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Content

Commander's Corner

Vigilance in Strengthening Critical Energy Infrastructure Protection

by **Col. Darius Užkuraitis, Director of NATO ENSEC COE**

Critical Energy Infrastructure Protection (CEIP) is a complex and ongoing endeavour that necessitates a focus on resilience in the face of evolving threats. The war in Ukraine exemplifies the consequences of infrastructure disruptions, emphasizing the urgency to enhance CEIP strategies. NATO's involvement in bolstering protection measures, particularly in underwater infrastructure, showcases its commitment to strengthening CEIP. This effort is a complex undertaking that encompasses various dimensions, including physical security, cybersecurity, supply chain resilience, and emergency response. Achieving 100% protection is a daunting task due to the ever-changing threat landscape and the interconnected nature of energy infrastructure. Resilience, therefore, becomes the key focus - a continuous battle to adapt and mitigate risks, even in the face of emerging threats. CEIP strategies must be forward-thinking, anticipating future challenges and investing in proactive measures to enhance resilience.

THE NECESSITY OF ENHANCING CEIP:

Energy Security and Stability: Strengthening CEIP is vital for ensuring energy security and stability. Disruptions in critical energy infrastructure can have severe economic consequences, affecting industries, businesses, and households. By enhancing protection measures, nations can mitigate risks and ensure the continuity of energy supply.

National Resilience: Protecting critical energy infrastructure contributes to national resilience. Robust CEIP measures reduce a nation's vulnerability to external pressures and potential hybrid threats. Strengthening energy infrastructure resilience enhances a country's ability to withstand and recover from energy disruptions, ensuring national security and stability.

Environmental Sustainability: CEIP is closely linked to environmental sustainability. Protecting renewable energy installations, such as offshore wind farms, contributes to achieving clean energy goals. Safeguarding critical energy infrastructure ensures the continuity of sustainable energy production, mitigates climate change risks, and reduces carbon emissions.

The war in Ukraine vividly illustrates the severe consequences of critical energy infrastructure disruptions. The temporary loss of energy assets had far-reaching implications for Ukraine's energy security and regional stability. It highlighted the urgent need for comprehensive CEIP measures to minimize vulnerabilities and mitigate the impact of potential disruptions. The war in Ukraine serves as a reminder that energy infrastructure is a prime target in conflicts and hybrid warfare strategies.

NATO's Energy Security Centre of Excellence (ENSEC COE) has played a pivotal role in fostering CEIP. Established in 2010 in Vilnius, Lithuania, the ENSEC COE serves as a hub for research, training, and coordination on energy security. It facilitates cooperation among NATO members and partners, enabling the exchange of knowledge and best practices in CEIP. As part of its efforts, ENSEC COE annually conducts "Coherent Resilience" Table-Top exercises (CORE TTX), which is usually focused on improving the resilience of critical energy infrastructure against various threats.

TTX CORE 23-Baltic is planned to be conducted in November 2023 in Latvia. Exercise will address critical energy infrastructure protection of the Baltic States and focus on maritime and offshore energy installations in the Baltic Sea. The goal of the exercise is to support the national authorities, regulators, and infrastructure operators of the Baltic States. Through scenario-based simulations, the exercise aims to enhance situational awareness, strengthen coordination, and test response mechanisms to potential energy disruptions. By bringing together stakeholders from the military, industry, and government sectors stakeholders, TTX CORE 23-Baltic will facilitate knowledge sharing, promote best practices, and improve the collective resilience of critical energy infrastructure in the Baltic region.

Editorial

By **Wsewolod Rusow,**
Defence Engineer and Chief-In Editor, NATO ENSEC COE

In this edition, the authors have attempted to outline the very broad term of Critical Energy Infrastructure (CEI) from a wide range of perspectives. On the one hand, there is the simple question: what does actually belong to the CEI? As the examples showed, it is not just the power plants, pipelines and fuel depots. The variety of facilities and objectives is much wider. On the other hand – what dependencies inevitably arise, if you shift the focus of energy supply or fail to relocate it? Finally yet importantly – how easy it is to jeopardize the energy security of entire regions with the smallest of resources and unforeseen events. Those are the questions and the driving objectives of the energy security research nowadays.

CEI has always been a pillar in geopolitics, our world is an industrial world and it is simply unthinkable without the energy, which fuels it. However, something has changed since February 2022. CEI has not necessarily became more important (it has always been more important than ever), no, it has become much clearer and more tangible to all of us, how dependent we are on energy and how vulnerable our society is, if and when free access to energy becomes more difficult.

The public desire for 100% secured energy infrastructure – from the source of origin up to the consumer is understandable. It is as understandable as it is impossible to guarantee, either for individual states or for the alliance. So, what can science and research offer to the society, if not the 100% security? Obviously, there is no simple solution to this. Whatever walls we try to raise, hiding our "energy treasures" behind, we will fail, when the costs for protecting the energy exceed the actual energy costs and that can happen sooner than we think. What is the main subject of public concern? *A stable and reliable access and supply of required energy forms and quantities* – this is the definition of *Energy Security*. Once the actual goal is clear and defined, the science can provide suitable solutions.

A promising approach is – energy resilience. It is not a solution that you set up once and do not touch anymore. Rather, it is a strategy, a sum of conceptual measures and verified procedures. The constant and recurring work cycle, which has to prove itself anew every day. It is a behavioral methodology and psychology at the end of the day. Of course, as with any change that is to be lived through sustainably and successfully, the first step is insight. Our society may need to start by recognizing that we are dependent on energy and if we want to maintain our current level of technology (current life's standards) – then **we will remain dependent on energy**. Consequently, as a corollary to that, we have to accept that this dependency makes us extremely vulnerable. Once this understanding has been reached, further steps are all the more plausible. It is never a question of whether one energy source is more secure than the other is. The goal is to have unimpeded access to the required amounts of energy.

Finally, a heretical thought (purely in the sense of free research) is allowed: it is essentially a matter of re-shaping the perception of energy, from the public's point of view. Perhaps energy is far too valuable to be treated as a commodity.

Costs of building new energy infrastructure and transporting energy for a future sector-integrating energy system with a focus on Europe

By **Dr. Jutta Lauf** and **Dr. Reiner Zimmermann**

THE ENERGY PARADIGM SHIFT

Volatile power production by renewable production facilities and consequently volatile energy prices (Figure 1)[1] are a serious obstacle for further economic growth, especially in industrialized countries. This holds true besides the current turbulences on the traditional, i.e., fossil carbon based energy markets. Globally, most nations declared their strong commitment to moving away from fossil carbon based energy sources and to reach greenhouse gas (GHG) neutrality until the mid of the 21st century. This in consequence means that the renewable energy production sector has to undergo a dramatic expansion in the next few decades in order to cover the European demands. Most renewable energy technologies for this change are currently based on using solar or wind energy, while geothermal and the highly controversial nuclear energy play a relatively minor role.

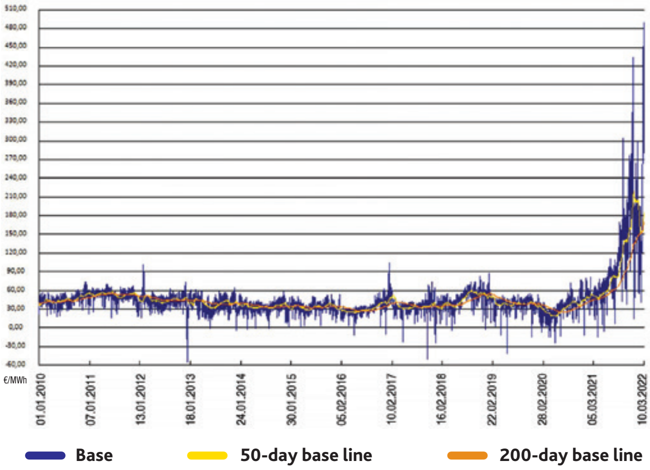

Figure 1: Mean daily spot prices for electricity at the European Energy Exchange in Leipzig (Germany)[1]. Blue line: Hourly minimum prices (Base). Yellow line: Fifty days running mean of the hourly base prices. Orange line: two hundred days running mean of the hourly base prices. The Figure was made by Curth[2] and was changed by Lauf.

by **Dr. Jutta Lauf** and **Dr. Reiner Zimmermann**

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THE GEOSTRATEGIC ENERGY CHALLENGES

Two geostrategic challenges result from this paradigm shift in energy production policy: (1) Renewable energy has to be produced where solar or wind energy are available in a sufficient and reliable quantity and (2) the energy produced has to be transported to the consumers. Further challenges to be addressed are the questions which technologies to use, which energy forms to produce and how to store and transport large quantities of energy (electricity, gases, liquids) between producers and consumers. For e.g., most European industrialized countries this is a question of survival by maintaining their industrial competitiveness in the future, because even major expansion of the European renewable energy sector (solar and wind) will not be sufficient to cover the demand. Europe faces a tough choice: Either large quantities of the needed renewable energy have to be produced somewhere else (e.g., in the global Sunbelt countries) and be transported to Europe – or the energy intensive industrial sector has to migrate to where the renewable energy is produced. Europe is trying an intermediate path: Expanding local renewable energy production and exploring the options for energy imports. In any case, huge investments have to be made in building up renewable energy infrastructure and energy transport systems for future sector-integration of energy production and industrial production.

SECTOR INTEGRATION AS THE KEY ELEMENT OF AN AFFORDABLE AND ROBUST ENERGY SUPPLY

Sector integration is considered to be the key element of an affordable and robust energy supply as well as for tackling the climate crisis. It means linking the various energy uses (electricity, heat, and cold) with each other and with the end-use sectors (buildings, transportation, industry) which are traditionally separated. A recent successful example of sector integration is the combined heat and power waste-to-energy plant "Amager Bakke" in Copenhagen (Denmark). It was inaugurated in 2017 and incinerates up to 560 000 t of solid municipal waste per year. 50 000 households are supplied with electric power and 120 000 with heat by a district heating system. It also is home to an artificial ski slope, a hiking and a climbing park and several other leisure activity options (Figure 2).[3]

Several industries which are potential candidates for sector-integration in order to create a sustainable energy economy were already discussed by the authors of this article in a previous volume of Energy Highlights[5]. The present article will focus on the costs of building and running transportation infrastructure. Sector integrated facilities may be thousands of kilometres apart and therefore new transport infrastructure projects are needed and long distance energy transportation costs become even more relevant.

Electrification of as many aspects of industry and mobility is currently perceived as the best solution to the climate crisis and becomes a clear economic trend. For supporting climate mitigation electric power must be generated by renewable power plants. In the case of excess electricity – which cannot be used by customers in the moment of production – the energy must be stored e.g. in pumped hydropower stations or in synthetic fuels (synfuels) which can be re-transformed into electricity on demand[6–8]. Elec-

Figure 2: Aerial view of Amager Bakke, also known as Copenhill, a combined heat & power waste-to-energy plant and sports facility in Copenhagen (Denmark)[4].

	KPI	Unit	Value
Mean for all topography types	CAPEX	[10^3 US$ MW^{-1} km^{-1}]	400 – 600 (1)
Overhead cable (AC, DC, 500 KV)	CAPEX	[10^3 US$ km^{-1}]	3 000 (1)
	CAPEX	[10^3 US$ GW^{-1} km^{-1}]	900 (1)
	Line costs	[US$ MWh^{-1}]	1.8 (1)
Overhead cable (AC, DC 380 kV)	CAPEX	[10^6 €/km^{-1}]	2.0 – 2.2 (2)
Underground cable (AC, DC 380 kV)	CAPEX	[10^6 €/km^{-1}]	6.0 – 11.5 (2)
Deep see cable	CAPEX	[10^6 € km^{-1}]	3.2 (3,4)

Table 1: Real, projected, and calculated costs of the construction and operation of power lines and the transportation electricity.

KPI = key performance indicator; CAPEX = capital expenditures. Sources are referenced in numbers as follows: (1) = Leighty and Holbrook (2012)[9]. (2) = Netzentwicklungsplan Strom (2020)[10]. (3) = RWE (2019) [11]. (4) = TenneT (2020)[12].

tricity transmission lines connecting the place of production and storage with the places of consumption are essential.

This article will start with discussing the transportation of electric power. Subsequently we will discuss the costs of transport infrastructure for alternative gases or liquid fuels such as hydrogen (H_2) and ammonia (NH_3). Finally, we will cover infrastructure and transport costs for synthetic carbon based fuels like methane (CH_4, natural gas) or diesel/kerosene and carbon dioxide (CO_2) as base chemicals for the production of synthetic fuels.

ELECTRICITY TRANSPORT

Electrification started in the 1880ies. At the beginning alternate (AC) and direct (DC) current systems compete against each other. Nowadays customers are usually supplied with AC power. However, high voltage, long distance transmission lines are preferably operated as DC systems. Solar plants supply DC power, while turbines of any kind supply AC power.

Costs of power production follow the general economic laws of production. Costs in companies are typically split into capital expenses (CAPEX) and operational expenses (OPEX). Typical CAPEXs are the funds needed for acquiring assets such as CSP plants. Typical OPEX are the costs of running the plant, e.g. maintenance. The principles were shown on the H_2 production from renewable electricity sources in a previous issue of Energy Highlights[7].

OVERHEAD AND UNDERGROUND CABLE

For building new transmission lines, capital expenses (CAPEX) for a 500 kV, AC or DC line are between 400 - 900 * 10^3 US$ GW^{-1} km^{-1} are reported, depending on the respective topography and type of line - overhead, underground, deep sea - (Table 1).[9] The unit US$ GW^{-1} km^{-1} is a measure of the total transmission service provided by the system. It is useful for comparing transmission cost means and building strategies[9].

The German national transmission network operators published the estimated costs for their 2030 project plans. CAPEX for AC and DC 380 kV aerial cables do vary between 2.0 – 2.2 *10^6 € per km. Costs for AC and DC underground cables (AD and DC 380 kV) do vary between 6.0 – 11.5 *10^6 € per km. Several options for retrofitting existing power transmission lines were incorporated into the calculation as well as the supporting structures[10].

DEEP SEA CABLE

The most recent as well as the longest European deep see cable project "NordLink" connects Wilster (Germany) with Tonstad (Norway)[12; 13]. Its aim is to stabilise the power grids of both countries and to store surplus power from German renewable electricity plants in Norwegian hydro power stations. The power surplus in Germany occurs usually in autumn and winter when wind turbines generate plenty of power, suppling German and Norwegian customers. During this period the water in the hydro dams is saved for periods with no surplus power from German renewables, usually in summer. Then the Norwegian hydro power plants in turn supply Norwegian and German customers. This demonstrates the stabilising power of the interconnection of electricity grids between countries (Energiewende)[6]. However, surplus power on the international energy market (in this case from Germany to Norway) is very cheap, while power on demand (e.g., from Norway to Germany) comes at a cost.

The NordLink sea cable was commissioned on 28th of May 2021[13] and covers 623 km of which 516 km is a deep see cable. It is a high voltage direct current (HVDC) ca-

Figure 3: NATO's Central European Pipeline System with pipelines, ports and airports[15].

ble with a capacity of 1.4 x 10^9 W. Total costs are estimated to approx. 2 x 10^9 € [11], resulting in CAPEX of 3.2 x 10^6 € km^{-1} [11].

OIL AND LIQUID FUEL TRANSPORT

Oil pipelines have a long history of operation. The first pipeline was built a few years after the first oil wells in Pennsylvania (USA) were developed in 1878. It was 109 miles long and should circumvent the railway monopoly to lower transportation costs.[14] The construction of oil pipelines is very expensive but the costs per mile are lower than transportation by truck or train. Intercontinental shipment of oil by ships was established after WWII.

Even NATO owns and operates several pipeline systems. The Central European Pipeline System (CEPS) is the largest, with a length of approx. 5 300 km with parts in France, Germany, Luxembourg, Belgium and The Netherlands (Figure 3). It contains, among other facilities, 71 high-pressure pump stations, 36 depots with a capacity of approx. 1.2 x 10^6 m^3, six seaport entry stations, 12 refineries, four petroleum laboratories and several truck and train loading stations. Only refined products are transported[15].

OIL PIPELINES

The *Global Energy Monitor* lists major global oil and gas pipeline projects for the years to come. As a consequence of future energy markets moving away from liquid fossil fuel, only 14 new oil pipeline projects are listed, all to be built onshore. Natural gas pipelines are more likely to be built than oil pipelines. The projected costs per km vary in a great range (1.2 – 10.0 10^6 US$ km^{-1}, Table 2).[16]

The last building period monitored – 2014 to 2015 – which lists projects finished in that period, was the most expensive ever experienced. No denominator of the costs per km could be identified. However, the costs per km show a tendency to decline with the length of the pipeline and to rise in densely populates areas.[16]

NAVAL OIL TRANSPORT

Long distance transport of crude oil is mostly by ships from offshore platforms, storage tanks and harbours to refineries. Normally, the largest vessels are used for crude oil (2 * 10^6 barrels = 317 975 m^3). Refined products from refineries to sea entry ports and customers are normally transported in smaller vessels (1 * 10^6 barrels = 158 988 m^3 or 0.6 * 10^6 barrels = 95 393 m^3). Customers are normally charged per day. Daily transport costs are driven by demand and may vary by a factor of three [17]. Between 1996 and 2017 the daily costs for the largest naval carriers (2 * 10^6 barrels) varied between 20 and 72 * 10^3 US$ day^{-1} (Table 2)[17].

	KPI	Unit	Value
Pipeline (new, onshore)	CAPEX	[10^6 US$ km^{-1}]	0.7 – 10.0 (1)
Ship (2 Mio barrel ship = 317 975 m^3, mean 1996 – 2017)	OPEX	[10^3 US$ day^{-1}]	15 (2)
	Transportation (fee for charterer)	[10^3 US$ day^{-1}]	20 – 72 (2)

Table 2: Real, projected, and calculated costs of the construction and operation of pipelines and the transportation of oil products.

KPI = key performance indicator; CAPEX = capital expenditures; OPEX = operational expenditures. Sources are referenced in numbers as follows: (1) = Global Energy Monitor (2020)[16]. (2) = EURONAV (2017)[17].

	KPI	**Unit**	**Value**
Pipeline			
New (all environments, without support systems, ref. year 2000)	CAPEX	$[10^6\ \text{US\$ (2000) km}^{-1}]$	0.2 – 1.8 (1)
New (onshore and offshore) All projects	CAPEX	$[10^6\ \text{US\$ km}^{-1}]$	0.01 – 160 (2)
without most expensive project	CAPEX	$[10^6\ \text{US\$ km}^{-1}]$	0.01 – 35 (2)
Ship			
160 000 m^3 vessel (without boil off gas)	CAPEX	$[10^6$ €]	163 (3)
	OPEX	$[10^3$ € $\text{day}^{-1}]$	1 466 (3)
	Transportation (Qatar – Japan)	[€-ct kg CH_4^{-1}]	1.2 (3)

Table 3: Real, projected, and calculated costs of the construction and operation of pipelines and the transportation of natural gas.

KPI = key performance indicator; CAPEX = capital expenditures; OPEX = operational expenditures. Sources are referenced in numbers as follows: (1) =Schoots et.al. (2011)[22]. (2) = Global Energy Monitor (2020)[16]. (3) = Al-Breiki and Bicer (2020)[23].

NATURAL GAS TRANSPORT

The gas industry started about 200 years ago in western industrialised countries. By the mid of the 19th century, cities were supplied with town gas which was normally produced locally from coal. It contained approx. 50% H_2, 10% CO, 20% CH_4, 20% N_2 and traces of other gases [18; 19]. By the mid of the 20th century, gas networks were transformed to natural gas. This effort included the exchange of appliances, private, corporate and network owned. A similar effort is currently performed in northern Germany, due to a change in the CH_4 content in the natural gas supply[20; 21].

GAS PIPELINES

CAPEX of projected pipelines varies in the range from 0.01 – 160 * 10^6 US$ km^{-1}. One reason for this enormous span are the distances covered which reach from 8 to 7.000 km and include onshore and offshore installations. Regarding the most expensive project as an outlier, the typical costs range from 0.01 – 35 * 10^6 US$ km^{-1}. This figure is used in the following analysis.[16] Historic sources show a much smaller variation in the past ranging from 0.2 to 1.8 * 10^6 US$ km^{-1} with costs calculated at the value of the year 2000 (Table 3)[22]

NAVAL GAS TRANSPORT

Shipment of liquified natural gas (LNG) has intensified in the last decades. Several terminals have been built globally, typically in the Gulf-region, Europe and Japan. A detailed estimated cost analysis was performed by Al-Breiki and Bicer for the shipping route between Qatar and Japan for a 160 000 m^3 vessel. The published OPEX were used to calculate OPEX per day. It has to be noted, that with longer routes and larger vessels costs tend to decrease. OPEX were calculated to be 1 466 * 10^3 € day^{-1}. Transportation costs (Qatar – Japan) were calculated with 1.2 €-ct kg CH_4^{-1} (Table 3)[23].

HYDROGEN TRANSPORT

Hydrogen is a commodity of the fertiliser and chemical industry. It is mostly produced close to the site of demand. Transportation by pipeline, ship and truck is common. All components in direct contact to H_2 have to be immune to hydrogen embrittlement across the entire pressure and temperature range as well as to hydrogen corrosion and cracking (pressure > 2 * 10^7 Pa and temperature > 200 °C)[22].

HYDROGEN PIPELINES

In 1938 the first H_2 pipeline was built in the Rhine-Ruhr area (Germany), which is still operational. Since then, several thousand km of pipelines were built in Europe and North America[22]. In 2016, the H21 Leeds city project (cooperation of several gas related companies) examined the technical and economic aspects of a transformation to a pure H_2 gas network for the town of Leeds, one of the major cities in the UK. They concluded, that a transformation is possible[20].

On a European perspective, the *European Hydrogen Backbone* report from 2020 (cooperation of 11 network operators in 10 countries) examined the possibilities of a European pure H_2 gas grid. A map of a mature network for the European mainland to be built until the year 2040 is shown in Figure 4. The construction of this network within 20 years' seems feasible due to the possibility of retrofitting former CH_4 pipelines (22 900 km)[21].

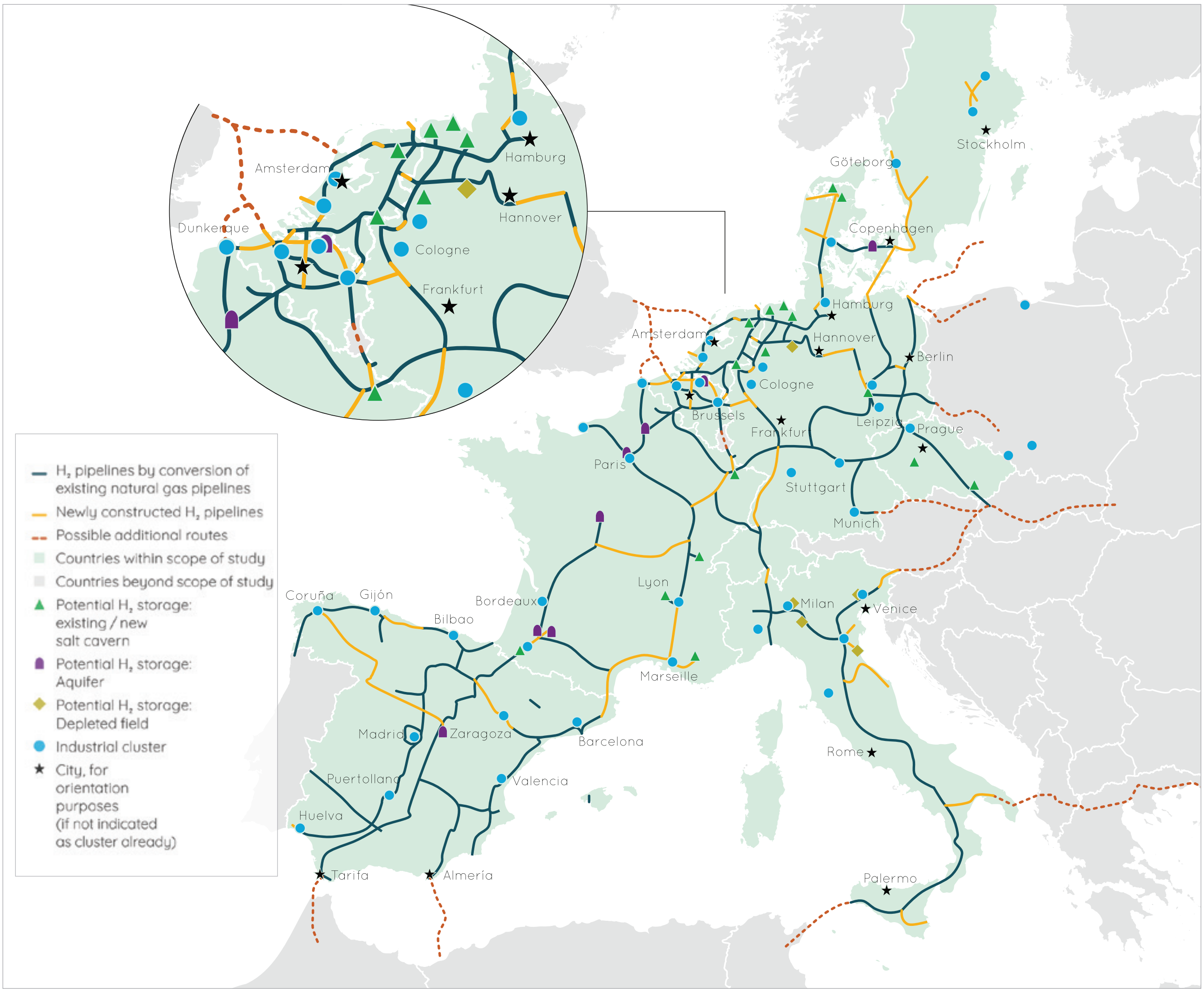

Figure 4: Map of the projected mature hydrogen pipeline backbone system created by 2040[21].

Experience and technical competence for changing gas systems and handling H_2 rich gases is available and gas network operators pursue now this task[20; 21].

CAPEX of H_2 pipelines of approx. 560 * 10^3 US$ per GW-km, without supporting systems e.g. compression stations were calculated by Leighty and Holbrook (Table 4)[9]. Schoots et.al. calculated mean CAPEX of existing H_2 pipelines in costs referenced to the year 2000 of approx. 854 * 10^3 US$ per km (costs without supporting systems). The cost range is substantial (376 – 1 129 * 10^3 US$ per km) as all topography types are included. Supportive systems do normally account for an additional 10 – 15% of CAPEX. Reliable learning curve effects were not found and seem not probable in coming years.[22]

An easy to build, quick fix alternative to stainless steel pipes for hydrogen gas are rollable, reinforced thermoplastic pipes. They withstand pressures of up to 42 bar (4.2 x 10^6 Pa) and are installed in a pilot project in the Groningen Seaports[26].

NAVAL HYDROGEN TRANSPORT

A detailed estimated cost analysis for liquified hydrogen transport was performed for the shipping route between Qatar and Japan for a 160 000 m³ vessel. The published OPEX were used to calculate OPEX of 1 257 * 10^3 € day^{-1}. Transportation costs (Qatar – Japan) were calculated with 6.0 €-ct kg CH_4^{-1} (Table 4) [23]. Real costs for a much smaller vessel (1 250 m³) commissioned in 2019 in Japan are not available[27].

AMMONIA TRANSPORT

Ammonia is a poisonous and corrosive carbon free gas. It liquefies at ambient temperature at about 10 bar (1.0 x 10^6 Pa) or at ambient pressure at -33 °C. Pipelines and storage containers are of moderate wall strength and made of low-alloy and low-cost carbon steel. Pressurized NH_3 storage and delivery infrastructure is very similar in design and performance to that of propane (liquefied petroleum gas = LPG). Therefore, any equipment for handling natural gas or

	KPI	Unit	Value
Pipeline			
New (onshore)	Transportation	[€ kg H_2^{-1} 1 000 km^{-1}]	0.16 – 0.23 (1) 0.23 (2)
		[US$ kg H_2^{-1} 1 610 km^{-1}]	0.70 – 3.22 (3)
Retrofitted (onshore)	Transportation	[€ kg H_2^{-1} 1 000 km^{-1}]	0.07 – 0.15 (1)
European backbone (onshore, 75 % retrofitted)	CAPEX	[10^3 € km^{-1}]	1 179 – 2 794 (1)
	OPEX	[10^9 € year^{-1}]	1.6 – 3.5 (1)
	Transportation	[€ kg H_2^{-1} 1 000 km^{-1}]	0.09 – 0.17 (1)
New (all environments)	CAPEX	[10^3 US$ GW^{-1} km^{-1}]	560 (4)
New (all environments, without support systems, ref. year 2000)	CAPEX	[10^3 US$ km^{-1}]	376 – 1 129 (5)
Ship			
160 000 m^3 vessel (without boil off gas)	CAPEX	[10^6 €]	183 (6)
	OPEX	[10^3 € day^{-1}]	1 257 (6)
	Transportation (Qatar – Japan)	[€-ct kg H_2^{-1}]	6.0 (6)

Table 4: Real, projected, and calculated costs of the construction and operation of pipelines and the transportation of hydrogen.

KPI = key performance indicator; CAPEX = capital expenditures; OPEX = operational expenditures. Sources are referenced in numbers as follows: (1) = CIM-CCMP (2020)[21]. (2) = Peters et. al. (2020)[24]. (3) = Bartels (2008)[25]. (4) = Leighty and Holbrook (2012)[9]. (5) = Schoots et.al. (2011)[22]. (6) = Al-Breiki and Bicer (2020) [23]. Ref. year = reference year in terms of worth of money.

Figure 5: Flexible pipeline systems for hydrogen transportation and distribution by SoluForce (The Netherlands)[26].

	KPI	Unit	Value
Pipeline			
New	CAPEX	$[10^3\ \mathrm{US\$}\ \mathrm{GW}^{-1}\ \mathrm{km}^{-1}]$	320 (1)
	Transportation	$[\mathrm{US\$}\ \mathrm{kg}\ \mathrm{NH_3}^{-1}\ 1\,610\ \mathrm{km}^{-1}]$	0.0344 (2)
Ship			
160 000 m^3 vessel (without boil off gas)	CAPEX	$[10^6\ €]$	137 (3)
	OPEX	$[10^3\ €\ \mathrm{day}^{-1}]$	1 583 (3)
	Transportation (Qatar – Japan)	$[€\text{-ct}\ \mathrm{kg}\ \mathrm{NH_3}^{-1}]$	0.8 (3)

Table 5: Real, projected, and calculated costs of the construction and operation of pipelines and the transportation of ammonia.

KPI = key performance indicator; CAPEX = capital expenditures; OPEX = operational expenditures. Sources are referenced in numbers as follows: (1) = Leighty and Holbrook (2012)[9]. (2) = Pipelife Nederland B.V. (2020)[25]. (3) = Al-Breiki and Bicer (2020)[23].

petroleum i.e. pipelines could be easily retrofitted to carry NH_3.[9]

Ammonia is produced on a global scale. It is mostly processed into solid fertilisers e.g., ammonium nitrate or urea and shipped as such. Nonetheless, ammonia is distributed across the world in well-established networks via pipelines, railroads, barges, ships, road trailers and storage depots. Several long range NH_3 pipelines do exist globally. For example, in the USA a pipeline network of approx. 5 000 km connects the Mississippi region with the central regions and the corn belt of the USA[28; 9; 25]. In Eastern Europe a 2 400 km long pipeline connects Samara (Russia) with Odessa (Ukraine), however, the current status is unknown. Pipeline transport in the European Union is not as significant as in the USA or Russia. Only smaller pipelines are in operation. Alternatively, railroad cars, barges and trucks are used. Western Europe alone transports around 1.5 x10^6 tonnes of NH_3 by railway each year. Regulatory and safety measures are well established[29] and the industry has a decade-long track safety record [28].

	KPI	Unit	Value
Onshore	CAPEX	$[10^3\ \mathrm{US\$}\ \mathrm{inch\ diam.}^{-1}\ \mathrm{mile}^{-1}]$	50 – 300 (1)
	OPEX (3 – 8 % of CAPEX)	$[10^3\ \mathrm{US\$}\ \mathrm{inch\ diam.}^{-1}\ \mathrm{mile}^{-1}\ \mathrm{year}^{-1}]$	1.5 – 2.4 (1)
Offshore	CAPEX	$[10^3\ \mathrm{US\$}\ \mathrm{inch\ diam.}^{-1}\ \mathrm{mile}^{-1}]$	700 (1)
	OPEX (3 – 8 % of CAPEX)	$[10^3\ \mathrm{US\$}\ \mathrm{inch\ diam.}^{-1}\ \mathrm{mile}^{-1}\ \mathrm{year}^{-1}]$	21.0 – 56.0 (1)
New (all environments, without support systems, ref. year 2000)	CAPEX	$[10^3\ \mathrm{US\$}\ \mathrm{km}^{-1}]$	113 – 2 767 (2)

Table 6: Real, projected, and calculated costs of the construction and operation of pipelines and the transportation of carbon dioxide.

KPI = key performance indicator; CAPEX = capital expenditures; OPEX = operational expenditures. Sources are referenced in numbers as follows: (1) = CO2 Pipeline Infrastructure (2014)[31]. (2) = Schoots et. al. (2011)[22]. Ref. year = reference year in terms of worth of money.

	CAPEX (Mean)	OPEX (*5% of CAPEX)	Charter fee
Electricity			
Land cable	2 915 [10^3 € km^{-1}]	146 [10^3 € km^{-1}]*	--
Deep see cable	3 200 [10^3 € km^{-1}]	160 [10^3 € km^{-1}]*	--
Oil			
Pipeline	4 744 [10^3 € km^{-1}]	237 [10^3 € km^{-1}]*	
Ship (2 * 10^6 barrel = 317 975 m^3)	--	--	39 [10^3 € day^{-1}]
Natural Gas (CH_4)			
Pipeline	8 177 [10^3 € km^{-1}]	409 [10^3 € km^{-1}]*	--
Ship (160 000 m^3)	163 [10^6 €]	1 466 [10^3 € day^{-1}]	--
Hydrogen (H_2)			
Pipeline	1 033 [10^3 € km^{-1}]	52 [10^3 € km^{-1}]*	--
Ship (160 000 m^3)	183 [10^6 €]	1 257 [10^3 € day^{-1}]	--
Ammonia (NH_3)			
Pipeline (new)	271 [10^3 € km^{-1}]	14 [10^3 € km^{-1}]*	--
Ship (160 000 m^3)	137 [10^6 €]	1 583 [10^3 € day^{-1}]	--
Carbon Dioxide (CO_2)			
Pipeline	560 [10^3 € km^{-1}]	16 [10^3 € km^{-1}]*	

Table 7: Real, projected, and calculated CAPEX, OPEX and costs of transportation transformed to €, km and m^3.

Data from Table 1 to Table 7 were used. * = OPEX were calculated as 5% from CAPEX for electricity cables and pipelines. OPEX for vessels without boil off gas losses [23]. Barrels were transformed to m^3 with the factor of 0.1589873. Miles are transformed to km with the factor of 1.6093. As a mean exchange rate from US$ to € in the years 1999 to 2019. The factor 0.847 was used[32].

AMMONIA PIPELINES

The costs of NH_3 pipelines can be compared with natural gas (CH_4) pipelines. CAPEX of approx. 320 * 10^3 US$ per GW-km are reported, compression systems included. [9]. Bartels calculated transportation costs of 0.0344 $ kg NH_3^{-1} for a 1 610 km long pipeline in 2008 (Table 5)[25]

NAVAL AMMONIUM TRANSPORT

Only a few ammonia carriers are in service. The costs are prone to market fluctuations[30]. A detailed estimated cost analysis was performed for liquified NH_3 the shipping route between Qatar and Japan for a 160 000 m^3 vessel. The published OPEX were used to calculate OPEX of 1 583 * 10^3 € day^{-1}. Transportation costs (Qatar – Japan) were calculated with 0.8 €-ct kg CH_4^{-1} (Table 5)[23].

CARBON DIOXIDE TRANSPORT

Carbon dioxide for industrial use is mainly transported by pipelines. Transport costs of higher quality and purity grades for the food and medical industries by truck are not discussed in this report. Pipelines for gaseous CO_2 transport are mostly established in recent years in carbon capture utilisation and sequestering projects (CCUS). They connect carbon sources and sinks. The purity of the gas streams depends on the source as well as the technology used for capture. All pipelines transport gas with a minimum of 95% CO_2, approx. one third of the transport volume exceeded 99%. Retrofitting of oil and natural gas pipelines is common in many countries[22; 31].

Twenty nine pipeline building projects were examined in terms of their cost profiles by IEAGHG[31]. Six of these pipelines had on- and offshore sections. The longest pipeline was 810 km long. CAPEX range from 50 to 700 x 10^3 \$ per inch of diameter and per mile for pipelines on flat dry ground to offshore pipelines (Table 1). Values for OPEX do vary significantly. The highest values given (3 – 8% of CAPEX) were used in this article as a worst case scenario.[31]

CAPEX of historical CO_2 pipeline construction costs referenced to the year 2000 are approx. 788 * 10^3 US\$ per km, without supporting systems (Schoots et. al.) The variation is substantial (113 – 2 767 * 10^3 US\$ per km, Table 6) as all topographies are included. Supportive systems do normally account for an additional 10 – 15 % of CAPEX. Cost reducing learning curve effects were not found and seem not probable in coming years.[22]

COMPARING INFRASTRUCTURE AND TRANSPORTATION COSTS

Real, calculated and projected CAPEX, OPEX and transmission costs for electricity cables, pipelines and vessels were published in recent years and show large variations. Information on CAPEX and OPEX were widely available, though OPEX is often calculated as percentage of CAPEX.

Only a few authors report transportation costs for pipelines as € per km per delivered unit (kWh for electricity, kg or m^3 for gases and liquids). This is plausible, as the degree of capacity utilisation varies. The same is true for electricity transmission lines. Therefore, transportation costs for pipelines and cables are not further discussed. In contrast, transportation costs for vessels are more easily calculated. Although, charter fees are often published, they do reflect the availability of vessels in the particular market situation. Calculations about profit contribution of the charter fees are not published.

The units of the published data differ in terms of volume, length, currency, and the value of the currency. Therefore, such data are not readily comparable and cannot be used for strategic decisions. The cost information from Table 1 to Table 6 is normalised to €, m^3 and km and shown in Table 7. As mean exchange rate from US\$ to € the factor 0,847 was used. It represents the mean value from 1999 to 2019 [32]. Barrels are transformed to m^3 with the factor of 0.1589873. Miles are transformed to km with the factor of 1.6093. OPEX for electricity lines as well as fore pipelines are calculated furthermore as 5 % from CAPEX, which is the mean margin given in the IEAGHG report for CO_2 pipelines[31].

CABLES AND PIPELINES

Research by Schoots et. al. showed that the variations in CAPEX for natural gas, CO_2 and H_2 pipelines in 1 577 projects covering 80 141 km of pipeline, varied in a huge range and did not decrease with time. Learning curve effects were not identified over the period from 1976 to 2008. The authors explained this with the variation of the specific project topographies, increasing safety standards, variations in global prices for pipes, planning capacity etc. as well as the relatively small numbers of projects with

	CAPEX (Mean)	OPEX (*5% of CAPEX)	Charter fee
Electricity			
Land and deep see cable	2 963 [10^3 € km^{-1}]	148 [10^3 € km^{-1}]*	--
Oil			
Pipeline	4 744 [10^3 € km^{-1}]	237 [10^3 € km^{-1}]*	
Ship (2 * 10^6 barrel = 317 975 m^3)	--	--	39 [10^3 € day^{-1}]
H_2, NH_3, CO_2, LNG			
Pipeline	2 294 [10^3 € km^{-1}]	115 [10^3 € km^{-1}]*	--
Ship (H_2, NH_3, LNG160 000 m^3)	161 [10^6 €]	1 435 [10^3 € day^{-1}]	--

Table 8: Mean construction and operating costs from real, projected, and calculated projects were calculated for (a) cables, (b) oil pipelines and (c) gas pipelines for all capacities and environments.

Data from Table 7 were used. * = OPEX were calculated as 5% from CAPEX for electricity cables and pipelines. OPEX for vessels without boil of gas losses[23].

Harbour (loading point)	**Harbour** (entry to Europe)	**Distance** [km/miles]	**Sailing time** [days]	**Total Transportation Costs** [10^3 €]	
				Liquid Synfuels	**Gaseous Synfuels**
Casablanca (Morocco), Mediterranean Sea	Rotterdam (The Netherlands), North Sea	1 500 2 420	2.7	163	3 901
Port Said (Egypt), Mediterranean Sea	Marseilles (France), Mediterranean Sea	1 700 2 740	3.1	184	4 421
Port Headland (Western Australia), Indian Ocean	Southampton (UK), North Sea	11 600 18 670	21.0	1 261	30 167
Reykjavik (Island), North Sea	Middlesbrough (UK), North Sea	1 000 1 609	1.8	108	2 600
Reykjavik (Island), North Sea	Bergen (Norway), North Sea	920 1 481	1.7	100	2 393

Table 9: A selection of potential routes for shipping of alternative fuels to Europe and the associated total transport costs. Distances were calculated using SailingEurope[36].

Miles are transformed to km with the factor of 1.6093. Mean sailing speed was estimated with 20 knots = 888 km day^{-1} [23]. Distance, sailing time and total costs of the trip for the charterer are approx. figures.

comparable parameters [22]. Data from the Global Energy Monitor for natural gas pipelines (52 projects) and for oil pipelines (15 projects) also shows huge variation in CAPEX, although no explanations were given[16].

It can be assumed, that the absence of learning curve effects in oil and gas pipelines can be expanded to electricity lines and that they will not occur in future projects. In many industrial societies aboveground cables and pipelines are becoming less approved by the public. Future infrastructure will be installed increasingly underground, resulting in increasing CAPEX and OPEX. The upside of this development is an increased robustness against extreme weather events.

Because of the wide range of CAPEX, the absence of learning curve effects and because no clear defining denominator of costs was identified, the mean CAPEX for all capacities and topographies were calculated from Table 7 for (1) cables, (2) oil pipelines, (3) H_2, NH_3, CO_2 and natural gas pipelines. OPEX was calculated as 5% of CAPEX. (Table 8). The calculated costs are used in further discussions with respect to whether power or gas/liquids should be transported.

VESSELS

CAPEX and OPEX for ships are seldom published and mostly calculated. The means for all gases from the data shown in Table 7 are calculated and shown in Table 8.

Often ships are rented out for a charter fee. This fee must at least cover the OPEX, otherwise a permanent financial loss is generated. The mean charter fee for approx. 320 000 m^3 oil tankers was approx. 35 times lower than the OPEX for the 160 000 m^3 vessels for H_2, NH_3 and LNG. This may be explained as followed: (1) Safety, insulation and material specifications are much stricter for cooled, toxic and corrosive gases than for crude oil. (2) Costs tend to decrease in bigger vessels. (3) The economic lifetime of vessels transporting cooled gas was assumed to be 20 years[23]. In contrast, oil tankers stay up to 30 years in service, resulting in lower costs.

Customers chartering vessels are normally charged per day. In general, these fees are prone to huge variations due to changes in demand[17; 30]. Owning a vessel improves the availability of the vessel and predictability of costs but increases the risk of losses during an economic downturn.

Neither the chartering fee nor the OPEX does include the cargo-losses due to boil-off gas. Boil off gases arise due to the evaporation of the cooled and/or liquefied gases. Pressure in the tanks builds up and gas must be vented to prevent the failure of the tank. These losses occur in significant amounts for H_2 (0.52% of cargo daily), NH_3 (0.03% of cargo daily) and fossil and synthetic CH_4 (0.12% of cargo daily). Up to 50% of the total transportation costs for H_2 may be due to boil-off losses. In principle, the boil-off gas could be used as fuel for the ships own propulsion. In addition to the financial cost mentioned, environmental costs may occur. Methane is a more potent greenhouse gas than CO_2. Ammonia is oxidised in ambient air to the problematic components nitrogen oxides (NO_x) and nitrous oxide (N_2O) which are also greenhouse gases.[23; 33] In summary, due to boil–off losses and others considerations (e.g. occupational health and safety, piracy[34; 35] etc.) shipping times and routes should be as short as possible.

For a selection of shipping routes Table 9 presents a calculation of distance, sailing time and costs (without considering additional harbour time). Shipping costs of fuels from their production sites to the entry points into Europe depend strongly on the location of their production. Fuels produced in wind and solar farms in North Africa, the Middle East and Western Australia could be disembarked in Southampton (UK), in Marseilles (F) or Rotterdam (NL), the latter two being starting points of the NATO CEPS (Figure 3). The closest entry ports for fuels produced in Iceland could be Middlesbrough (UK) or Bergen (N) for further distribution via pipelines in Europe.

Shipping is generally affected by e.g., threats of piracy or by complications in e.g., the Suez and the Panama Canal. The intensity of international piracy is varying. The most dangerous regions are the Java Sea, the Gulfs of Aden and the Guinea and the Caribbean Sea [34; 35]. The Suez and the Panama Canal are major shipping routes which can easily be disrupted by accidents, political discord, or war. The latest accident in the Suez Canal in April 2021 blocked it for approx. one week and led to oil price disruptions in Europe and the US [37]. In addition, the middle eastern region is political unstable and the southern entrance to the Suez Canal is also known for piracy[35; 34]. Transport of alternative fuels to Europe should be preferably done from areas which can be reached along secure shipping routes.

OPTIONS FOR TRANSPORTING RENEWABLE ENERGY TO AND WITHIN EUROPE

The shortest routes for direct transport of renewable energy produced in the Sunbelt region outside of Europe (either by electric power lines or pipelines) exist between North Africa and Europe. These are the straits of Gibraltar (14 km) and Sicily (145 km).

TRANSPORT BY ELECTRIC POWER LINES

Electricity can be used either directly in electric appliances and engines or as a “feedstock” for subsequent fuel production. It should be used with priority as electricity without intermediate physical or chemical storage in order to minimize energy losses. Spatial and temporal supply and demand of electric power vary considerably.

If electricity is chosen as a primary form of transmitting energy to and within Europe, a network of large power transmission lines must be built to level out such varying demands. Long range cables, which connect regions, nations and continents with different renewable power sources are most important. The NordLink cable between Germany and Norway is an important example[12; 13]. A possible future cable between Iceland (geothermal power production) and the UK or Norway (hydro power production) would be an equally important milestone.

CAPEX for building electricity lines are higher than for gas pipelines (Table 8). However, the CAPEX for generating the fuel producing plants, the energy losses during the production processes and the transport to customers are not considered in these figures. A detailed comparison of costs of (1) long range transportation of electricity to the fuel production plant which is located close to the consumer and (2) fuel production close to the power generation site and long range transport of fuel to the consumer should be performed.

HYDROGEN TRANSPORT

The second best option (compared to using electricity) in terms of minimizing energy losses is the production of hydrogen (H_2) by electrolysis from water and electricity. Hydrogen can be used for power generation, heating, mobility and as a base chemical in the fertilizer and chemical industry. Wang et al. state that H_2 transport via pipeline is much cheaper than by ship. However shipping may become relevant in the early years of the establishment of a renewable energy system and for regions where pipelines are either not yet available or their construction is not financially feasible.[21] Globally, several H_2 pipelines are operational. European pipeline operators are planning a European H_2 pipeline network, spanning from Spain to the Czech Republic and from Sweden to Italy by the end of 2040 (Figure 4). Connections to North Africa with its potentials in H_2 production sites from renewable sources are projected[7].

Until these connections to the European pipeline network are established, H_2 transport by ship is easily possible. Tankers, which transport H_2 from future productions sites in (1) North Africa may sail from Casablanca (Morocco) to Rotterdam (The Netherlands) or (2) the Middle East may sail from Port Said (Egypt) to Marseille (France) in approx. 72 hours (Table 9).

Up to date the obvious possibilities of H_2 production in areas with ample geothermal energy like Iceland or even Italy are rarely considered. Energy transport from Reykjavik to Bergen (Norway) or Middlesbrough (UK) by vessel is possible in safe and unobstructed waters in less than 2 days. H_2 production costs would be lower compared to facilities in North Africa or the Middle East because of high capacity usage of geothermal and hydro-dam electricity production[7] and shorter transportation routes. Iceland is also a reliable member of NATO[38]. Further deep geothermal energy options for producing renewable energy in Europe exist e.g., in Italy. From there even terrestrial energy transport by electric transmission lines or pipelines would be possible.

For example, the city of Leeds (UK) plans to transform its natural gas grid into a pure H_2 grid. The respective feasibility study cited North Africa, the Middle East, and Western Australia as possible H_2 sources. Shipping from Port Headland (Western Australia) to Southampton (United Kingdom) would take approx. 21 days and is prone to piracy and/or disruption in the Suez Canal[34; 35]. However, the two much closer supply options for H_2 obtained from electrolysis to Leeds were not considered in the feasibility study [20; 39]. These options would be either to use surplus power from Scottish wind turbines or energy from deep geothermal plants in Iceland.

AMMONIA TRANSPORT

The energy intense production of ammonia (NH_3) requires both, hydrogen (H_2) and nitrogen (N_2). Ammonia can be used for power generation, heating, mobility and as a base chemical in the fertilizer industry. NH_3 is stored, traded, and transported on a global scale in established routes. It can be assumed, that an additional demand will be met with the existing fertilizer plants used to capacity or that the respective sites will be enlarged. Therefore, the electricity has to be delivered to the fertilizer production site. NH_3 as a fuel is a relatively new topic[40]. While e.g., Japan is already moving towards ammonia as a future fuel, the discussion of large scale enlargements of the existing transportation infrastructure has not yet gained momentum in Europe. Costs for pipeline construction and transport or shipping are comparable for hydrogen and ammonia.

CARBON DIOXIDE AND CARBON BASED SYNTHETIC FUEL TRANSPORT

Carbon dioxide

The production of synfuels requires – in addition to power and H_2 - a carbon source. Normally, carbon dioxide (CO_2) of secondary origin is assumed to be this source. Historical or projected costs for shipping of CO_2 are not available. The transport of CO_2 from a pure and highly concentrated source to a distant production site for carbon based synfuels may be economically sensible. Direct air capture (DAC) facilities can be built anywhere, but they require very large areas and pure water. Therefore, CO_2 transport from high concentration sources in industry may become profitable in the future[8]. The discussion about large scale synfuel production and transportation has just begun. While pilot production sites exist, the construction of large scale infrastructure projects is in its infancy. Given the current political perturbations on the energy market and the need for a stable and secure synthetic (liquid) fuel production at least for parts of the civil and military traffic sector (trucks and aviation) the production of carbon neutral synfuels may see a significant acceleration in the near future.

Methane

Methane (CH_4) is a possible product of the Fischer-Tropsch-synthesis[19; 18]. It is mostly used in heating and in power production. Fischer-Tropsch-production plants must be newly built. Site selection close to existing pipeline or port infrastructure is sensible. Short pipeline links which connect these plants with the nearest existing pipeline may have to be build. Like natural gas, synthetic CH_4 can easily be transported by pipelines and as liquefied gas in ships. Since natural gas will phase out within the next few decades, the existing pipelines can be used without retrofitting by synthetic methane. Thus, expensive new infrastructure projects can be avoided.

Pipelines are considered commercially feasible for natural gas or methane for distances over 2 000 km. However, long distance shipping of liquefied natural gas has become more common in the past years and allows a much more flexible producer-customer market [23]. Remarks on global shipment of H_2 with respect to production sites and ports can be applied accordingly to CH_4.

Detailed studies comparing the costs of (1) long distance transportation of electricity vs. a CH_4 production plant (Fischer-Tropsch- and DAC-plant) in the proximity of the consumer and (2) CH_4 production plants near the power generation site and long range transport to the consumer are still missing.

Liquid synthetic fuels

Synthetic fuels being equivalent to fossil diesel, kerosene or gasoline can be produced by Fischer-Tropsch-synthesis[19; 18]. Such liquid synfuels require the highest energy input of all alternative fuels produced from renewable sources. Production plants for liquid synthetic fuels (PtL) must be newly built. The site selection close to existing pipelines or port infrastructure seems sensible. Pipelines and shipping transport infrastructure and facilities for refined oil products, such as diesel and kerosene are well established. The use of liquid synfuels is already well tested. Their unsurpassed energy density, easy storage, transport and handling make them ideal for aviation and heavy terrestrial transport, especially for the military. Also, no new propulsion technologies have to be developed.

Synfuels fulfil the existing norms of their fossil analogue and can be fed into pipeline systems at any given existing entry point. Short pipeline linkages which connect synfuel plant with the nearest existing pipeline may have to be build. As fossil based diesel and kerosene will phase out within the next few decades, the existing pipelines, storage places and terrestrial transport infrastructure can be used.

While liquid synthetic fuels are the most expensive form of renewable energy, many militaries as well as the civil long distance aviation sector are preparing the transition from fossil to synthetic PTL fuels. The global oil company BP (British Petroleum) states in its mission statement the transformation to a green-energy supplier[41]. It can be assumed, that other oil companies will follow the lead of BP towards PtL production.

CONCLUSIONS

The coming decades will see major infrastructure projects on a global scale to provide energy from renewable sources – electricity, synthetic gases and liquid fuels – in order to make the transition from fossil fuels to carbon neutral or carbon free energy. Since these projects will be very expensive, the necessary large investments require that the new infrastructure has to be operational for decades.

A major challenge from a geopolitical point of view will be the site selection for renewable power generation. The locations where renewable power is available in sufficient quantities require often access to critical basic infrastructure and production materials (e.g., to water in the Sunbelt) and skilled personnel for operation. The infrastructure for production and transport of renewable energy has to withstand future climate change challenges like sea level rise, higher temperatures[42; 43] or thawing permafrost soils in arctic regions[44]. Additionally, geostrategic and energy security aspects must be considered when choosing plant and transport routes.

In the near future it can be expected that the limited solar and wind potential for renewable energy production in Europe as well as geopolitical and strategic considerations will force Europe to import large quantities of energy. This energy will be produced in the global Sunbelt region of Western North Africa, South America, the Near East or even Australia. Based on these new dependencies, we expect that the so far underrated use of geothermal energy in the European region might gain more attention and importance on the long run.

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European energy crunch and its impact on energy markets

by **Marju Kõrts, Research Estonian SME, Research & Lessons Learned Division**

Since the invasion of Ukraine in February 2022, Russia's aim has been to make gas supply to Europe as unpredictable as possible and thus undermine economic confidence and EU resolve on sanctions. At the end of July, 2022, Russia reduced gas flows to Europe via the Nord Stream 1 pipeline to 20% capacity. Efforts to replace Russian gas with other pipelines and liquefied natural gas (LNG) have yielded some results, but cannot go much further in the short term given the limited availability of global LNG supplies and the regional regasification terminals. Governments in countries with the highest share of Russian gas in total imports announced new plants to cut reliance in the short/medium-term, in particular Germany and Italy. In Germany there were 3 onshore LNG terminal projects and 4 floating storage and regasification unit (FSRUs) projects accelerated, in Italy, respectively 2 FSRU projects under development. Europe's surging pursuit of LNG to phase out Russian pipeline supply and limited global LNG export capacity additions raise the risk of prolonged tight market (IEA, 2022)[1]. Although at the end of 2022 and at the beginning of 2023 many gas market analysts believed that this winter gas season opens with extreme natural gas price levels and volatility, caused by unprecedented uncertainty of supply as Russia steeply curtails its pipeline deliveries to Europe. In reality, energy prices have recently fallen in the European Union (EU), easing slightly the energy crisis for consumers and businesses caused by the Russian war in Ukraine. The European emergency measures, diversification of supplies and a mild winter have all helped to reduce energy costs, which tremendously increased after Russia curtailed fossil fuel exports with the aim of pressing the EU to reduce support for Ukraine, and in response to EU sanctions on Russia.

In December 2022, European governments agreed to cap gas prices, with the aim to better protect European households and businesses from price spikes, which have fueled inflation and undermined economic growth. In January 2023, the European Commission proposed a Net-Zero Industry Act, which envisaged a number of[2] clean technology objectives for 2030, as a response to the US's vast green subsidy package, the "Inflation Reduction Act"[3]. Nevertheless, the efforts recently made, the difficulties in securing Europe's energy supply in the long term will not be easily overcome (European Parliament, 2023).

Based on the International Energy Agency's (IEA) quarterly gas market short and medium-term forecast[4], pressure on the European and global gas markets has eased since the beginning of 2023 due to favorable weather conditions and timely policy measures. By the end of Q1 2023 European hub and Asian spot liquefied natural gas (LNG) prices have fallen below their summer 2021 lev-

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Leading importing countries of liquefied natural gas worldwide in 2022 (in billion cubic meters)

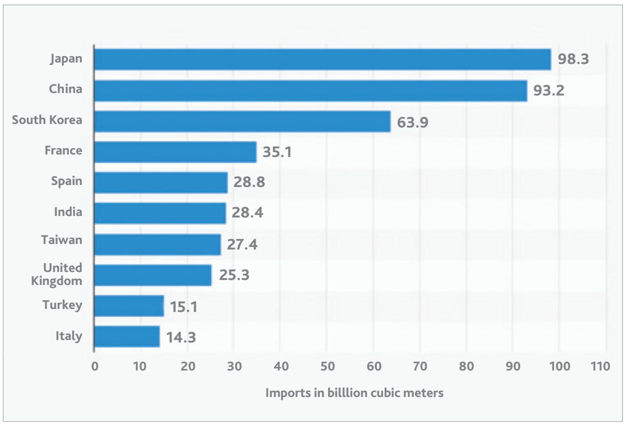

Figure 1.

els, but still remaining above their historic averages. The steep decline in natural gas demand reduced the need for storage withdrawals in Europe and the USA over the 2022/2023 winter. As a result, storage facilities closed the heating season with inventory levels standing well above their five-year average.

Although, it is worth mentioning that the improved outlook for gas markets in 2023 is no guarantee against future volatility. Global gas supply is set to remain tight in 2023 and the global balance is subject to unusually wide range of uncertainties. These include adverse weather factors, such as a dry summer or a cold winter, lower availability of LNG and the possibility of further decline in Russian gas deliveries to Europe. Energy efficiency measures, more rapid deployment of renewables, heat pumps and behavioral change can further reduce gas use in the residential and commercial sectors by 37 billion cubic meters (bcm) by 2030 according the REPowerEU Plan[5]. Most of the remaining demand for Russian gas would be concentrated in the landlocked Central and Eastern European countries (especially Hungary, the Czech Republic and Slovakia), which have historically been the most dependent on Russian gas. Central European countries will be the worst hit as they will not only face gas shortages this winter, but also suffer from the effects of gas rationing in the German industrial sector, given their integration into German supply chains. Hungary, the Czech Republic and Slovakia have historically relied on Russia for almost all of their gas supply needs, and do not have access to LNG terminals given their landlocked position. Alternative supplies would have to come via countries that are also set to run short of gas (Germany, Italy and Austria).

The skyrocketing electricity prices witnessed in 2022 across Europe are intrinsically linked to the high price of gas, which increases the price of electricity due to the role of gas-fired power-plants in covering demand and setting price. Prices started rising last summer when the world economy picked up after COVID-19 restrictions were lifted. Subsequently, Russia's invasion of Ukraine and its weaponization of gas supply have exacerbated the situation with electricity retail prices having increased by almost 50% year-on-year from July 2021 (European Commission, 2022)[6]. The use of energy as leverage has already massively disrupted energy markets – from trade flows to state intervention – and threatens to derail the global economy recovery. The emerging new post-Ukraine war global energy architecture also has profound implications for the energy transition, accelerating it in some places, pressing the pause button in others.

Normally, a larger market might reduce the price for consumers. Natural gas was so in demand a year ago that it is why it is expensive as it has not been in years. In Europe, these high gas prices have been exacerbated by Russia's somewhat petulant decision not to send more gas through its pipelines into Ukraine and the rest of the continent. Oil is primarily used for transportation, but it is important too for some industrial processes. It is also a swing fuel, generating electricity. Oil is both supply-constrained and under high demand: EU consumer spending has returned to its pre-pandemic levels. High natural gas prices have caused some grids to switch to oil production. This gas-to-oil switching was using more oil than Organization of the Petroleum Exporting Countries (OPEC's) planned increase. Despite the increased demand, OPEC announced that it would not increase oil production above its previous target. Renewables are so far mostly exempt for this – except in Europe. In most of the world, renewables are filling in the gap that natural gas has left. The one exception is in Europe, which now uses wind power for 13 percent of its electricity generation. Its energy crunch has been intensified by a lack of strong offshore wind this season, worsening its need for natural gas. Thus, the current crisis can be a turning point for clean energy, highlighting the way in which policy actions of major economies – such as the *Inflation Reduction Act* in the USA and the *Fit for 55* package in the European Union – are turbocharging the growth prospects for key low-emissions technologies like electric cars and accelerating the emergence of the new global energy economy.

Definitely, the current problem of high prices is not caused by the dysfunctioning of electricity markets, but by the exceptional trend in gas prices. In order to decrease electricity prices, it is necessary to decouple power prices from natural gas prices. That is why, a deep and comprehensive reform of the electricity market is being carried out. In March 2023, the European Commission proposed to reform the EU's electricity market design to accelerate a surge in renewables and the phase-out of gas, make consumer bills less dependent on volatile fossil fuel prices. One of the objectives is to better protect consumers from future price spikes and potential market manipulation, and make the EU's industry clean and more competitive.

The European Union has had an efficient, well-integrated electricity market for over twenty years, allowing consumers to reap the economic benefits of a single energy market, ensuring security of supply and stimulating the decarbonization process. The energy crisis spurred by Russian invasion of Ukraine has highlighted the need to quickly adapt the electricity market to better support the green transition and offer energy consumers, widespread access to affordable renewable and non-fossil electricity (European Commission, 2023)[7]. Although before re-designing electricity market we will lose the benefits of the current design, one being the reliable profits that renewables can make that incentivize further investment. On the other hand, decoupling gas and power is easier said than done. Several proposals have been put forward in 2022. To mention, just a few, Greece had long proposed a mechanism to split power exchanges between low- and high- marginal cost generators. On the other hand, Spain and Portugal have already adopted a mechanism with similar goals and which has been provisionally approved by the European Commission. The EU Commission itself put out proposal for a Regulation which, among other things, aims to cap the revenues of infra-marginal electricity generating technologies (Energy Post, 2022)[8].

Market interventions are already in full flow, and appear to be having a domino effect. For example, the push for a price cap on Russian oil exports largely emerged to blunt the price impact of EU embargoes on Russian crude and products coming into force in December 2022 and February 2023 respectively. This move could pose financial and technical difficulties for Russia but it would also deprive the world of 1-2% of its global supply as inflation is on the rise and an economic recession looms. While secondary US sanctions on producers like Iran and Venezuela have become standard, the Group of Seven (G7) price cap[9], if implemented would mark the broadest and most complex (consumer-side) intervention in oil markets ever, with hardly predictable side effects. As a result of the above-mentioned price cap, it can be expected that some ships are changing their countries of origin and trading entities being moved beyond the G7 to evade the plan. Russia would incur costs from having to conduct longer voyages and being relegated to subpar insurance and financing.

Energy subsidies are also emerging as a major fiscal drain on governments' budgets, and risk blurring market signals. A recent study by the OECD and international Energy Agency of 51 countries shows government support for fossil fuels almost doubling to 697 billion USD in 2021 compared to the previous year (Energy Intelligence, 2022)[10]. The European Union in particular is discussing unprecedented proposals to ease consumers and businesses' price pain, ensure energy companies' survival and reform its electricity market. Broadly, what policymakers are doing is starting "to step away from the competitive and liberalized market that has taken the Europeans 30 years to create".

While an oil crisis might influence people's ability to travel and commute, if gas were to run out, the consequences would be catastrophic. From heating homes to powering industrial production, the dependence on natural gas at this point in time is staggering. The oil market is also different because it is global, that is why it is easy to substitute imports. Although natural gas and oil share many characteristics (both are hydrocarbons, both are found and produced using similar methods and equipment, and both are often produced simultaneously), they contrast in the way they are sold and priced. Oil is sold by volume or weight, typically in units of barrels or tons. Different grades and sources of crude oil have different prices that are determined by the amount refiners are willing to pay for the crude oil. Global oil markets are very liquid, relatively transparent, and involve numerous intermediaries and open exchanges.

By contrast, natural gas is sold by units of energy. Common energy units include British thermal unit (Btu), Thermes, and Joules. Natural gas produced form a subsurface reservoir, contains a majority of methane plus various other heavier hydrocarbons and, undesirably, some impurities. The relative proportion of heavier hydrocarbons versus methane would determine the energy content of the gas when combusted and, thus, its ultimate value to a customer. In turn, customers pay for energy derived from gas, not for a specific volume of gas. In the past few years, countries have started to liquefy natural gas and trade it more readily across oceans – and not just through the point-to-point pipelines that were previously used. Besides to pipeline natural gas, there is one alternative, LNG, gas which is cooled to liquid form and can thus be exported in huge gas tankers. When ships reach their destination, the liquid can be turned back into gas[11] and transported using the existing pipeline network.

The gas crisis triggered by Russia's invasion of Ukraine in February 2022 has caused a series of market adjustments. European buyers have strongly increased their LNG procurement, resulting in market tightening and demand destruction in various importing regions. This has also had a visible impact on LNG contracting behaviors, with a return to more traditional features such as fixed destination and long duration contracts. Many traditional LNG buyers will neither procure spot gas or LNG nor renew or sign additional LNG contracts with Russian sellers. Spot prices have also been high and volatile, pushing many buyers towards long-term contracts. Additionally, some buyers are returning to long-term contracting on behalf of governments to protect national energy security. The European Union, whose member states are directly exposed to the threat of further supply cuts, has adopted a number of measures to enhance security of supply and market resilience ahead of the coming winter (IEA, 2022)[12].

European natural gas prices and Asian spot LNG prices spiked to record highs in the third quarter of 2022. This

Annual value of liquefied natural gas imported info the European Union (EU) from 2018 to 2022 (in billion euros)

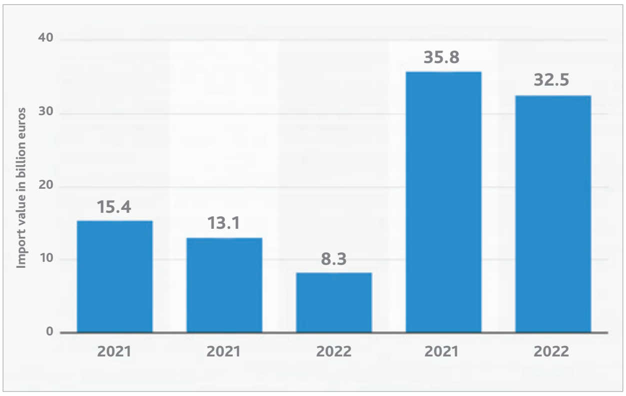

Figure 2.

reduced gas demand and incentivized switching to other fuels such as coal and oil for power generation. As LNG trade and markets become increasingly global, the impact of developments in one region can ripple through others with greater influence than before. European demand for LNG sets off global competition for supplies, even as demand tumbles in Europe and Asian growth stalls. For the first time in history, something approaching a truly global market in natural gas, in much the same way that a global oil market exists.

Aside from the rising prices of LNG, the IEA reports that the ramped-up production of American energy firms may not be enough to bail out Europe should Russia stop their supply. This in real life has already happened after the incidents with the Nord Stream 1 and Nord Stream 2 pipelines explosions that took place in 2022. In the short term, LNG would not be able to fully compensate for any natural gas shortfall from Russia, citing a lack of short-term capacity among exporters like the USA and Qatar. The scale and long-term impact of the changes are still up to debate. Based on the forecast of the International Energy Agency (IEA)[13], it can be seen that the energy crisis in Europe will probably last well into 2023 given stagnant global supply and the likelihood of increasing competition for LNG from a recovering China and other importers.

Figure 3. Main gas pipelines in Europe

Source: ENTSOG TP, retrieved 25 October 2022

LIQUIDITY CRUNCH AND THE POTENTIAL ENERGY POLICY MEASURES

Europe's problems in sourcing oil and gas this winter after a dispute with Russia may be exacerbated by a new crisis in the market where prices are already high: a liquidity crunch that could send them spiraling higher (Payne & Zhdannikov, 2022)[14]. Energy markets around the world are undergoing rapid deregulation, leading to more competition, increased volatility in energy prices, and exposing participants to potentially much greater risks.

As electricity production and demand must be in balance at all times, a trading platform is needed where supply and demand – electricity producers and electricity consumers – meet. This trading platform is called a power exchange. There are two types of power exchanges. Firstly, the power exchanges specialized in physical trading, where the electricity producers and consumers trade with the aim of the physical delivery of electricity from a producer to the consumer within a span of 24 hours (e.g. the Nord Pool power exchange in the Nordic-Baltic region). Secondly, there are derivatives exchange trades on future output of electricity. Companies use a derivatives exchange to hedge electricity price-related risks. The trading focuses on the coming months and years. Although, it is true that traded derivatives[15] are a relatively new concept in the energy markets, the structure have been around for centuries and contracts with derivative characteristics have existed in energy markets for decades. According to many analysts, at present, we have a dysfunctional futures market, which creates problems for the physical market and leads to higher prices, higher inflation. Energy companies are facing solvency issues due to the rising amount of "margin" or cash they must post at clearing houses in case of default on their future sales contracts.

The problem first came up to light in March 2022 when an association of top traders, utilities, oil majors, and bankers sent a letter to regulators calling for contingency plans. This was triggered by market players rushing to cover their financial exposure to increasing prices through derivatives, hedging against future price spikes in the physical market, where a product is delivered, by taking a "short" position. Any such drop in the number of players reduces market liquidity, which can in turn lead to even more volatility and sharper spikes in prices that can hurt even major players. Some particularly smaller companies, have been hurt so badly they have been forced to exit trading altogether as energy prices increased after Russia's invasion in Ukraine in February 2022, which made a general shortage worse.

At the same time European governments have only belatedly decided to offer financial support to power providers on the brink of collapse, in an effort to ease pressure on a market whose smooth operation is vital to keep people warm. Since late August, 2022, European Union governments have stepped in to help utilities such as Germany's Uniper. Germany has considered plans to nationalize the country's three largest natural gas companies – Uniper, VNG and Securing Energy for Europe (formerly Gazprom Germany) to shore up the country's faltering energy market. Among these, Uniper, with an equity infusion from the government, also made clear admission that it could acquire managerial control of the company.

Uniper is Germany's largest importer of Russian natural gas. After Russia cut supplies to Germany because of the Ukraine war and subsequent sanctions, the company had to compensate by buying expensive gas on the open market. The company, which imports approximately 50% of its gas from Russia, announced that reduced deliveries led to a 12 billion euro loss in the first half of 2022. Uniper announced lately that the German government will acquire a 99% stake in the company, having bought a 30% holding in July a part of a 15 billion euro bailout. In July, 15 billion euros so-called stabilization package was signed between Fortum, the German government and Uniper to rescue the company, whose losses were mounting due to gas supply cuts from Russia. The latest deal between the German Government and Uniper will also involve a capital rise that aims to provide a further 8 billion euros in cash for the company. Uniper has been struggling since Russia crimped gas supply to Europe in response to Western sanctions imposed after Russia invaded Ukraine. European natural gas prices have increased 300% this year, with Dutch TTF futures[16]. Nationalizing Germany's largest importer of Russian gas is the second move by the government to take control of an energy utility and is part of a wider European response to the winter crisis, including France taking over EDF[17]. The plan is also a sign that European governments may increasingly be forced to protect their energy companies from the turmoil Russia's was has caused.

The announced deal with Uniper means that Germany buy state-owned Finnish Utility Fortum's stake in Uniper for about 500 million euros and Fortum will also be repaid a 4 billion loan to Uniper. At present, the state-owned (51%) Finnish utility is the majority owner of Uniper (78%), its share will soon be diluted down to 56%. The news about the details of the bailout deal in Finland was received quite negatively (Euractiv, 2022)[18]. According to the Minister for European Affairs and Ownership Steering called Fortum's adventure and its end "regrettable". In hindsight, purchasing Uniper (with 7 billion euros) was a mistake and the decision back then was made without properly consulting the majority owner, the Finnish State.

The bailout also entails certain risks. Germany can risk being left holding 2.2 billion euros of unsellable Russian energy assets when it takes over Uniper SE at the end of the year. Namely, the Dusseldorf-based utility has so far failed to find a potential buyer for its Russian subsidiary Unipro since putting it up for sale in March 2022. The odds of a deal are vanishingly small amid Europe's energy conflict with Russia, which escalated lately after a key natural gas pipeline was damaged in what Germany called an act of sabotage. Uniper, one of the biggest casualties of the energy crisis, has to get rid of its Russian plants before its nationalization in the country's largest corporate bailout in at least a decade. Otherwise, the government risks becoming an owner of five coal and gas power plants that supply about 5% of Russia's total energy needs. Germany may have no choice but to give up the assets. Even if a sale were possible, President Vladimir Putin made it almost impossible for international energy companies to secure big financial gains when they exit Russia. Early this month, Shell Plc left from a liquefied natural gas project with nothing, while Equinor ASA posted a 1 billion USD impairment on its balance sheet as a result of leaving its Russian interests (Bloomberg, 2022)[19].

Increasing energy bills rooted in a global gas supply crunch have focused attention to the old problem: how can we better store power? For example, in the United Kingdom, the closure of the Rough gas storage facility in the North Sea left the UK with only enough storage to meet the demand of four to five winter days. As gas is being phased out, UK's growing reliance on renewables such as offshore wind and solar, does not solve the problem of intermittency (Ambrose, 2022)[20]. They key to securing affordable, low-carbon energy is more storage to make the most of the renewable energy available. Within the next five years, the International Energy Agency (IEA)[21] expects global power storage capacity to expand by 56% to reach more than 270 GW by 2026, driven by an increasing need to create flexible electricity systems which rely more on renewable sources.

Well-established lithium-ion batteries are expected to dominate, according to a report by Bloomberg New Energy Finance, but their capacity is measured in hours rather than days. New energy technologies, which can store energy for longer periods, have found renewed favor within the power industry as winter energy crisis has unfolded. Long-duration storage can be understood that long-duration should be able to discharge continuously for multiple hours (more than 4, or even 10) up to even weeks. For long-duration storage in the weekly to seasonal timeframe, technologies are either still in the development or the potential left in the EU is limited/located in some member-states only. Policy discussions are strongly related to the need for further development of long-duration energy storage technologies' technical performance and costs. There are four long-range energy storage options

Distribution of comulated electric energy storage capacity worldwide in 2022, by region

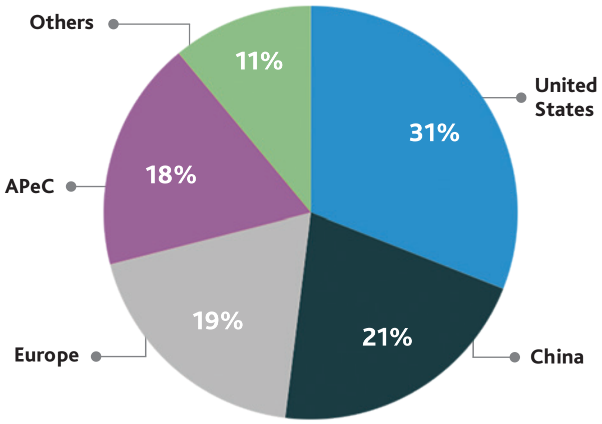

Figure 4.

which are worth mentioning taking into account technology's maturation level and some operational facilities: gravity storage, concentrated solar power storage, green hydrogen and cryogenic energy storage to highlight some of the energy storage technologies.

Gravity storage is a concept with which unprecedentedly large quantities of power can be stored for a long time of 6-14 hours, and can be made available again. The fundamental principle is based on the hydraulic lifting of a large rock mass. Using electrical pumps, as already used today in pumped storage power plants, water is pumped beneath a movable rock piston, thereby lifting the rock mass. During times of insufficient generation of renewable power, the water which is under high pressure from the rock mass, is routed to a turbine, as in conventional hydroelectric plants, and generates electricity using a generator.

The cheapest way to store solar energy over many hours, such as the five to seven hour evening peak demand now found in more places around the world is in thermal energy storage. As solar PV adoption has risen – covering daylight hours – peak demand now typically is during the evening. Energy storage is a key to a renewable energy-powered world. As the thermal dispatchable form of solar, concentrated solar power (CSP) is ideally suited to storing solar thermally and delivering solar on demand. There are several ways the CSP technologies receive the heated fluid to store thermal energy from the sun, but once ready to store, a huge metal tank stores the hot liquid, whether in molten salts (at about 565 degrees Celsius) for power tower CSP or in a heat transfer fluid (at about 400 degrees Celsius) for parabolic trough CSP (Energy Technology Network, 2017)[22].

Demand for hydrogen made from water and renewable energy is expected to boom in the decades ahead as governments plan to replace the fossil fuels used in power plants, factories and heavy transport with green alternative. At the same time green hydrogen can also be used as a form of energy storage. This storage system includes the major components of an electrolyzer, hydrogen storage tank, and a fuel cell system. The excess from the renewable sources (e.g. solar and wind) is directed towards an electrolyzer to generate hydrogen by electrolyzing water into hydrogen and oxygen. The hydrogen is stored in the storage tank and when the renewable sources fall short in meeting the demand, the fuel cell draws on this stored hydrogen and generate electricity (usually by taking oxygen from air)[23].

Cryogenic energy storage refers to a technology that stores energy in a material at a temperature significantly lower than the ambient temperature. The storage material can be a solid (e.g., rocks) or a liquid (e.g., salt solutions, nitrogen, and air). In October 2019, Highview Power announced that it planned to build a 50 MW/250MWh commercial plant in Carrington, Greater Manchester. Construction began in November 2020, with commercial operations planned for 2022. At 250 MWh, the plant would match the storage capacity of the world's largest existing lithium-ion battery, the Gateway Energy Storage facility in California. In November 2022, Highview Power stated that they were still trying to raise money to construct the facility.

THE MAIN LESSONS LEARNED FROM THE EUROPEAN ENERGY CRISIS IN 2022

Starting in September 2021 and greatly reinforced by the war in Ukraine, the energy crisis has strongly affected all European member states. This particular crisis has shown the weakness of the current model. The lessons learned from the crisis inspired the rethinking of the electricity market design. During the crisis it became obvious that there were some elements of the market that could be scrapped and that could be designed in a better way to help facilitate the energy transition, to help facilitate ad speed up the deployment of renewable energy, but also to protect consumers and to create the best possible investment additions for project developers and for those operators in the market.

The political focus on potential short-term fixes of the electricity market design might miss the point: the current crisis is and remains a crisis of (imported) fossil fuels, the best way to address it is limiting the price impacts through collective action. For example, joint EU purchasing of gas has been introduced in response to the energy crisis triggered by the Russian invasion of Ukraine. It is part of the EU's efforts to phase out its supplies of Russian gas as soon as possible, under the REPowerEU Plan (Directorate General for Energy, 2023)[24]. Another piece in this solution is massively accelerating the transition towards low-carbon energy to reduce this dependency. Wind and solar energy at present represent the cheapest form of electricity in most of the world, and in the near term, the cost of running coal and gas-fired power plants for electricity generation will be greater than those of building solar and wind farms. Furthermore, a massive rollout of domestically produced energy, like renewables, will not only reduce import dependence but also cut carbon emissions. That is why, it is important to consider the energy crisis and the climate crisis as two parallel crisis. Therefore, it is important to align the energy response with climate action. The European Green Deal – more renewables, more energy efficiency – would the best way to make us more secure, not only bearing in mind green or affordable energy, but also energy security and economic security. The REPowerEU pillars[25] are in complete alignment with that drive for climate neutrality.

Definitely the dependence on Russian gas was a weakness for the European Union, but simultaneously, there were also a few strengths in place – the EU internal market, interconnectedness, existing infrastructure, and the ability to work together, and investment conditions. The energy sector could and should aim at improving the resilience of the sector without forcing privately held firms to take an excessive risk in the future. Utilities often create natural monopolies and consumers cannot choose to stop consuming water, gas, or electricity, therefore, the logic of the free market starts to break down. The stakes could not be higher – now and in the future. Natural gas is not just used by households but for a wide range of goods. Fertilizer plants shut down when prices rise too much, threatening food security. Natural gas also feeds into input costs for metallurgical firms, food and beverage makers, automotive manufacture, and more. High bills increase costs, compounding the risks of greater unemployment in the event of recession.

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[25] Launched in May 2022, REPowerEU is helping the EU (1) to save energy, (2) produce clean energy, and (3) diversify its energy supplies.

North Africa and the European Union: An option for technically controllable and politically reliable solar electricity supply?

by **Jutta Lauf** and **Dr. Reiner Zimmermann**

I. CLIMATE CHANGE AND ENERGY PRODUCTION

CLIMATE CHANGE, CONFLICTS, AND THE PRODUCTION OF ELECTRICITY

Man-made and accelerated climatic changes are the most fundamental challenges the world is facing. Global warming, rising sea-levels, more frequent and intensive extreme weather conditions threaten entire natural ecosystems, agricultural production, infrastructure and human well being[1]. The political, social and economic consequences of these changes increasingly affect the global security agenda e.g. through "water-wars", conflicts over resources or land grabbing - often leading to famines, increasing numbers of climate refugees, social unrest and even military conflicts and open wars[2; 3]. There is general agreement that the major cause of current climate change is the increasing atmospheric concentration of greenhouse gases (GHG) due to fossil carbon burning. Electricity generation, industry, mobility and buildings, agriculture and forestry do contribute significantly to the emission of greenhouse gases. The most important greenhouse gas with respect to the electricity generation is carbon dioxide (CO_2)[4; 5] Thus most nations agreed to the urgent need for drastically reducing GHG emissions in order to mitigate the current process of global warming.

HUMAN IMPACT ONTO THE "BLUE PLANET"

The Intergovernmental panel on Climate change (IPCC) is a United Nations body for assessing the science related to climate change. In its most recent report (published in autumn 2021) it concluded that climate change is already affecting every inhabited region across the globe, with humans contributing to many of the observed changes. Most obvious to humanity is the rise in hot weather events as shown below.[1]

The European Union (EU) aims to be climate-neutral by 2050, which means an economy with net-zero GHG emissions. This objective is at the heart of the "European

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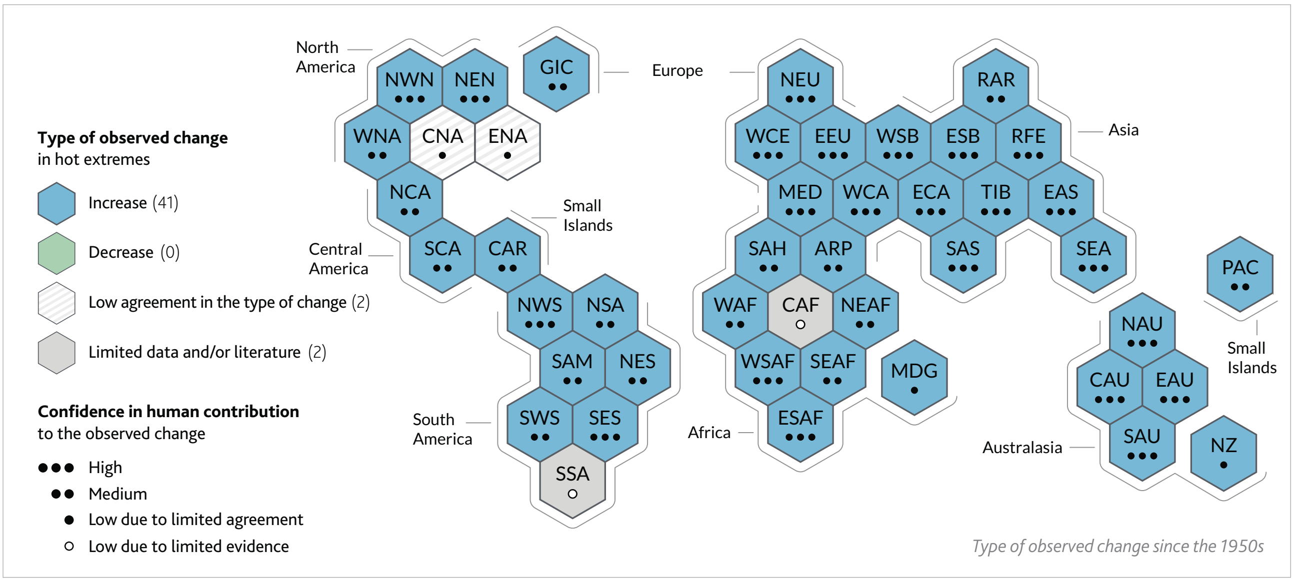


Figure 1: Synthesis of assessment of observed change in hot extremes and confidence in human contribution to the observed changes in the world's regions[1.]

Each hexagon corresponds to one of the IPCC AR6 WGI reference regions: North America: NWN (North-Western North America, NEN (North-Eastern North America), WNA (Western North America), CNA (Central North America), ENA (Eastern North America), Central America: NCA (Northern Central America), SCA (Southern Central America), CAR (Caribbean), South America: NWS (North-Western South America), NSA (Northern South America), NES (North-Eastern South America), SAM (South American Monsoon), SWS (South-Western South America), SES (South-Eastern South America), SSA (Southern South America), Europe: GIC (Greenland/ Iceland), NEU (Northern Europe), WCE (Western and Central Europe), EEU (Eastern Europe), MED (Mediterranean), Africa: MED (Mediterranean), SAH (Sahara), WAF (Western Africa), CAF (Central Africa), NEAF (North Eastern Africa), SEAF (South Eastern Africa), WSAF (West Southern Africa), ESAF (East Southern Africa), MDG (Madagascar), Asia: RAR (Russian Arctic), WSB (West Siberia), ESB (East Siberia), RFE (Russian Far East), WCA (West Central Asia), ECA (East Central Asia), TIB (Tibetan Plateau), EAS (East Asia), ARP (Arabian Peninsula), SAS (South Asia), SEA (South East Asia), Australasia: NAU (Northern Australia), CAU (Central Australia), EAU (Eastern Australia), SAU (Southern Australia), NZ (New Zealand), Small Islands: CAR (Caribbean), PAC (Pacific Small Islands)

Green Deal" and in line with the EU's commitment to global climate action under the Paris Agreement. With nearly 80% of the EU's GHG emissions being related to the energy sector, it is evident that a renewable energy transformation which causes much less GHG emissions is key to mitigate global warming by achieving climate neutrality. The need to shift from a fossil energy supply to renewable energy sources became even more pressing by the open military conflict between Russia and the Ukraine in 2022 which led to a massive increase in fossil energy prices and a bottleneck in the energy supply of gas and oil, though it may boost the deployment of renewable energy production.[6] So, both the GHG reduction for climate change mitigation and the de-coupling from the strategic dependence on fossil energy are strong motives for European nations to increase and diversify their renewable energy portfolio. Large amounts of the renewable energy will have to be produced abroad, transported or transmitted over large distances to Europe and distributed within the EU and partner countries.

In general, the amount of electricity production from renewable energy sources like solar and wind is not controllable because it depends on the locality and the weather conditions. Electric energy can currently only be stored in very limited amounts. Also, transmission losses during long distance transport are unavoidable[7]. Within the framework of uncontrollable power generation from renewable sources and a high and continuous electricity demand, load management of the electrical grids becomes increasingly challenging.[8] Enlarging storage capacities and the interconnectivity of power grids are generally deemed as key elements for solving this problem.[9]

The terrestrial solar and wind generation potential in Europe is limited and will soon reach its limits with respect to available spaces and social acceptance. Off-shore installations still have considerable potential. However they incurring large infrastructure investments and maintenance costs. The remaining gap between supply and demand could be closed by importing renewable energy from regions in the global sun belt (e.g., in North Africa and the Arabian Peninsula) where solar and wind energy are available at an ample scale. The geothermal potential for electric power generation from geothermal sources in Iceland is an interesting alternative to solar and wind power but is not within the geographic scope of this article. For Europe, the closest neighbours within the global sun belt are Morocco, Algeria, Tunisia and Libya. These nations have a high potential for producing renewable energy while the transport (transmission) distance to Europe would be manageable. Of these four nations, only Morocco enjoys a relatively high political stability.

The technical prospects to produce and export electricity generated in renewable power plants from North Africa to Europe are given. North Africa has some of the highest solar power potential in the world[10] as well as a good potential for wind energy[11]. Harnessing only a fraction of the Sahara Desert's renewable energy potential with solar and wind farms could supply enough electricity to meet both, the current and the future global electricity demand[12; 13]. Investing in and supporting North African countries to deploy renewable energy for export and domestic use could be attractive to the European nations and the EU for several reasons. Importing renewable energy from resource rich neighbouring countries could be a means of achieving European climate targets more cost efficiently. Electricity could be obtained with up to 60% lower support costs in comparison to domestic production in Europe[14]. This rationale has for instance been addressed in the EU's "Directive on Renewable Energies", which allows renewable energy cooperation with "third states" and for member states to include it into their national accounting[15]. Within the norms and regulations of the EU, a third state or a third country refers to states, which neither belong to the EU nor to the European Free Trade Agreement (EFTA)[16]. Utility-scale renewable power plants in the middle east and north African countries (MENA) could thus enhance energy security through a diversification of suppliers and energy sources while securing the affordability and sustainability aspects. Yet several attempts of realizing this vision in the previous decades have failed primarily due to political difficulties, e.g., the Desertec Industrial Initiative (DII)[17; 12].

THE CONUNDRUM OF NUCLEAR POWER

The "Directive on Renewable Energies" lists nuclear power as "green energy", alongside other power generating technologies[18; 15]. This classification has caused controversy, as nuclear power plants do not emit CO_2 during power production, but the used uranium fuel is not renewable, and the waste disposal problem is not solved. The assumed advantage of nuclear power plants – their ready to go and controllable power production capabilities – have turned into a liability in the era of global warming, as the dependency of water for cooling purposes became obvious. During the 2022 summer drought in central Europe environmental laws to protect valuable river and lake ecosystems from overheating forced the operating companies to reduce production or even to shut down the plants completely. Especially hard hit was France, which on average produced about 60% of its total power demand via nuclear plants. During the heat wave, with its increasing electricity demand for air condition cooling, France imported power, mostly generated by hydro, wind and solar.[19]

In this paper we will first discuss whether the power demand of the highly industrialized European Union can be met by an electric grid which is mainly supplied by renewable energy sources. Then we present a selection process for such an electricity producing country by physical, political, social, and economic criteria in North Africa. This resulted in Morocco as a potential candidate. Finally, we present a roadmap for a possible cooperation between Morocco and the EU for successful electricity exporting/importing projects. We focus on electric power generation and transmission since the production of hydrogen and carbon-based synthetic fuels, their transport and final energy conversion processes result in very large energy losses.

II. ELECTRICAL GRIDS AND POWER PRODUCTION COSTS

COVERING ELECTRICITY DEMAND WITH "CLEAN ENERGY"

GRIDS DOMINATED BY RENEWABLE POWER PLANTS

Electricity generation is moving away from fossil and nuclear power plants to renewable sources. While the Ukraine-Russian conflict increased the short term use of coal and lignite as well as imports of liquefied natural gas (LNG) from non-Russian suppliers,[20] the long term trend of de-fossilization in the energy sector will persists. Because Western countries try to substitute Russian gas[21]; [22], it is assumed, that in the long run this conflict will actually speed up the production and use of renewable energy. It is generally assumed that this will increase the production of electricity and of hydrogen via electrolysis of water. The high demand of energy in the EU inevitably leads to two key questions: Where can all the "clean" energy be produced and how can it be transported and distributed to the EU nations?[23]

Controllable and storable renewable energy-forms are needed for this transition to be a success. Photovoltaic (PV) and wind generated energy is non-controllable and, in the magnitudes needed, non-storable. Concentration solar power (CSP) plants without thermal energy storage (TES) are also non-controllable. New CSP plants are regularly equipped with TES of up to 12 h of full generator capacity. CSP plants with TES are a game changer as they store the first form of energy harvested which is heat. Heat can economically and on a large scale be stored (e.g., in salt solutions). TES on a kWh basis is 80 - 90% cheaper compared to battery storage[24]. The stored thermal energy can be - on demand - transformed into electrical energy by conventional steam turbines. Since CSP-TES plants can be classified as controllable and storable energy providers, it can be expected that the most likely technological solution for energy generation for European customers will be provided by CSP plants with TES and conventional steam turbines for electric power generation. Sufficient amounts of solar energy for e.g., the power demand of the EU can only be obtained in the global sun belt region. The closest sun belt region to Europe is the MENA area and CSP plants with TES would provide a controllable energy input to the electric transmission lines to Europe and the electric grids of the EU consumer nations. Currently, the global CSP power production is small compared to the total global power production. Countries with the highest production – Spain and the USA – are not even located in the global sunbelt. The technology of CSP plants is described by the authors in an earlier Volume of *Energy Highlights*[8].

MAGNITUDE OF THE EU ENERGY DEMAND

The EU (27) countries – without the UK, which left the Union on 31st of Jannuary 2020 – consumed 16.7 TWh of primary energy in 2021. The primary energy consumption from 1990 – the year of the fall of the Berlin Wall – to 2021 varied approx. ± 9% due to economic booms and crises (Figure 2). Electricity contributed with 13% in 1990 and 17% in 2021 to the total primary energy consumption of the respective year.[25]

Models do predict that for 100 kW PV capacity 2 – 3 kW CSP-TES capacity is needed to secure the energy supply in an increasingly fossil free power production. CSP-TES plants must be built as huge instalments in the global sunbelt region because they require direct and high solar irradiance and the economy of scale for being profitable

It appears possible, that future energy demands can be completely covered using renewable sources. This has been demonstrated by modelling the combined renewable power production during a fictitious week in May 2030 in Spain (Figure 3). In this scenario non-controllable and/or non-storable electricity sources will provide as much power as possible e.g., wind and solar PV. CSP-TES plants will supply power when PV production is not possible (e.g., at night). Biomass/biogas power plants will cover peak demands while wind, hydro and combined heat and power plants (district heating systems) serve the base load[24; 26]. For this scenario to become possible, supply and demand sites must be connected via trans-national and trans-continental high-capacity electricity grids.

TRANS-NATIONAL AND TRANS-CONTINENTAL ELECTRICITY GRIDS

Suppling the grid with the necessary capacity is a demanding task, because most renewable energy sources which are currently used (wind and PV) are neither controllable nor storable[8]. Trans-national and trans-continental power grids would theoretically reduce the volatility of energy production because renewable power production is always possible somewhere on the earth. However, such an global approach would require the installation and maintenance of a multiple of electric power generation capacity compared with the actual energy needed and thus is economically inefficient and expensive.

Currently electric grid networks are shaped by political and geographical criteria. For example, the Continental European synchronous area consists of most countries in Central Europe as well as Morocco, Algeria, and Tunisia in North Africa (Figure 4A). However, only a few cables connect North-West Africa with Spain (Figure

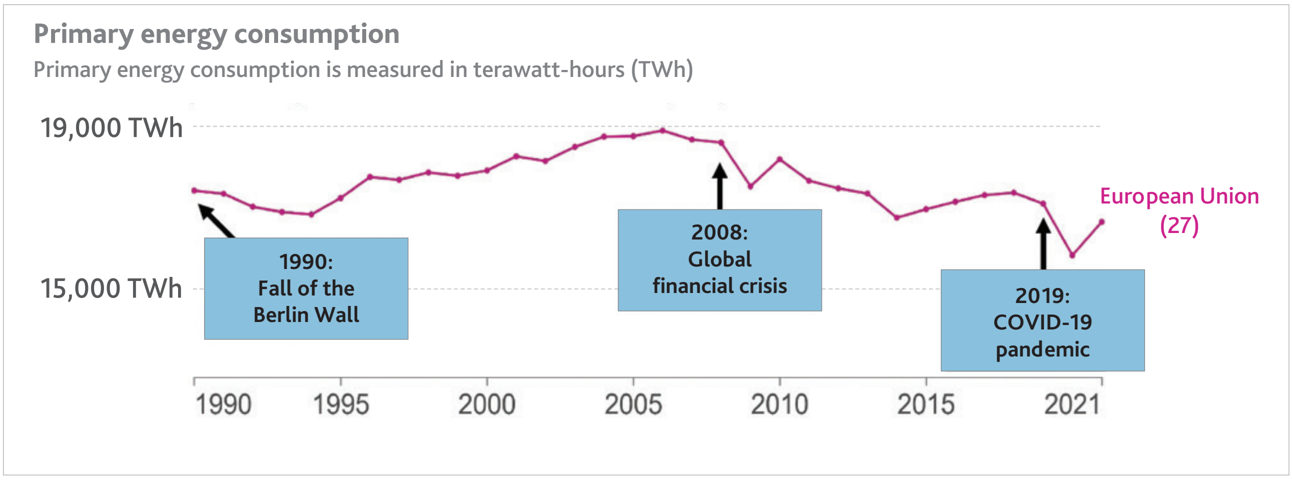


Figure 2: Primary energy consumption in the EU (27) from 1990 to 2021. Altered after Ritchie and Roser[25].

EU (27) refers to the EU without the UK. In 1990 the Berlin Wall fell and in the subsequent years the economy of the former German Democratic Republic (e.g., Easter Germany) was collapsing. 2008 marks the start of the global financial crisis with several EU economies in severe downturn. 2019 marks the start of the COVID-19 pandemic with shutdowns in all EU countries following in 2020 and 2021.

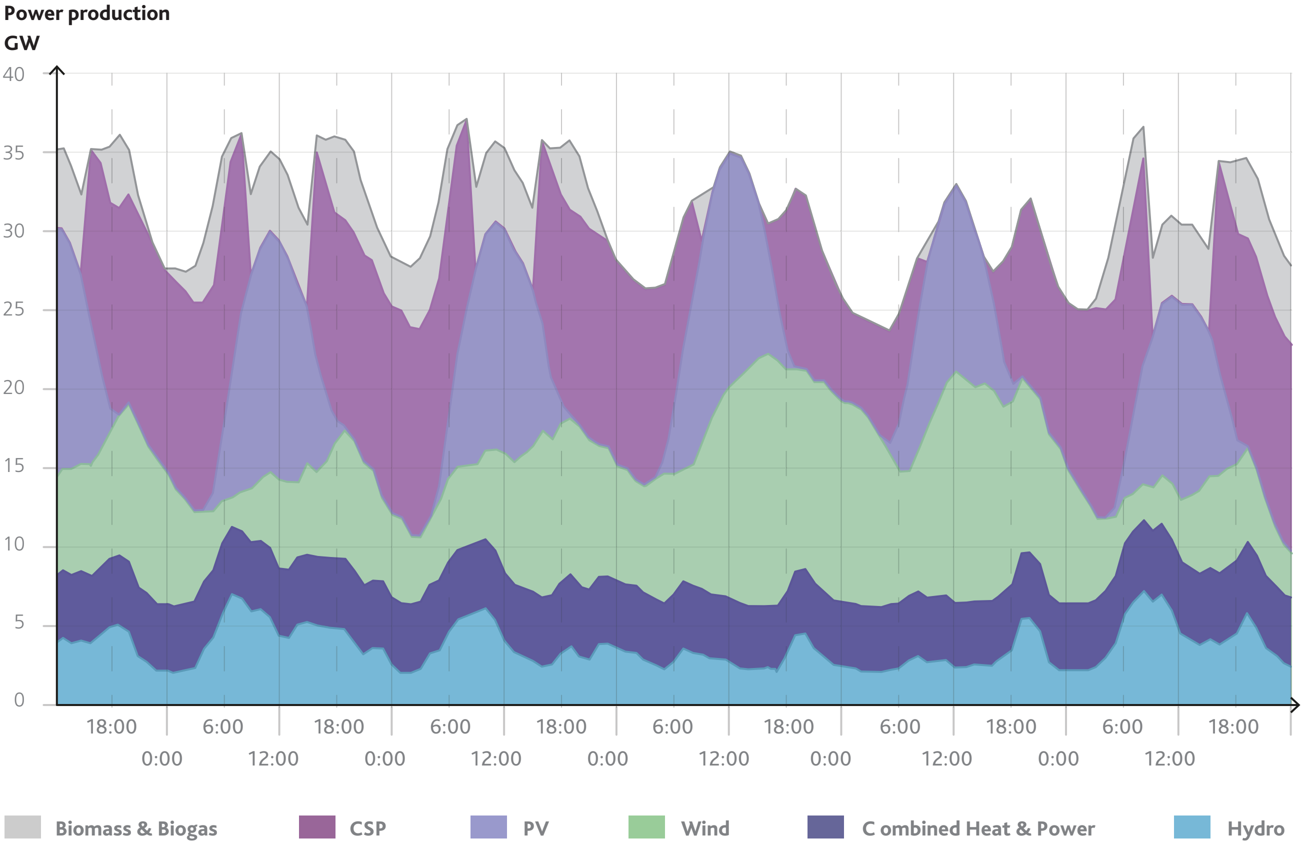


Figure 3: Modelling of a future energy mix, generated from renewable sources only, in Spain for 5 days in Mai 2030. The model starts on Sunday 25th and ends on Wednesday 29th.

Hydropower and combined heat and power plants do serve the base load in addition with wind generated power. PV power will be injected into the grid at full capacity when available while CSP-TES will be used as power supply when the sun is not shining. Peak demand will be met with biomass or biogas power plants. Modified after Daniel Benitez et al.[26]

4B).[27] A new deep sea cable is currently build to connect Egypt with Crete. Commissioning should be in 2023[28; 29]. Connections between non-synchronous grid areas are made by high voltage direct current (HVDC) cables. Examples are the NordLink connection between Germany and Norway which was commissioned in 2021[30; 31] and the connection between the British and the Irish synchronous areas.

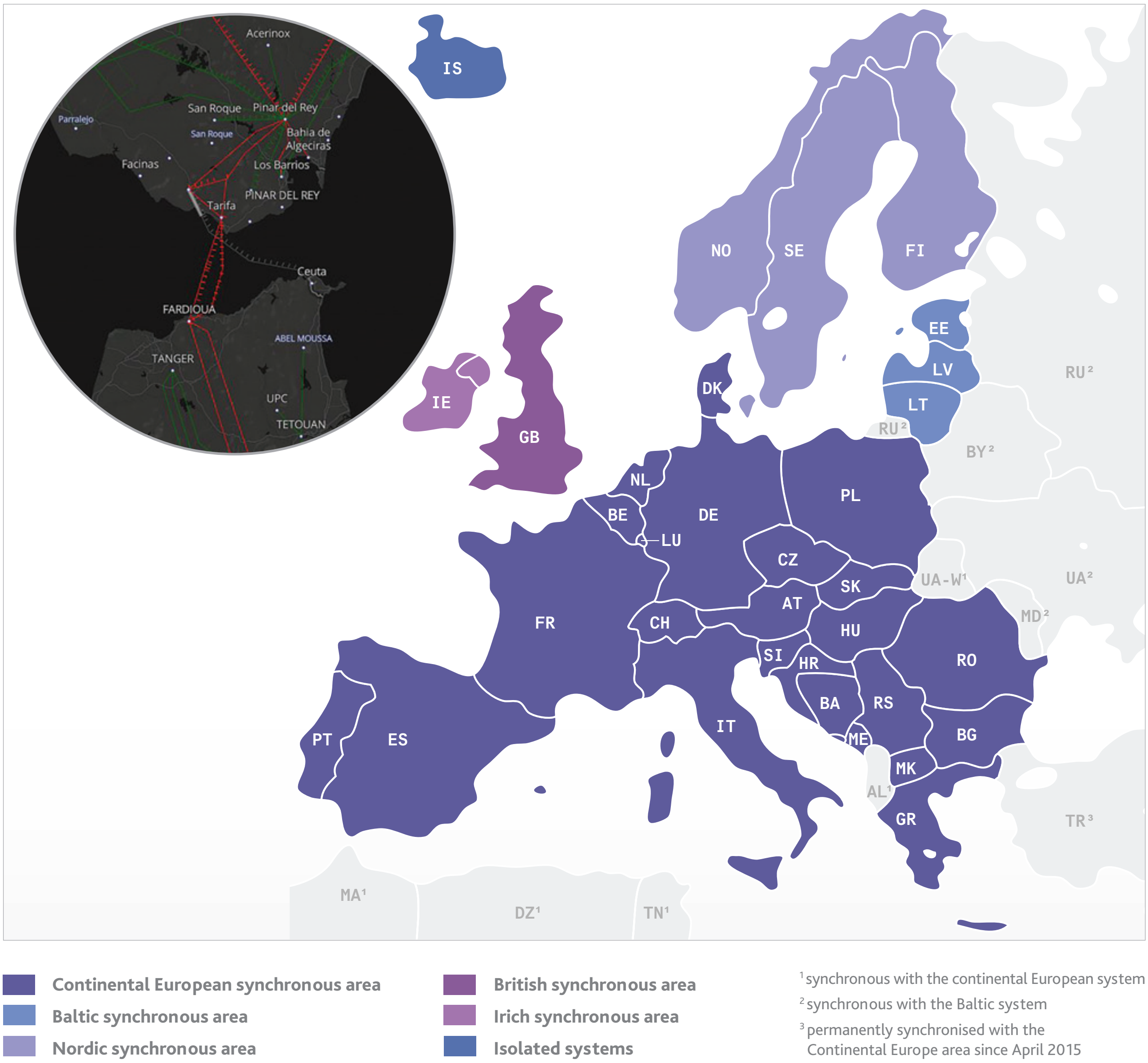
SYNCHRONOUS AREAS

Synchronous areas are groups of countries that are connected via a compatible power grid system. The benefits of synchronous areas include: (A) pooling of power generation resulting in lower power production costs. (B) common provisioning of reserves resulting in cheaper reserve power costs for instance in cases of disturbances or outages and (C) mutual assistance in the event of disturbances. Within a synchronous area, the electric frequency is coupled and disturbances at one single point in the area will be registered across the entire zone. Different synchronous areas can be linked using direct current (DC) interconnectors[32].

Maintaining a constant grid frequency of 50 Hz within the European synchronous areas is of upmost importance. Normal grid operation is maintained within a deviation of ± 10 mHz (0.01 Hz). In the case of larger deviations of ± 10 mHz to ± 200 mHz normal operation is regained by activating or deactivating additional power plants. Long-term maximum deviations of ±180 mHz, and for short periods even ± 200 mHz, are allowed. The frequency range in normal operation is thus kept between 49.8 Hz and 50.2 Hz. In case of the breakdown of some supplying or consuming capacity, short-term deviations up to 800 mHz are allowed (49.2 Hz to 50.8 Hz). Such large frequency fluctuations may lead to self-induced shutdowns or even damages in high-end technical appliances. With even higher deviations, a massive grid failure is very likely. In this case, load shedding – disconnecting producers or consumers – is used to stabilize the grid. If even load shedding fails, the entire network will cease operation, leading to a full blackout. After such a breakdown, the entire network has to be restarted gradually. As a consequence of their technical importance, net frequency controlling units are considered as critical infrastructure and are highly protected units globally.[34; 35]

Power grids, which are fed by great shares of volatile renewable energy, are inherently less stable and need to be re-thought. Decentralized power production e.g., by wind or PV is dependent on uncontrollable weather conditions. Therefore, the currently unsolved obstacle of a missing large-scale electricity storage option demands a stable grid operation and the creation of very large grids which connect several time and climate zones. The situation and options for Europe were studied by the Desertec Foundation in 2009 (Figure 5)[12]. The planned grid for the (never realised) Desertec project should span facilities from Iceland to the Sahel region (approx. 4 000 km) and from the Arab peninsula to the Atlantic ocean (approx. 5 700 km).

After the 2011 Fukushima Daiichi nuclear disaster[36] and the resulting power shortages in Japan a wealthy Japanese businessman founded the “Renewable Energy Institute” (Japan) with the goal - among others – to create a highly



[1] synchronous with the continental European system

[2] synchronous with the Baltic system

[3] permanently synchronised with the Continental Europe area since April 2015

Figure 4: Synchronized power grids in Europe and grid connections between North Africa and Europe.

(A) Synchronized power grids in Europe until 15th of March[32]. On 16th of March Ukraine and Moldova were integrated into the Central European synchronous area[33]. Morocco, Algeria, and Tunisia belong to the Continental European synchronous area.

(B) Three electricity cables crossing the Street of Gibraltar are the only power connections between North Africa and Europe. Two 380 - 400 kV alternate currency cables (shown in red) with several circuits each do connect Morocco and Spain. A third 132 – 150 kV cable with several circuits (shown in grey) is connecting the Spanish EU-territory of Ceuta in North Africa with mainland Spain. (Modified after[27])

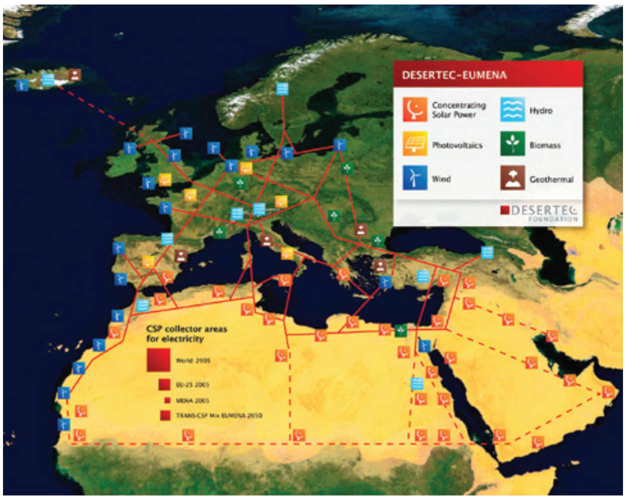


Figure 5: Concept of a transcontinental power grid supplied by renewable energy proposed by the Desertec Foundation in 2009[12].

connected east Asian electricity grid to prevent future blackouts. This "Asia Super Grid" was designed to connect Russia with Malaysia (approx. 7 000 km) and Japan with India (approx. 6 000 km)[37; 9]. Currently interconnectors within China and between Japan and India are in a planning phase. Singapore is receiving hydropower from Laos via Malaysia and Thailand since the beginning of 2022.[38]

NATO'S MEDITERRANEAN DIALOGUE AND THE DESERTEC INDUSTRIAL INITIATIVE (DII)

NATO started in 2007 the Science for Peace and Security project "Sahara Trade Winds to Hydrogen: Applied Research for Sustainable Energy Systems" with Morocco and Mauretania. Both countries are Mediterranean Dialogue partners. The aim was to create an independent network of industrial and academic expertise, to exploit the regional wind energy resources and to adapt state of the art technology to real world application.[39]

The Desertec Industrial Initiative (DII) was founded in 2009 by several, predominant German enterprises e.g., Munich Re (reinsurance company), Deutsche Bank, Siemens and the two German energy providers RWE and EON. The objective was to supply Europe with electricity produced in North Africa and the Arabic peninsula and to contribute to the self-supply of the Middle East North Africa region (MENA). DII predominantly relied on the concepts of the Desertec Foundation, a non-profit organisation mainly driven by scientists. By 2015 most of the shareholders had backed out of DII. Since 2015 only three shareholders and several cooperation partners remained. DII was relocated from Munich to Dubai and has continued operations in a renewed framework.[12]

Schmitt (2018)[12] tried to analyse the causes of the failure of DII. Dominant explanations are the global financial crisis of 2008/2009 which led to a sharp drop in electricity demand, the Arab spring from 2010 onward with the resulting social unrest and the dramatic reduction und production costs of PV modules (Figure 6), which were installed in large quantities on rooftops especially in Germany. Other cited causes were the focus on technological feasibility and the omission of social aspects and accusations of cultural imperialism.[12]

INVESTMENTS IN ELECTRICITY LINES

End customers of electric power are usually served with alternate current (AC) lines. High voltage lines (convention: > 1 kV AC or > 1.5 kV DC) are currently operated as direct current (DC) lines. Energy losses in AC transmission due to the need for three phase cables (high capital expenditures) and the skin effect in large conductors (high operational expenditures) severely restrict AC technology application for very long-distance power transmission. While conversion of high voltage DC to low voltage AC for the end consumer is more expensive than using AC-AC transformers, the overall costs for operating DC high voltage connections (HVDC) for long distance transport of electricity are substantially lower.

The intercontinental connection in the European Synchronous Area between Europe and North Africa is currently

Table 1: Real, projected and calculated capital expenditures for the construction of power lines.

CAPEX = capital expenditures. Sources are referenced in numbers as follows: (1) = Leighty et. al. (2012)[41]. (2) = Netzentwicklungsplan Strom (2020)[42]. (3) = RWE (2019)[43]. (4) = TenneT (2020)[30].

Kind of transmission line	Unit	Value
Overhead cable (AC, DC, 500 kV), (1)	$[10^6\ \text{US\$ km}^1]$	3.0
Overhead cable (AC, DC 380 kV), (2)	$[10^6\ \text{€ km}^1]$	2.0 – 2.2
Underground cable (AC, DC 380 kV), (2)	$[10^6\ \text{€ km}^1]$	6.0 – 11.5
Deep sea cable, (3,4)	$[10^6\ \text{€ km}^1]$	3.2

served by several 380 – 400 kV power lines between Morocco and Spain (Figure 4B). An additional 132 – 150 kV line in the strait of Gibraltar connects Spain and the Spanish autonomous city of Ceuta located in Africa[32]. Ceuta belongs to the European Union. In a future scenario of large-scale power transfers from Morocco to Europe additional power lines must be built.

Investment costs (CAPEX) for the construction of electricity lines do vary by a factor of five with respect to length, environment (land, sea), implementation (above ground, underground or deep sea) and the population density (rural or urban). The costs range from 0.9 * 10^6 € km^1 for overhead cables to 11.5 * 10^6 € km^1 for underground cables (Table 1)[40]. The transmission lines and the electricity producing plants and typically owned and operated by separate companies.

COST OF ELECTRICITY PRODUCTION WITH EMPHASIS ON CSP-TES

The costs of electricity production are typically expressed as Levelized Cost of Electricity (LCOE). They reflect a measure of the live time (production) costs of the plant and the produced amount of electricity (kWh). They are used to compare technologies either within a fuel (i.e., energy) category or over different fuel categories. LCOE follow the general economic laws of production, which means that the costs per unit of output decrease with increasing output[44; 45].

Since 2010 the LCOE for PV show the steepest decline compared to CSP, offshore and onshore wind. This development was due to the enormous roll-out of new PV panel production plants (Figure 6)[46]. Economy of scale effects for onshore wind were nearly as huge as for PV and LCOE are in the same order of magnitude. For CSP the effects of economy of scale have not yet reached its full potential due to the small market penetration. Decreasing LCOE for CSP depends on constant high-level output of new plants in the coming years. Up to 2019 approx. 100 CSP plants with a capacity of 6.2 GW were installed[26] compared to approx. 100 GW of PV plants[47].

LCOE of renewable power plants is now in the same range for conventional fossil fuel plants, or as in case of PV and onshore wind even lower. This trend will probably continue. Mean LCOE for the three commercially used CSP technologies – with and without TES - ranged in 2015 from 13 – 41 €-ct kWh^{-1} (14 – 45 €-ct kWh^{-1})[48] and thus

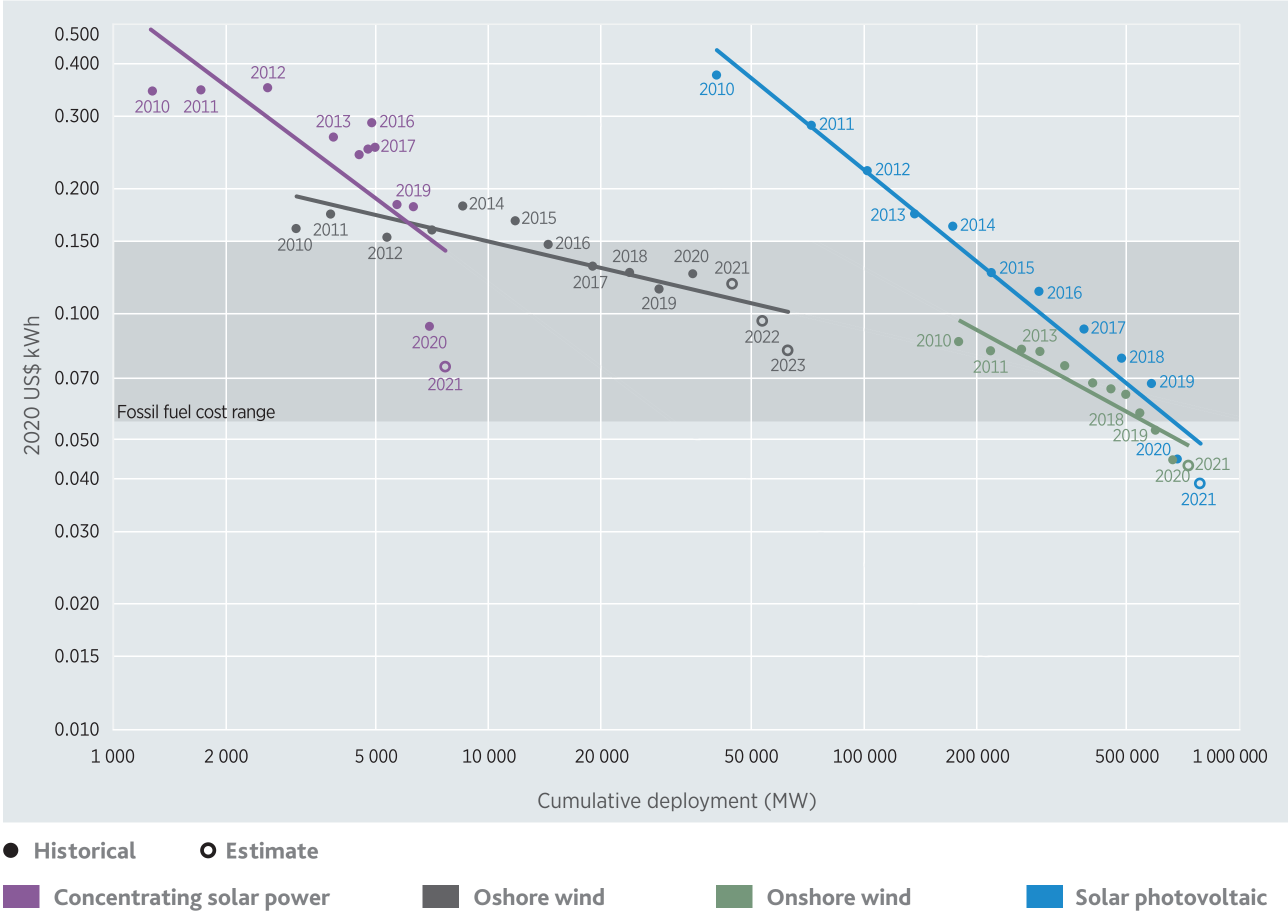


Figure 6: Global weighted average LCOE learning curve trends for solar PV, CSP, onshore and offshore wind from 2010 – 2020 as well as estimated LCOE 2021/23 The grey marked area marks the costs for fossil fuel plants.[46]

are still the highest of all available renewable power generating technologies and most conventional fossil fuel technologies. Only gas turbines, typically using fossil gas, show LOCE in the same order of magnitude as CSP-TES plants (11.0 – 22.0 €-ct kWh or 13.0 – 25.9 US$-ct kWh). Gas turbines are used to cover fast peaking demands and therefore have low working hours and high costs. CSP-TES can also meet this requirement and may in the future compete with gas turbines.[49; 50; 46] In 2011 the US government started the *Sun Shot* initiative in an effort to dramatically reduce the LCOE of CSP-TES plants and project results are implemented in advanced research plants.[51]

The technological challenges for the implementation of new large scale technological projects are huge but manageable. Most projects in democratic countries are stopped in various phase of their development due to civil society obstacles like property rights to land or water, unequal distribution of the benefits between locals and elites, or a general mistrust against the project itself or foreign investors. Therefore, the "soft aspects" of a project must be managed with great care. In the following, we focus on the geographically closest MENA nations of Algeria, Egypt, Morocco, and Tunisia.

III. BUSINESS MODELS FOR COOPERATION

POLITICAL, SOCIAL, AND ECONOMIC ENVIRONMENT IN ALGERIA, EGYPT, MOROCCO AND TUNISIA

The four MENA countries considered in this article are Morocco, Tunisia, Algeria, and Egypt. They were chosen based on their location within the global sunbelt, their geographic proximity to Europe and their relative political stability compared with neighbouring MENA countries like Libya. All four countries are not members of the EU or of EFTA and qualify for the European Union as "third countries" where cooperations are allowed to increase the share of renewable energy used within the framework of the "European Green Deal".

Social and political indicators of nations also called key performance indicators (KPIs) are published on a regular basis by several independent international organizations. A selection of ten important indicators for investments are categorized into political/social, technical/environmental and safety/security related topics for Algeria, Egypt, Morocco, and Tunisia (Table 2). The highest and the lowest scoring countries are also given as comparison. The selection was chosen in accordance to Brunström (2021)[17]. More detailed KPI's are available, which may provide a better understanding of the specific situation in a country.

In the political, economic and social sector, the KPI's for the fragility of the state, GDP per capita, corruption and populations growth show no great difference between the four countries investigated. An exception to this is the level of education in which Morocco is significantly lagging behind.

The four countries have high ambitions for the further development of their existing renewable energy sector. Algeria wants to increase its share of renewable energy usage tenfold within the next 10 years. Morocco starts with a high base level and plans to double its share during the next decade. Since most of the new capacity will be used to satisfy growing national demands, only small surplus production may be used for supplying the European market. This small production for export would match the currently very limited capacities for power transport to Europe.

No international sanctions are imposed against any of the four countries. Internal security in Morocco is e.g., considered to be 12 times better than in Egypt. Morocco is within the best 10% of all countries investigated in this category while Egypt is part of the last 50%. The countries are members of NATO's Mediterranean Dialogue partners[39.] With respect to all the criteria discussed, Morocco seems to be best suited for a renewable energy cooperation with the EU and is discussed in detail in the following chapters.

FINANCING - A SELECTION OF POSSIBLE BUSINESS MODELS

Financing large infrastructure projects is a major task with many obstacles to overcome, especially when different legal systems and cultures have to be considered. The choice of the appropriate business model depends on the partners involved (Table 3). Big infrastructure projects are often laden with prestige and scrutiny and in many cases either do not survive the concept and planning phase like the Desertec Industrial Initiative[12] or were not successfully implemented like the container terminal in Mombasa (Kenia)[60].

Any electricity import-export business encompasses at least three parties: the producer/supplier (exporter), the procurer (importer), and the grid operators in several countries. The producing site may consist of two companies, one that owns the facilities and one that runs them. The procurer - with a registered office in the EU - generally is one entity, which, for a sustainable, long-term business model, needs local European customers and purchasing guarantees. These may be industrial customers, public power suppliers, or - in very rare cases - the procurer itself, e.g., a chemical or steel producing company. Without long-term contracts, which cover most of the procured electricity, any business model will fail. The power grid operation is a necessary service, often overlooked. The existence of the power grid connections (i.e., transmission lines) is a precondition for the viability of the enterprise. The grid operating companies will not expand

Table 2: Section of political/economic/social, technical/environmental and security/safety key performance indicators (KPI's) for Algeria, Egypt, Morocco, and Tunisia as well as the highest and the lowest ranking countries for comparison.

* A connection is under construction. Commission is planned for 2022.

Criteria	Algeria	Egypt	Morocco	Tunisia	Max and min ranks
Political/economic/social KPI's					
Fragile State index[52] (2020)	74.6	86.0	71.2	68.1	Most stable: Finland 16.6 Most unstable: Yemen 112.4
GDP per capital (US$) (2020)[53]	3 974	3 019	3 204	3 317	Highest: Monaco 173 688 Lowest: Burundi 239
Corruption[54] (2020)	36	33	40	44	Highest: Denmark/New Zealand 88 Lowest: Somalia/South Sudan 12
Population growth (%) (2019)[55]	1.8	1.9	1.2	1.1	Highest: Bahrain 4.5 Lowest: Moldavia -1.6
Mean years of education (2019)[56]	8.7	7.6	4.8	7.1	Highest: Germany 14.1 Lowest: Burkina Faso 1.4
Technical/environmental KPI's					
Operating power connections to Europe	No	No*	Yes	No	---
Renewable energy share of electricity capacity (%) (2020)[57]	2.8	10.1	30.9	6.0	Highest: Lesotho 99.8 Lowest: Turkmenistan 0
Renewable energy usage ambitions (% of total production), (reference year)[17]	27 (2030)	42 (2035)	52 (2030)	30 (2030)	---
Security/safety KPI's					
Global terrorism index (2020)[58]	2.696	6.419	0.565	3.858	Highest: Afghanistan 9.529 Lowest: e.g., Iceland 0.000
International sanctions (2022)[59]	No	No	No	No	Highest: Democratic People's Republic of North Korea

transmission capacities or build new lines without guarantees from the supplier and the procurer.

The contracting parties may be private sector companies, governmental backed companies, or governmental entities. In the case of foreign direct investment, all partners are private sector companies. In the case of private electricity procurement contracts, the procurer is a private sector company while the supplier side may involve governmental or private sector companies. Interstate treaties only involve governmental agencies. In the case of import/export of electricity between Morocco and the

EU interstate treaties are very unlikely, as both countries have private sector economies.

SWOT-analyses (Strength-Weakness-Opportunity-Threat-Analysis) for the various business models depends on the specific point of view of the involved partners. One partner's advantage may be the others disadvantage. Perceived advantages can turn rapidly into disadvantages by changes in the political or economic environment e.g., a global health crisis like COVID-19, conflicts like the Russian invasion of the Ukraine or political and military unrest.

Depending on the bargaining power and the preferences of the contracting parties, the agreed common understanding may shift. Preferences of the involved parties may exclude each other e.g., high selling prices for the north African producer contradict low procuring prices of the EU buyer. A selection of long-term political decision preferences is listed in Table 4.

A checklist of critical business-related topics within the set political framework comprises three main stakeholders.

COMPANIES

- Control over business affairs: State control is decreasing in the following order: governmental entity > governmental backed company > private sector company.
- Distribution of profits in the case of foreign direct investment: Host country or EU Country.
- Financing: Private or public funds, local or international banks e.g., Islamic Banking rules.
- Stability of contracting partners: Risk of business (insolvency) or state failure (examples are the financial crisis in 2008/2009 or the Arab Spring 2010/11).
- Technology transfer: Training and education or intellectual property theft.
- Pricing policy: Fixed prices, flexible prices depending on demand or prices fixed to another commodity e.g., oil.

SUPPLIER (STATE LEVEL) – MOROCCO

- Domestic policy: Rivalry with other public projects e.g., building hospitals, increasing GDP etc.
- Cultural influence: Western influences to be maximized or minimized.
- Distribution of local resources: Development or exploiting of local resources and communities.
- Distribution of profits: Local communities or distant elites.

PROCURER (STATE LEVEL) – EU MEMBER STATE

- Security issues: Decreasing migration pressure into the EU due to economic opportunities and retaining skilled people in the North African country.
- Skilled personnel: Efforts on long-term education of the local population for building and running the plant or importing of skill workers from the EU.

Contracting Partners		
Electricity supplier North Africa		Electricity procurer EU
Investment	**Operation**	**Distributer**
Foreign (European) direct investment		
Private sector company	Private sector company	Private sector company
Private electricity procurement contract		
Government	Government	Private sector company
Governmental backed company	Governmental backed company	Private sector company
Private sector company	Private sector company	Private sector company
Interstate treaty		
Government	Government	Government

Table 3: Selection of possible contract designs for the electricity delivery contract between the electricity supplier e.g., Morocco and the electricity procurer e.g., an EU member state.

Table 4: Selection of best interest long term preference of the contracting partner.

North African state	Producers within North African state	Procurer within the EU	European Union
• New income source (foreign exchange) • Social and economic development • Environmental protection of construction sites • Creation of a skilled workforce	• Selling at high prices • Secure investment • High profits • Long term contracts	• Procuring at low prices • Secure investment • High profits • Long term contracts	• Low electricity prices with the EU • Energy security • Diversified power supply mix • Reaching climate goals

The multiple levels of expectations to be managed requires sophistication and clear goals. The lack of commitment and changing environments can easily lead to failure.

HISTORY OF CSP - COOPERATION AND COMPETITION BETWEEN MOROCCO AND SPAIN

In 2016, Spain had the highest operational capacity for producing electricity from CSP on a global scale. The existing 50 plants with a capacity of 2.3 GW were commissioned between 2008 and 2012 with huge subsidies from the Spanish government. TES were included in approximately one third of the plants and can store up to 9 hours of full power generator capacity. In 2012, the governmental subsidy scheme (feed-in renumeration) was stopped due to the high costs for managing the financial crisis of 2008/2009 which nearly resulted in state bankruptcy. Since then, no more CSP plants were commissioned. During the more than 10 years of service time, the power supply has proved very stable due to constant improvements and maintenance. In 2019 CSP and PV plants covered 8% of the total Spanish power consumption[12; 61]

In 2020, Morocco was producing approx. 8% (20 TWh) of its power production with renewable sources (wind, solar and hydro). Many of the plants where build on sites already identified by Moroccan scientists involved in the Desertec foundation[12]. The share of hydropower was 3 TWh in 2020 but is fluctuating highly on a yearly basis depending on the rainfall in the region. The electricity produced by windfarms was constantly rising since 2010 reaching now 13 TWh due to new installments[62]. The largest wind park in North Africa is located in Tarfaya in the south of the country where 131 turbines with an installed capacity of 301 MW do cover an area of 8 900 ha[63].

By 2016 Morocco was producing more power from CSP than the combined rest of the Middle East and North Africa region (MENA)[64]. Most important for this production is the Noor solar plant complex ("noor" in Arabic means light) near the ancient town of Quarzazate (Figure 7). It contains state-of-the art parabolic trough (Noor I and II) and power tower (Noor III) technology with integrated TES for up to 7h. Noor IV is a PV plant (Table 5). The plants were established in cooperation with Spanish partners. The complex is situated in proximity of a water reservoir, as the water demand for cooling the power generators and cleaning of the mirrors is considerable. Electricity is sold for 19 US$-ct per kWh, which is more expensive than LCOE from fossil and nuclear plants (Figure 6)[65; 49; 46.]

Morocco built the Noor complex (Figure 7) with the support of funds for clean energy research and development and renewable energy production[66.] Simultaneously, Morocco achieved in 2015 the complete electrification of all its households, up from 48% in 1990[67] and thus has reached the UN's Sustainable Development Goal 7 of "Affordable and clean energy" well bevor the target year of 2030[68]. All these efforts were in line with Morocco's own pledges and targets to the *Paris Agreement* from 2019[69]. Morocco therefore is a poster child for sustainable development within the 1.5°C *Paris Agreement* temperature goal although 73% of its total power production comes from fossil fuels[61].

The Noor solar plants are operated by Masen, the Moroccan Agency for Sustainable Energy, which is a governmental backed company[70.] The Noor plants were financed – among others - by the World Bank, the European Investment Bank, the French Development Bank (Agence Française de Développement), the German Kreditanstalt für Wiederaufbau with a mandate from the government and the Clean Technology Fund of the African Development Bank Group (French: Groupe de la Banque africaine de développement)[65].

In the aftermath of the global financial crisis of 2008/09 the idea of producing power in Morocco for the Europe-

Table 5: Technical details of the Noor Solar complex near Quarzazate (Morocco). See also Figure 7. TES = Thermal energy storage.[65]

Plant	Technology	Commission	Area [ha]	Capacity [MW]	Energy [GWh]	TES [h]
Noor I	Parabolic through	2016	450	160	370	3
Noor II	Parabolic through	2018	680	200	600	7
Noor III	Power Tower	2018	530	150	500	7
Noor IV	PV	Not yet		72		--

an market came to a hold and was finally blocked by Spain. Spain's economy shrunk substantially and state revenues as well as electricity demand were reduced. Homegrown renewable power production exceeded the demand and the thought of importing cheap power from Morocco was politically not sustainable. The transfer of the power to France was not possible in the short term because of missing high voltage power lines.[12; 71; 72]

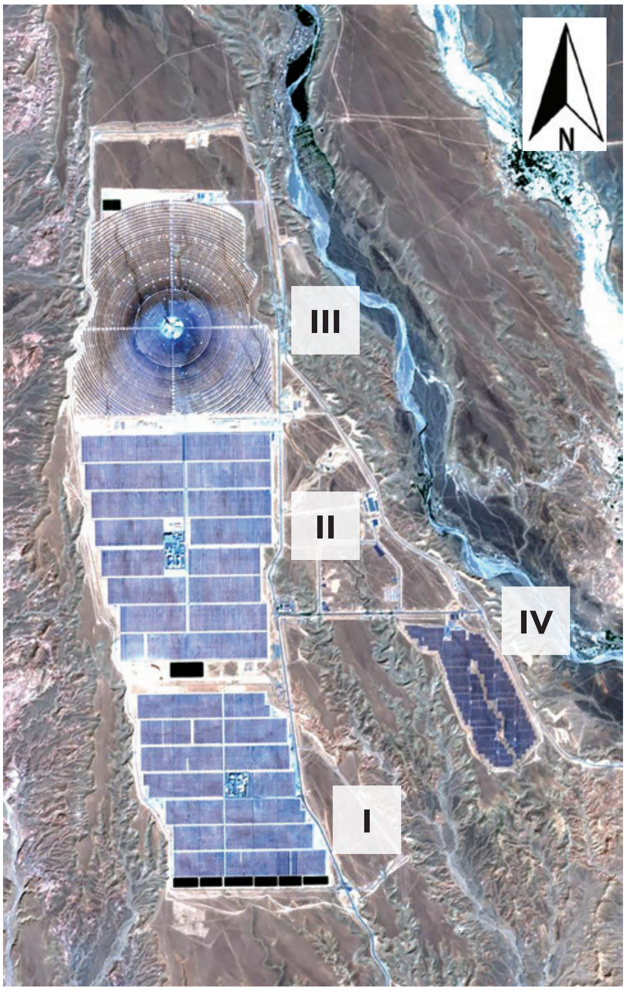


Figure 7: Aerial photo of the Noor I – IV CSP-TES and PV complex including the fresh water source near Quarzazate (Morocco). The CSP-TES plant covers approx. 1660 ha.[65] For details see Table 5.

ROADMAP FOR A FUTURE ENERGY COOPERATION BETWEEN MOROCCO AND THE EU

When proposing a roadmap for a future energy cooperation between Morocco and the European Union, the experiences of the past do offer valuable information for future actions. The major lesson learned is that technical feasibility does not automatically result in social acceptance[12]. Therefore, political issues on the inter- and suprastate level should be dealt with from the very beginning of a future project. Also, some of the below mentioned tasks should be dealt with in parallel rather than in sequence.

CONSENSUS OF THE VALUE OF CONTROLLABLE ELECTRICITY PRODUCTION IN THE EU

Electricity plants with uncontrollable power output like PV and wind plants have been subsidised in many countries. These measures led to an increase in production and a decrease in costs (Figure 6). However, this causes overshoot peaks of electricity in the power grid when the sun is shining, and the wind is blowing (Figure 3). When the grid is at full capacity, these plants either have to shut down or the controllable power plants (e.g., nuclear or fossil fuel power plants) have to reduce their output.

As coal, lignite and in some countries nuclear power plants are decommissioned, controllable renewable power plants like CSP-TES are needed. PV has come out as a niche product during the past 10 years. The process of establishing sufficient controllable power capacity must be pushed by respective subsidies, which renumerates the controllability within the importing country and intense cooperation with Morocco

CONSENSUS OF ROUTES FOR NEW POWER LINES WITHIN THE EU

Large-scale electricity transport from Morocco to the EU requires additional power lines. The implementation of large infrastructure projects in Europe is difficult and agreement of the governments and the public is almost impossible without tangible benefits for the transit countries. The following we focus on the transit section from the coast of Morocco to the EU.

The shortest connection between Morocco and an EU member state is to Spain through the strait of Gibraltar. The usage of the already existing and well established pathways would reduce planning costs but requires new power lines inside Spain and a connector to France (Figure 4B). As an alternative, a deep-sea cable could be established from Morocco to Marseilles in France with a short land connection to one of the nuclear power plants on the valley of the Rhone and the usage of their grid infrastructure further on. Deep-sea cables are cheaper to build as landlines and easier and quicker to plan. On the other hand, they are more difficult to protect, as they may pass through international waters[73]. The damage inflicted on the Nord Stream pipelines in the Baltic Sea in September 2022 highlighted these threats (see below).

A consensus within the EU is of paramount importance in order to avoid any discord between the member states as well as the creation of stranded assets. As a recent negative example is the Nord Stream 2 project. There, the Baltic states , Poland, the USA and other neighbours strongly objected the project even before the construction of the gas pipeline from Russia to Germany started[74]. The pipeline construction was finished shortly before the Russian invasion into Ukraine and since then never became operational[75]. On the 26th of September 2022 both, the Nord Stream 1 and 2 pipelines were severely damaged. The pressure maintenance methane gas leaked into the air and seawater entered the pipeline which may permanently damage the pipes. Repairs of the pipeline may take several years.[76]

LETTER OF INTENT AND TREATIES BETWEEN MOROCCO AND THE EU

The political environment defines the framework of business opportunities and possibilities. As the EU is interested in long-term power purchasing contracts, a letter of intent followed by state treaties should secure the basis of private sector actors. Similar formal agreements were recently reached for the cooperation between Germany and Morocco for the production of hydrogen from renewable electricity[77] as well as between the EU and Morocco[78]. Such legally binding agreements secure the governmental backing of large projects. Topics of interest are the share of local power consumption and power export, the share of local and foreign investment, the share of local and foreign workers, the possible zones for the power plants and lines as well as non-electricity related projects, training programs and the duration of the cooperation, to name only a few. Given such a secure base, private sector actors are then able to develop their projects.

CREATING BUSINESS CONTRACTS

Businesses are most likely involved in the creation of the letters of intent and state treaties. Parts of the cooperation project may be covered by inviting tenders. Finding suitable business partners can be a pain-stricken process. A wide range of sometimes contradictory issues must be considered. First and foremost a company's proven expertise should have priority and outcompete any other considerations. Nepotism may be a problem. Official or inofficial boycotts against companies located in - or with ties to – e.g., Israel may exist in Morocco. The same may be the case for Spanish companies, as Spain has irritated Morocco with a new position on the conflict in the West-Sahara[79]. European or North American based businesses partners may face allegations of neo-colonization while Moroccan companies may be involved in business links to countries boycotted by the EU or NATO.

After the “social – soft” criteria are covered, the work on the technical topics can be started. Conflicts with local communities and authorities will occur in these phases, but the general commitment of the governments involved will aid to resolve them.

BUILDING OF RENEWABLE ELECTRICITY PLANTS AND POWER LINES

Once the framework is set, the technical decisions can be made purely on terms of best practice experiences and possible advanced technologies. The selection of the sites, the technologies used and the installed capacity for power plants are among the decisions to be made.

Finding suitable sites for CSP plants is not easy. In theory, already a tiny fraction of the Sahara Desert would cover the global energy demand. However, semi-arid regions and deserts consist of many different landscapes (Figure 8). Ergs (sandy deserts) pose the problem of abrasion and dust storms and Wadis can be episodically flooded. Oases are densely populated and used for agriculture. Mountain regions may be used but show problems of lateral wind obstruction and shading. Only the semi-arid shrublands (with open vegetation cover) and the regs (regions with rocky or stony surfaces) are suitable for solar and wind power plants[13]. Additionally, water availability is of importance and the workers of the plant, and their families need an adequate infrastructure. A power plant of the scale of e.g. the Noor complex requires approx. 2 000 workers and their families[12].

Semi-arid shrubland

Reg

Wadi

Oases

Erg (sand dunes)

Mountains

Figure 8: Typical desert landscapes. Only the landscape types of regs and semi – arid shrublands provide possible locations for CSP plants[13].

Semi-arid shrublands and regs (stone deserts) allow the construction of solar and wind plants by avoiding problems caused by potential flooding (Wadis), population and horticulture conflicts (Oases), sand blast (Erg) or solar and wind shading (Mountains).

INAUGURATION

After the CSP plants and power lines for long distance transmission of electricity are operational, the new network has to be connected and integrated into the European network system. This requires a substantial effort in technical coordination and international contractual agreements with respect to net stability, load distribution, emergency procedures and financial compensation. It is also challenging to show improvements and milestones to the public in order to ensure the social and political acceptance of such a project.

IV. CONCLUSIONS

Global economies depend on a steady, reliable, and affordable energy supply. Prolonged disruptions of this supply and its ripple effects lead to increases in energy prices. The immediate negative economic consequences can be seen in the wake of the current invasion of Russia into Ukraine. The reduction of gas delivery to Europe by Russia already caused economic fallouts and political disagreements in Europe. Even third-party countries in other continents are affected: reduced options of fertilizer production and delivery result in increased poverty, hunger crises and even the potential failure of whole states. In the wake of the current ongoing military conflict between Russia and the Ukraine, these effects are obvious on a global scale as energy supply is used by Russia as a means of warfare against Ukrainian allies.

A diversified energy supply is of utmost importance as it may soften the shocks of disruptions of any kind[19]. As the global energy demand may rise in the coming decades and the effects of global warming becoming more obvious, GHG-poor or GHG neutral energy sources have to be developed and rolled out. Many countries, federation of states e.g. the EU and supranational entities like NATO have committed themselves to become GHG emission free and carbon neutral in the future[5; 80]. Cooperation between countries with a high but untapped renewable energy potential (e.g., in the global sunbelt for solar power or on the coastlines for wind power) and countries with a currently high fossil energy consumption are needed to reach these goals. If managed well, the direct and indirect benefits of such cooperation will reach all parts of society in the contributing countries.

Large international energy infrastructure projects are prone to political, economic, social and security related problems[12; 60]. Technical challenges are normally handled without jeopardizing the entire joint enterprise. However, even for earmarked flagship projects operations commissioning is not guaranteed[12]. To avoid stranded assets[75] lessons learned from successful and even more important from unsuccessful endeavours should be considered during planning and implementation[75]. For all these reasons existing political, economic, and infrastructural ties as well as cultural similarities should be used to increase the chances of achieving the goals (e.g., in the H_2Altlas Africa initiative[81]). Supply chains should be as short as possible to reduce cost and possible disruptions.

For the EU with its high-energy demand, a closer cooperation in the renewable energy sector with North African countries appears to be inevitable. Especially Morocco seems to be a promising and reliable partner as the basic conditions for renewable energy production and power transmission are present. Power lines between Morocco and Spain already exist, and Morocco is already part of the Central European Synchronized Area[33]. In the future, Egypt may also become a promising partner as new submarine HVDC power lines will be connecting Egypt with mainland Greece via Crete by the end of 2023[28; 29].

Within the EU, major infrastructure projects will be necessary to transport the energy to the consumer. Additional overhead and underground HVDC power lines are needed. In most industrialized western countries such infrastructure projects usually are time consuming because of public opposition. The current war between Russia and the Ukraine and the resulting energy crunch may have changed the public opinion with respect to the urgent need of building a new, diversified, and resilient infrastructure system for electric power.

Ramping up power production and transportation from the western MENA countries to the EU will be a long-term task with requires major development projects in the producing, transporting and consuming countries. However, if successfully implemented, this will not only improve the reliability of European Energy supply but may also strengthen the economic and political ties between Europe and North Africa.

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Is de-carbonising the construction industry possible?

An overview of advances in materials and processes

by **Dr. Jutta Lauf**

Cement, a key product for construction, is by mass the largest manufactured product on Earth. Combined with water and mineral aggregates it forms cement-based materials (e.g., concrete and mortar), the second most used substance in the world after water. Cement based building materials are energy and cost efficient[1], but the globally large scale usage (4.6 $*10^{12}$ tons in 2015)[1] led to 3% of globally emitted carbon dioxide (CO_2) in 2020[2]. Additional advantages are the wide availability of the raw materials, a sufficient long period of time before settling and its longevity. All these properties make it a versatile material, which is used in many of NATO's infrastructures (Figure 1).

The traditional form of cement is the so-called ordinary Portland cement (OPC). The production process requires grinding and calcining (heating to high temperature of approx. 1450 °C) a mixture mainly consisting of limestone and clay. The resulting intermediate material - known as clinker - is ground to a fine powder with 3–5% gypsum added to form OPC. The production of OPC generates on average 842kg CO_2 per ton of clinker. Fossil fuel combustion is responsible for less than 40% of total CO_2 emissions, while limestone ($CaCO_3$) decomposition during calcination to calcium oxide (CaO) is responsible for the remainder [1; 5].

In essence, CO_2 emissions from clinker production is a mixture of both, an unavoidable chemical reaction, and the heating process to start the chemical reaction. Therefore, increasing the energy efficiency of clinker production is not sufficient to significantly reduce emissions. Carbon capture technologies are necessary to achieve this goal. Significant reductions in CO_2 emissions are also possible after clinker production along the entire construction value chain by reducing the amount of clinker in cement, reducing the amount of cement in concrete and mortar, applying the lowest possible construction norms, prolonging the service live of constructions, recycling the materials after de-construction as well as by decarbonizing transport process and power consumption (Figure 2). [1; 5; 6]

The Global Cement and Concrete Association (GCCA) has issued a roadmap in October of 2021 to decarbonise the value chain of the construction industry by 2050 (cradle to grave). The measure with the highest CO_2 reduction potential (36%) is carbon capture and storage/utilisation (CCS/CCU), followed by design optimization of structures and recycling of demolition waste (22%). The reduction potentials during the physical production steps are clinker (11%), cement (9%) and concrete production (11%). The re-carbonation of concrete in finished structures can contribute only 6% (Figure 3).[6] CCS/CCU tech-

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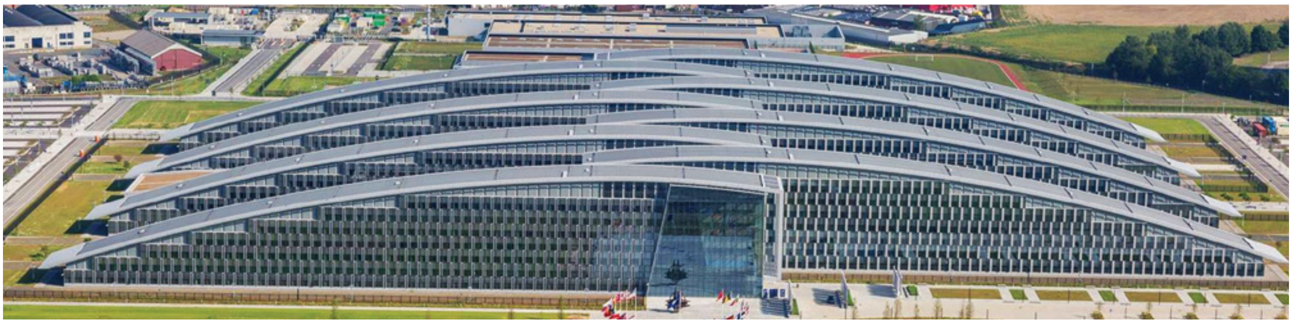

Figure 1: NATO headquarter in Brussels, Blvd Leopold III, 1110 Brussels, Belgium. It was constructed as a "Green building" mainly from concrete. Generally the "green" credentials are related to the operation of the building, not its construction.[4; 3]

nologies are usually more expensive than the implementation of "CO_2 avoiding" technologies and are therefore preferred because they keep cement and cementitious materials cheap.[1]

In the following chapters, we discuss a selection of measures (according to the value chain shown in Figure 2), their scientific background, related challenges as well as already developed new businesses models. The colour code of the following headlines corresponds with the colours used in the GCCA roadmap.[6]

CLINKER PRODUCTION AND PRECAST BUILDING ELEMENT

ENERGY DEMAND AND FUELS

Major efforts to increase energy efficiency began after the energy crisis of the 1970's. It is unlikely that there will be significant gains in best available technology in clinker production, rather than a progressive upgrade of old technology. Modern cement kilns are very flexible machines, which allow the cement industry to change fuels relatively simply. They may change from one type of fuel to another and use any type of fuel which is high in energy, e.g., fossil fuels, biomass or waste.[1] The carbon dioxide reduction potential resides in the increased usage of waste as fuel and in the decarbonisation of electricity used in clinker and in cement production.[6]

ALTERNATIVE RAW MATERIALS FOR CLINKER PRODUCTION

The CO_2 emissions from the chemical reaction of CaO formation can be reduced by several means. Clinkers with lower amounts of $CaCO_3$ in the raw mix will result in cements with lower CO_2-emssions from the chemical reaction as well as from fuel consumption. The properties of

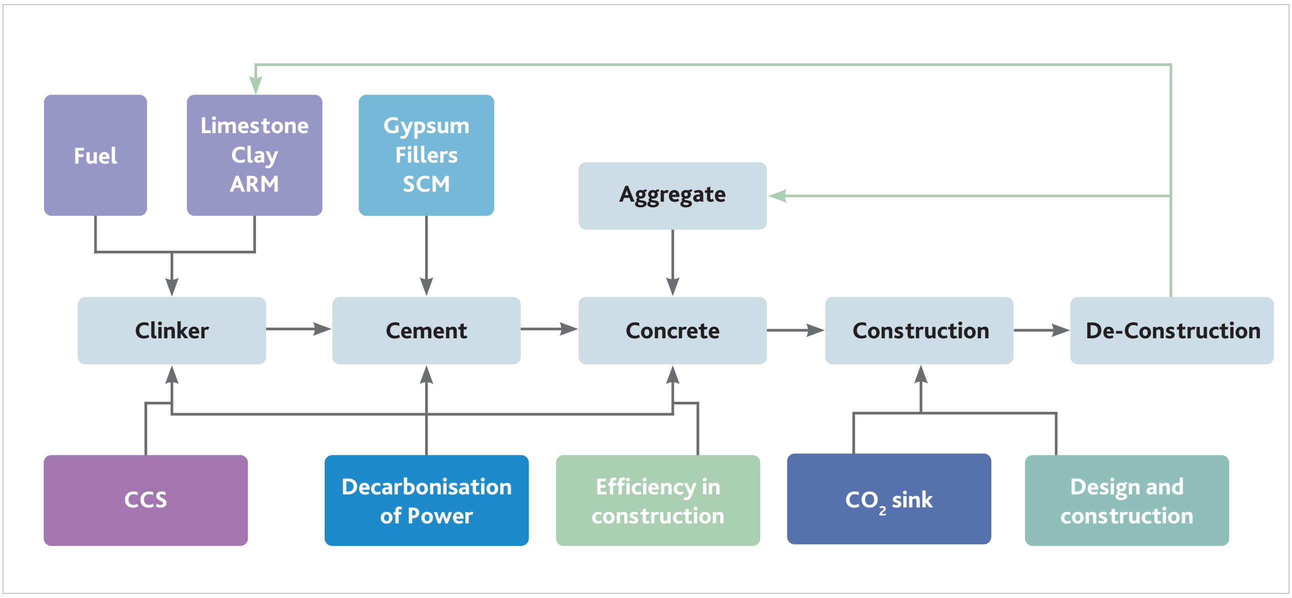

Figure 2: Simplified value chain of cementitious products and points of intervention for reducing the carbon dioxide footprint. Above the value chain raw materials are shown, below the respective concepts. ARM = alternative raw materials. CCS = carbon capture and storage, CO_2 = Carbon dioxide, SCM = supplementary cementitious materials. Colours correspond to the colours used by the GCCA roadmap in Figure 3.

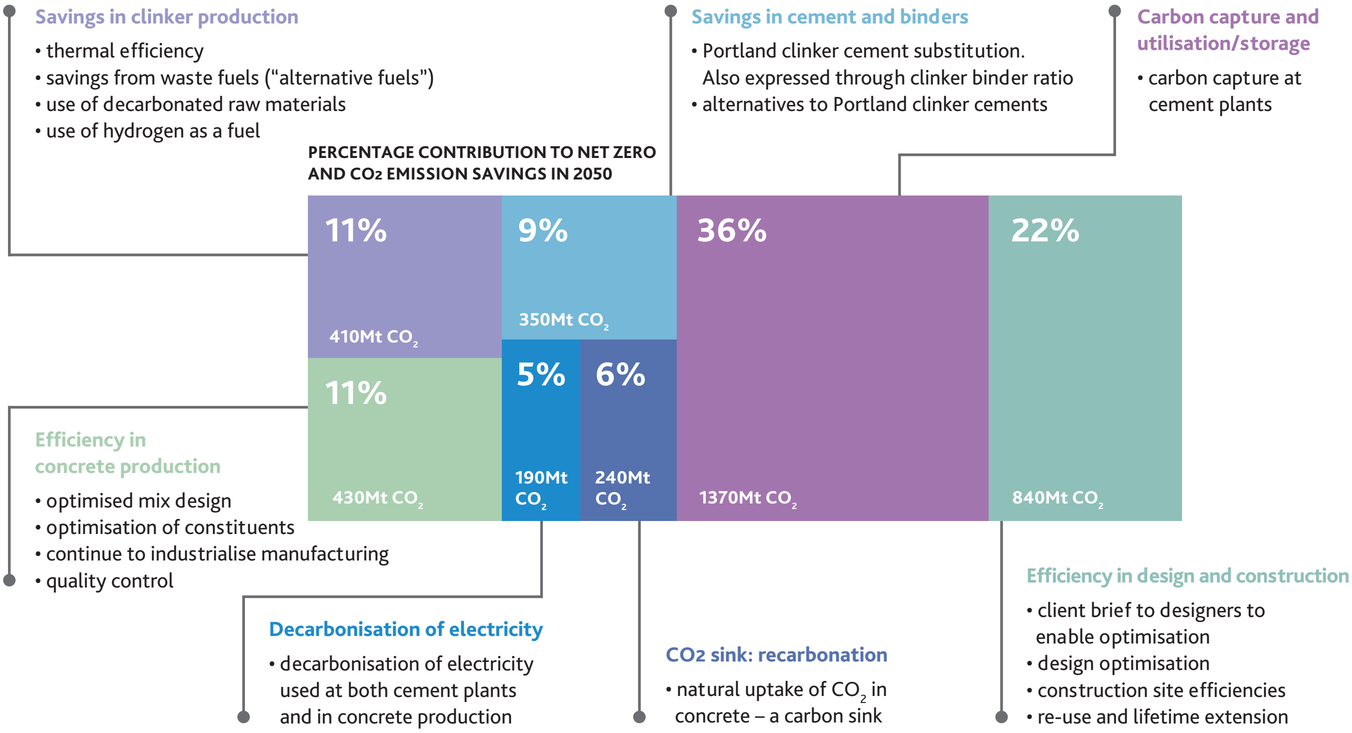

Figure 3: The Global Cement and Concrete Association's (GCCA) plan for reaching a net zero CO_2 emission industry by 2050[6].

the resulting cement are altered and such a product is for specialized niche markets only.[1]

Magnesium oxide (MgO) based clinkers use globally abundant ultramafic rocks instead of limestone. These rocks have the inherent capacity to capture CO_2, which results in a truly carbon-negative clinker. Yet, no viable energy-efficient industrial manufacturing process has been developed. This area merits further research.[1]

Newly developed special calcium silicate clinkers made specifically for carbonation curing instead of water curing with mature precast products are available since several years (Solidia, USA)[7]. These products are no more expensive than OPC. CO_2 emissions from heating and from the calcination reaction are lower than in OPC. These clinkers can only be cured rapidly in a controlled atmosphere of almost pure CO_2. This requires some modification of the concrete curing chambers typically used for precast products. If the CO_2 for curing is procured from carbon capture facilities, a net zero cement is produced.[1; 7]

The US start-up company Sublime Systems has created an electrochemical CaO production from $CaCO_3$. With renewable power used, no CO_2 is emitted through energy usage while the CO_2 originating from the chemical reaction will be captured with carbon capture technologies. This combination will create a CO_2-free clinker. Further research is needed to develop this technology.[8]

CARBON CAPTURE AND STORAGE OR USE

Carbon capture and storage or use is the main strategy to reduce CO_2 emissions of the industry. CCS is still not sufficient proven for large-scale use. CCU may produce commodity chemicals or fuels. However, this technology is a long way from being economically viable at present. Another possibility is the mineral capture of CO_2 which has the potential to permanently capture significant volumes of CO_2 globally to make useful construction products. Solida cements[7] are an example of this approach. Regardless of the technological challenges, CCS and CCU would significantly increase cement production cost.[1] CCS/CCU technologies are described in more detail in previous issues of the journal "Energy Highlights"[9; 10].

CEMENT

OPC contains >90% Portland cement clinker and gypsum. A well-established strategy for the reduction of energy demand is the substitution of clinker with supplementary cementitious materials (SCM) and fillers. SCM are amorphous Silicon und Aluminium rich substances of various origins. Fillers are normally inactive unburnt limestones. The most common clinker substitutes are by-products from other industries, e.g., granulated blast furnace slag

(GBFS), fly ash (FA), natural pozzolans, calcined clays or limestone. The usage of these SCM has levelled off as their availability is modest compared to the demand of the cement industry with the exception of calcined clays. The raw products of calcinated clays are readily available from the waste of the porcelain industry. Limestone fillers are also widely available.[1]

CONCRETE PRODUCTION AND USE

The OPC consists of more than 90 % clinker (clinker factor >0.90). The reduction of the clinker content to 60% seems possible. However, realising this level of clinker substitution will require increased research and education efforts, particularly with users.[1]

The concept of easy to use "general purpose" cement is built in in most of modern concrete standards. This leads to the application of unnecessary high cement contents in at least 75% of all concrete types used. High cement contents are only be needed in a certain subsection of steel reinforced structures. If cements standard would clearly designate a specific category for use with steel reinforced concrete, such cements would almost certainly sell at a premium price. Low cement content products could sell for a lower price, encouraging their use in non-steel reinforced applications.[1]

One of the many appeals of cement is its longevity, hardiness, and its simplicity of use. The decisions and skills of the user in formulation cement-based mixtures determine the amount of cement used for a given application. In general, untrained personnel use mostly bagged cement and tend to use more cement than necessary. Industrial clients mostly prefer bulk delivery and tend not to overdose cement. The market of bagged cement is a rough estimate of inefficient use of cement.[1] The education of small scale individual users may be the key to reducing CO_2 emissions from overdosing, although it may be a difficult task to fulfil.

CONSTRUCTION

Many structures use concrete of a higher strength than needed for the design, which amounts to a waste of materials.[11; 12] This problem can only be solved by a deep integration of all parties involved in construction, e.g., architects, structural and civil engineers as well as construction companies.

The CO_2 footprint of a construction is profoundly influenced by its service life. Although the amount of cement used for repairing degraded structures is rather small, every effort for improving the durability of structures should be taken.[1]

Cement based materials are typically expected to have a service life of at least several decades. Fifty years is standard, although often the expectation is for much longer. The overwhelming majority of problems of concrete durability (probably > 90%) are related to steel reinforcement corrosion, which is related mostly to chloride ingress, and less commonly to carbonation. Only a very small proportion of cement use is at risk, because only about 25% of cement use is in reinforced concrete. Of this only a tiny fraction is exposed to conditions posing durability risks.

DE-CONSTRUCTION

Significant efforts have been made in recent years to recycle concrete and other cement-based waste. Concrete contains approx. 70% aggregates and approx. 30% hydrated cement. Recovering aggregates will reduce the stress on virgin aggregates and reduce demolition waste going to land fill. Although important in themselves, these measures do not significantly reduce the CO_2 footprint, as the production and transportation of virgin aggregates accounts to less than 10% of cement production.[1] Crucial to the production of high quality recycled aggregates is the removal of the cement (paste) which is attached to the aggregate's surface. These technologies are energy intensive and improvements are intensively researched.[13] Recycling also results in a high amount of CaO rich fines, which may be recycled as raw materials for clinker production and thus reduce the chemically related CO_2 emissions from clinker production.[1]

Circular economy in the building sector is possible, as demonstrated by the price winning ReConcrete-360° initiative of the German cement producer HeidelbergCement AG. Aggregates and hydrated cement are retrieved from demolition waste[14] and are used in the production of EcoCrete®. This commercially viable product shows an up to 66% reduced CO_2 footprint – including all parts of the production value chain - compared to current standards of the industry.[15]

The multi-university program UK FIRES has developed a new cementitious material derived completely from recycled materials. Demolition waste was crushed and separated to aggregate and cement powder, which was used instead of lime-flux in steel recycling. During the melting process the flux forms a floating slag on the hot steel. After tapping off the steel, the slag is cooled rapidly and ground into a powder, which is virtually identical to clinker. Further research and development is currently underway.[16]

TRANSPORT

Technologies for the de-carbonisation of the transport of raw materials, cement, concrete, pre-cast element and demolition waste are currently not available on an industrial scale. Prototypes for e.g., hydrogen, methanol and ammonia ships are under construction as well as fuel cell trucks[9; 10]. Although, pilot projects are currently developing.

The Norwegian shipping company Egil Ulvan Rederi AS[17] is currently building a bulk carrier with a hydrogen combustion engine and additional rotor sails with an expected commission in 2024. The price winning vessel *With Orca*[18] is planned to enter into a long-term transport service contract sailing both, the German cement producer HeidelbergerCement AG[19] (aggregates) and the Norwegian agribusiness Felleskjøpet Agri[20] (grain) and by this reducing empty sailing.

GOVERNMENT

The mitigation potential of each of the technologies discussed will depend on its success in the market. For this to happen, the authorities have to create new and binding norms and standards for segmented markets on the cement, concrete and construction level.

Governments are among the largest consumers of cement-based materials, especially when investing in infrastructure. Therefore, the use of public purchase power can be decisive in accelerating market penetration.[1] A successful example of purchasing power is the development and implementation of a customized low-carbon concrete for one of Meta's (USA) data centres in the USA with the support of artificial intelligence at Cornell University (USA)[21]. Although similar mixtures as the implemented in the data centre are in use in Europe since several decades[22], it is a proof of concept in terms of the usage of AI, the willingness of the authorities to authorize a new product and the purchasing power of customers.

More involvement of governments is needed in providing research funding, influencing educational policies for civil engineers and architects, and promoting environmental awareness.

The construction industry itself is confident that it can decarbonise until 2050[6]. The main measure will be CCS/CCU, which is the costliest technology of all. Cheaper alternatives are welcomed, mainly to keep concrete the low-cost building material that it was in the past. The selection of research results, business initiatives and governmental responsibilities described in this article demonstrate both, the progress already made and the efforts to be made to reach this goal and to build a net carbon free future in construction.

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Maritime Improvised Explosive Device (M-IED) Threat to Energy Security

by **H.Ceyhun TURE**

INTRODUCTION

Mitigating strategic vulnerabilities, enhancing Energy Security, investing in stable and reliable energy supply, suppliers, and sources are of significant importance. Together with Maritime Security focused on critical energy infrastructure and trade achieves peace and prosperity for the Alliance and Partners.[1]

Energy Security is a critical component to the common security of NATO. NATO's role in energy security, first defined in 2008 at the Bucharest Summit, has since been emphasized as part of the seven baseline requirements of resiliency for civil preparedness. The NATO Energy Security Centre of Excellence in Vilnius, Lithuania has led NATO's initiatives to assist Allies and Partners awareness and preparedness against hybrid threats to Energy Security since 2012.[2] The readiness of Allies and Partners to successfully execute military operations can be compromised through disruptions of energy supplies. Although the primary responsibility for addressing these concerns lies with individual member states, in accordance with Article 3, NATO members consistently engage collectively in consultations regarding Energy Security.[3] NATO has prioritized its role and efforts into three focus areas; Raising Energy Security Awareness, Supporting the Protection of Critical Energy Infrastructure and Enhancing Energy Efficiency in the Military Operations.[4]

In accordance with the NATO Strategic Concept approved in 2010, NATO's focus on **Maritime Security** was further developed through the Alliance Maritime Strategy document in 2011. The NATO Maritime Security Center of Excellence in Istanbul/Turkiye, actively supports NATO in maritime security matters, aiming to expand the capabilities of NATO and partner nations by providing comprehensive, innovative, and timely expertise in the field of maritime security operations.[5] The Alliance Maritime Strategy document emphasizes the importance of safeguarding the freedom of navigation, sea-based trade routes, critical infrastructure, energy flows, protection of marine resources, and environmental safety as essential components of the security interests of Allies. Additionally, NATO's maritime forces are prepared to contribute to energy security, including the protection of critical energy infrastructure and sea lines of communication.

After defining NATO's approach to Energy Security and Maritime Security, it becomes clear that these two areas are closely interconnected and require a coordinated and comprehensive approach to effectively address shared concerns, specifically focusing on the protection of critical energy infrastructure in the maritime domain. In addition, numbers are incredibly remarkable: water covers 70% of the Earth's surface, approximately 80% of the global population resides within a 100-mile radius of the coastline, and about 90% of global trade is conducted

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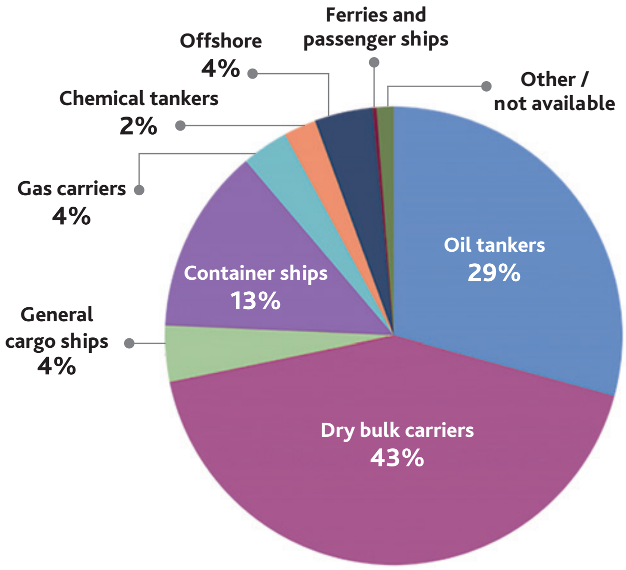

Figure 1. World fleet by principle vessel type in 2018, by share of dead-weight tonnage.

Review of Maritime Transport 2018, United Nations 2018

through maritime routes[6] and tankers play a crucial role in transporting more than 50% of the world's oil. [7] As depicted in Figure 1, approximately 33% of the commodities transported globally by sea consist of energy products.[8] Moreover, when considering energy-related products as well, this percentage has the potential to further increase.

In Addition, maritime energy infrastructure has experienced significant growth and transformation in recent decades. One of the notable developments is the increasing utilization of the sea as a source of energy, with larger wind farms being constructed further offshore.[9] Additionally, the use of underwater pipelines has become the most cost-effective, secure, and efficient method for transporting oil and gas, leading to a global increase in investments in this area.[10] However, maritime energy shipping faces numerous threats[11], including maritime improvised explosive devices (M-IEDs), particularly in chokepoints as illustrated in Figure 2.

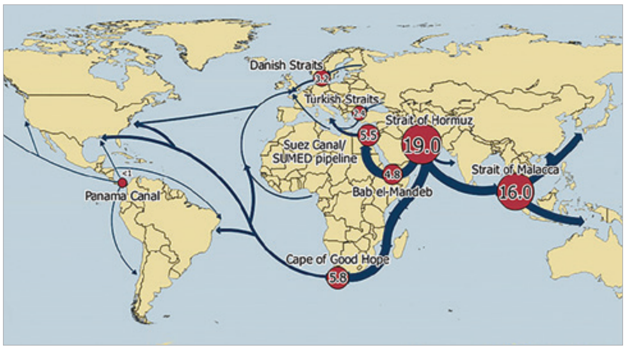

Figure 2. Daily transit volumes through world maritime oil chokepoints. Source: EIA, U.S.

Energy Information Administration.

Furthermore, it is important to recognize that critical underwater infrastructures, such as underwater pipelines, offshore windfarms, and electrical cables are increasingly vulnerable targets for terrorists and adversaries. These infrastructures play a vital role in various sectors, including energy production and transmission. Terrorists or adversaries may use M-IEDs to target these underwater assets to disrupt energy supplies, cause economic damage, or gain a strategic advantage.

While addressing the threat of M-IEDs, it is important to conduct a thorough examination of the risks and consequences associated, particularly to emphasize and increase awareness of the M-IED threats and challenges in protecting critical energy infrastructure in the maritime domain. In this regard, this article will focus on the following sections: "Why Terrorists Target Energy Infrastructure", "Improvised Explosive Devices (IEDs)", "Analyzing Maritime Improvised Explosive Devices (M-IEDs)", and finally, "Conclusions."

WHY TERRORISTS TARGET ENERGY INFRASTRUCTURE

Terrorism directed towards the energy sector is an escalating global phenomenon.[12] Statistics reveal a notable increase in such attacks over the years. In 2003, they accounted for 25% of terrorist incidents, which rose to 35% in 2005. In 2016, there was a 14% surge in terrorist attacks specifically targeting the oil and gas industry, making up nearly 42% of all attacks.[13] Terrorists generally do not display irrational behavior in their actions; instead, they carefully assess vulnerabilities, evaluate potential consequences, and aim to maximize their impact while minimizing costs and risks.[14]

Besides, attacks on maritime critical energy infrastructure or oil tankers could have significant strategic effects. They have the potential to influence global energy prices and even geopolitical dynamics, as seen in the aftermath of incidents such as the Nord Stream pipeline explosions. This factor alone can serve as a major motivation for adversaries or terrorist organizations to target such infrastructures.

Furthermore, the characteristics of energy infrastructures contribute to their attractiveness as targets for terrorists. The restricted mobility and expansive geographic footprint of these infrastructures makes them vulnerable and easier for potential attacks to go undetected and non-attributable. The extensive coverage area, coupled with the difficulties in effectively patrolling and controlling such vast spaces, presents significant challenges for security forces. Moreover, the intricate legal framework in maritime domain, especially in international waters, adds further difficulties.

Threat and vulnerability matrix below presents a risk as-

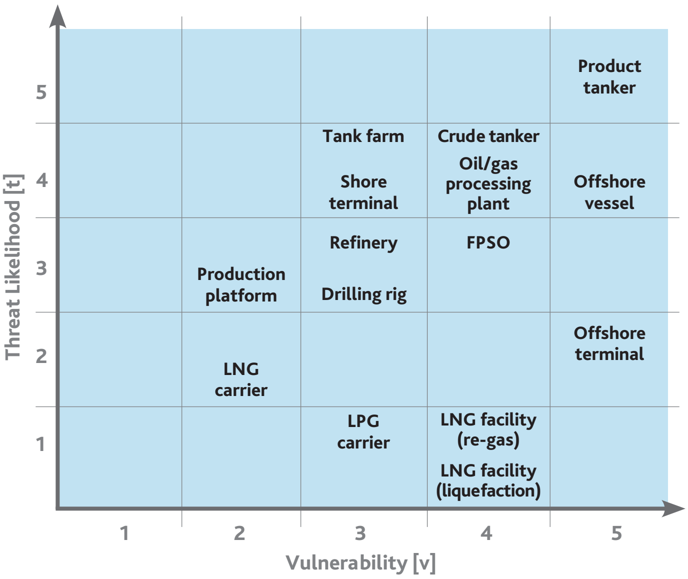

Figure 3. Energy Security at Sea (Vulnerabilities and Threats)

sessment that highlights the varying degrees to which different types of infrastructure and vessels have been targeted. Certain assets, such as product tankers, VLCCs (Very Large Crude Carrier), offshore vessels, tank farms, and oil and gas processing plants, continue to face threats due to their physical and operational vulnerabilities.[15]

In accordance to Figure 3, tankers and offshore vessels are particularly vulnerable to attacks, during the loading/discharging process, slow speeds in pilotage waters or anchorages, and transiting chokepoints. However, it is important to note that despite these vulnerabilities, oil tankers are not easily destroyed, sunk, or rendered a total loss as evidenced during the 1984–1988 Tanker War.[16] The combination of their structural robustness, double hulls, compartmentalization, and the inherent difficulty in igniting crude oil make it challenging for terrorists or saboteurs to achieve the desired catastrophic effect. While it is not impossible for an attacker with the right weapons or sufficient explosives to destroy a large crude oil tanker, it presents significant difficulties.

Besides the oil sector, the LNG sector is currently experiencing accelerated growth in the number of new tankers and portside liquefaction facilities. These assets are valuable in the processing and delivery of LNG, which is a low-carbon fossil fuel utilized by countries as part of their efforts to move towards net-zero emissions. Currently, this infrastructure is not classified as high risk. As a historical example, during the Iran-Iraq war in October 1984, an LNG cargo vessel took a direct hit from an Exocet anti-ship missile. The ship did not explode, and the crew was able to contain the fire.[17] However, this does not diminish the need for robust security measures for these assets. Instead, it emphasizes the importance of implementing effective preventive security measures. [18]

Alternatively, a fire in the pipes of a liquefaction facility in Freeport, Texas, USA, in June 2022, brought operations to a standstill for almost a year. Output from the Freeport LNG Facility made up 18% of US LNG exports.[19] This disruption came at a time when Europe was at its most vulnerable, facing a potential shortage of gas in preparations to weather the 2022/23 winter. These types of disruptions to global energy supply and markets are attractive motivations for terrorists and adversaries to exact their demands or objectives. Kinetic destructive methods currently in use and growing are Improvised Explosive Devices (IEDs) used to target critical points within the supply chain of oil, gas, and LNG.

IMPROVISED EXPLOSIVE DEVICES (IEDs)

IED is a device placed or fabricated in an improvised manner incorporating explosive material, destructive, lethal, noxious, incendiary, pyrotechnic materials or chemicals designed to destroy, disfigure, distract or harass. They may incorporate military stores but are normally devised from non-military components.[20] We can categorize the main types of IEDs as Victim-Operated IEDs, Command-Operated IEDs, Time-Operated IEDs and it is generally accepted that the main components of an IED include: Switch, Power source, Initiator, Compartment and Explosive (SPICE).[21]

As referred the "the cannon of the 21st century" or "weapon of poor" IEDs have significantly affected operations with their powerful and disproportionate effects. IED threats stems from their low cost and simplicity in production, which gives those who use them an advantage in asymmetric warfare. Their straightforward construction and ability to cause extensive harm present a significant challenge for security forces and civilians alike, requiring increased alertness and countermeasures to reduce the danger.

As it is widely recognized, countering IED attacks demands the imperative of close cooperation among a range of stakeholders, encompassing; diplomatic, military, law

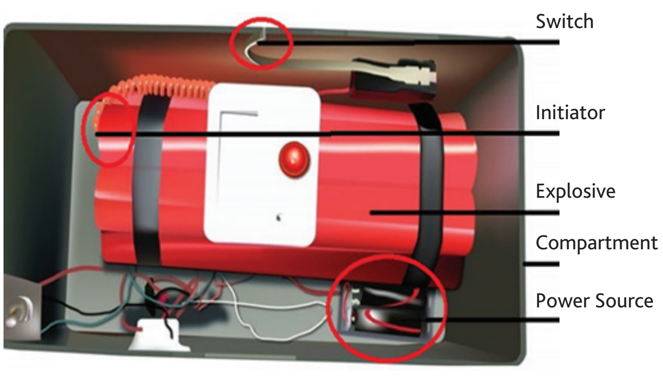

Figure 4. Main Components of an Improvised Explosive Device (IED)

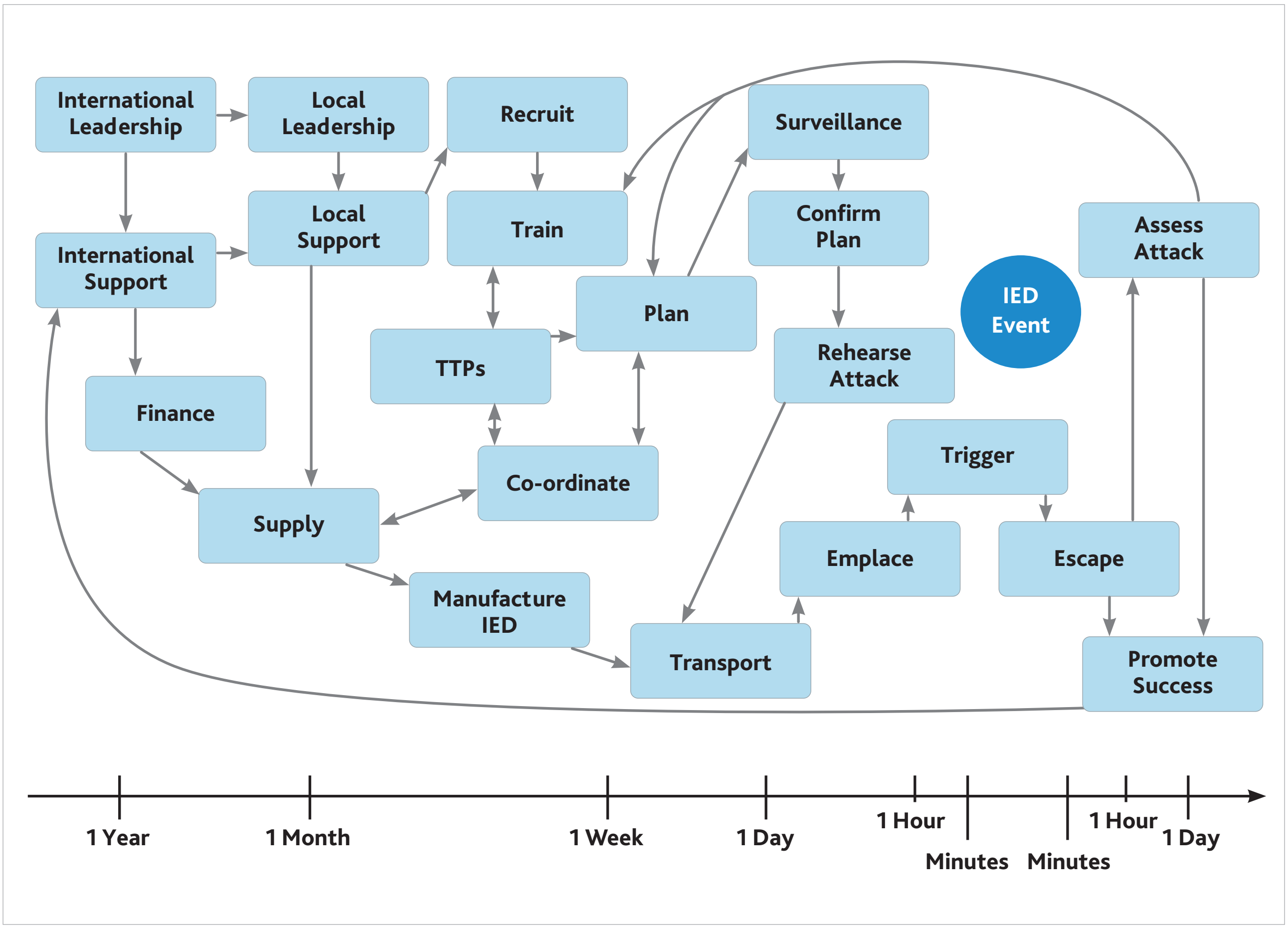

Figure 5. Activities Take Place Before and After IED Attack, (Source: AJP-3.15)

enforcement, economic, information, academic, and private sector entities. Figure 6 illustrating the, IED Attack Planning & Phases, shows the necessity for this collaboration.

In this regard, NATO took measures to coordinate and standardize joint efforts within the coalition, resulting in the establishment of STANAG 2295 (AJP 3-15), with the objective of fostering mutual comprehension and coordination between nations, this endeavor is referred to as "Counter Improvised Explosive Devices (C-IED)". The purpose is to promote a shared understanding and interoperability among participating countries. In accordance to this publication, C-IED has three main pillars: Attack the Network (Atn), Prepare the Force (PtF) and Defeat the Device (Dtd).

However, the document primarily focuses on land operations because historically the most prominent and observable threat was on land. The emerging threat, which is not addressed, is Maritime Improvised Explosive Devices (M-IEDs). IEDs in the maritime domain pose a growing challenge for governments and industries to address and mitigate their impacts.

ANALYZING MARITIME IMPROVISED EXPLOSIVE DEVICES (M-IEDs)

Historically, the maritime domain accounted for 2% of all IED incidents worldwide since 1969. This relatively low percentage can be attributed to the challenges and limitations that the maritime environment imposes on perpetrators, including planning, logistics, and technical difficulties. As a result, incidents involving IEDs in the maritime environment are less prevalent compared to land-based IED events.[22] However, it should be noted that attacks utilizing IEDs at sea have seen an increase in recent years. Adversaries and various terrorist groups have developed a certain level of maritime capability and new technologies provide terrorists and adversaries with opportunities to explore and develop novel methods.

Notorious Terrorist Abdul Al-Rahim Al-Nashiri, widely recognized as the so called "Prince of the Sea", served as the mastermind behind lots of maritime terrorist operations. Terrorist Al-Nashiri's strategy encompassed four key elements: utilizing a zodiac speed boat laden with explosives to collide with a ship, employing medium sized boats as explosive devices near docks or ports, employing aircraft to target boats through collisions, and incorporating underwater demolition teams.[23]

Below are the six primary categories of M-IEDs, along with explanations, suggestions, and insights derived from past M-IED attacks.

A. DRIFTING M-IEDs

In the context of drifting IEDs, it is important to note that these explosive devices can be disguised in various forms, such as rafts, life boats, unattended boats, plastic bins, large bags, floating sea mines or other amorphous objects.

Drifting IEDs can be detonated either by the perpetrator remotely or through victim-operated mechanisms. The victim-operated aspect means that the IED is designed to explode upon contact with a person or object, often resulting in harm or damage. It is less likely for Drifting IEDs to be time-delayed, the nature of drifting IED situations, where the devices are subject to water currents and movement, makes it tactically rare for time-delayed IEDs to be employed in such scenarios. Drifting IEDs can pose a significant challenge for freedom of navigation and energy shipping.

B. SUICIDE BORNE M-IEDs

The challenges of operating at sea, including distance, water currents, and limited access points, can make it more challenging for terrorists to carry out remote-controlled or timed IED attacks effectively. As a result, terrorists may resort to employing suicide-borne IEDs, where individuals willingly undertake a suicide mission by using small boats or vessels laden with explosives. These individuals aim to approach their target vessel closely and detonate the explosives upon impact, causing significant damage or destruction.[24] These M-IEDs are very similiar with the historical Shinyo suicide boats used by the Japanese Imperial Navy in World War II. These boats had the capacity to carry over 500 pounds of explosives and could reach speeds of nearly 30 miles per hour.[25]

Figure 6. Drifting M-IED (Guided by a Suicide Bomber – E. Mediterranean Sea, 17 January 2003)

Figure 7. Aftermath of M/V Limburg Suicide Borne M-IED Attack, 6 October 2002

On 6 October 2002, a small boat made of fiberglass, carrying 100 to 200 kg of TNT explosives and guided by two suicide terrorists, deliberately collided with VLCC named MV Limburg, while she was 3 km off the port of Al-Shihr with the assistance of a pilot in order to load its crude oil. At the time of the attack, the MV Limburg was leased to the Malaysian state petroleum company, Petronas, and it was carrying 400,000 barrels of crude oil. As a result of the collision, approximately 90,000 barrels of crude oil spilled into the Gulf of Aden. This event led to a direct increase of $0.48 per barrel in oil prices, due to higher insurance costs for ships visiting Aden.[26]

C. REMOTELY CONTROLLED M-IEDs

Remotely controlled IEDs provide adversaries with the capability to maintain control over an attack and detonate the explosive device at a specific location and time of their choosing. One option for achieving remote attacks is through the use of Radio Controlled IEDs (RCIEDs). However, conducting an RCIED attack within the maritime domain requires additional considerations.

To carry out an RCIED attack, terrorists generally require a spotter or observer to continuously monitor the target area. Without observing both the IED and the intended victim, they cannot trigger the detonation and achieve their objective. Hence, in maritime settings, terrorists are restricted to areas where they can maintain visual observation, like harbors, piers, shallows, narrow straits, choke points, or facility entrances. However, adversaries may overcome this limitation by utilizing drones or powerful telescopic equipment for observation, enabling them to extend their reach beyond remote distances. Moreover, terrorist organizations or adversaries now have the capability to employ advanced technologies such as remote-controlled, autonomous, or unmanned maritime vehicles.

Figure 8. Video Screenshot, Final Stage of Maritime IED Attack on 30 January 2017

On 30 January 2017, a frigate was targeted using a remote-controlled small boat. Initially, it was believed to be a Suicide Borne IED attack, but subsequent investigations revealed that the boat had been prepared using advanced technology. It was equipped with various advanced components, such as a remotely operated video camera, an autopilot compass, a GPS system, a throttle controlled by a servo-motor, a purpose-built computerized guidance system, and two powerful outboard engines. In essence, the boat was converted into a Remotely Controlled Unmanned Maritime IED. The attack occurred approximately 30 kilometres away from the Yemeni coast, highlighting the effective utilization of technology to carry out remote assaults from a distant location by terrorists.[27] It should be emphasized that the terrorist's future target could potentially be an oil tanker while it is sailing at a significant distance from the shore.

D. M-IEDs AT HARBORS AND ANCHORAGE

When ships are at harbours, anchorage, or approaching these locations, they become more vulnerable to a range of potential IED threats. These threats can be encountered on the surface, underwater, or the airborne domain.[28] These situations can include:

Remote-controlled or suicide boat attacks: Terrorists may employ small boats loaded with explosives to conduct remote-controlled or suicide attacks targeting ships or maritime infrastructures. Drifting IEDs can also pose a potential threat. Therefore, during periods of anchorage or when at harbor if possible, it is crucial to establish a security perimeter with a minimum radius of 100 meters.

IEDs attached to a ship's anchor/hull: Devices that are designed to explode when the ship hoists its anchor pose a potential threat, as they can cause damage or harm to the vessel. Additionally, limpet mines have the capability to be attached to specific sections of a ship's hull. Therefore, in the event of any suspicious situation, it is strongly advised to assign the Navy EOD Team with the task of conducting hull inspections.

IEDs emplaced under or close to piers: Devices that are hidden or placed in proximity to piers, potentially targeting ships during their docking or departing process. Therefore, it is advisable to assign the Navy EOD Team with the responsibility of inspecting the pier before entering the harbour and boarding.

Drone/UAV Attacks Drones can be used to deploy explosive devices onto ships or other targets, and they can also be utilized for direct kamikaze attacks. Therefore, it is crucial for all units, both afloat and ashore, to be equipped with anti-drone electronic warfare devices.

E. DRONE/UAV ATTACKS IN MARITIME DOMAIN

Due to rapid advancements in Drone/UAV technology, terrorist organizations have increasingly exploited this advantage to engage friendly forces in asymmetric warfare.[29] Maritime assets, whether ashore or afloat, are vulnerable to drone threats. Shore facilities, energy or oil supply facilities, as well as afloat units at harbors, anchorage, or while underway, may confront this threat and suffer casualties or damage from explosives released by drones. The potential threat posed by drones can originate from various directions. Failure to direct radar systems accurately and timely may result in the inability to detect an imminent drone attack.[30] Terrorists or adversaries can utilize drones for various purposes, including:

Engaging by releasing explosives from above: Drones can be weaponized to carry and release explosives, enabling adversaries to engage friendly forces by conducting aerial attacks. This method allows them to target specific locations or personnel with precision.

Figure 9. Drone with ordnance and camera to aim the target

Figure 10. Damage Caused by a Drone Attack on the Oil Tanker (Mercer Street)

Engaging through kamikaze attacks: Drones can be used as kamikaze vehicles, where they are deliberately flown into targets to cause damage or inflict casualties. By sacrificing the drone itself, adversaries can conduct suicide attacks without putting their own lives at risk. In addition, swarm kamikaze attacks involves a large number of individual units, which can overwhelm defenses and make it more difficult to track and neutralize each threat. Traditional defense systems may struggle to handle simultaneous attacks from multiple directions. Drone swarming demands advanced capabilities, such as individual drones being able to maintain distance, avoid air collisions, and anticipate the positions of other drones within the swarm at any given moment.[31]

A notable instance occurred off the coast of Oman, on 29 July 2021, when three kamikaze drones launched an assault on the Mercer Street oil tanker. While two of the drones failed to hit the tanker in their initial attack, one managed to successfully fly into the bridge during a subsequent strike. Regrettably, this attack resulted in the loss of life for a security guard and the vessel's captain.[32]

Acting as observation tools for planning and executing IED attacks: Drones serve as valuable observation tools, allowing adversaries to monitor the movement of friendly forces and gather intelligence. They can use this information to plan and execute IED attacks at desired locations and times, maximizing the potential impact.

Recording videos for propaganda: Drones equipped with cameras can capture video footage of attacks, which can then be used for propaganda purposes. These videos can be disseminated online or through other channels to amplify the impact of their actions and spread fear or misinformation. In addition, these videos also let terrorist organizations to develop their TTPs and studying the tactics and techniques of Allied forces responding to IED incidents.

F. UNDERWATER IEDs

The specific capability and prevalence of underwater IEDs among terrorist groups is not widely known. However, it is a fact that adversaries have been actively dedicating resources to develop sophisticated underwater military capabilities, which could potentially jeopardize the security interests of member states of NATO and their allies during a crisis situation.[33] NATO issues a warning about adversaries actively surveying and mapping critical energy infrastructure belonging to allied nations, both on land and underwater.[34] Hence, after those critical energy infrastructure mappings, adversaries with the necessary expertise, resources and training could employ divers or remotely operated vehicles to plant and position explosive devices in underwater environments. This method offers several advantages, including the ability to access specific locations, attach devices discreetly, and potentially evade detection.

Additionally, using Underwater IEDs with time-delayed mechanism allow the perpetrators to retreat to a safe distance before the explosive device detonates. The combination of time-delayed underwater IEDs with a remote control (RC) component represents an alarming tactic that adversaries may employ in the maritime domain. This combination allows for greater control over the detonation of the explosive device, enabling perpetrators to remotely trigger the explosion at a desired time and location. The effects of underwater explosions can result in various destructive outcomes, such as harming ships, submarines, critical underwater energy infrastructures, as well as impacting any maritime operations.[35]

Moreover detecting underwater IEDs presents significant challenges due to their concealed nature. Sonar systems, underwater sensors, and advanced surveillance technologies are employed to identify and mitigate these threats. Divers and specialized underwater explosive ordnance disposal (EOD) teams are required for the identification, neutralization, and disposal of underwater IEDs. It is important to highlight that, certain IEDs deployed underwater might specifically aim to target Navy EOD personnel. This observation underscores the added risks faced by these highly trained individuals while carrying out their crucial tasks.

As seen on Nord Stream explosions on 26 September 2022 has brought attention to the susceptibility of undersea energy pipelines and communication cables. As a result, NATO Allies have taken substantial measures to enhance their military presence around maritime underwater critical infrastructure.[36] On 15 February 2023, NATO Secretary General Jens Stoltenberg declared the establishment of a Critical Undersea Infrastructure Coordination Cell at NATO Headquarters. This initiative aims to facilitate improved coordination between essential military and civilian stakeholders, as well as

Figure 11. Saildrone Explorer in the Persian Gulf on 7 October 2022

the industry, regarding a matter that is crucial for our security.[37] Besides the collective efforts of NATO, individual nations have also undertaken diverse initiatives, investing in seabed warfare[38] and innovative underwater surveillance technologies.[39] "Saildrone" unmanned surface vessels could be a good example of energy-efficient and innovative seabed surveillance technologies, utilizing wind energy for the vessel and solar energy for the sensors.[40]

CONCLUSIONS

In conclusion, the close interconnection between Energy Security and Maritime Security highlights the importance of a coordinated and comprehensive approach to effectively address shared concerns. The maritime energy infrastructure has witnessed significant growth and transformation in recent decades. However, it is crucial to recognize that alongside maritime energy shipping, critical maritime energy infrastructures such as underwater pipelines, offshore wind farms, and electrical cables are progressively becoming more susceptible to threats from adversaries and terrorists. The use of M-IEDs to target energy shipping & critical underwater energy infrastructures poses significant risks.

Countering the IED threat in the maritime domain necessitates a fluid and comprehensive approach, taking into account the unique characteristics of the maritime environment. This approach requires three-dimensional planning that encompasses not only the surface and air but also the underwater environment. Protecting critical underwater energy infrastructures from challenges like M-IEDs is uniquely difficult due to the vast maritime area and accessibility. It requires specialized equipment, surveillance technologies, research, innovation, intelligence sharing and most importantly coordination among all stakeholders.

At this point, international collaboration among nations is vital to prevent duplication of efforts, maximize resource utilization, effective crisis management and establishing a common legal framework. NATO ENSEC COE's Tabletop Exercises, like Coherent Resilience Baltic-23 "focus on Maritime Critical Energy Infrastructure Protection" provide excellent opportunities for this close cooperation among nations, ministries, private companies (responsible for underwater infrastructure, aerial or underwater surveillance systems, unmanned maritime patrol vessels ext.), military personnel (especially Patrol Vessels & Navy EOD personnel), and academics.

Ensuring a reliable and stable energy supply is of utmost importance, and it is crucial to acknowledge and prioritize the responsibility of protecting critical energy infrastructure. There is no doubt that adversaries and terrorists consistently strive to develop novel methods and technologies to execute attacks on maritime critical energy infrastructures. As the threat of M-IEDs advances in complexity and lethality, collective NATO investments in innovative surveillance solutions and coordination between nations are needed to thwart or minimize the impacts of such attacks.

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