehicle powered by a fuel cell system with a goal of 60 days of endurance [32].

OTHER MILITARY APPLICATIONS

Aside from transport and vehicle use, fuel cells can be applied for other uses, in particular to power static or mobile military equipment. Through the Corps of Engineers Research and Development Centre Construction Engineering Research Laboratory (ERDC-CERL), the United States is already using fuel cells to power their military infrastructure and some expeditionary bases. For example, they have developed the Silent-Camp concept system, where diesel generators are coupled with fuel cells and hydrogen storage. The aim is to reduce noise, heat and chemical pollution while also decreasing and optimising fuel consumption. Overall, this technology is still lacking robustness to be more commonly used in operational theatres. [33] With further technological advancements, different fuel cell technologies could contribute positively to the energy security of operational environments.

Fuel cells can also prove themselves worthy in the domain of lightweight and wearable power systems, which provide electricity to soldiers in the field for their portable devices such as GPS, radios, computers, medical equipment, and lighting. Indeed, portable fuel cells provide more energy for less weight when compared to batteries, even Li-Ion ones. They can also be refuelled quicker than a battery is recharged. Among a few examples are the H3-TEYA of the French enterprise Pragma Industries and Nexter electronics. Certified by the US and French military standards (Mil STD and AECTP), the H3-TEYA uses chemical hydrides for refuelling. [34]

CONCLUSION: THE ROLE OF FUEL CELLS IN THE MILITARY ENERGY TRANSFORMATION PROCESS

In conclusion, where most NATO papers focus on static or wearable[3] [35] use of fuel cells, we can see that this technology can cover more fields which should be considered in medium to long term planning. For the militaries, fuel cells could allow important fuel savings as well as more autonomy, from the tactical to the strategic execution. Fuel cells have a wide range of potential military applications, but are not yet mature enough for implementation. The most striking example of the existing benefits of fuel cells is the combination of them with the AIP technology in the submarine field, which has turned fuel cells into a key contributor to the advanced technology of shipyards.

There are some hindering factors in fuel cell technology development in the NATO military sphere. For example, the jet propellant JP8[4], which is used as part of NATO's single fuel policy, contains large quantities of sulphur. It is a chemical component that is harmful for fuel cells and it is obtained when reforming jet propellant. There are ongoing studies on the desulfurization of JP8. [36] Furthermore, the use of very high tech devices or parts in the making of fuel cells increases the dependency over rare materials such as rare earth metals, which are crucial to the development of this technology.

Yet, for this technology to be more commonly used, fuel cell promoters have to solve issues such as energy storage, robustness, costs, efficiency, reliability, and fuel availability. If research and development is able to overcome these challenges, fuel cells can deliver cleaner, more efficient, and more independent sources of energy. Operational energy providers are pushing fuel cell actors towards enhancing capacities and correcting flaws.

[3] that can be included in the soldiers' equipment
[4] NATO code F34

SUMMARY TABLE OF REVIEWED APPLICATIONS

No.	Name of the application/ project/vehicle	Domain/field of application	Country/ organisation/ enterprise concerned	Year of development or establishment	Short Description	Additional Notes
1	Chevrolet Colorado ZH2	Land vehicle; off-road pickup truck	USA / TARDEC, General Motors	2016	Hydrogen fuel cell powered off-road vehicle developed by General Motors and the TARDEC.	Tests since 2017 in field conditions by the US Army in Fort Carlson, Colorado.
2	M1 Abrams	Land vehicle; battle tank	USA / TARDEC	2010	Implements fuel cells to power for the support of more on-board electrical devices.	No public information on the project since 2010.
3	Silent Utility Rover Universal Superstructure (SURUS)	Land vehicle; mobile platform	USA / General Motors	2017	Hydrogen powered mobile 4x4 platform that can be manned or unmanned.	Commercially designed platform that can be adapted for military use.
4	AIP Fuel Cell Second Generation (FC2G)	Modular fuel cell section; designed for submarines	France / Naval Group	2014	Modular fuel cell section; can be adapted to submarines with diameter of at least six meters; hydrogen production performed on-board through a reformer.	Projected to be used for Naval Group's next attack submarine, the SMX 3.0.
5	Class 212A / Todaro-Class submarines	Sea vehicle; Attack submarine	Germany, Italy / TKMS, Fincantieri	1994	Fuel cell system using oxygen and hydrogen directly stored on board as fuel, to power an AIP engine.	German/Italian cooperation, first submarine delivered in 2002.
6	Class 214 submarines	Sea vehicle; Attack submarine	Germany / TKMS	2004	Based on the 212A but larger and destined for the export market.	Used by South Korea, Greece, Turkey and Portugal.
7	S-80 Plus class (Isaac Peral class) submarine	Sea vehicle; Attack submarine	Spain / Navantia	2004 (program started)	AIP engine. Fuel cells are provided with UTC power (USA) fuelled with bioethanol through a processor manufactured by Abengoa (Spain).	Massive delays and cost increases, not related to fuel cells (1.8 billion euros estimated at the beginning of the project to 3.7 billion euros at present).
8	H2QUAD 1000	Air vehicles; unmanned aerial vehicles	Canada / EnergyOr	2016	Fuel cell powered multirotor UAV that can operate longer than classic battery powered systems.	Provided to the French Air Force's "Centre d'Expertise Aérienne Militaire" for a trial period.

9	Ion Tiger UAV	Air vehicles; unmanned aerial vehicles	USA / US Naval Research Laboratory	2009	Fuel Cell Powered UAV.	Proved long range endurance through various tests.
10	Propulsion for unmanned aerial vehicles	Air vehicles; unmanned aerial vehicles	Canada / Ballards Power Systems	2017	Hydrogen powered fuel cell propulsion for unmanned aerial vehicles. Has been tested on a drone platform; ScanEagle.	Has dual use; civilian and military.
11	Unmanned Undersea Vehicle	Sea vehicle; Unmanned Undersea Vehicle	USA / General Motors, US Navy Office of Naval Research	2016	Unmanned Undersea Vehicle powered by a fuel cell system.	Goal is to reach an endurance of 60 days in operation.
12	SilentCamp	Power generating equipment; fix use	USA / Corps of Engineers Research and Development Centre Construction Engineering Research Laboratory	2010	Concept system to power military camp through the use of diesel generators coupled with fuel cell and hydrogen storage.	Concept assumed to have developed since 2010 inception.
13	H3-TEYA	Power generating equipment; mobile use	France / Pragma Industries, Nexter electronics	2014	Portable device made to power soldiers' equipment when in the operational theatre. It uses chemical hydrides in order for refuelling.	Certified by the US and French military standards.

land

submarines

aerial drones

unmanned underwater vehicle

fixed use (campsite)

portable use

BIBLIOGRAPHY

[1] The French Alternative Energies and Atomic Energy Commission. 20.07.2016. L'essentiel sur … L'hydrogène. http://www.cea.fr/comprendre/Pages/energies/renouvelables/essentiel-sur-hydrogene.aspx

[2] North Atlantic Council, NATO. Defence policy and planning Committee. Green Defence Framework, February 2014.

[3] The United States of America Department of Defense: Office of the Under Secretary of Defense for Acquisition, Technology, and Logistics. Fiscal Year 2016 Operational Energy Annual Report, 24.07.2017.

[4] Gould, Joe. "All-electric brigades? US Army official says it's coming sooner than you'd think." Defensenews.com, 11.10.2017. https://www.defensenews.com/digital-show-dailies/ausa/2017/10/11/all-electric-brigades-us-army-official-says-its-coming-sooner-than-youd-think/

[5] North Atlantic Council, Petroleum com-

mittee. Petroleum Committee Vision on future fuels policy, 17.04.2014.

[6] North Atlantic Council, NATO. NATO Policy on Power Generation for Deployed Force Infrastructure, February 2014.

[7] The United States of America Office of Energy Efficiency and Renewable Energy, Fuel cell Technologies Office. Fuel Cells. https://www.energy.gov/eere/fuelcells/fuel-cells

[8] The United States of America Office of Energy Efficiency and Renewable Energy, Fuel cell Technologies Office. Comparison of fuel cell Technologies, April 2016. https://www.energy.gov/sites/prod/files/2016/06/f32/fcto_fuel_cells_comparison_chart_apr2016.pdf

[9] The United States of America Office of Energy Efficiency and Renewable Energy, Fuel cell Technologies Office. Fuel Cell Basics. https://www.energy.gov/eere/fuelcells/fuel-cell-basics

[10] FuelCellToday, MCFC (Molten carbonate fuel cells). http://www.fuelcelltoday.com/technologies/mcfc

[11] Condliffe, Jamie. "The fuel cell isn't dead yet." MIT Technology Review, 07.04.2017. https://www.technologyreview.com/s/604115/the-fuel-cell-isnt-dead-yet/

[12] European Commission, Community Research and Development Information Service. Fuel cell technology in inland navigation, technical report in the framework of EU project CREATING (M06.02). http://www.ecn.nl/docs/library/report/2005/rx05177.pdf

[13] The French Alternative Energies and Atomic Energy Commission home page. http://www.cea.fr/english

[14] The United States of America Office of Energy Efficiency and Renewable Energy, Fuel cell Technologies Office. Comparison of fuel cell Technologies, April 2016. https://www.energy.gov/sites/prod/files/2016/06/f32/fcto_fuel_cells_comparison_chart_apr2016.pdf

[15] Groizeleau, Vincent. "Sous-marins: La bataille des AIP est engagée." (translation) "Submarines: The battle of the AIP is engaged" Mer et Marine, 30.05.2016. https://www.meretmarine.com/fr/content/sous-marins-la-bataille-des-aip-est-engagee

[16] FuelCellToday, "U36: Another fuel cell submarine for the German navy." 16.05.2013. http://www.fuelcelltoday.com/news-archive/2013/may/u36-another-fuel-cell-submarine-for-the-german-navy

[17] Ministry of Defence for Spain, Armada Española. S80 Class Submarine. http://www.armada.mde.es/ArmadaPortal/page/Portal/ArmadaEspannola/buquessubmarinos/prefLang-en/02s80--03sistemas-en

[18] Expansión.com. "Navantia entregará el primer S-80 a la Armada en 2013, con un año de retraso." (translation) "Navantia will deliver the first S-80 to the Navy in 2013, one year late."13.12.2007. http://www.expansion.com/2007/12/13/empresas/industria/1068322.html

[19] Naval Technology. SSK S-80 Class Submarines. https://www.naval-technology.com/projects/ssk-s-80-class-submarine/

[20] Gonzalez, Miguel. "El submarino S-80 Plus, del sobrepeso al sobreprecio." (translation) "The submarine S-80 Plus, from overweight to surcharge" El Pais, 11.02.2018. Link: https://elpais.com/politica/2018/02/10/actualidad/1518278999_683988.html

[21] Navy Recognition. DCNS unveils SMX®3.0, the submarine concept ship tailored to the needs of Generation Z. 17.10.2016. http://www.navyrecognition.com/index.php/news/naval-exhibitions/euronaval-2016/4454-dcns-unveils-smx-3-0-the-submarine-concept-ship-tailored-to-the-needs-of-generation-z.html

[22] Groizeleau, Vincent. "DCNS relève le défi des piles à combustible de seconde génération." (translation) "DCNS takes up the challenge of second-generation fuel cells." Mer et Marine, 30.05.2016.

[23] Osborn, Kris. "Army testing fuel cell technology for Abrams tank." U.S. Army, 17.06.2010. https://www.army.mil/article/40980/army_testing_fuel_cell_technology_for_abrams_tank

[24] General Motors, Corporate Newsroom. "Mission-ready Chevrolet Colorado ZH2 Fuel Cell vehicles breaks cover at U.S. Army Show." 03.10.2016. https://media.gm.com/media/us/en/gm/vehicles.detail.html/content/Pages/news/us/en/2016/oct/1003-zh2.html

[25] Ganz, Andrew. "Chevrolet Colorado ZH2: first ride in hydrogen fuel-cell Army truck." Green Car Reports, 05.07.2017. https://www.greencarreports.com/news/1111351_chevrolet-colorado-zh2-first-ride-in-hydrogen-fuel-cell-army-truck

[26] Judson, Jen. "Hydrogen fuel cell technology could bring stealth to Army vehicles." DefenseNews. 03.04.2017. https://www.defensenews.com/land/2017/04/03/hydrogen-fuel-cell-technology-could-bring-stealth-to-army-vehicles/

[27] General Motors, Corporate Newsroom. "GM Outlines Possibilities for Flexible, Autonomous Fuel Cell Electric Platform." 06.10.2016. https://media.gm.com/media/us/en/gm/home.detail.html/content/Pages/news/us/en/2017/oct/1006-fuel-cell-platform.html

[28] Valdes-Dapena, Peter. "GM unveils futuristic self-driving army truck." CNN-Business, 06.10.2017. https://money.cnn.com/2017/10/06/technology/gm-self-driving-army-truck/

[29] Froese Michelle. "Ballard launches next-generation fuel-cell system for drones." Wind power engineering and development. 28.12.2017. https://www.windpowerengineering.com/business-news-projects/ballard-launches-next-generation-fuel-cell-system-drones/

[30] sUAS News. "Energyor delivers fuel cell H2 Quad 1000 to French air force." 3.01.2017. https://www.suasnews.com/2017/01/energyor-delivers-fuel-cell-h2-quad-1000-french-airforce/

[31] U.S. Naval Research Laboratory, Laboratory for Autonomous Systems Research. "Ion Tiger Fuel Cell Powered UAV". https://www.nrl.navy.mil/lasr/content/ion-tiger-fuel-cell-powered-uav

[32] General Motors, Corporate Newsroom. "GM and U.S. Navy Collaborating on Fuel Cell-Powered Underwater Unmanned Vehicles". 23.06.2016. https://media.gm.com/media/us/en/gm/home.detail.html/content/Pages/news/us/en/2016/jun/0623-gm-us-navy.html

[33] Boland Rita. "Fuel Cell power military bases." SIGNAL Media, July 2010. https://www.afcea.org/content/fuel-cells-power-military-bases

[34] Pragma industries, "H3 TEYA." Homepage: https://www.pragma-industries.com/products/military/

[35] North Atlantic Treaty Organization Science and Technology Organization. "Fuel Cells and Other Emerging Manportable Power Technologies for the NATO Warfighter – Part I: Power Sources for Manportable/Manwearable Applications", October 2014. ISBN 978-92-837-0210-8.

[36] Tran, Dat T., Jessica M. Palomino and Scott R.J. Oliver. "Desulfurization of JP-8 jet fuel: challenges and adsorptive materials." RSC Adv., no.8 (14.03.2018): 7301-7314. DOI: 10.1039/C7RA12784G.

[37] Schumm, Brooke. Fuel Cell. Encyclopaedia Britannica. https://www.britannica.com/technology/fuel-cell

[38] FC-2G Second-generation fuel cell AIP operating principle (Diagram from Naval Group (was DCNS) via Mer et Marine). https://www.meretmarine.com/fr/content/sub-marines-dcns-unveils-fuel-cell-aip

Renewable Energy Infrastructure: Physical and Cyber Vulnerabilities Assessment

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ABSTRACT

Renewable energy sources (RES) are considered to be one of the cornerstones in energy transitions towards low carbon energy systems all over the world. In most cases, NATO nations are leading the progress. According to the International Energy Agency, in 2040, renewable energy sources could represent as much as 40% of the whole electricity capacity in North America and over 60% of the capacity in Europe. If materialized, these projections would have momentous effects to the whole energy landscape of NATO countries, especially with the scheduled transformation in the transportation sector from fossil-fuel to electric, consequently increasing the demand of electricity[2]. Even though RES currently represent a small and unequally distributed part of installed production capacity in NATO countries, they are on their way to becoming a central feature in electricity production. Nevertheless, like traditional thermal or nuclear power plants, renewable energy infrastructure also includes vulnerable facilities that could be the target of state or criminally sponsored attacks as they are subjected to a large number of security risks related to kinetic and non-kinetic threats[3]. This article will assess three kinds of vulnerabilities: kinetic threats, cyber-related threats and the lack of awareness across NATO nations.

RES INDUSTRIAL DESIGN DIFFERS FROM TRADITIONAL FOSSIL FUEL POWER PLANTS

Renewable energy infrastructure is by its nature distributed, decentralized and less-defended than traditional power plants. The infrastructure facilities can occupy large portions of land which is, by essence, harder to defend than more compact fossil fuel infrastructure. Even if they appear less critical due to their smaller generation capacity per unit, renewable energy power plants are on the verge of becoming a decisive element in NATO countries' energy security. With interconnected electricity networks and, for the moment, without major storage capabilities, a series of attacks against weakly defended

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wind farms or solar power plants could provoke severe blackouts and extend their effects into the whole grid. Any kinetic attack against renewable energy infrastructure by another state actor would in all likelihood constitute an Article 5 situation in terms of NATO's global response.

However, renewable energy infrastructure could prove to be a lucrative target for non-kinetic attacks in the form of cyber-attacks as well. A non-kinetic cyber-attack on the industrial control system of a renewable energy facility or the transmission grid is easier to perform anonymously and from afar than a kinetic strike. And, unlike when faced with a kinetic attack, without a clear armed attack against the energy infrastructure, it is questionable whether even the most severe non-kinetic attack would result in an Article 5 type of situation.

The first security issue regarding renewable energy sources comes from their industrial design and construction. Contrary to traditional thermal power plants, renewable energy, such as wind or solar plants, are comprised of a large number of turbines or panels, which are commonly used as a part of a local network to produce electricity. Wind turbines or solar panels are complex industrial objects and their technical performance relies on the ability to transform wind energy or particles of light into electricity. The technology itself is not that new. The rotor model for wind and water turbines and the photovoltaic conversion for solar panels have been well known for decades. However, the technological advancements of the last decades in the field of RES have brought about increases in the production capacities and better utilization rates of turbines and panels, thus creating a more compelling market for the products.

KINETIC THREATS

Like with fossil fuels, there are several known vulnerabilities along the whole value chain of RES. These include the global commercial availability of the materials and minerals, the geopolitical significance the commodities have throughout the supply chain from the excavation site to the industrial sector, and the heavy control of the RES production with only a few big players worldwide. Of these, China is the largest in terms of assets it owns around the world [2].

On the infrastructural level, the RES have some inherent vulnerabilities due to their specific size, extension and security management policies. The RES facilities – except for certain hydropower dams – are by nature distributed facilities. The need to group a large number of industrial objects (e.g. wind turbines; water turbines for cascading dams; or solar panels) into a single power plant leads to a spatial extension far more important than for thermal or nuclear power plants. A study from the National Renewable Energy Laboratory in the United States estimated that, for a wind farm, the land use is four megawatts per square kilometre [3]. An 800 MW wind farm would use no less than 200 km2 of land, far more than the surface space of a thermal or nuclear power plant with the same generation capacity.

In this perspective, the management of perimeter security is far more complicated and costly than in a traditional thermal or nuclear power plant to achieve a similar level of protection. The only type of large-sized renewable power plants widespread today are hydraulic dams. With the increase in installed capacity, they also occupy greater land spaces than fossil fuel power plants. As an example, the Jiraù dam in Brazil that has the same generation capacity as a European nuclear

[2] Nevertheless, a global increase in the share of electric vehicles could also lead to a better energy efficiency with vehicle-to-grid technologies.

[3] "Kinetic Means" are often defined as "the ability to create effects that rely on explosives or physical momentum (i.e., of, or relating to, or produced by motion)" and "Non-Kinetic Means" as "the ability to create effects that do not rely on explosives or physical momentum (e.g., directed energy, computer viruses/hacking, chemical, and biologica effectsl)." [1]

power plant (3750 MW), is 1500 meters long and has a reservoir of 258 square kilometres.

Moreover, in terms of risk management, the RES facilities are out of the Seveso directive of the European Union [4] and, de facto, less controlled than traditional energy facilities as the risk of industrial catastrophe appears limited. As they are not using explosive or naturally dangerous materials such as hydrocarbons, radioactive materials or corrosive chemicals, RES facilities are not considered as dangerous facilities. Thus, most of the time there are no security management procedures specific to protecting the facilities and they appear less defended than traditional power plants, even with a larger perimeter to protect. As a consequence, they could become specific targets for terrorist groups even with a limited probability [5]. The infrastructure in renewable energy facilities has also proven to be a lucrative target for looting, as the sites usually contain high technology equipment or expensive materials such as copper in wind turbines [6].

Specific vulnerabilities also exist for renewable energy sources set in the maritime domain. The dispersion of larger size offshore wind turbines could create issues for the navigation of boats during bad weather conditions. Collisions between boats and offshore wind turbines has already occurred in Northern Europe and the development of offshore wind farms in straits or canals (such as in the Northern Sea, the Baltic Sea, the Channel, etc.) would lead to an increase in potential obstacles to maritime traffic. Depending on the class of a ship and the size of the turbine, this could have dramatic effects [7].

Moreover, from a military point of view, maritime infrastructure, especially those that are far away from the coastline, are more vulnerable to kinetic attacks from the sea or underwater. In case of a conventional conflict, RES situated in a maritime environment would constitute as vulnerable assets. Depending on their importance in the national electricity mix, attacks on these assets could cause regional or even national black-outs. In the United States, the target of 20% of wind power in the national mix would be achieved by installing several offshore wind farms in the Atlantic [8]. Considering that offshore energy installations have already been targeted by military forces – the United States operation Nimble Archer against two Iranian oil rigs in 1987 for example - a large amount of electricity coming from offshore wind farms could transform these assets to military targets with a dramatic importance on national energy security.

The last category of infrastructure vulnerability are the occurring natural hazards. The evolution in the size of the RES facilities, especially wind (onshore and offshore) and solar, gives them a greater exposure to risks stemming from natural disasters. The risk of offshore wind turbines to be destroyed by high-class hurricanes is significant in certain areas, especially in the Atlantic coast of the United States [9]. Thus, the increase in both frequency and intensity of severe natural disasters, caused by the changing climate conditions, could be an increasing threat to large RES installations. With the EU target to increase the amount of renewable energy sources in member states' energy mixes to 27% by 2040, there could be major risks of grid black-out due to an overstress of the grids. The development of new technologies that provide better resistance to wind turbines and solar panels against natural disasters would enhance energy security. However, this could be counterbalanced by the suspected increases in the sizes of turbines and solar panels. The increase in size creates greater exposure to risks such as high-speed wind and storms.[4]

CYBER VULNERABILITIES

The last, and arguably, the most important, vulnerability created by the integration of

[4] The medium power capacity of an onshore wind turbine is 0.8-2 MW; in the more modern turbines, especially in the offshore ones, the capacity might reach 10-12 MW by unit, with a blade span of more than 100-150 m.

large amounts of renewable energy sources into a nation's electricity mix, concerns cyber-aggressions targeted towards these facilities. Implementing a renewable energy -based electricity system means creating a decentralized production system that differs significantly from the traditional electricity system. In the traditional model, a large capacity power plant is built within a close distance from the market consumers through a single electricity network that is governed by distribution and transmission system operators.

However, the current trend of using multiple electricity producing energy sources, such as wind turbines or solar panels, creates the need to put in place a complex command and control system [10]. This kind of decentralized system changes the paradigm of the whole national electric power system from a production oriented approach to a demand oriented approach. Having a real-time management of electric power production to fulfil the demand, there is a necessity to enhance the industrial control system with an important data management part. The command and control systems, especially the SCADA (Supervisory Control and Data Acquisition), rely on a large stream of data used to pilot these decentralized wind farms or solar power plants. This stream is made by the gathering of each turbine data and has a more important role in plants that utilize RES than in the traditional thermal ones. Regulating the production and sometimes changing the orientation of the plant's elements (e.g. wind turbine blades), the SCADA system helps the operators of RES power plants to control multiple producing turbines at the same time.

The complexity in piloting multiple industrial elements, all of them sensitive to weather conditions, requires adding more sensors to the turbines in order to optimize their use. More sensors that are connected to a distant SCADA also means more cyber points of access to the system. A presentation at the Black Hat USA Conference in 2017 demonstrated the inherent weaknesses of wind farm control systems [11]. The weak physical security, with a larger perimeter to manage than in a thermal power plant, increases the vulnerability to cyber-physical attacks if the aggressors manage to enter the perimeter of the plant to plug a device directly into the system.

The same issues apply for all distributed networks of production, including solar power plants, as all the panels have to be piloted or monitored individually [12]. They are also often connected to the Internet, as a simple request on the Internet of things search engine Shodan reveals [13]. The increasing reliance on smart systems means larger implementation of remote-based control of the facilities, especially with decentralized producing infrastructures such as small hydro, or mid-sized wind farms. [14] This reliance on supposedly smart systems also means an increase in the number of sensors to monitor the production and to allow for a more precise management of the facility. On the other side, it also means an increase in the number of remote access points to the system, which opens a window of opportunity for distant cyberattacks. In addition, different communication protocols, especially wireless ones (such as Wi-Fi, 3G, 4G, and ZigBee) give cyber-aggressors an easier access to the system than with wired connections. The distributed nature of RES power plants tends to increase the use of wireless protocols to facilitate their management through remote controls. Their connected essence – further developed with the use of cloud computing for SCADA data processing - increases the possibility of sabotage oriented cyber-attacks.

The wind turbines, as any other power plants, could also be targeted by ransomware or by hostile takeover of the system as their cybersecurity level could, most of the time, be considered as quite low. An aggressor could infiltrate the system using physical vulnerabilities or remote control access to introduce malware (e.g. Petya, WannaCry, etc.) to the system. The loss of revenues of a paralyzed wind farm could be estimated to be between USD 252 000 and USD 750 000 per day [15].

Past cyber-attacks such as the 2010 Stuxnet against the Natanz uranium enrichment plant in Iran or the uncontrolled shutdown of a smelter in Germany in 2015 demonstrate both the vulnerability of industrial control systems based on SCADA and the damages that a hostile takeover of the system could perform. In the Stuxnet case, a worm entered the Natanz nuclear facility´s system through internal complicity, using a USB dock. The malware was able to cause damage to the centrifuges of the system that were responsible for separating the different atoms needed for the enrichment of uranium. In Germany, an adversary intruded the smelter´s office software network, then proceeded to penetrate the production management software where they took control of most of the plant´s systems. By using the human error through "spear phishing", the adversary managed to cause significant damage to the infrastructure [16].

Even with the existence of global standards for industrial control systems – ISA 99 for example - the lack of precise cyber security regulations and protocols for renewable energy sources could be a major threat to national grids with the projected increasing role of renewables in countries' energy mixes. In this view, RES power plants could constitute the ideal gateway for cyber-aggressors to enter the whole national – or multinational, as the EU is pushing for ever more interconnected system – power grid.

For the moment, the loss of considerable amounts of electricity is considered as the only risk related to any breakdowns in RES facilities. This is usually taken into consideration in the form of cogenerating facilities and other quick means of ramping up traditional power production. However, there is no proper risk evaluation done on other vulnerabilities, such as the effects of cyber sabotage on a wind farm that could cause a massive fire. On the contrary, the physical risks associated with other energy sources, especially with nuclear power plants, have been established already decades ago. The IAEA (International Atomic Energy Agency) regulations regarding physical and cyber risk management are far more influential than in RES. Mitigating the risk in industrial control systems (ICS) is the core of cybersecurity in nuclear power plants, as the large number of documents [17] and training sessions of the IAEA Office of Nuclear Security – including the Cyber Security Programme – demonstrates[5].

The cyber risk in renewable energy power plants is mostly constituted by both the distributions of entry points to the plant's network and the lack of specific procedures – human and computer oriented – in protecting the ICS. Both the increasing interconnectivity of various energy systems and the importance of RES in Western countries' electricity production mixes could lead to major security issues.

Using these vulnerabilities, middle or high skilled determined hackers could breach into the whole electricity system of a country and create regional or national black outs. In terms of global security there is a risk of economic disruption far more severe than the result of the 2007 cyber-attack against the Estonian government and its banking system [19]. Cyber security policies that specifically address the risk related to renewable energy producing facilities should be implemented in Western countries according to the national level of cyber awareness and the level of consciousness regarding specific RES plants' risks.

At the EU level, the 2016 Clean Energy for All Europeans proposal made by the Commission specifically mentioned the need to address the specific issue of cybersecurity

[5] It is worth to say that nuclear power plants have been a target of choice for cyber-aggressors in the past years, explaining this strong policy; see [18]

in RES facilities. In the most advanced NATO cyber countries such as the US, or France, the awareness of cyber security risks to RES plants and how to deter these risks are slowly being included in their strategic white papers and documents [20] [21]. There is still a gap to fill before they are properly included in national policies.

NATO COUNTRIES' FRAMEWORKS AND AWARENESS

The different reports made at national or multi-national (especially EU) levels do not tackle properly the issue of cyber vulnerabilities towards RE power plants. At the European level, regulations regarding cyber security are at crossroads. The EU Commission has tried for years now to promote its Digital Single Market Strategy through legislations such as the Network and Information Systems (NIS) Directive [22]. However, the enormous differences between the member states, in terms of both capabilities and awareness, limit the harmonization of regulations by leaving it to the goodwill of each member state. The EU has taken steps to impose an important change in this cyber-security policy, switching from a national-based policy to an EU-based policy. Trying to transform the European Union Agency for Network and Information Security (ENISA) into a cyber-security agency responsible for the certification of cyber devices for the whole Europe, the EU Commission intends to gain an upper-hand over cyber security issues. The unresolved issue is on the level of cyber security ENISA would base its certification on. The most advanced countries in terms of cyber security, especially France and Germany, were afraid that the chosen level is inadequate and would not ensure a proper level of protection against determined aggressors. In May 2018, the proposal for the EU Cybersecurity Act finally limited the transformation of the ENISA into a European Cybersecurity agency in charge of the harmonization of national regulations.

The US cyber security awareness in the electricity sector seems to be more advanced than its European counterparts, even if far from being fully comprehensive [23]. In Europe, on the other hand, there is a much larger diversity regarding the cyber vulnerabilities that target the energy sector in general [24]. The evolution of EU regulations in cyber security are for the moment limited to operators of vital importance and, even if power grid operators and conventional power plant operators are part of them, RE facility managers are not. As for security, whether it is cyber or physical, a chain is only as strong as its weakest link. Therefore the cyber security policies in Europe need to be defined in a way that they include RE facility managers and producers as well.

Moreover, the components used in renewable energy facilities, whether industrial (such as wind turbines, and solar panels) or cyber (like command and control systems or remote terminal units), are mostly made outside NATO countries. The importance of China both as a producer of these elements as well as a producer of the intelligent technology raises concerns over the possibility of what the US DoD considers as a level-5 cyber-vulnerability: the intrusion inside a system through a hidden vulnerability (backdoor) that could be triggered at any time [25]. Security-by-design policies are, for the moment, at a declarative level and no proper regulation has been put in place in order to ensure that no hidden vulnerabilities would be created by the aggregation of components from various origins. Cutting down the costs of RES production to improve their market competitiveness should not come at the expense of decreased cyber security measures.

POTENTIAL CONSEQUENCES

The analysis of different vulnerabilities underlines the lack of security policies taking into account the specific nature of RES facilities. In contrast to conventional thermal or nuclear power plants, RES power plants appear far less protected not only against traditional kinetic threats but also in the cyber security sphere. As they are, for the moment, only a limited part of the entire installed power generation capacity of NATO countries, this issue could seem secondary to policymakers and security and defence stakeholders.

Nevertheless, the global paradigm change towards low carbon-based energy sources toppled with the change of view from an energy production oriented view to a more demand oriented view, is set to change the role RES play in NATO countries' energy mixes in the future. By switching to a demand-based model, especially giving an important role to energy efficiency devices, the electricity production sector would evolve towards the phase off of redundant production facilities. A policy oriented towards the curbing of the amount of electricity producing facilities – with the closing of versatile thermal power plants – could lead to lower the resilience of the whole electricity system. Within the interconnected European electricity grid, a major failure in a national electric system could lead to a cascading effect all over the continent.

The issue of strategic metals needed to produce RE infrastructure, is, for the moment, addressed broadly by various NATO countries. In the United States, strategic metals are mostly identified as a defence issue with the Defense Logistics Agency being responsible for strategic stockpiles. Moreover, President Trump issued an executive order in December 2017 that elaborated on a strategy to ensure "Secure and Reliable Supplies of Critical Minerals" [26]. In Europe, the EU updates a list of critical metals that includes the required metals and minerals of all European industrial sectors without any specific focus[6]. In this perspective, nothing specific is done regarding RES. The same applies to the physical protection of RE facilities, as they are currently not considered particularly strategic or potentially damaging to the environment.

Within the three areas analysed in this paper, one question remains open: should RE facilities be considered as subjects of vital importance to a country´s electricity system in the same way as traditional power plants are considered? For the moment the answer seems to be in most cases negative, but the different vulnerabilities assessed (namely ill-protected plants covering wide areas, and increased cyber vulnerabilities because of the interconnectedness, combined with their limited importance in national energy mix in most NATO countries) – and the severity of their potential consequences - advocates for a deep change in this view.

In this perspective, NATO has to consider the creation of legally binding standards for its members, so that each member state will strengthen its cyber-response framework for the better of the Alliance. An attack, whether kinetic or non-kinetic, could have a dramatic impact over the security of the whole Alliance, especially in Europe. Transnational black-outs could cause panic in the civil society, damage the economy and, in the most pessimistic view, be the ideal preparation for a military action.

REFERENCES

[1] Hurley W. J., C. R. Bucher, S. K. Numrich, S. M. Ouellette and J. B. Resnick. Non-Kinetic Capabilities for Irregular Warfare: Four Case Studies. IDA Institute for Defense Analyses, 2009. http://www.dtic.mil/dtic/tr/fulltext/u2/a501354.pdf

[2] Mazzucchi N. The Dependence over Strategic Materials in Renewable Energies and Energy Efficiency: A New Energy Security Issue. Presentation at the World Energy Congress, Istanbul, Oct. 2016.

[3] Denholm P., M. Hand, M. Jackson and S. Ong. Land-Use Requirements of Modern Wind Power Plants, in the United States,

[6] This specific policy explains the absence of Lithium in the EU 2017 list, whereas Lithium is one of the most important items for energy storage; see [27]

National Renewable Energy Laboratory, A national laboratory of the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, 2009. https://www.nrel.gov/docs/fy09osti/45834.pdf

[4] Directive 2012/18/EU of the European Parliament and of the Council of 4 July 2012 on the control of major-accident hazards involving dangerous substances, amending and subsequently repealing Council Directive 96/82/EC, Chapter 15 Volume 031 P. 77 – 113. https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX%3A32012L0018

[5] Lilliestam, J. "Vulnerability to terrorist attacks in European electricity decarbonisation scenarios: comparing renewable electricity imports to gas imports", Energy Policy, no. 66 (March 2014): 234-248. https://doi.org/10.1016/j.enpol.2013.10.078

[6] Haas, Benjamin. "Daylight robbery: thieves steal chunk of China's new solar highway." The Guardian, 09.01.2018. https://www.theguardian.com/world/2018/jan/09/china-solar-highway-thieves-steal-panels

Greensolver Blog. "Wind Farm Security: how to protect your wind energy assets?" 22.09.2015. https://blog.greensolver.net/en/site-security-solutions-how-to-protect-your-wind-energy-assets/

Sharpley, Nic. "Keeping thieves out of windfarm sites." Windpower Engineering and Development, 2.09.2014. https://www.windpowerengineering.com/business-news-projects/uncategorized/keeping-thieves-wind-farm-sites/

[7] Bela, Andreea, Pire, Timothée, Buldgen, Loïc, and Philippe Rigo. "Ship collision on Offshore Wind Turbines". PIANC Yearbook (2015): 189-194. http://hdl.handle.net/2268/196917

[8] U.S. Department of Energy and U.S. Department of the Interior. National Offshore Wind Strategy, 2016. https://www.energy.gov/sites/prod/files/2016/09/f33/National-Offshore-Wind-Strategy-report-09082016.pdf

[9] Rose Stephen, Jaramillo Paulina, Small Mitchell J., Grossmann Iris and Jay Apt. "Quantifying the hurricane risk to offshore wind turbines." Proceedings of the National Academy of Sciences, 109 (9) (February 2012): 3247-3252. http://www.pnas.org/content/109/9/3247

[10] Sun Chih-Che, Liu Chen-Ching, and Jing Xie. "Cyber-Physical System Security of a Power Grid: State-of-the-Art." Electronics, 5(3) 40 (July 2016): 1-18. https://doi.org/10.3390/electronics5030040

[11] Staggs, Jason. "Adventures in Attacking Wind Farm Control Networks", Presentation given at Black Hat USA 2017. Available at: https://www.blackhat.com/docs/us-17/wednesday/us-17-Staggs-Adventures-In-Attacking-Wind-Farm-Control-Networks.pdf

[12] Fleming, Paul, Ning, Andrew, Gebraad, Pieter and Katherine Dykes. "Combining Wind Plant Control With Systems Engineering." Presentation slides from 2015 Wind Energy Systems Engineering Workshop, Colorado. U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy. Available at: https://www.nrel.gov/docs/fy15osti/63584.pdf

[13] Shodan website. Link: https://www.shodan.io/explore

[14] Brewster, Thomas. "Hundreds Of Wind Turbines and Solar Systems Wide Open To Easy Exploits." Forbes, 12 June 2015. https://www.forbes.com/sites/thomasbrewster/2015/06/12/hacking-wind-solar-systems-is-easy/#360564064d5c

[15] Staggs, Jason. "Adventures in Attacking Wind Farm Control Networks", Presentation given at Black Hat USA 2017. Available at: https://www.blackhat.com/docs/us-17/wednesday/us-17-Staggs-Adventures-In-Attacking-Wind-Farm-Control-Networks.pdf

[16] Sentryo website. "Cyberattack on a German steel-mill." https://www.sentryo.net/cyberattack-on-a-german-steel-mill/

[17] International Atomic Energy Agency. "Computer Security at Nuclear Facilities", (Vienna: IAEA Nuclear Security Series No. 17 Technical Guidance, 2011).

[18] World Energy Council. "World Energy Perspectives – Executive Summary." (London, 2016). https://www.worldenergy.org/wp-content/uploads/2016/09/Resilience_Managing-cyber-risks_Exec-summary.pdf

[19] Huyghe, François-Bernard, Kempf, Olivier, and Nicolas Mazzucchi. "Gagner les cyberconflits". Paris: Economica, 2015.

[20] In France the 4th recommendation of the General Council for Economy report (2017) regarding the opportunities of the energy transition specifically addresses the challenge of strengthening the cybersecurity level of infrastructures.

[21] Ingram Michael and Maurice Martin. "Guide to Cybersecurity, Resilience, and Reliability for Small and Under-Resourced Utilities." U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy. January 2017. Available at: https://www.nrel.gov/docs/fy17osti/67669.pdf

[22] European Commission website. "Cybersecurity". Available at: https://ec.europa.eu/digital-single-market/en/cyber-security

[23] Advanced Energy Economy Institute. "Cybersecurity in a Distributed Energy Future." January 2018. Available at: https://info.aee.net/hubfs/Cybersecurity_FINAL_WP_AEEInstitute_1.18.18.pdf

[24] EECSP. "Report on Cyber Security in the Energy Sector, Recommendations for the European Commission on a European Strategic Framework and Potential Future Legislative Acts for the Energy Sector." Brussels, Energy Expert Cyber Security Platform (February 2017). https://ec.europa.eu/energy/sites/ener/files/documents/eecsp_report_final.pdf

[25] The U.S. Department of Defense. Task Force Report: Resilient Military Systems and the Advanced Cyber Threat. (Washington: Office of the Undersecretary of Defense for Acquisition, Technology and Logistics, 2015).

[26] The White House. "Presidential Executive Order on a Federal Strategy to Ensure Secure and Reliable Supplies of Critical Minerals." 20.12.2017. https://www.whitehouse.gov/presidential-actions/presidential-executive-order-federal-strategy-ensure-secure-reliable-supplies-critical-minerals/

[27] Mazzucchi, Nicolas. "Transition énergétique et numérique: la course mondiale au lithium." (translation) "Energy and digital transition: the global lithium race." Recherche et documents n°5/2018, Fondation pour la Recherche Stratégique (March 2018). https://www.frstrategie.org/web/documents/publications/recherches-et-documents/2018/201805.pdf

Notes

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