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Content

Editorial

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Russia's unprovoked invasion of Ukraine has plunged the European continent into its worst military conflict since World War II. It also ratcheted up NATO-Russia tensions to unprecedented heights and exposed Europe's acute dependency on Russian energy supplies.

Although it's difficult to estimate the outcome of the war in Ukraine and to assess its broader implications, one thing is eminently clear: this war is a watershed event with profound consequences for European energy security. It will not only facilitate Europe's decoupling from Russian energy supplies, but it will also likely accelerate Europe's clean energy transition.

After all, by doubling down on the deployment of renewables and embracing innovative energy technologies European leaders can hit two birds with one stone. Not only they can cut greenhouse gas emissions and help fight climate change, but also make Europe more energy independent.

The NATO Energy Security Centre of Excellence is keenly aware of the challenges our Allies are facing. As a result, in this issue of Energy Highlights we will examine the prospects of clean energy innovation both in the military and civilian domains, while also looking at the threats of climate change.

In the first article of this issue, I review existing nuclear propulsion systems and examine if the development of nuclear-powered vehicles and weapon delivery systems would benefit NATO forces. However, instead of focusing on the potential impact of this technology on strategic stability, this article shifts its attention to the more technical, political and operational issues related to the development of nuclear propulsion systems in the air, land and sea domains.

Meanwhile, in their contribution Dr. Jutta Lauf and Dr. Reiner Zimmermann focus on the clean energy transition and the increasing need to develop and deploy completely new energy infrastructure. In other words, they argue that as governments increase investments in renewable power generation, they will also have to think about how to store, transport and distribute this energy.

Later, Dr. Sijbren de Jong and Can Ögütcü explain how climate change poses a serious challenge for countries like Russia. The authors examine how rising global temperatures and the melting of permafrost will likely affect everything from budget revenues from energy exports to energy infrastructure in the High North.

In the final piece of this issue, Dr. Jutta Lauf and Dr. Reiner Zimmermann discuss the negative effects of climate change on military infrastructure. More specifically, they focus on how rising temperatures increase the number and severity of tropical storms and how these extreme weather events pose a risk to military bases along the Caribbean and Atlantic coastlines of the United States.

We hope that you'll find these articles valuable and thought-provoking, and that they will shed some light on the challenges of the clean energy transition, while also highlighting the growing risks of climate change.

The Future Role of Nuclear Propulsion in the Military

by **Mr. Lukas Trakimavičius**

INTRODUCTION

The splitting of the atom is without a doubt one of humanity's greatest technological achievements. Regardless if one is a fan or foe of nuclear fission, the fact that scientists have found a way for this tiny speck of matter to generate large amounts of heat and power is nothing short of spectacular. Even more remarkably, in just seventy years nuclear power became a major source of energy for many countries across the globe. Nowadays, it accounts for some 10 percent of the world's electricity supply, it is a key source of power for countries such France or Ukraine, and some of the militaries also use it to propel their ships, submarines and aircraft carriers.

Given the versatility of this source of energy, it is hardly surprising that some countries have decided to take it further and came up with even more innovative ways of harnessing the atom. The most notable example of this is Russia, whose President Vladimir Putin announced back in 2018 the development of a flurry of so-called "doomsday weapons".[1] Some of them will use nuclear energy as their primary source of propulsion. These include: an autonomous, submarine-launched, nuclear-powered and nuclear-capable underwater vehicle, called *Poseidon*, and a nuclear-powered, nuclear-armed cruise missile, called the *Burevestnik*. [i]

In the West, this announcement was met with mixed reactions. There were those who claimed that these weapons – provided they would ever leave the testing grounds and become deployment-ready – could have a significant impact on the global security landscape and somewhat tilt the balance of power in Russia's favor.[2] Others claimed the opposite and argued that these weapons are unlikely to bring anything particularly useful to the table.[3] Then there were also those who stressed that these technologies were neither as new nor as innovative as they may have initially appeared. This was done by highlighting the fact that both the United States and the Soviet Union had toyed around with similar ideas at the height of the Cold War.[4]

by **Mr. Lukas Trakimavičius**

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[i] While these weapons were introduced to the public at large during the address to the Federal Assembly in March 2018, they were anything but new. First public evidence about the development of the Poseidon surfaced back in 2015 and first glimpses of the development of the Burevestnik missile appeared in 2016.

Regardless of what one thinks about these "doomsday weapons", it is eminently clear that, if anything, Moscow has succeeded in drawing everyone's attention. Therefore, it is only reasonable to assume that as Russia continues to develop these weapon systems, some security analysts or media pundits will eventually start raising questions if Western powers should follow in Moscow's footsteps? In other words, should the West – in a bid to fill some perceived military technology gap (a theme all too common in history) – revisit long-abandoned, Cold War-esque plans for nuclear propulsion? Or, as small and micro modular reactor technology makes nuclear energy more accessible, the atom could finally be used to power land vehicles, small surface ships or even airplanes?[II] And, if so, would there be any operational advantages for Western militaries to gain from these developments? Questions about the future of nuclear propulsion might also be asked in light of the growing pressure for the military to tackle climate change and decrease its acute reliance on fossil fuels.

This is where this article comes into play. It will review existing nuclear propulsion systems and examine if the development of nuclear-powered vehicles and weapon delivery systems would benefit Western militaries. However, instead of focusing on the potential impact of this technology on strategic stability and nuclear deterrence, this article will shift its attention to the more technical, political and operational issues related to the development of nuclear propulsion systems.

This article will be broadly divided into three parts. First, it will provide a brief history of the use of nuclear propulsion in the military. Second, it will review the existing nuclear propulsion technologies and plans for future development.[III] Third and finally, it will review the potential pros and cons of developing new nuclear propulsion-based military vehicles and weapon delivery systems in the air, land and sea domains.[IV]

HISTORY OF NUCLEAR PROPULSION IN THE MILITARY

Earliest records suggest that serious thinking about nuclear propulsion began even before the end of World War 2. Once the secrets of the atom were cracked and controlled fission was achieved, both the United States and the Soviet Union quickly realized the untapped military potential of this source of energy. The atom promised a seemingly endless supply of power and, at the time, it seemed that the prospects of long-range flight could prove to be a decisive factor in the Cold War rivalry that was slowly taking shape.

In the US, research on nuclear propulsion began in 1946 when the Air Force initiated the *Nuclear Energy for the Propulsion of Aircraft* project, later known as the *Aircraft Nuclear Propulsion* (ANP) program. In one of the research projects, the scientists decided to place a small nuclear reactor within a converted *Convair B-36 "Peacemaker"* bomber and see if the airplane could fly with a functioning nuclear engine on board (though it did not actually power the aircraft). In total, the *Convair NB-36H* (the name of the experimental aircraft) completed some 47 test flights (with the reactor being switched on during most of them) between 1955 and 1957, and it was proven that it is technically possible to mount an operational nuclear reactor on a flying aircraft. However, the ANP program was eventually scrapped in 1961 as the development of nuclear-powered aircraft proved to be far more difficult than initially expected.[5] The program was also plagued by a number of problems, including difficulties of shielding the aircraft crew from deadly doses of nuclear

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[II] For a discussion about small modular nuclear reactors and their potential use in the military see: Lukas Trakimavičius, "The future role of small modular nuclear reactors (SMRs) in the military", Energy Highlights, 2 December 2020, https://www.enseccoe.org/data/public/uploads/2020/11/02.-solo-article-lukas-smr-eh-15-web-version-final.pdf

[III] This article will only focus on more or less mature technology. It will omit the discussion of such futuristic technologies as nuclear fusion, because, as the joke goes, nuclear fusion is 30 years away...and always will be. On a more serious note, even if nuclear fusion would somehow manage to achieve significant technological breakthroughs over the next decades, it is rather unlikely that nuclear fusion reactors could somehow be used by the military anytime soon.

[IV] While space is becoming increasingly viewed as an operational domain by militaries and international organizations alike, it is still unclear when, and if at all, it will become as militarily important as the three traditional military domains. Therefore, for practical purposes, this article will not include any broader discussions about the militarization of space.

radiation, high development costs, and public concerns about the dangers of a nuclear reactor flying overhead.[6]

In 1957, the Air Force also initiated a program called *Project Pluto*, which sought to develop nuclear-powered engines for use in cruise missiles. The project was somewhat more successful than the ANP program, but in 1964 it was also cancelled.[7] By that time, the emergence of intercontinental ballistic missiles (ICBMs) such as the *Atlas, Minuteman* and *Titan*, and the introduction of heavy payload bombers like the *B-52 "Stratofortress"* reduced the need for nuclear-powered cruise missiles. Moreover, there were serious concerns that the unshielded reactor core of these cruise missiles would emit copious amounts of radioactive exhaust along its flight path, endangering everyone between the launch site and the target.[8]

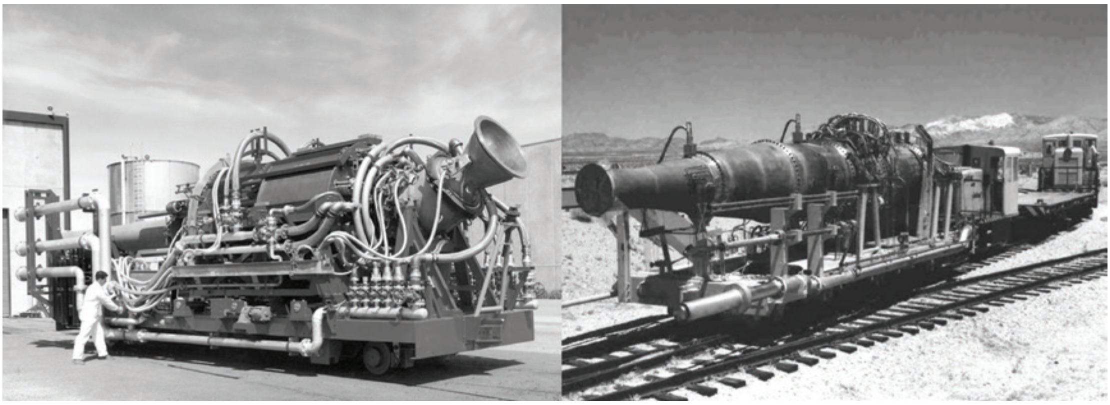

Figure 1. Engines used for Project Pluto (Tory II-A, Tory II-C), left to right.[A]

Meanwhile, in parallel to the Air force, in 1948, the US Navy also began research on nuclear-propelled vessels, from submarines to aircraft carriers. Its research program proved to be vastly more successful than that of the Air Force and, in 1954, it built the *USS Nautilus*, the world's first nuclear-powered submarine. In 1959, the Navy launched *USS Long Beach*, the world's first nuclear-powered missile cruiser, and, one year later, it launched the *USS Enterprise* — the world's first nuclear-powered aircraft carrier.

Given the enormous potential of this technology, it is not surprising that right from the start of the Cold War, the Soviet Union was also busy developing an extensive naval nuclear propulsion programme. In a bid not to fall behind in the arms and technology race against the US, the Soviets initiated work on a nuclear-powered submarine in 1952.[9] Despite a series of setbacks, including radiation leaks and engine problems, the first Soviet submarine, the *K-3 Leninsky Komsomol*, entered service in 1958.[10] Much later, in 1977, the Soviet Navy launched its first nuclear-powered missile cruiser, named *Kirov*. Finally, in 1988, the Soviets started working on the *Ulyanovsk* — the country's first nuclear-powered aircraft carrier. However, after the collapse of the Soviet Union the project was cancelled in 1991.

Back in 1955, the Soviet government also started work on a nuclear-powered aircraft. Following years of research, the designers inserted a small nuclear reactor within the bomb bay of a retrofitted *Tupolev Tu-95* bomber, which began its test flights in 1961 (see Figure 2.). In total, the *Tupolev Tu-95LAL* (*Letayushchaya Atomnaya Laboratoriya* or "flying nuclear laboratory" in English) made some 40 missions with the reactor switched on only on a few of the flights.[11] As it was the case with the US-built *Convair NB-36H*, the reactor did not actually power the aircraft and the main goal of these flights was to test radiation shielding. However, the project was scrapped in 1969 as the idea of nuclear-powered aircraft proved to be far too impractical. It was challenging to shield

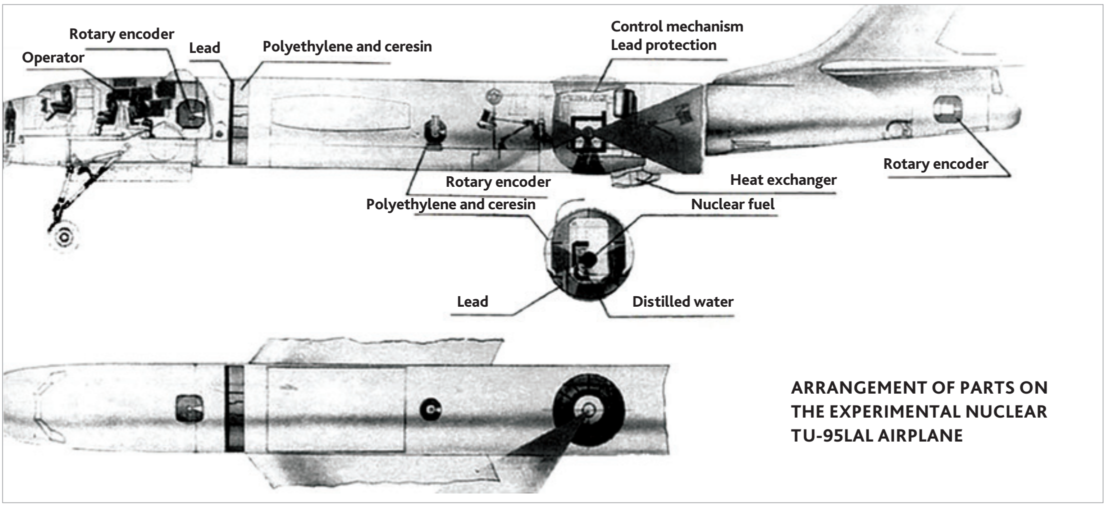

Figure 2. Tupolev Tu-95LAL blueprint.[B]

the crew from nuclear radiation, the emergence of ICBMs made the high costs of nuclear-powered aircraft unwarranted and there also were concerns that the crash of such a plane would lead to catastrophic consequences.[12]

At around the similar time, the Soviets were also considering the development of cutting-edge nuclear engines for airplanes. For this reason they designed a prototype of the *M-60* long-range bomber, which, it was planned, would rely on four turbojet nuclear engines.[13] The bomber was supposed to take off and land using conventional engines, but, once in the air, it would turn on the nuclear reactors. In theory, these nuclear turbojet engines should have provided the *M-60* with an estimated range of at least 25,000 kilometres and maximum speed of 3,200 kilometres per hour. However, the *M-60* did not make it out of the planning stage and, because of reasons similar to those of the ill-fated *Tupolev Tu-95LAL* (and the US-built *Convair NB-36H*), the program was shelved in 1959.[14]

Overall, during the Cold War the militaries of the US and the Soviet Union had by far the most advanced and extensive nuclear propulsion research programs. Due to a number of reasons, including cost and utility, other countries had fairly little interest in nuclear propulsion beyond the realms of naval engineering.[V]

THE SCIENCE BEHIND NUCLEAR PROPULSION

In most cases, at least in the naval domain, the concept of nuclear propulsion is relatively straightforward. Nuclear reactors are basically heat engines, which drive the propulsion plant of a ship or submarine. The heat comes from the fissioning of nuclear fuel (mostly uranium) contained within the reactor. Since the fissioning process also produces radiation, shields are placed around the reactor so that the crew is protected. In fact, it is estimated that on some ships well over 100 tons of lead shielding is used for the reactors.[15]

To date, virtually all militaries have relied on pressurized water reactors (PWRs) to power their vessels. PWRs are the most common type of nuclear reactors and around two-thirds of all reactors in the world are of this type. These reactors make use of light water (basically, ordinary tap water)

[V] The first British nuclear submarine, the HMS Dreadnought, was commissioned in 1963, and the first French nuclear submarine, Le Redoutable, was commissioned in 1971. The first Chinese nuclear submarine, the Changzheng 1, went into service in 1974.

as their coolant and neutron moderator, as opposed to other reactors that use heavy water (a type of water that contains high amounts of the hydrogen isotope deuterium), or gasses (such as helium) or liquid metals (sodium, lead, etc.). A notable exception to this rule is the Soviet Union, which during the Cold War operated a number of lead-bismuth cooled nuclear reactors on its submarines. The US military also entertained idea of using sodium-cooled nuclear reactors (it temporarily had one on board the 1955-built *USS Seawolf*), but eventually it dropped this design (due to technical and budgetary reasons) in favour of using PWRs on all of its ships.[16]

In general, PWR-based naval propulsion systems use two basic circuits – a primary and a secondary one (see Figure 3.). In the primary circuit, the coolant (in this case water) is pumped under high pressure to the reactor core, where it is heated by the energy released from the fission of atoms. The heated, high pressure water then flows to a steam generator, where it transfers its thermal energy to lower pressure water of a secondary circuit. Subsequently, in the secondary circuit, the steam flows from the steam generators to drive the turbine generators, which supply the ship with electricity, and to the main propulsion turbines, which drive the propeller.[17]

Though PWRs can reliably power surface ships and submarines, due to a number of technical difficulties (mostly related to weight), this technology is wholly unsuitable for flight. As a result, most experimental nuclear reactors that were designed to power either aircraft or missiles used other types of reactors. For example, the ANP program that was developed by the US Air Force used a molten-salt reactor on board the *Convair NB-36H*, which employed molten fluoride salts as the primary coolant. This type of reactor was smaller and lighter than a PWR, but, for all intents and purposes, it was still too unwieldy to be used for flight.

Meanwhile, an honourable mention should be made of the scientists behind the US Air Force's *Project Pluto* who decided to opt for an even more radical engine design for its nuclear-powered cruise missile. They created the world's first nuclear ramjet — an air-breathing jet engine that operated with no major moving parts (regular jet engines rely on either axial or centrifugal compressors). This engine had a fairly simple design: the missile pushed air in through the front of the missile, an unshielded nuclear reactor heated the air and then the hot air was expanded at a high speed through a nozzle at the back, providing thrust. If deployed, it is believed, the *Project*

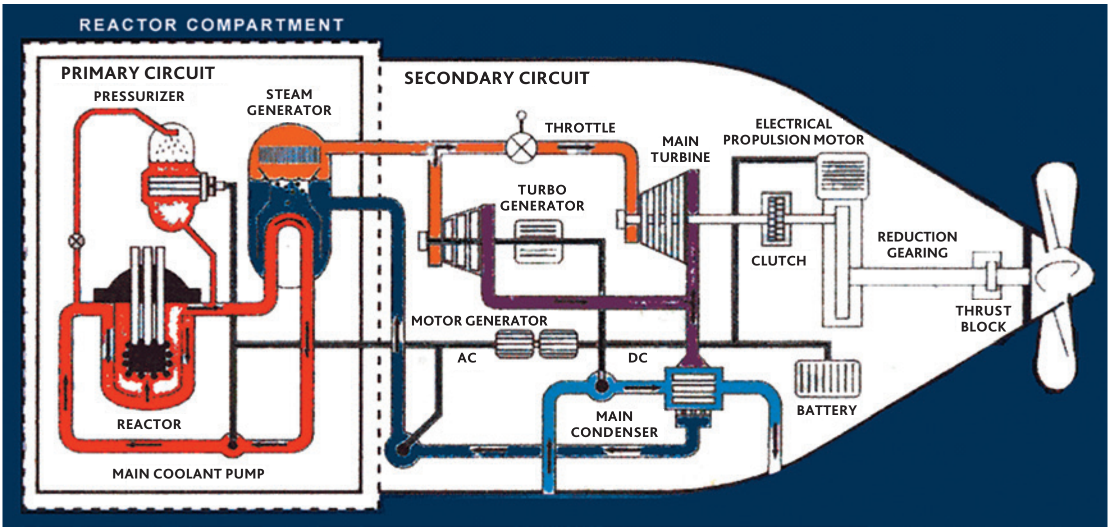

Figure 3. Pressurized-water naval nuclear propulsion system.[C]

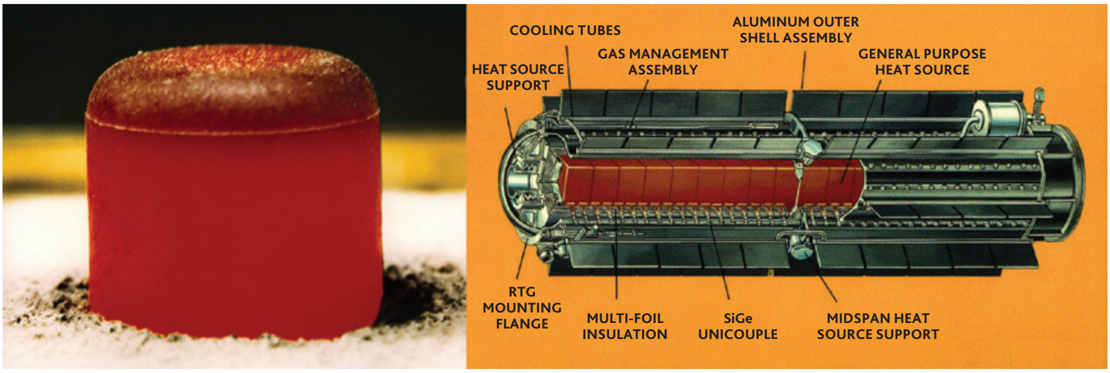

Figure 4. Red hot pellet of Pu-238; blueprint of a basic RTG, left to right.[D]

Pluto missile would have flown at three times the speed of sound, while the red-hot reactor would produce a deafening roar of 150 decibels and incinerate everything in its path.[18]

ALTERNATIVE NUCLEAR SOURCES OF ENERGY

Though unrelated to military vehicles, weapon delivery systems or nuclear propulsion *per se*, there are other ways how radioactive materials have been used to power various equipment. For example, satellites and spacecraft such as the *Voyager* and the *Cassini* probes, or the most recent *Perseverance* rover, just to name a few, use radioisotope thermoelectric generators (RTGs) to power their systems.[VI] Thought technically they could not be classified as nuclear reactors because there is no fission involved, they still draw energy from either the same or similar materials as nuclear reactors. Highly radioactive materials, such as plutonium, give off heat as they decay, which in turn can be converted into electricity.

At first glance, RTGs may seem as ideal sources of power for the military, but at closer inspection, nothing could be further from the truth. One of the advantages of RTGs is that they are simple, compact and relatively robust. They have no moving parts and there is not much that can break down. However, the main problem with RTGs is that thermoelectric modules have a very low conversion efficiency, and, therefore, they cannot generate much power compared to other sources of energy. Therefore, most RTGs are only suitable to power equipment that requires a few hundred watts or even less. For instance, the *Cassini* space probe used three RTGs that each produced some 292 watts of electricity at the beginning of its mission.[19]

On top of that, there is also the issue of cost. Plutonium (Pu-238 in particular) is one of the most expensive substances known by weight, with some sources giving a price estimate of around €4,000 per gram.[20] Hence, hypothetically speaking, the sheer amount of plutonium that would be needed to power a small land vehicle would inevitably result in a price tag that would run into the tens of millions, if not much more.

There are also alternatives that sit between low-power RTGs and full-blown nuclear fission reactors, which are called Stirling radioisotope generators, or SRGs in short. They tend to produce power more efficiently than RTGs and require significantly less radioactive fuel, but come with a downside of having some moving parts that may break down over time.[21] Still, considering their relatively low energy output (if compared to combustion engines), potential fuel costs and safety and security matters, it is very unlikely that SRGs could see any meaningful use on military vehicles or weapon delivery systems. As a result, it is fair to conclude that if the military would decide to significantly expand the use of

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[VI] Countries like the US and the Soviet Union also used RTGs to power various remotely-located equipment on the Arctic coast, including lighthouses, navigation beacons, etc.

nuclear propulsion anytime soon, the technology most likely would have to involve some degree of fission.

MILITARY INTEREST IN NUCLEAR PROPULSION

As it was the case during the Cold War, out of all the military branches, the navies are still the only users of nuclear propulsion. Currently, there are over 160 vessels, which are powered by more than 200 nuclear reactors.[22] Most of them are submarines, but they also include aircraft carriers.[VII] These are driven by PWRs with power ranges everywhere between 48 megawatts (MW) (French *Rubis*-class submarines) to around 700 MW (US *Gerald Ford*-class aircraft carriers). The vast majority of all the nuclear-propelled vessels belong either to the US or Russia. Countries such as China, the United Kingdom, France and India also maintain vessels that rely on nuclear power. As things stand right now, it seems that over the next decades all of these countries seem to be planning to either expand or modernize their nuclear-powered fleets.[23]

Out of all the countries, Russia is the only one that has future plans for nuclear propulsion that goes beyond the naval domain.[VIII] Over the coming years it not only plans to receive a number of new *Yasen-M* class nuclear submarines, upgrade its nuclear-powered *Kirov* class battlecruiser, but also develop an array of so-called "doomsday weapons", some of which will use nuclear energy as their primary source of power.[24]

POSEIDON

One of these "doomsday weapons" is the autonomous, nuclear-powered and nuclear-capable underwater vehicle, called *Poseidon*.[IX] Though there is relatively little reliable information about this weapon delivery system on the public domain, media sources describe *Poseidon* as a giant nuclear-powered torpedo, which might become operational in 2027.[25] It reportedly measures around 1.6 meters in diameter, about 24 meters in length, and relies on a tiny nuclear reactor to power a pump-jet propulsion system.[26] The torpedo is also believed to have an operational speed of up to 70 knots (around 130 kilometres per hour) and is rumoured to be able to dive as deep as 1,000 meters.[27] It is claimed that this weapon will be carried on specially equipped *Belgorod*-class nuclear submarines, which would operate in both Northern and Pacific fleets. Media reports also suggest that each of these submarines would be capable of carrying up to six of these torpedoes.[28] In turn, these torpedoes could reportedly deliver either a conventional payload or a nuclear warhead with a yield of around two megatons.[X]

Based on publicly available sources, it is believed that the *Poseidon* torpedo would likely be used as a second strike weapon. It not only would avoid missile defence systems, but it could also inflict damage against enemies, even if a first nuclear strike seriously degrades Russia's ability to retaliate with ICBMs. In fact, back in in 2015, a leaked Kremlin briefing slide stated that the

Figure 5. Snapshot of the Poseidon/Kanyon nuclear-powered torpedo.[E]

[VII] Russia also operates the world's only nuclear-powered icebreaker fleet. However, it's operated by FSUE Atomflot (a subsidiary of ROSATOM) and these ships are generally used for civilian purposes (cargo transportation, tourism, etc.).

[VIII] One exception to this rule is the Defense Advanced Research Projects Agency (DARPA), the Pentagon's research and development arm, which is funding the construction of the world's first nuclear thermal propulsion system for spacecraft. However, even if successful, this technology could not be used for military mobility needs i.e. for powering aircraft or land vehicles.

[IX] Formerly this weapon was known as Status-6 Oceanic Multipurpose System. Its NATO reporting name is Kanyon.

torpedo was aimed at "damaging the important components of the adversary's economy in a coastal area and inflicting unacceptable damage to a country's territory by creating areas of wide radioactive contamination that would be unsuitable for military, economic, or other activity for long periods of time."[29] However, in practice it is somewhat unclear to what extent this weapon would be capable of causing this much havoc. This is because upon the detonation of an underwater bomb, most of the explosive energy would be lost and only a small part of it would go into a wave.[30]

BUREVESTNIK

The *Burevestnik* ("announcer of the storm" in English) is another of Russia's nuclear-powered weapon delivery systems, which is currently under development.[XI] In terms of concept and design, this cruise missile looks as if it was taken straight from a Cold War-era playbook and is rather similar to the US Air Force's *Project Pluto* weapon concept. To date, the *Burevestnik* has been shrouded in secrecy and only limited information about this missile is publicly available. Still, based on the imagery provided by the Russian military, it can be assumed that the missile is likely around 12 metres in length and up to 1.5 metres in diameter.[31] It has been speculated that the *Burevestnik* has a booster engine (that likely uses solid fuel) to lift the missile into flight speed and that it has a small nuclear reactor, which then carries the missile to its target. Some sources claim that the missile employs a nuclear ramjet, others claim that it uses a nuclear turbojet engine.[32] Regardless of what the engine is, it is thought that *Burevestnik* could fly at a subsonic speed, maintain an altitude of 50-100 metres throughout most of its flight and cover distances as long as 20,000 km.[33] To date, there has been no indication about the yield of this missile and it is unclear when it would become deployment-ready.[XII]

According to open source data, *Burevestnik* is intended to be a second-strike, retaliatory weapon. It is claimed by the Kremlin that this missile was developed in response to the US withdrawal from the Anti-Ballistic Missile Treaty and its advancements in missile defense systems.[34] More specifically, it is believed by some that the main rationale for the *Burevestnik* stems from Russia's general fears that Washington's missile defense systems could neutralize Moscow's nuclear arsenal (and, by extension pose a threat to its great

Figure 6. Snapshot of the Burevestnik/SSC-X-9 Skyfall nuclear-powered cruise missile.[F]

[X] Initial estimates and media reports put the nuclear yield of the Poseidon torpedo to around 100 MT. This would have meant that it would have been twice as powerful as the Soviet Tsar Bomba (50 MT yield), the most powerful nuclear explosive that was ever created. However, more recent estimates greatly reduced this initial number, which was likely deliberately overinflated for political purposes. See: Amy Woolf, "Russia's Nuclear Weapons: Doctrine, Forces, and Modernization", Congressional Research Service, 20 July 2020, https://fas.org/sgp/crs/nuke/R45861.pdf

[XI] Its NATO reporting name is SSC-X-9 Skyfall.

[XII] In 2019, reports have surfaced that the Burevestnik may become deployment-ready in 2025. However, realistically, its deployment could be a decade away, if ever. See: Jill Hruby, "Russia's New Nuclear Weapon Delivery Systems: An Open-Source Technical Review", Nuclear Threat Initiative, 13 November 2019, https://www.nti.org/analysis/reports/russias-new-nuclear-weapon-delivery-systems-open-source-technical-review/

power status). Though, admittedly, few Western security analysts have this much faith in the effectiveness of missile defense systems.[XIII] Or, alternatively, *Burevestnik* could be used as a bargaining chip in future arms control negotiations.[35] Regardless, when President Putin announced the development of his "doomsday weapons", he emphasized how the missile "can reach any point in the world" and how it is "invincible against all existing and prospective missile defence and counter-air defence systems."[36]

THE FUTURE POTENTIAL OF NUCLEAR PROPULSION IN THE MILITARY

As things stand right now, it is very unlikely that, with the exception of Russia, nuclear propulsion would see any military use outside the navy. Evidence clearly suggests that all other countries are only interested in developing either nuclear-powered aircraft carriers, nuclear submarines or both.

However, it does not necessarily mean that it will always remain so. It is only fair to assume that, as Russia continues to develop (and eventually might even deploy) its "doomsday weapons", some militaries in the West might feel the pressure to follow a similar path. The fear of falling behind in this new arms race, coupled with the necessity to maintain a competitive edge against other strategic rivals, can force some of the militaries to reassess the potential utility of nuclear propulsion for vehicles or weapon delivery systems.

Yet, before starting the commissioning of feasibility studies and delving too deep into the matter, it would be wise to examine the potential of this technology at a more general policy level. Granted, it is important to note that even such a broad analysis is no easy task. This is because one has to heavily rely on incomplete and speculative data, and do a lot of guesswork. As a result, any conclusions reached about the advantages and the disadvantages of nuclear propulsion should be taken with a hefty grain of salt. Still, based on the historical experience from the Cold War, the lessons (indirectly) learned from Russia's ongoing experiments with its "doomsday weapons", and some rough scientific estimates, it is possible to make at least a number of fairly educated guesses about what might and might not work, and why.

SEA

Out of all three military domains, sea has arguably the greatest potential of seeing nuclear propulsion being used much more frequently in the decades to home. This is not surprising, as some Western countries have hundreds if not thousands of accident-free reactor years under their belts, and nuclear submarines and aircraft carriers have long been the staple of their naval might. Also, unlike land vehicles or planes, warships – even as small and lightweight as corvettes or frigates – could be reasonably well suited to accommodate heavy nuclear reactors and their components.[XIV]

At first glance, the reasons for installing nuclear reactors on relatively small surface ships can seem rather compelling. First, nuclear propulsion could significantly expand their operational capabilities. For example, nuclear-powered aircraft carriers can go around 20 years without refuelling (though they still need to stop for water, food and other provisions), and, by some estimates, nuclear-powered ships can go about 50 percent faster than petroleum-fired ships of the same size.[37] Second, nuclear propulsion could play an important role in reducing the greenhouse gas (GHG) emissions of the navy. Unlike petroleum-fired engines, nuclear reactors produce electricity via fission rather than combustion. As a result, nuclear-powered ships would not produce

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[XIII] It is generally believed that Russia's existing nuclear arsenal is too large and too diversified to be successfully intercepted by the US missile defense system. At the same time, the current track record of US missile defence system against short- and medium-range ballistic missiles, not to mention ICBMs, does not inspire great confidence. See: Jeffrey Lewis and Shea Cotton, "The Global Missile Defense Race: Strong Test Records and Poor Operational Performance", Nuclear Threat Initiative, 16 September 2020, https://www.nti.org/analysis/articles/global-missile-defense-race-strong-test-records-and-poor-operational-performance/

[XIV] Icebreakers can also accommodate nuclear reactors. Thanks to global warming, the Arctic will increasingly become ice-free in the summer and it is likely that this area will become a geopolitical flashpoint by the mid-21st century. Yet, as it is the case with Russia's nuclear-powered icebreakers, these vessels would likely be owned by and operated by civilians, and, therefore, they will not be included in this analysis.

any GHGs while operating and could seriously decrease the navy's consumption of fossil fuels. This is particularly important as the bulk of the military's petroleum is used for operational purposes i.e. the actual use of planes, ships and land vehicles.[38] Last, but not least, nuclear propulsion could make the vessels more future proof. Nuclear reactors could allow surface ships to meet the energy demands of even the most power-hungry equipment, such as advanced radars, energy weapons and other high-tech systems, which otherwise could not be installed on smaller ships without some negative trade-offs.

While all this sounds great, there are also major drawbacks to deploying nuclear reactors on some of the smaller surface ships. By far the greatest problem is the price tag. Nuclear reactors are incredibly expensive to build, and, by most accounts, the life-cycle costs of a nuclear-powered ship are significantly higher than those of a petroleum-powered ship.[39] For example, a 2011 US Congress Budget Office study concluded that the acquisition-cost premium for a nuclear-powered destroyer type of warship, would be about €900 million per unit, and that for such ships to be cost-effective, oil prices should over time increase to well over €200 per barrel.[40] While in other countries the construction costs might somewhat differ, given the soaring costs of nuclear technologies, there are no doubts that the acquisition-cost premiums of nuclear-powered vessels are still very great.[41] Therefore, even if the development of small modular nuclear reactors (or similar technological advances) could trim the average reactor costs by a considerable margin, it is still unclear if it would make much sense to install nuclear reactors on warships other than very large and heavy ones.[XV]

Then there is also the issue of nuclear waste. If, hypothetically speaking, over the coming decades we would see a development surge of hundreds of new nuclear warships, then, at some point, there would be a lot of nuclear waste in the form of spent fuel and contaminated equipment[XVI] This would seriously aggravate the existing problem of the global nuclear spent fuel stockpile, which, according to the Stimson Centre, a US think-tank, currently totals some 400,000 tons (and is poised to grow some 11,000 tons annually).[42] Also, more vessels would eventually have to be retired and undergo a time-consuming and costly decommissioning process, thereby further reducing their economic appeal. The decommissioning of a nuclear-powered vessel can take up to a couple of decades, and, according to some estimates, it could cost more than €100 million to scrap a single nuclear submarine.[43]

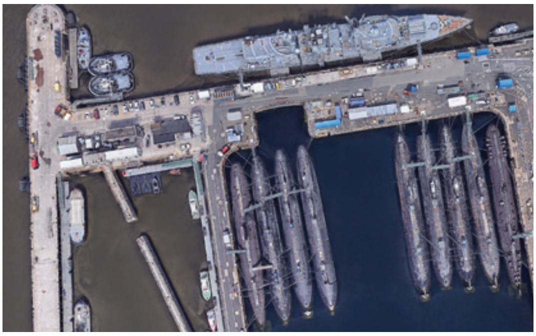

Figure 7. Retired nuclear submarines await decommissioning at Plymouth, United Kingdom.[G]

Nuclear-powered torpedoes or unmanned underwater vehicles, however one puts it, like the Russian-built *Poseidon* is also a technology that is worth to be mentioned. However, it should be viewed as an example of what should not be done for several reasons.

Despite the seemingly impressive features of torpedoes like the *Poseidon* (near-unlimited range, stealth, etc.), the military utility of such water vehicles would actually be pretty low. To begin with, even at 70 knot speeds (the presumed top speed of *Poseidon*), it would likely take up to a day or more before a torpedo could reach the shores of a strategic rival, if launched from Western coastal waters.[44] By contrast, it would take an ICBM like the *Minuteman III* under an

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[XV] By some estimates, petroleum-powered submarines and aircraft carriers are significantly more expensive to build and operate than their nuclear-powered counterparts. However, it is generally believed that nuclear-powered submarines and aircraft carriers have a clear strategic and operational advantage over non-nuclear ones, which justifies their costs.

[XVI] The average lifespan of a nuclear submarine is some 20-30 years.

hour to reach a major target of a strategic rival, if launched from the US mainland. In addition, because a nuclear-powered torpedo would likely be faster than a regular torpedo, it would create more noise and could likely be easier detected by sonars.[45] Though this does not mean that these torpedoes could be easier to intercept, it does mean that the country that is being targeted could make timely adjustments to their second strike capabilities. Ultimately, there is little sense in resorting to the use of underwater nuclear bombs to shower radioactive waste upon coastal towns or naval facilities. Such wanton destruction and killing of (mostly) civilians not only rests on dubious morality, but also is unlikely to achieve any strategic objectives, which could not otherwise be met without crossing the nuclear threshold.

AIR

The idea of nuclear-powered flight has long been a dream for aircraft enthusiasts and military planners alike. And rightly so. In theory, the atom holds the promise of unlimited flight, which would allow planes to circle the globe and operate without refuelling for days, weeks, if not more. Moreover, such planes would not emit any GHG emissions, which would help the military to slash its reliance on fossil fuels.

Yet, this is where the advantages end and the problems with nuclear-powered airplanes begin. Just as it was the case some sixty years ago, the issue of reactor shielding remains the main reason why these planes are not going to fly anytime soon, if ever. Nuclear fission reactors emit high amounts of radiation (alpha, beta, gamma and neutron), which can relatively easily go through less dense materials and might pose a threat to the airplane crew. Therefore, nuclear reactor designers have to use large amounts of dense (and usually very heavy) materials such as steel, lead, concrete, cadmium or tungsten (or a combination of them) to block the radioactive rays. By contrast, in order to be able to take off, airplanes have to be as light as possible. All of this means that planes with adequate reactor shielding would either become too heavy to fly, or, if the shielding would be somewhat thinner, the crew would be at risk of being exposed to dangerous levels of radiation, especially if there would be a reactor malfunction.

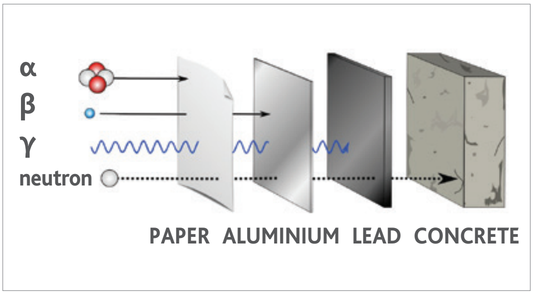

Figure 8. Penetration power of different types of radiation.[H]

Moreover, if, theoretically speaking, due to some breakthroughs in reactor shielding technology it would be possible to safely install a nuclear reactor on an airplane, it is still rather unlikely that such a plane would be ever approved to leave the testing grounds. Even if the odds of plane accidents are quite low, it is almost certain that no nuclear reactor shielding would survive a fall from a cruising altitude of some 10 kilometres and a head-on collision with the ground. This means that virtually every single nuclear airplane accident, however infrequent, would result in a mini-Chernobyl disaster, which would spew large amounts of radioactive materials across of the crash site. Considering that nearly every airplane crash would result in a nuclear catastrophe, it is also rather inconceivable that any government would allow such an airplane to get anywhere near a place where it could be at risk of being shot down.

Now, some may argue that in this day and age it is no longer necessary to have people on board of a nuclear-powered aircraft, and that such vehicles could easily be controlled from a distance. This, by extension, would mean that it would be possible to reduce if not completely eliminate the need for heavy reactor shielding. While technically this may be true, it still would be a pretty bad idea to develop either nuclear-powered unmanned aerial vehicles (UAVs) or cruise missiles. There are plenty of reasons for this, but one of the most obvious is that it is rather unlikely that any democratic government, nuclear regulator, international body or the public at large would be willing to accept the idea of nuclear reactors whizzing over or even anywhere near any populated areas. For instance, it is worth mentioning that, according to media reports, in 2012, a US research facility seemed interested in exploring the prospects of nuclear-powered UAVs. These UAVs would have reportedly been developed by Sandia National Laboratories and the defence contractor Northrop Grumman. However, the whole idea of nuclear-powered UAVs was extremely short-lived because it was nearly immediately shut down due to worries that public opinion would not accept the idea of such a potentially hazardous technology.[46]

Moreover, in the unlikely event that the military would somehow get a go-ahead from the government to proceed with the development of a nuclear-powered UAV or a cruise missile, it still would be incredibly dangerous and irresponsible — even in a test environment — to send a virtually unshielded nuclear reactor into the air. In fact, back in August 2019, five Russian nuclear scientists were killed due to likely radiation poisoning during a failed test of the *Burevestnik* missile at the Nenoksa testing facility.[47]

Finally, if a UAV or, more likely, a nuclear-powered cruise missile would rely on a ramjet engine for thrust, there is the very real risk that it would spew radioactive exhaust wherever it goes and endanger everyone and everything in its path. This is one of the main reasons why the US's *Project Pluto* was abandoned in the 1960s and the probably the primary explanation why no one in the West wanted to continue work on nuclear-powered cruise missiles ever since. Besides, this explains why the *Burevestnik* missile, which presumably uses a ramjet engine, has frequently been referred to as a "flying Chernobyl" by Western and Russian media alike.[48]

LAND

While at first glance, the prospects of near unlimited range and zero GHG emissions might pique some interest in the development of nuclear-powered land vehicles (either transport or combat), it would generally be unwise to pin any greater hopes on this technology. The reasons for that are legion, but for all intents and purposes, they could be boiled down to three basic categories: safety, security and economics.

First and foremost, the idea of installing nuclear reactors on land vehicles is a pretty risky one. Even if, in the extremely unlikely event, engineers would somehow manage to squeeze a nuclear reactor into a Unimog truck or a Humvee, it would still be rather dangerous to have these vehicles on the roads, hurling at speeds of around 100 kilometres per hour. More likely than not, a head-on collision with another vehicle or some static object would obliterate the (presumably thin) reactor shielding and spread nuclear waste. On top of that, as it would be the case with nuclear airplane crashes, there is the likelihood that such a vehicle accident could cause a criticality event (basically an uncontrolled nuclear fission chain reaction within the reactor), which could kill everyone that has not been directly involved in the collision, and shower the area in deadly radiation. Similarly, it goes without saying that it would be an even worse idea to install a nuclear reactor on a battle tank or some other vehicle, which could be exposed to enemy fire. In the event that such a vehicle would suffer critical damage, it is fairly likely that its reactor would quickly become unsta-

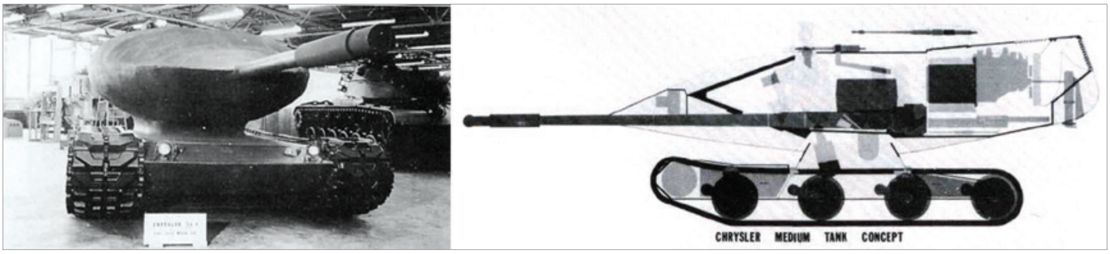

Figure 9. The Chrysler TV-8 was supposed to be world's first nuclear-powered tank. Predictably, it did not go beyond the drawing-board stage.[I]

ble and engulf the whole area in a cloud of nuclear waste, killing friend and foe alike, and contaminating the land for decades if not centuries to come.

Furthermore, a nuclear-powered land vehicle could be a serious nuclear proliferation liability. From a security perspective, it is vastly more difficult to protect a small and moving vehicle than a large, well-protected nuclear power plant or a 100,000 ton nuclear aircraft carrier, closely guarded by an entire carrier battle group that may include fighter aircraft, frigates, destroyers, anti-submarine and anti-aircraft ships. Therefore, if a nuclear-powered land vehicle would somehow end up being captured by a terrorist organisation or a pariah state, then they could use the radioactive fuel from the reactor for the construction of a "dirty bomb". Alternatively, there is also the theoretical possibility that the adversaries could convert some of the captured nuclear reactors from the land vehicles into fast breeder reactors, which could then be used to produce weapons-grade fissile material.[49] Granted, the likelihood of such an event is very slim as not that many countries (not to mention non-state actors) have the technological know-how for such a conversion. Yet, there is still the risk that a stolen nuclear reactor could one way or the other inadvertently contribute to nuclear proliferation.

Ultimately, nuclear-powered land vehicles would make even less economic sense than small surface ships. While it is unclear if it would even be possible to install a miniaturized nuclear reactor on a truck or a battle tank, the costs of such a vehicle would be astronomical. Even in the most optimistic scenario, it is reasonable to assume that it would cost tens of millions of euros to fit a nuclear reactor into a truck or a tank (the economics of adding a nuclear reactor on a light transport vehicle like a Humvee do not even warrant consideration). By contrast, the most expensive main battle tank in the world, the South Korean *K2 Black Panther*, carries a price tag of around €7 million, and the one of the most expensive military trucks, the German-built *Man HX81*, costs some €1 million.[50] All of this means that with existing technology it is almost inconceivable to come up with a scenario where it would be cost-effective to install a nuclear reactor on a land vehicle.

On the whole, nuclear propulsion seems to offer rather interesting opportunities for the military across the sea, air and land domains. However, the keyword here is "interesting". While it impossible to deny that nuclear reactors might offer some theoretical advantages over conventional combustion engines, in most cases, the cons far outweigh the pros. Nuclear reactors are extremely expensive to build and maintain, they could become serious security liabilities if not handled carefully and they would also result in a lot of radioactive waste that would have to be dealt with.

CONCLUSION

The splitting of the atom and the dawn of nuclear propulsion were arguably some of the most important military technological developments of the 20th century. They gave rise to nuclear submarines that can navigate the oceans without refuelling for months and those mammoth-sized nuclear aircraft carriers that have become almost mystical symbols of naval strength. Owing to their immense success at revolutionizing naval warfare, it is unsurprising that there had also been attempts to develop nuclear-powered missiles and planes. These, it was believed, could also have a game-changing effect on the Cold War balance of power.

Much has changed since the first experiments with nuclear propulsion took place, and, thanks to a number of technological advances, hitherto science fiction-like ideas like nuclear-powered flight are not as impossible as they were before. After all, some fifty or sixty years ago it was almost inconceivable that it would be possible to control an aircraft from the safe confines of a military base thousands of kilometres away. However, this does not mean that it would be wise for Western militaries to re-visit some of these Cold War-esque ideas or emulate countries like Russia by developing exotic weapon delivery systems like the *Burevestnik* or *Poseidon*.

In general terms, there are hardly any good reasons why nuclear reactors should be installed on mobile military equipment, other than submarines, large warships or aircraft carriers. There are some merits to the arguments that nuclear propulsion could significantly reduce the military's acute reliance on fossil fuels, cut its greenhouse gas emissions, and offer some operational advantages. However, the benefits are clearly outweighed by the drawbacks.

In terms of naval capabilities, nuclear-powered ships tend to have much greater lifecycle costs than those with combustion engines and, over time, they also produce significant amounts of nuclear waste. Meanwhile, nuclear-powered torpedoes are unlikely to bring any operational advantages that would justify their costs. When it comes to aircraft or missiles the situation is even more lopsided. Nuclear-powered airplanes are not only difficult (if not impossible) to build, and would be too dangerous to operate. Moreover, nuclear-powered cruise missiles are not only way too risky to be developed, but it is also unclear if they would provide any significant advantages over existing missile systems, ballistic or otherwise. Finally, nuclear-powered land vehicles would pretty much always be a terrible idea. Not only would they create more problems than solve, could contribute to nuclear proliferation, but they also would make zero economic sense.

There are perfectly good reasons why Western researchers have long abandoned plans for exotic nuclear-powered vehicles or weapon delivery systems and have never looked back. Briefly put: nuclear fission is a dangerous and unstable process, if not handled properly, and it is generally always a bad idea to install fragile nuclear reactors — which emit copious amounts of radiation — on equipment that may crash into a wall or would be flung into the air with minimal protection. Therefore, Western militaries should not be swayed by Russia's development of its "doomsday weapons", or any calls from external observers to mirror its moves, as these weapon delivery systems would likely prove to be greater liabilities than assets.

Instead, Moscow's current posturing should be understood for what it really is: a desperate attempt to cling to the past and its great power status, a bid to impress domestic audiences and a general inability to adjust to the realities of the post-Cold War era.

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[H] “Penetrating power of different types of radiation - alpha, beta, gamma and neutrons”, Wikipedia Commons, 26 February 2017, https://commons.wikimedia.org/wiki/File:Penetrating_power_of_different_types_of_radiation_-_alpha,_beta,_gamma_and_neutrons.svg

[I] “Chrysler TV-8”, Wikipedia Commons , 21 January 2017, https://en.wikipedia.org/wiki/File:Chrysler_TV-8.jpg

Connecting production facilities and transport infrastructure for creating robust and carbon-neutral sector-integrated energy systems

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

INTRODUCTION

Energy security of nations is a precondition for developing economic wealth and maintaining political power. As a means of international politics it is becoming increasingly important. Also, there is a growing political consensus that humanity must steer towards a carbon neutral future by shifting from fossil carbon-based fuels to renewable sources of energy. However, the pathways for such a transition are highly debated. An often overlooked problem in this global transformation process is the need to create completely new infrastructures, not only for renewable power generation, but for energy storage, transport and distribution beyond national boundaries and continents. Such new structures will dramatically re-arrange the political and economic importance of many nations, as well as their ability to generate revenues from energy production.

The three largest energy consuming sectors are power generation, transportation and heating/cooling. Currently the sectors are mostly separated, resulting in higher costs and pollution. For example the heat from electricity production is seldom used for district heating systems. Enhancing the transfer of energy and energy related by-products within these sectors is called "sector integration" and is widely discussed as one of the solutions to the climate crisis. This article discusses new components and intercon-


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nections of energy consuming and producing sectors to create a robust energy system. Its security and resilience will be increased by multiple and technologically different production processes.

All this will come with higher energy costs, as economies of scale are missing or starting with a time lag, especially in the early stages of the transition. The measures to be taken will take decades and require huge financial investments. However, the environmental and human costs of the climate crisis with all its consequence are expected to be higher than that. A new energy system should be robust in terms of disruptions of any kind, renewable in terms of not emitting CO_2 and sector integrated in terms of using synergy effects across all possible applications. Implemented wisely, this new energy system may contribute to a more equal global distribution of wealth and, therefore, may stabilise societies globally.

PERCEPTION CHANGES IN ENERGY SECURITY

The security of an uninterrupted and affordable energy supply was for a long time taken for granted by industrialized nations. The first concerns regarding the availability of - at that time almost exclusively fossil energy - were caused by the international oil shortages in 1973 and 1979/80 when geopolitical disruptions resulted in supply problems and two global oil price shocks.[1] Surprisingly, in the aftermath of these events most industrial nations did not take any serious actions to reduce the dependency from fossil fuels, especially for their transportation and heating sectors. Energy security as a means of international politics was “off the radar” because strategic alliances with oil producing countries were well established and the shale oil boom and new fracking technologies in North America led to lower oil prices. Since then, the political situation for Western nations changed dramatically due increasing conflicts in many oil producing regions of the Middle East and North Africa, rising tensions with Russia and the disruptive politics of the new economic powerhouse of the People’s Republic of China.

GROWING ENVIRONMENTAL CONCERNS

In addition, growing political concern among parts of the general public in North America, Europe as well as a number of Asian countries have increasingly pressured governments to address the environmental and climate problems caused by the burning of fossil fuels. Rapid reduction of global carbon emissions is not only demanded by organisations like *Fridays for Future or Greenpeace*, but also by most political and economic stakeholders of industrial nations.[2] This resulted in the United Nations’ effort in 2015 for a legally binding international treaty on climate change. The treaty was adopted by 196 countries at the COP 21 conference in Paris in 2015 and entered into force on the 4th of November 2016. Its goal is to limit global warming to well below 2.0 and preferably to 1.5 degrees Celsius, compared to pre-industrial levels, primarily by significantly reducing fossil carbon emissions. Ambitious goals for carbon emission reduction were declared by individual nations of the Western world, most notably by the European Union members, who unveiled the “Green Deal” package. This policy plan provided a comprehensive and detailed action plan how the EU can become fully carbon neutral by 2050.[3]

NEW ENERGY INFRASTRUCTURES

Internationally the political consensus is growing that humanity must steer towards a carbon neutral future by shifting from fossil carbon-based fuels to renewable and whenever possible even carbon free energies. However, the technological pathways and ecologically sound solutions for such a transition, as well as the type of renewable energy resources used to achieve a carbon neutral energy sector, are highly debated. Focussing on more wind-, solar- and geothermal energy resources will inevitably change the geopolitical and economic significance of many nations. An often overlooked problem in this debate is the need to create completely new infrastructures, not only for renewable power generation, but for storage, transport and distribution of energy beyond national boundaries and continents. Such new structures will dramatically re-arrange the relative geostrategic importance of many nations and will impact their ability for generating revenues from energy production and transport. Thus, over the coming years, it will become a crucial task for industrialized nations to invest in new technologies and infrastructure projects in order to become reliable energy producing partners.

INTEGRATING THE ENERGY SECTORS

Globally, the three largest energy consuming sectors are power generation, transportation and heating/cooling, which usually depend on often very long energy and material supply routes (pipelines, shipping, trucking). The three sectors still heavily rely on fossil fuels and only on rare occasions exchange energy with each other. The enhancement of the transfer of energy and energy related by-products within these sectors is called "sector integration". It is widely considered as one of the solutions to the climate crisis, as sector integration has the potential to (1) reduce greenhouse gas (GHG) emissions, (2) reduce long term energy costs and (3) increase energy supply security. For example, in a combined electric power and heat generation plant, the fuel is used for both producing electric power for the grid and heat for district heating systems.

The usage of surplus electricity from renewable power plants is regarded as a key element for sector integration and for the creation of an energy supply completely fed by renewable power plants. Surplus electricity occurs when renewable power plants produce electricity, which is neither instantly demanded nor stored. In windfarms this leads to intentional idling of wind generators and in solar parks to intentional shorting of the arrays, both resulting in a reduction of the economic (reduced working hours) and ecological gains (fossil powered plants will produce cover the demand). However, such excess power could be used in district heating systems.[4] Other options include the conversion of electric energy into storable hydrogen by electrolysis of water or into ammonia (NH_3) by using N_2 and the Haber-Bosch process.[5] Yet another alternative could be the production of carbon based synthetic fuels from H_2 and a carbon source.[6] The potential for pumped storage in hydro power stations is limited and further expansion generally meets strong opposition from environmentalists and the society at large.[7] Overviews of renewable energy technologies and challenges involved can be found in recent issues of "Energy Highlights" for H_2 producing technologies, carbon based synthetic fuels and nitrogen based fuels.[8]

CREATING ROBUST SECTOR-INTEGRATED RENEWABLE ENERGY SYSTEMS

This article will provide an overview of the infrastructure demands for creating a robust sector integrated renewable energy system and the expected costs. The energy source of this system is electric power generated from renewable sources. The system analysis includes the costs of raw materials, production sites, and transmission of electricity and transport of energy products such as ammonia, methane and synthetic carbon-based fuels. We will look at alternative fuels as means of renewable energy conversion and storage in the form of hydrogen (H_2), ammonia (NH_3) or synthetic carbon-based fuels (synfuels). As a caveat, it has to be stated that all alternative fuels are currently much more expensive than fossil fuels. This is a major obstacle in convincing less technologically and financially endowed nations, as well as most producers of fossil fuels, to switch to carbon neutral or even carbon free technologies. In this paper we will use geographical Europe as a case study, because it is an industrial powerhouse with many components of a future energy system already existing or being planned. Other aspects like technological safety as well as physical security (e.g. kinetic attacks) and cyber security (e.g. hybrid warfare) are also important, but will not be part of the discussion in this article.

BUILDING BLOCKS OF A FUTURE SECTOR INTEGRATED ENERGY SYSTEM

A robust electricity system depends on a reliable and flexible energy supply, preferably from multiple and – if possible – technologically different sources. The necessary energy generation resilience requires also some degree of robustness and redundancy of production sites, intermediate storage and transmission/transport options. This inevitably increases the costs. Besides reliability and flexibility, carbon neutrality is a new and integral requirement for future sustainable energy generation from renewable sources. This can only be achieved if technologies for carbon capture are fully integrated into carbon-based energy generation processes or completely carbon free energy systems are installed. Carbon capture, as an integral part of the energy production process, will be discussed more in detail in the next chapter of this article.

Electricity has to be supplied to electric grids in real-time synchronisation with the demand. Any significant fluctuations in energy production lead to blackouts. While any intermediate storage of electricity is costly, various storage technologies are available: (1) electrically - in batteries, (2) physically - in pumped hydropower dams or kinetic flywheels, (3) chemically - in energy rich compounds e.g. in synthetic fuels. Hybrid systems like Redox flow-batteries are also available.[9] Due to its low energy storage/weight ratio, energy storage in batteries is limited in capacity as well as in spatial and temporal reach. Batteries are expensive in production, maintenance and recycling and require intensive use of rare earth metals. Only a few large battery arrays have been built so far in Australia and Japan.[10] A major battery storage project associated with a 215 turbine wind farm is to be built in Scotland by 2021. The battery storage site would have the size of half a football pitch.[11] Batteries are typically used for small-scale solutions i.e. for private households or small businesses. Physical storage can reproduce electricity on demand with minor energy losses. Pumped hydropower dams have the potential for long term storage but are only possible in a very limited set of geographic conditions. The construction of hydro dams has decreased in recent years because of the social and environmental damages they inflict. Flywheel storage is used to stabilise the power supply fluctuations from renewable power plants in time scales of hours, but long term storage has not yet been achieved.[12]

Currently, the most promising solution for large scale energy storage is chemical storage, which is possible by generating H_2, NH_3 or carbon-based synthetic fuels (though other options also exist). The electricity demand for the production of these fuels increases from H_2 and NH_3 to carbon-based gases and liquid fuels. An additional advantage of such synthetic fuels is the relative ease of adapting existing and proven technologies for their transport, storage and use.[13] Nevertheless, all alternative fuels are currently significantly more expensive than fossil energy. This remains the major economical obstacle for implementing non-fossil carbon neutral and carbon free technologies.

The usage of electricity in a future sector integrated energy system should follow the principle of highest energy efficiency. A possible pathway is illustrated in Figure 1. Electricity from renewable power plants and CO_2 capture from secondary sources are the two resources. Electricity should be used directly throughout the sectors in order to obtain the best energy efficiency. The capture of CO_2, which is essential for obtaining carbon neutrality of all processes involving the production of carbon-based synfuels, is an energy intensive process. It should be primarily done by using highly enriched industrial sources (e.g. cement production, biogas plants, bioethanol production) and as a second option only from ambient air by direct air capture (DAC).[14] In the context of synfuel production carbon capture technology temporarily recycles CO_2, but does not remove it permanently from the atmosphere as it is released again by the combustion of the synfuel. In the context of sector coupling and energy production, any CO_2 capture is for the atmosphere a carbon neutral process only. CO_2 capture from fossil fuel burning plants is not discussed in this article, because fossil burning will be phased out in the coming decades in most industrialized countries. Some countries may lag behind this process because of the great abundance of cheap fossil fuels and the lack of funds for building up new plants.

Hydrogen is the least energy intensive product when converting electric power into an alternative fuel. It is also the chemical base compound for producing other alternative fuels. Hydrogen gas is produced by electrolysis of pure water and can be used in heating, mobility and power production.[15] Hydrogen and N_2 from ambient air are needed in NH_3 production in Haber-Bosch-plants.[16] Hydrogen and CO_2 is needed to produce carbon-based synfuels such as methanol (CH_3OH), methane (CH_4) and liquid fuels for internal combustion and jet engines like non-fossil diesel or aviation fuel types. All the fuels discussed - alternative as well as fossil based - are often difficult to handle and safety precautions have to be established. Hydrogen, methane, alcohols, and all fossil fuels are flammable or even explosive. While ammonia is not flammable it is still a potentially harmful substance. Base materials for production like carbon dioxide and nitrogen are chemically inert. However, carbon dioxide in higher concentrations is suffocating to humans.

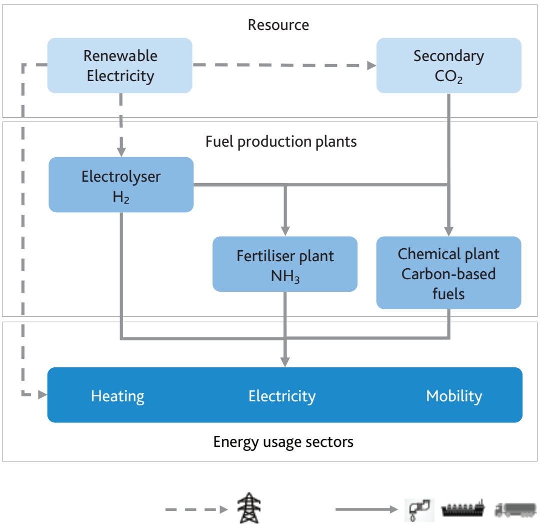

Figure 1: Components and possible pathways of a sector integrated renewable energy system for production of alternative fuels. Resources are electricity from renewable power plants and secondary CO_2. Fuel production plants are production facilities for H_2, NH_3 and synthetic carbon-based fuels (synfuels). Energy usage sectors include heating, electricity and mobility. Solid arrows = liquid or gaseous transport by pipeline, ship or truck. Dotted arrows = electric transmission lines.

A key element of a robust future sector integrated renewable energy system is an efficient and frictionless transport of energy from and to power productions sites, alternative fuel production plants, industrial customers and industrial as well as private customer fuel distribution networks. In the following chapter we will discuss several important resources and production plant options with respect to their main production processes and the site selection of the plants. In the last chapter, we will present and discuss the construction and maintenance costs of power transmission facilities and alternative fuel transport infrastructure.

RESOURCES AND PRODUCTION OF ALTERNATIVE FUELS

The production of most carbon neutral fuels from renewable energy as well as carbon capture technologies requires a carbon source of high purity and concentration. In a robust future energy system industrial sites may function as a source (by supplying CO_2 or energy) as well as a consumer (by using H_2 for heating purposes or as a feedstock for chemical synthesis). In this chapter three examples of renewable energy and raw material sector coupling are presented. First, the cement industry is globally a huge carbon emitter and may become a CO_2 source for the production of carbon-based synthetic fuels and a H_2 consumer for heating purposes. Second, the fertilizer industry uses large amounts of H_2 for the production of ammonia. In the case of a downstream urea production plant, carbon dioxide is needed and can be supplied from secondary sources. Fertilizer plants could increase their production of NH_3, which will be used as a carbon free fuel. Third, conventional oil refineries may become important facilities for the future purification of the mixtures of organic components retrieved from Fischer-Tropsch-synthesis of carbon-based synfuels.

CEMENT INDUSTRY AS BASE MATERIAL PROVIDER FOR SYNFUEL PRODUCTION

The magnitude of global cement production and associated CO_2 emissions is enormous: if the global cement industry would be concentrated in one single country, it would be the third largest CO_2 emitter worldwide.[17] Cement producing plants are located on all continents (Figure 2) and the amount of the emissions is closely related to construction activities. Hardened cement contains 58–66 % of calcium hydroxide ($Ca(OH)_2$) and is obtained from heating limestone ($CaCO_3$)

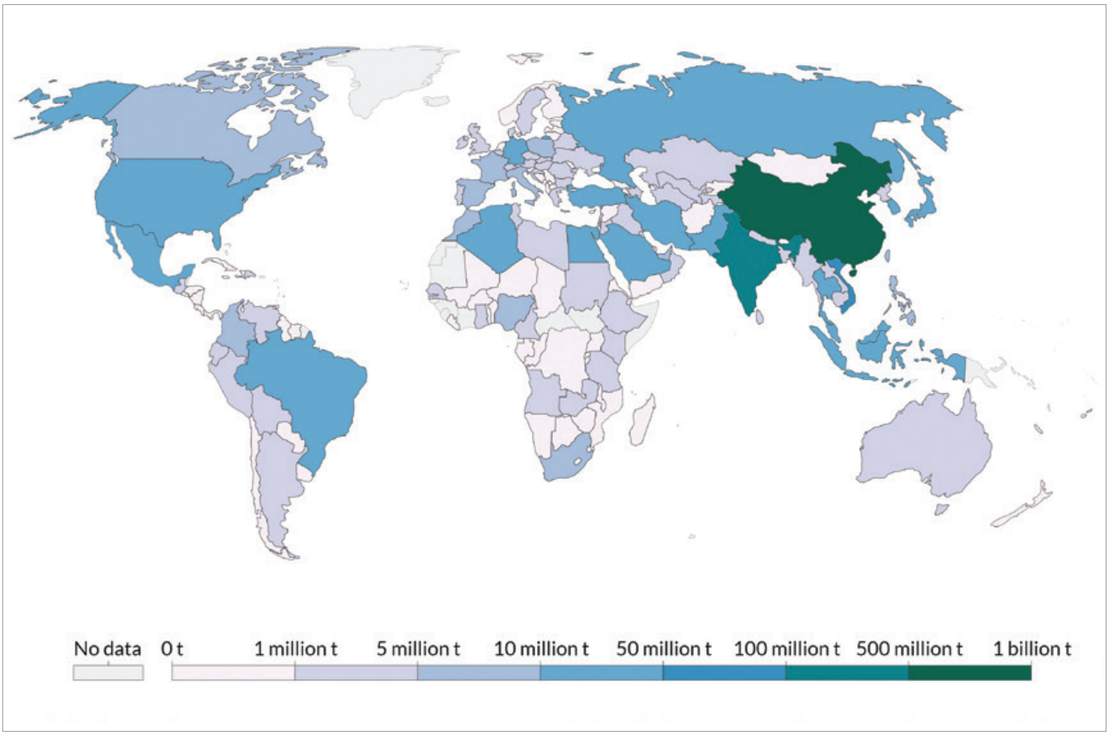

Figure 2: Global CO_2 emissions from cement production in 2018.[19]

at high temperature (>1 000 °C) while releasing large amounts of CO_2. The heat is normally provided by fossil fuels and therefore additional CO_2 is emitted during cement production.[18]

The limestone needed for cement production is mined in quarries. Therefore, cement producing plants are generally located in close proximity to these deposits to reduce the transportation costs of the bulky and heavy raw material.[20] This is shown in Figure 3 using Germany as an example.[21]

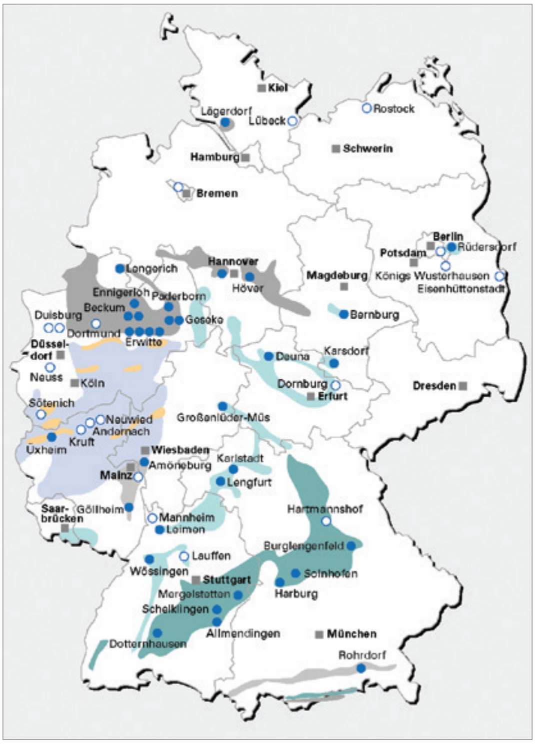

Figure 3: Location of raw material deposits and cement plants in Germany. Deposits are marked in areas of light grey = Tertiary, dark grey = Cretaceous, dark blue = Jurassic, middle blue = Middle Trias, light blue = Devonian, light yellow = compact limestone. Cement plants are marked in blue dots = plant with cement clinker production and withe dots = plants without cement clinker production. Cement clinker is a limestone based stone while bricks are clay based stones.[22]

Several pilot projects have been started to capture the CO_2 emissions from the production process as well as using H_2 as a heating material. Cement plants supply cheap CO_2, as it is highly enriched in the waste gas. Usable industrial waste heat is not produced, as it is already used for the pre-heating of the raw material.[23]

FERTILIZER INDUSTRY AND N-FUEL PRODUCTION

Ammonia is a globally used commodity in agriculture, the chemical and the cooling industry.[24] The global fertilizer production in 2014 was approx. 113 x 10^6 tonnes. The production, transportation and distribution capacities and handling know-how exists on all continents (Figure 4).[25] Countries with large agricultural sectors typically have high levels of production.

The production of NH_3 via the Haber-Bosch process requires H_2 and N_2.[27] Industrial ammonia production plants may use compressed ambient air (78% N_2 content) or for generating high purity N_2 via air separation technology.[28] For H_2 as source material several options are available: (1) Typically H_2 is produced by steam reforming of fossil fuels at Haber-Bosch plants, releasing huge amounts of CO_2. However, only when the NH_3 is further processed into urea, the CO_2 is used in the production process.[29] (2) H_2 production from the electrolysis of water is currently used in countries with large amounts of cheap electricity.[30] However, both production pathways mentioned above are very cost intensive. A third and promising option might be (3), the usage of waste H_2 from industrial chemical production. In the Netherlands waste H_2 from a "Dow Benelux" production plant is transported to the fertiliser production plant of "Yara" because "Dow Benelux" has no usage for the waste H_2.[31]

All major European countries produce nitrogen-containing fertilisers.[32] The required increase of nitrogen output for alternative fuel production should be easily manageable, as existing plants may simply increase their production capacity

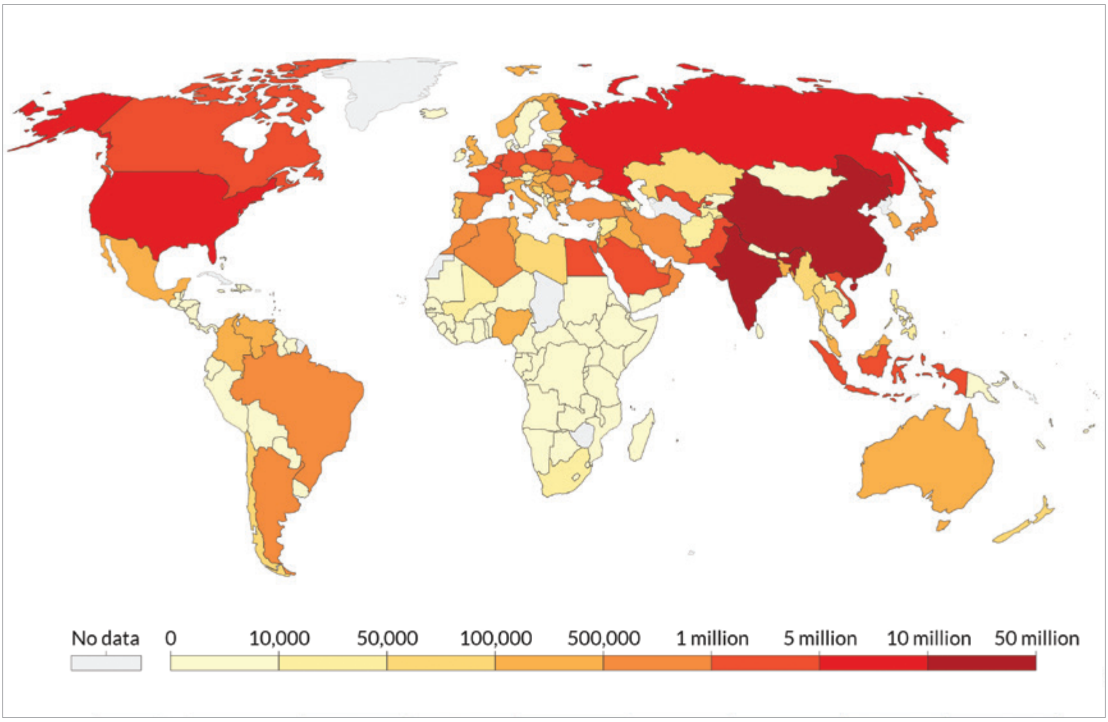

Figure 4: Global nitrogen fertilizer production in 2014 by countries. A total of 113.31 * 10^6 tonnes was produced worldwide.[26]

and no limitations with respect to availability of the raw materials, technological know-how and trained personnel exist globally.

OIL REFINERIES FOR PURIFYING SYNTHETIC CARBON-BASED FUEL MIXTURES

Crude oil has to be processed and upgraded in refineries in order to be used as base material or energy source. Refineries are normally located in close proximity to the oil fields or along transport routes like pipelines or shipping terminals. Separate pipelines, ships and shipping terminals for crude and refined products are also in use. A good example of a refined product transport structure is the Central European Pipeline System (CEPS), which is operated by NATO in Europe.[33] While crude oil and its refined products for energy generation will be eventually replaced by renewable energies, the fossil carbon itself may remain an important base material for the chemical industry for quite some time. It is important to note that the entire existing refinery infrastructure can be easily used or modified to accommodate non-fossil based processes and constitutes an important asset in future efforts for sector coupling.

Chemical syntheses – such as the Fischer-Tropsch synthesis for producing synfuels – produce a mixture of components. Generally, these mixtures are not fit for further use and have to be purified. In the case of synfuels the required process is a fractionated distillation similar to the one performed for crude oil. Existing crude oil refineries are huge industrial complexes. The main and also the largest components are the towers for fractionated distillation. Depending on the boiling point, several fractions are differentiated: at ambient air pressure these are (1) liquefied petroleum gas (<20 °C, ambient air temperature), (2) petrol (20 - 150 °C), (3) Kerosene (150 - 200 °C), (4) Diesel (200 - 300 °C), (5) fuel oil (300 - 370 °C) and (6) residues containing lubricant oil, paraffin wax and asphalt (370 - 400 °C). All fractions are mixtures of several chemical components, which are determined by the origin of the oil. The main components are: (1) aliphatic saturated hydrocarbon (alkane), (2) cyclic saturated hydrocarbons (naphthene) and (3) cyclic unsaturated hydrocarbons (aromatic hydrocarbons). Since chemically homogeneous products are needed for further use e.g. as petrol fuel, these are obtained by cracking (breaking down of longer chain alkanes to lower chain alkanes) and reforming (cyclising, dehydration and isomerisation of alkanes to naphthene and aromatic hydrocarbons).[34] Oil refineries often host both crackers and reformers. By the end of 2020, ninety oil refineries were operational in Europe with a capacity of 665 x 10^6 t per year.[35] Retrofitting these refineries for processing synfuels is possible.

The global oil company BP (formerly British Petroleum) announced in its recent mission statement the goal to transform itself into a green-energy supplier.[36] It can be assumed, that other oil companies will follow the lead of BP in the coming years and that the existing infrastructure of pipelines, ships and refineries may be re-fitted for synfuel refining and transportation.

Electrolyser, synfuel plants and DAC production sites are not discussed here, as they have no specific placement demands and have to be newly built anyways. Strategic transport considerations should define the decision process for their construction and location.

SECTOR INTEGRATION

Sector integration is generally deemed essential for tackling the global climate crisis. In the energy systems to come, electricity will play a key role. The production costs of electricity from renewable power plants commissioned in 2018 are lower than from fossil or nuclear plant commissioned during the same period. Considerable further reductions in production costs are predicted for the years and decades to come, with higher cost reduction effects for renewable technologies than for fossil and nuclear power plants.[37] Electricity will become a low price commodity, while the energy storage problem for providing a stable supply still needs to be solved. Long range transport and the production of alternative fuels may soon become economically feasible under these circumstances. A robust renewable energy system must have reserves in terms of capacity as well as various options for fuel usage and for long distance electricity and fuel transport.

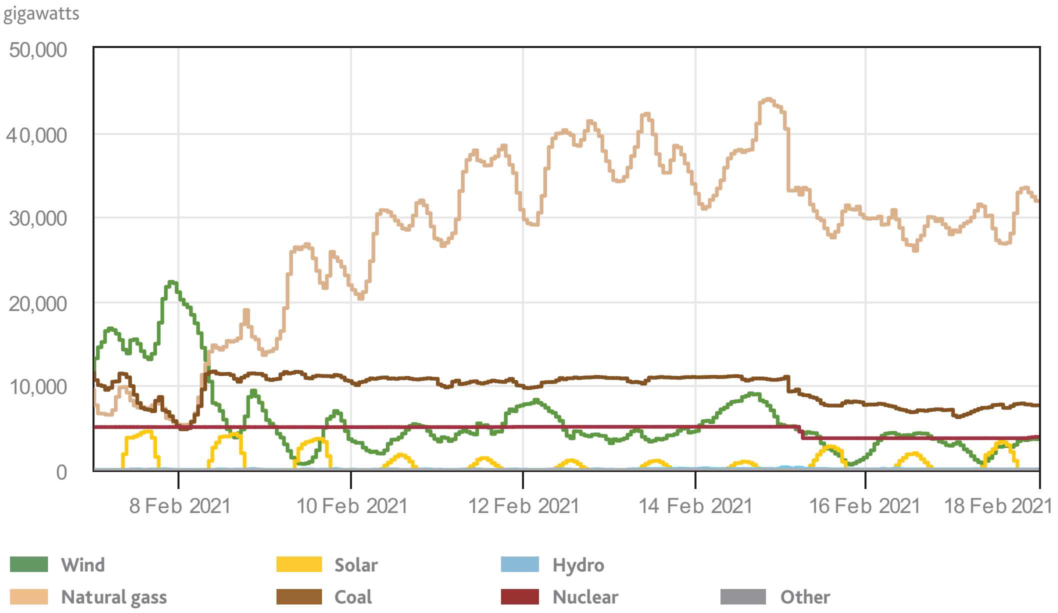

Figure 5: Hourly net power generation in Texas, USA by energy source [GW] from Sunday, 7th of February until Wednesday 17th of February 2021. Harsh winter conditions started on 7th of February and caused non-frost-proof wind rotors to freeze up. Natural gas and coal power plants had to step up their production n to compensate for the failure of wind and solar. From 14th of February on even gas, nuclear and coal power plants dropped in energy production due to failures caused by severe cold climate.[39]

Energy systems which are primarily based on electricity must be designed in a robust and resilient manner. A recent example for the failure of an energy system due to inappropriate design assumptions was a large scale power outage in February 2021 in Texas, USA. It caused the largest insurance damage in the history of Texas, even larger than the damages caused by hurricane Harvey in 2017 and even 47 fatalities. An unusual cold and long lasting weather situation caused not only renewable but also fossil and nuclear power production facilities to fail (Figure 5). At the same time about 16 GW of electricity could not be covered by renewable power plants (mainly wind turbines). Texas covers about 20 % of its power demand from renewable sources, mainly wind. Wind turbines in cold regions are self-defrosting. The power providers in Texas however, had decided not to install such safeguard mechanisms to keep costs low. 30 GW power production capacity from fossil and nuclear plants were also lost, mostly because of frozen pipelines and valves in the natural gas and water system. One block of the South Texas Nuclear Power Station had to be shut down because of failing water supply for cooling. While energy production dropped dramatically, consumers demanded more power than usual for heating, which could not be provided within the closed power grid of Texas. To prevent the power grid of Texas from collapsing entirely, the grid managers had to deliberately disconnect whole regions from the power supply. Power providers in Texas are not bound to provide emergency capacities. In Texas the electricity grid is almost entirely isolated from the rest of the US power grid due to mutual political decisions. The weather conditions in the coming years will be more unpredictable than in the past and consequently, historical records are not usable for predictions of future extreme weather events.[38]

Future robust and resilient energy systems must be able to cope with ever more severe and unpredictable weather events. An interconnected system of small- or medium seized decentralised plants is always more stable than large single plants with equal capacity. The innovative interconnection of production and consumption sites as well as the transportation/transmission of input materials, electricity and finished products is a key element of such a system. A possible scheme is shown in Figure 6 and explained in the following.

Electricity base load settings are characterised by a reliable, predictable and controllable power supply and should cover base load demands. The produced power is directly fed into the power grid for immediate consumption. Currently power plants that run on biomass, deep geothermal heat, hydropower dams and solar parabolic trough setups do meet these requirements. Vast and untapped renewable electricity production possibilities from deep geothermal heat and buffered by hydropower dams are e.g. available in Iceland. A deep sea cable between Iceland and Scotland was repeatedly discussed in the past years, but it was never build because of cheap electricity supply from fossil sources.[40]

Solar and wind power plants have unpredictable and thus unreliable production properties. Therefore, such power should be fed into the electricity grid with first priority in higher than base load situations. The then still available surplus power should be used with the following priority: (1) physical storage in pumped hydropower dams, (2) alternative fuel production, and (3) district-heating systems.

The minimum power supply needed for the operation of chemical storage production plants should be generated by renewable power plants exclusively built for this purpose. Otherwise, the minimum of 4 000 FLH (Full Load Hours) for cost effective production cannot be guaranteed. The variable surplus power from "grid supplying" renewable power plants could be used in addition.

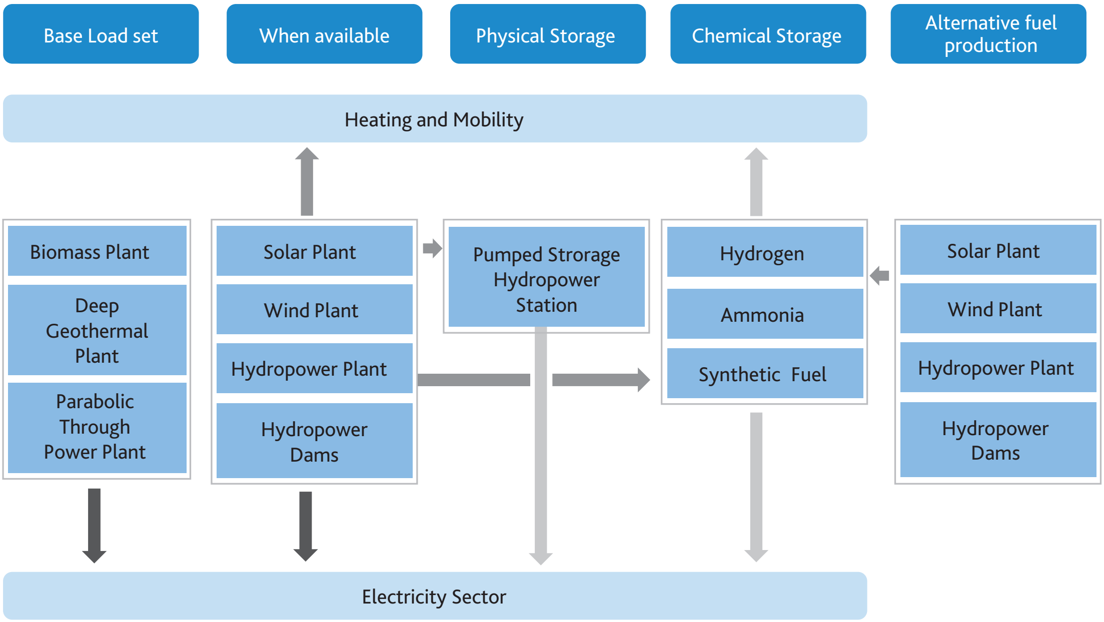

Figure 6: A robust and resilient sector integrated electricity system may consist of: (a) "Base load sets" which are able to run without interruptions to meet the demands of the base load. (b) "When available" plants with unpredictable production. (c) "Physical" storage and (d) "Chemical storage" (e) "When available" plants with unpredictable production like (b) which were built solely to supply alternative fuel production plants. Dark grey arrows: Direct use of electricity. Grey arrows: Excess electricity from unpredictable sources feed into physical or chemical storages. Light grey arrows: Electricity or fuels fed into the energy system.

Both power supplies combined increase the degree of capacity utilisation of the alternative fuel plants.

It must be stated again, that the direct usage of electricity for appliances, motors or heating is economically and environmentally much more sensible than any kind of alternative fuel production and subsequent on-demand re-conversion into electricity in power plants. Direct electric power usages should therefore be prioritised. Large scale electricity production from renewable sources in close proximity to the customer is in most cases not feasible because wind, solar and geothermal plants are typically located in remote areas. Therefore national, continental and intercontinental electricity grids are needed to make full use of regional variations in renewable power production. High Voltage Direct Current technology can fulfil this task and new transmission line projects like NordLink will be started in the future.[41] However, covering the entire future power demands with renewable electricity alone seems currently not possible. Alternative fuels will still be needed for terrestrial and air mobility and naval transportation. Whether the electric power is transported to alternative fuel production plants or the alternative fuel plants are located in close proximity to renewable power production sites, has to be decided on a case by case basis.

The most cost effective alternative fuel is H_2 from direct electrolysis of water. It can be produced in close proximity to renewable electricity plants. The electrolyser technology is well established, needs not much space and is constantly refined.[42] However, the purified water demand for electrolysis is considerable. As many projected solar and wind farms are planned to be built in arid and semiarid regions, a shortage of water or even competition for water resources between people and power plants might become a serious issue.[43] In these cases, electrolysers could be installed in water rich regions with long distance power transmission lines from renewable power plants.

Ammonia production requires H_2 and Haber-Bosch-process plants. The limitations for H_2 generation from electrolysis apply as described above. Enlarging existing NH_3 production capacities seem easily possible. However, H_2 pipeline connections may have to be built if H_2 is produced off-site. Currently, H_2 is produced by steam gas reformation which uses natural gas i.e. a fossil carbon source. Retrofitting of these pipelines is possible. The German plant manufacturer Thyssen Krupp already offers a small-scale hydrogen plant powered by solar electricity which produces H_2 generated from electrolysis.[44]

The production of mainly liquid synfuels is the most innovative and less mature process of all alternative fuels. It requires several technologies and production steps: (1) Electrolysers for H_2 production, (2) CO_2 capture technology from CO_2 rich waste gases or from DAC, (3) reverse water gas shift reaction for CO production from CO_2 and H_2 (which is not yet in a mature stage of development) and (4) Fischer-Tropsch or methanolisation reactors. Such complex plants require a huge amount of investments and well trained operators.

The generation of climate neutral carbon (by not using fossil fuels such as in steam gas reforming processes) as base material for synfuels only seems sensible as direct CO_2 capture from DAC or capture from industrial plants where carbon emissions cannot be avoided (e.g. during cement production). CO_2 capture from fossil fuel burning processes does not seem sensible, because the big scale emitters will phase out in the coming decades and small-scale emitters are too expensive to be retrofitted for carbon capture. Carbon dioxide emitted from large industrial sites could be best captured at the source, while the CO_2 emitted from small sources (e.g. domestic heating, agriculture and small industrial plants) has to be captured via DAC. It should be kept in mind that DAC facilities require huge amounts of space, water and energy, and therefore have to be built in rural areas with a sustainable water supply. Using sea water is also possible, but it has to be desalinated first.

CONCLUSIONS

At the moment the design and development of robust and resilient renewable energy systems is in its infancy. An important obstacle is the fact that the technological and market preferences for alternative fuels are not yet clear. Various possibilities are currently discussed or exist as pilot projects or are in a small scale development phase. Which technological options for power and fuel generation will dominate the energy system in the future is currently not predictable. With several alternative fuels available, the resilience of energy systems to disruptions is certainly increased. However, the benefit of enhanced robustness and resilience comes with an increased price tag on energy costs, as economies of scales are missing or starting with a time lag, especially in the early stages of the energy sector's transition from fossil to renewable energy.

In terms of energy security the following priorities for a robust and resilient renewable sector integrated energy system are suggested:

1. Enhancing electricity production from base load facilities such as deep geothermal plants to meet the base load demand.
2. Increase physical storage possibilities for peak demand like pumped hydropower dams.
3. Increase electricity grid connectivity for geographically levelling out peak supply and demand.
4. Feed surplus power into alternative fuel production facilities, i.e. DAC and Fischer-Tropsch plants.
5. Supply alternative fuel production facilities with sufficient power from renewable plants to ensure a minimum of 4 000 Full Load hours per year.
6. Build or re-purpose power generation plants for alternative fuels use for covering peak demand, i.e. convert gas power station for natural gas to synthetic methane.
7. Re-purpose coal power generation plants for alternative fuels for covering base load demand.

These measures will take decades and require huge financial investments to implement. However, the environmental costs of climate change with all its negative consequences on infrastructure and societies are expected to be much higher than that. Implemented wisely, renewable sector integrated energy systems may contribute to a more equal distribution of wealth and, therefore, have a stabilising effect on societies globally.

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Russia's climate change conundrum

by **Dr. Sijbren de Jong** and **Can Ögütcü**

INTRODUCTION

Climate change represents a multifaceted challenge for Russia. From an economic standpoint, reduced government revenues from energy exports, as experienced during the COVID-19 pandemic due to a gradual phasing out of fossil fuels, led to budgetary constraints. Then there is the risk of stranded infrastructural assets: vulnerable energy infrastructure in Russia's Arctic region risks being severely damaged and rendered economically useless due to melting permafost. Politically, climate change risks reducing its capacity to exert influence abroad as Moscow's status of a global "energy powerhouse" may fade. The erosion of this status means that Russia risks losing political leverage over major oil and gas consuming nations.

RUSSIA'S APPROACH TO CLIMATE CHANGE

Russia is the fourth largest emitter of greenhouse gas emissions worldwide.[1] In terms of industrial greenhouse gas emissions, the Russian Federation is also home to one of the world's most polluting companies: state-owned gas company Gazprom.[2] Russia has been a party to the Kyoto Protocol and ratified the Paris Climate Agreement.[3] In its National Determined Contribution, Moscow pledged a reduction in emissions of 70% below 1990s levels, taking in account the maximum possible absorptive capacity of forests and other ecosystems, and subject to sustainable and balanced social economic development of Russia.[1] Although sounding ambitious, the target has actually been widely criticised as it takes the final years

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of the Soviet Union as its baseline. In 1990, Soviet heavy industry was still producing at full speed. Following the USSR's collapse into individual countries, and with it the demise of large parts of Soviet-era heavy industry, it is comparatively easy for Russia today to commit to reducing greenhouse gas levels, knowing that these are a mere fraction of what they were in 1990 for the Soviet Union as a whole. According to Carbon Tracker, an international environmental non-governmental organisation, under Russia's current policies, and after the effects of the COVID-19-related economic slowdown are considered, Russia's emissions are projected to decline between 32 and 37% by 2030.[II] If various carbon sinks (anything that absorbs more carbon from the atmosphere than it releases, such as plants, the ocean etc.) are considered, Russia's emissions are expected to decline between 38 to 43% relative to 1990 levels.[4] In other words, under its existing pledges, Russia can expect to see its greenhouse gas emissions stay below what it emitted in 1990. It should not come as a surprise therefore that the Kremlin views this as a kind of free pass to pollute at will and clinch onto its status of a major hydrocarbon producer.

PRIORITISATION OF HYDROCARBONS

In its new Energy Strategy to 2035, Russia speaks of vastly expanding its domestic production and consumption of fossil fuels, strongly emphasising growth in natural gas exports through liquefied natural gas (LNG). Sustaining export revenues, whilst maintaining social stability through reigning in domestic prices are among the government's top priorities. The climate agenda is the last point that received attention and is the lowest in order of the Strategy's priorities, as Russia can easily meet its Paris Climate Agreement targets without resorting to major investments.[5] Despite its own marginal contribution, Russia routinely criticises other – chiefly Western – nations for their historic responsibility in the fight against climate change. The United States' (US) pullback from the Paris Agreement in November 2020 was a welcome opportunity in this regard and Moscow happily jumped at the occasion.[6] Although the US has since re-joined the Paris Agreement, Russia continues – by referencing its own pledges, however negligible these may be – to turn the climate agenda into another avenue through which it may be able to pressure the West.

THE ECONOMIC AND POLITICAL COST OF CLIMATE CHANGE FOR RUSSIA

Russia is the leading oil and gas supplier to the European Union (EU) and the largest oil exporter to China.[7] Russia has shown scepticism to climate change mitigation efforts as its economic and political power hinges on remaining a 'global fossil fuel powerhouse'.[8] On the other hand, the EU and China - Russia's two largest energy customers - have commited to achieving carbon neutrality by 2050 and 2060 respectively.[III] This commitment to a distancing from fossil fuels (i.e. oil and gas) represents a major economic and geopolitical risk to Russia in the long term. Oil and gas exports make up 60% of Russia's total exports, and revenues from fossil fuels account for 30% of its GDP.[9]

The COVID-19 pandemic has given the world a prelude of the potential economic repercussions when global oil demand and oil prices collapsed during confinement measures and global lockdowns. Russia's oil export revenues contracted by 41% between January and November 2020.[10] Russia exported approximately $73 billion worth of oil in 2020, compared to $160 billion a year earlier.[11] Russia's largest oil company,

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[II] Relative to 1990 levels.

[III] The European Green Deal provides an action plan to boost the efficient use of resources by moving to a clean, circular economy and cut pollution. The plan outlines investments needed and financing tools available. The EU aims to be climate neutral in 2050. Meanwhile, Chinese President Xi Jinping announced in September 2020 China's objective to have a carbon neutral economy by 2060.

[IV] The European Green Deal is a set of EU policy initiatives introduced in December 2019 for achieving climate neutrality by 2050.

[V] Japan and South Korea announced in November 2020 its objectives to achieve a carbon neutral economy by 2050.

Figure 1: Russian infrastructure at risk from permafrost degradation.[14]

state-owned Rosneft, experienced a 79% decline in profits in 2020.[12] This financially challenging new environment may be temporary due to the ongoing COVID-19 pandemic. However, global efforts to drastically reduce carbon emissions by phasing out fossil fuels remain a long term threat to the Kremlin's powerbase. Reduced economic revenue may potentially affect Russia's ability to offer cheap utilities to its citizens and thus erode Russia's domestic political stability.

In December 2020, the EU unveiled its European Green Deal plan to decarbonise its economy by 2050.[IV] Throughout 2020, China, Japan and South Korea announced similar pledges.[V] Climate change mitigation may alter the EU's and China's relations with carbon intensive exporters such as Russia. For Russia, an EU carbon border tax could be established in 2025. It is estimated that such a tax could cost Russian exporters over $38 billion in tariffs between 2025-2030.[13] This may further complicate Russia's trade relations with the EU. Russia's push towards greater use of hydrocarbons may lead to further political isolation as the US, EU, China, Japan and South Korea move ahead towards carbon neutrality in the next decades.

Recent environmental disasters also show that climate change could have implications that stretch well beyond financial and environmental impacts on Russia and its long term energy policies. According to scientists, the Arctic region is warming twice as fast compared to the rest of the world and the melting permafrost could cost Russia $84 billion in infrastructural damage by 2050.[15] In 2017, the Arctic Council already highlighted that the region "will face greater difficulty in the long term in sustaining the infrastructure it holds since the 1980s".[16] This phenomenon puts Russia's oil and gas infrastructure and industry at risk as demonstrated by the oil spill in Norilsk in May 2020.[VI]

The need to overcome lower prices and reduced demand for fossil fuels due to climate change mitigation and the COVID 19 pandemic helped forge new political alliances in energy cooperation in a changing geopolitical landscape. Russia continues to cooperate with rival exporters of the Organization of the Petroleum Exporting Countries (OPEC) in the OPEC+ format to maintain stability in oil markets.[VII] Meanwhile, Russia also has attempted to diversify its energy customer base by expanding into China through the Power of Siberia 1 gas pipeline and double down on its existing market share in Europe by constructing the Nord Stream 2 and TurkStream natural gas pipelines.[VIII]

[VI] The oil spill in Norilsk is the largest ever recorded in the polar Arctic. On 29 May 2020, 20.000 tons of diesel leaked into the water and soil from a storage tank owned by Norilsk Nickel near Norilsk, turning the Ambarnaya River red. The company was fined $2.1bn in damages.

[VII] The OPEC+ format gathers 24 oil-producing economies, 14 members of OPEC and 10 other non-OPEC countries, including Russia. It aims, since 2017, to coordinate oil production in a bid to stabilise prices in a low priced challenging environment.

[VIII] The Power of Siberia 1 gas pipeline, completed in December 2019, has a capacity to export 38 billion cubic meters (bcm) of Russian gas to China annually. The pipeline spans some 2,200 km from the Chayandinskoye field (Yakutia) to Blagoveshchensk (Chinese border). Gazprom's TurkStream gas pipeline was inaugurated in January 2020. It includes a 930 km long offshore pipeline under the Black Sea from Russia to Turkey with a capacity of 31 bcm for the Turkish market and Eastern European markets via Bulgaria; Nord Stream 2 is a gas pipeline from Russia to Germany across the Baltic Sea with a capacity of 55bcm (1/4 of Russia's present gas export to the EU).

OPPORTUNITIES FOR RUSSIA STEMMING FROM CLIMATE CHANGE

Melting permafrost in the Arctic is as much an opportunity for Moscow as it is a potential catastrophe. Climate change opens up new shipping routes and enables access to Arctic oil and gas resources. The Russian government acknowledges the need to "move fast to get most of these reserves in the Arctic" as large hydrocarbon consumers (EU, China, Japan) are aligning themselves on carbon neutrality goals.[17] However, instead of diversifying its economy, Russia is keen on monetising the vast – but costly – resources in the Arctic before it is too late.[18]

The opening of the Northern Sea Route (NSR) from Asia to Europe offers a greater potential for maritime trade and for accessing vast reserves of oil, gas and minerals. Russia hopes to increase shipping via Arctic waters from 32 million metric tons (MMT) in 2020 to 80 MMT of cargo by 2024.[19] The Kremlin hopes that the NSR allows it to shift traffic away from the Malacca Strait and the Suez Canal in Egypt, and turn Russia's Arctic into a major global trade hub. Either way, the NSR is not estimated to be open year-round before 2050. Russia's upcoming chairmanship of the Arctic Council from May 2021 to 2023 may be consequential in shaping the navigational opportunities that climate change brings by way of the NSR.

RUSSIA IS COMMITTED TO PRESERVING ITS ENERGY "SUPREMACY"

Hitherto, Russia's role as a major energy supplier and owner of critical energy infrastructure has served as a shield against any external political and economic pressure.[20] Looking ahead, Russia is expected to try to preserve its energy "supremacy" and "lock in" customers before climate change mitigation puts its economic and political interests at risk. This means that Russia needs to capitalise on large-scale energy projects sooner rather than later in both Europe and Asia. This explains Moscow's emphasis on completing projects such as Nord Stream 2, Turk Stream 2 and the Power of Siberia 2, as these all provide long term economic and political security to Russia's hydrocarbon-dominated economy.

By contrast, growing energy independence from Russian energy sources among key consumer nations and the gradual phasing out hydrocarbons in general will intrinsically enable greater economic, political and environmental resilience. Specifically, Russia's attempts at further developing its Arctic natural resources risk upsetting the environmental balance in this pristine area with global repercussions, harming efforts to achieve carbon neutrality by 2050.

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Hurricane threats to military infrastructure in a warming world and possible adaption and mitigation strategies

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

INTRODUCTION

With respect to global warming, the armed forces differentiate between the impacts on infrastructure, facilities and operations, and the implications for peacekeeping and conflicts. The climate related stresses for military installations are well documented for e.g. the United States armed forces. This includes threats from flooding, droughts, wildfires and desertification. The most imminent threats are due to the rise in sea level and the frequency of major storms, both consequences of global warming. Heavy damage to mainly coastal military and civil infrastructure is expected as a result of more powerful hurricanes reaching further north than currently experienced. In this paper, the changing characteristics of hurricanes in the North Atlantic and the Caribbean between 1967 and 2018 are shown and new storm patterns due to the predicted rising in sea surface temperature are explained. Climate models show that future hurricanes exhibit stronger winds and massive precipitation as well as a slower decay and movement after landfall, resulting in severe damages and longer lasting flooding. The vulnerability of the Norfolk Naval Shipyard (USA) to such hurricanes is highlighted. Examples of short and long term, high and low cost, biological and technical adaptation and mitigation measures for protecting coastal installations are described.

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

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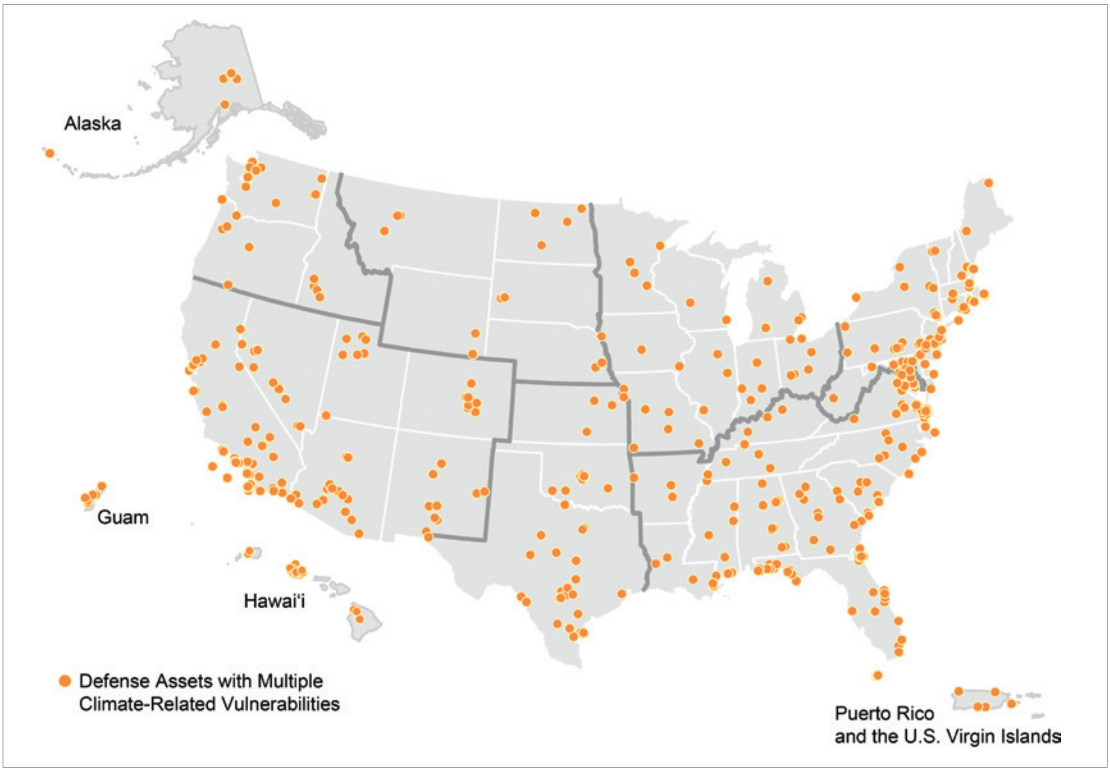


Figure 1: Map of US military assets with multiple climate-related vulnerabilities.[6]

SECURITY IMPLICATIONS OF GLOBAL WARMING

The military and intelligence communities tend to cluster the national security implications of global warming induced climate change into two overlapping areas. The first is how climate change will affect installations and military operations. This includes how the response to climate induced disasters will stress military operations and potentially detract from other military missions. The second area is, how climate change poses political and national security threats in peace and open conflict scenarios.

With respect to effects on military installations, the research on upcoming threats and already experienced stresses due to climate change has been done and published for several decades.[1] In 2019 the US Department of Defence reported that the US military is already experiencing the effects of global warming at dozens of installations (Figure 1). These include recurrent flooding (53 installations), droughts (43 installations), wildfires (36 installations) and desertification (6 installations) as well as the impairment of the physical stability of US military facilities in the Arctic.[2] The most urgent threat to US military infrastructure is that rising sea levels and major storms will inundate coastal infrastructure.[3] Recurrent flooding is already experienced at the Keesler Air Force Base Mississippi as well as the US Naval Base at Norfolk Virginia. Tyndall Air Force Base in Florida suffered severe damage in October 2018 by Hurricane Michael.[4]

In this article we will discuss the negative effects of the increasing number and severity of tropical storms on military installations. We will focus on existing and future damaging effects of hurricanes on military bases along the Caribbean and Atlantic coastlines of the US (Figure 1). Special attention is given to the situation at the U. S. Naval Base in Norfolk Virginia, which is the biggest naval base worldwide, and to the associated Naval Ship Yard.[5]

The National Climate Assessment released in late 2018 highlighted the special vulnerability of the Norfolk Naval base to flooding.[7] It was exposed to hurricane induced inundations in the past, as shown in Figure 2. Simulations of the possible vulnerability to sea level induced inundations caused by hurricanes of the categories 1 – 4 making landfall at or near Norfolk Virginia are performed by NOAA.[8] With respect to the Norfolk Naval Shipyard a category 1 storm will lead to minor inundations of less than 3 feet (91 cm) and affect 5 – 10 % of the area. In contrast, a category 4 storm will flood the complete Naval Shipyard and inundate most of the area with least 6 feet (182 cm) of sea water (Figure 10).[9]

Figure 2: "USS Kearsarge" at the Naval Base in Norfolk during the 2003 Hurricane Isabel, which causes nearly 130 * 106 US$ worth of damage on US marine bases.[10]

CHARACTERISTIC OF TROPICAL STORMS WITH FOCUS ON HURRICANES

Warm tropical ocean surfaces are the cause of strong tropical storms. These often violent storms are called "hurricanes" in the northern Atlantic and the north eastern Pacific Ocean, "typhoons" in the north western Pacific and "cyclones" in the southern Pacific and the Indian Ocean.[11]

Several preconditions are required for a tropical storm to build up and move into subtropical areas: a) a sea surface temperature (SST) of at least 26 °C in the uppermost 50 m of the water column, b) unstable climatic stratification of air masses, c) high air humidity in the mid troposphere (5 km height), d) existing disturbance in the lower atmosphere with organized rotation, e) low winds (< 37 km/h) and f) a starting point of at least 500 km North or South of the equator. Closer to the equator tropical storms do not form, because the Coriolis-force is too weak to establish a rotating storm.[12]

The driver of tropical storms is the thermal energy release during the condensation of water vapour in the air over warm tropical oceans.[13] At sea surface temperatures above 26 °C sea water evaporation from the ocean surface gets intense and warm moist air masses move upward until they condensate and precipitate as rain. During this condensation process large quantities of thermal energy are released and lead to further warming of the air. This forces air masses even further up until they release the remaining moisture. The strong uplift of air masses creates a large low pressure zone at sea level, which forces moist air masses to move with great speed into this low pressure area, i.e. into the "eye" of the hurricane. As long as further warm and moist air masses are moving into the low pressure system, the rotating hurricane is increasing its wind speed. Figure 3 shows the global sea surface temperature in October 2018 at the

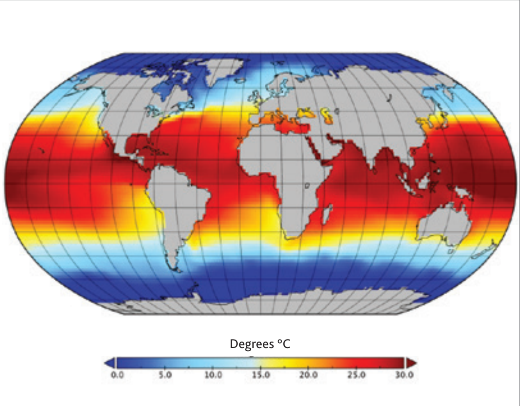


Figure 3: Global sea surface temperatures (SST) in October 2018 during the peak of the hurricane season in the North Atlantic and the Caribbean Sea.[14]

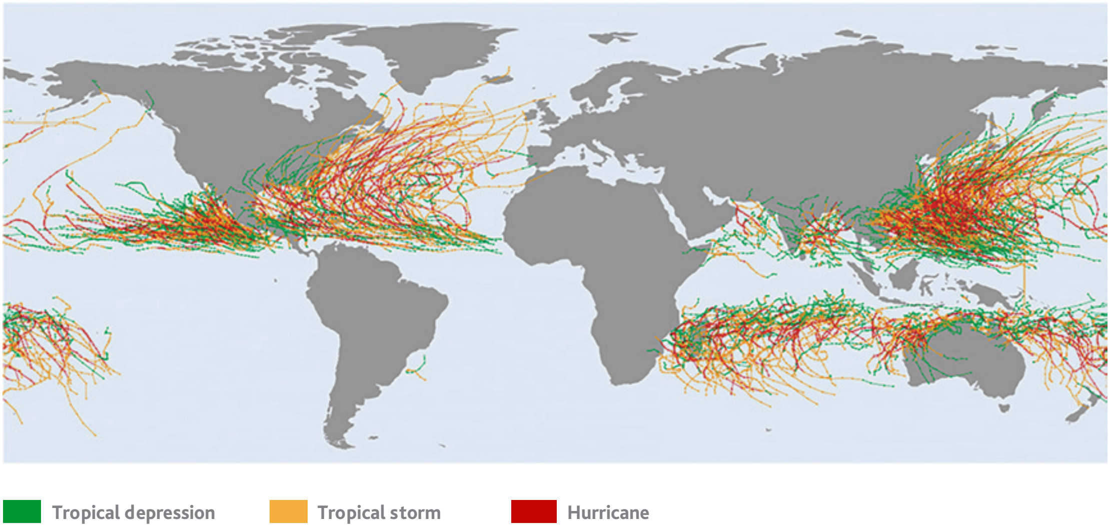


Figure 4: Tracks of tropical storms from 2004 to 2014.[20]

peak of the hurricane season in the North Atlantic and the Caribbean Sea. The Coriolis force causes the winds to form a cyclic pattern around the low pressure eye of the hurricane and the hurricane system itself moves slowly westward and towards higher latitudes.

The driver of tropical storms is the moisture of very warm tropical oceans.[15] With the SST rising in a warming world, the moisture supply is enhanced. This effect is shown in the phase diagram for water (Clausius-Clapeyron relation) where a rising SST directly leads to higher atmospheric humidity and, consequently, to higher hurricane intensities.[16] As early as 2008 a number of scientists found that the most pronounced intensification of tropical storms occurs in the North Atlantic.[17] Lower SST and land masses cut off tropical storms from warm and moist air masses at the surface and thus from the thermal energy supply.[18] As an immediate consequence their intensity decays rapidly after reaching the coastline. Therefore, the largest damage to humans and infrastructures is inflicted during the first 24 h after landfall.[19] The areas of origin and the pathways of tropical storms in the period from 2004 to 2014 are shown in Figure 4. The zones of origin do correspond nicely with the areas of the highest SST (Figure 3) while the areas of storm decay correspond to cooler SST-regions or land surfaces.

The intensity of hurricanes is classified by the Saffir - Simpson scale as shown in Table 1.[21] The defining criteria are wind speed (often termed intensity) and air pressure with wind speed as the most destructive aspect of a hurricane. Other parameters such as storm surge or precipitation are not included in the classification.

The hurricane season in the North Atlantic officially lasts from June to November. In 2020, the North Atlantic experienced a record breaking season when the World Meteorological Organization (WMO) registered 30 tropical storms.[23] By the end of the year, 30 tropical storms had been named, nine with Greek names. The only other year which needed Greek names was also the year 2005. It brought several deadly storms such as Katrina, which resulted in more than 1 800 lives lost and vast flooding in Louisiana and Mississippi.[24] Evidence suggests that for the time period from 1967 – 1992 a total of 26 hurricanes in the North Atlantic reached the coastline and lasted more than 24h after making landfall.[25] The number nearly doubled to 45 hurricanes of this type in the 25 years from 1993 – 2018.

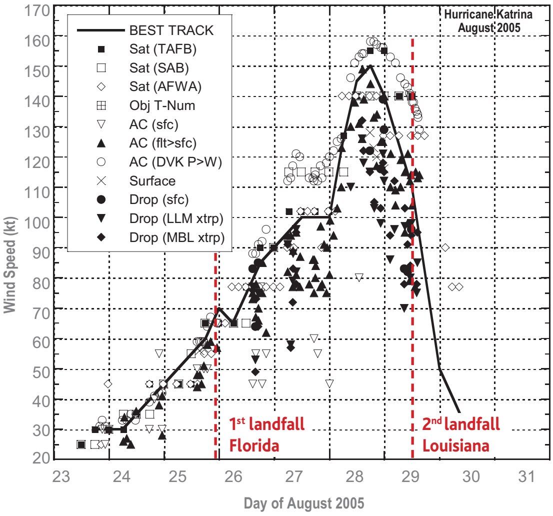
Table 1: Classification of hurricanes according to the Saffir- Simpson scale.[22]

Hurricane Category	Wind speed [km/h]	Wind speed [m/s]	Storm surge [cm]	Storm surge [feet]
Tropical Storm	63 – 118	18 – 32		
Category 1	119 – 153	33 – 42	120 – 160	3.9 – 5.2
Category 2	154 – 177	43 – 49	170 – 250	5.3 – 8.2
Category 3	178 – 208	50 – 58	260 – 370	8.3 – 12.1
Category 4	209 – 251	59 – 70	380 – 540	12.2 – 17.7
Category 5	> 251	> 70	> 540	> 17.7

THE EMERGENCE AND FALL OF THE DESTRUCTIVE POWER OF HURRICANES

The rise and fall of the destructive wind speed in dependence of the supply of warm moist air from the ocean surface is shown on the evolution of Hurricane Katrina in 2005 (Figure 5). On 23rd of August a tropical depression formed which strengthened over the Gulf of Mexico and reached hurricane status on the 25th. After the first landfall in Florida it was a Category 1 hurricane and moved westward for 6 hours over land while it weakened to a tropical storm. It moved into the Gulf of Mexico on 26th of August where the storm underwent two rapid intensifications becoming a Category 5 hurricane. Katrina reached its peak intensity on 28th of August over the Caribbean Sea and made its second landfall in Louisiana as a Category 3 storm on the 29th. Katrina weakened rapidly after moving inland, becoming a Category 1 hurricane on 29th and a tropical storm about 6 hours later.[26]

Figure 5: Selected wind observations and best track maximum sustained surface wind speed curve for Hurricane Katrina from 23rd to 30th of August 2005. Katrina made landfall on 25th of August at 23:00 UTC in Florida (USA) and on 29th of August at 11:10 UTC in Louisiana (USA). (Marked with red dotted lines) Wind speed in kt = knots. 1 knot = 1.852 km/h = 0,51 m/s.[27]



Hurricanes inflict their most severe damages within the first 24 hours after landfall. The storms velocity (V) decays exponentially in this period of time (Formula (1)).

$$V_{(t)} = V_{(0)}\ e^{-t/\tau} \qquad (1)$$

Where t is the time past landfall and τ, the decay timescale. τ is a single parameter that characterizes the rate of decay. After the first 24 hours $V_{(t)}$ can no longer be characterized by a single parameter as it is influenced by other parameters such as the land surface properties and the local weather conditions. The larger τ, the slower the decay, and therefore the stronger the hurricane. Two scientists from the Okinawa Institute of Science and Technology, Li Lin and Pinaki Chakraborty, have found that τ has increased in the period from 1993 – 2018 compared to the period from

1967 – 1992 confirming the recent trend to more extreme weather events (Figure 6).[28]

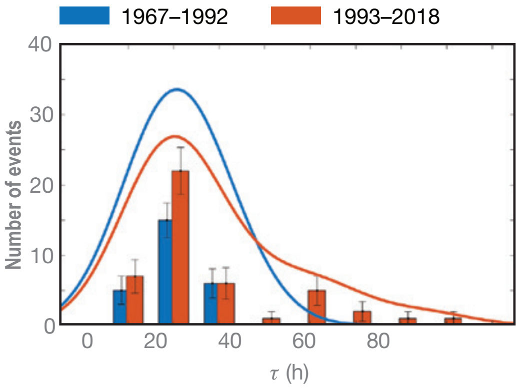


Figure 6: Histogram of τ (decay timescale) for 26 hurricane landfall events between 1967 and 1992 and 45 hurricane landfalls in the period from 1993 to 2018. Error bars are ± 1 standard deviation. Modified after.[29]

On a global scale most tropical storms never make a landfall. This is also true for hurricanes in the North Atlantic (Figure 4). However, coastal regions may well be affected by nearby passing storms due to the resulting coastal storm surge. A hurricane reaching a coastline inflicts damage due to a combination of extremely strong winds, coastal storm surges and additional flooding due to extensive coastal and inland rainfall. The storm surge and its effects are limited to coastal regions up to 20 km from the coast, whereas strong winds and flooding due to heavy rainfalls may affect regions hundreds of km inland from the coast.

FUTURE BEHAVIOUR OF HURRICANES AFTER LANDFALL

The rising global sea surface temperatures will increase the occurrence and intensity of hurricanes. There are already observations of slower hurricane decay after landfall, higher amounts of rainfall and a lower mobility of the storm itself. Also more hurricanes are now making landfall on the US East Coast as shown in Figure 7.[30]

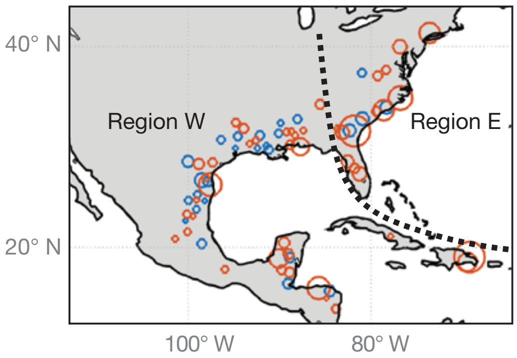


Figure 7: Selected hurricanes from 1967 – 2018 which lasted at least 24 h after landfall. Each circle marks the centroid of the positions of each hurricane during landfall and after 6, 12 and 18 hours over land. The size of the circle marks the decay time scale. Blue circles: hurricanes from 1967 – 1992. Red circles: hurricanes from 1993 – 2018. Region E = US East Coast. Region W = Gulf of Mexica and Caribbean.[31]

Lin and Chakraborty have also simulated hurricane formation using a SST between 300 °K (27 °C) to 303 °K (30 °C) in intervals of 1 K. The warmer the ocean SST, the greater the moisture supply and, consequently, the faster the intensification of the storm (Figure 8 a). When the hurricane intensities reached about 60 m/s (i.e. a Category 4 hurricane on the Saffir – Simpson scale) a complete landfall of the hurricane was simulated. In modelling terms this means, that the moisture influx to the hurricane was stopped instantaneously and further intensity increases are no longer possible (V). From this time onwards, only decreasing intensities (V) are possible and the decay of the hurricanes was modelled with identical parameters thereafter.[32]

Hurricane formation at 300 °K and 301 °K SST (27 and 28 °C respectively) is much slower than at higher temperatures. It took the tropical storm at least 4 days to reach the Category 4 class. SST equal or higher than 302 °K (29 °K) results in the build-up of a Category 4 storm in less than 2 days, leaving little time for e.g. evacuation measures. Although the intensity at landfall is the same for all four hurricanes of the model, their decay past landfall carries a clear signature of the development over the ocean before the landfall (Figure 8 a). The intensities of the hurricanes that developed over warmer oceans decay at a slower rate

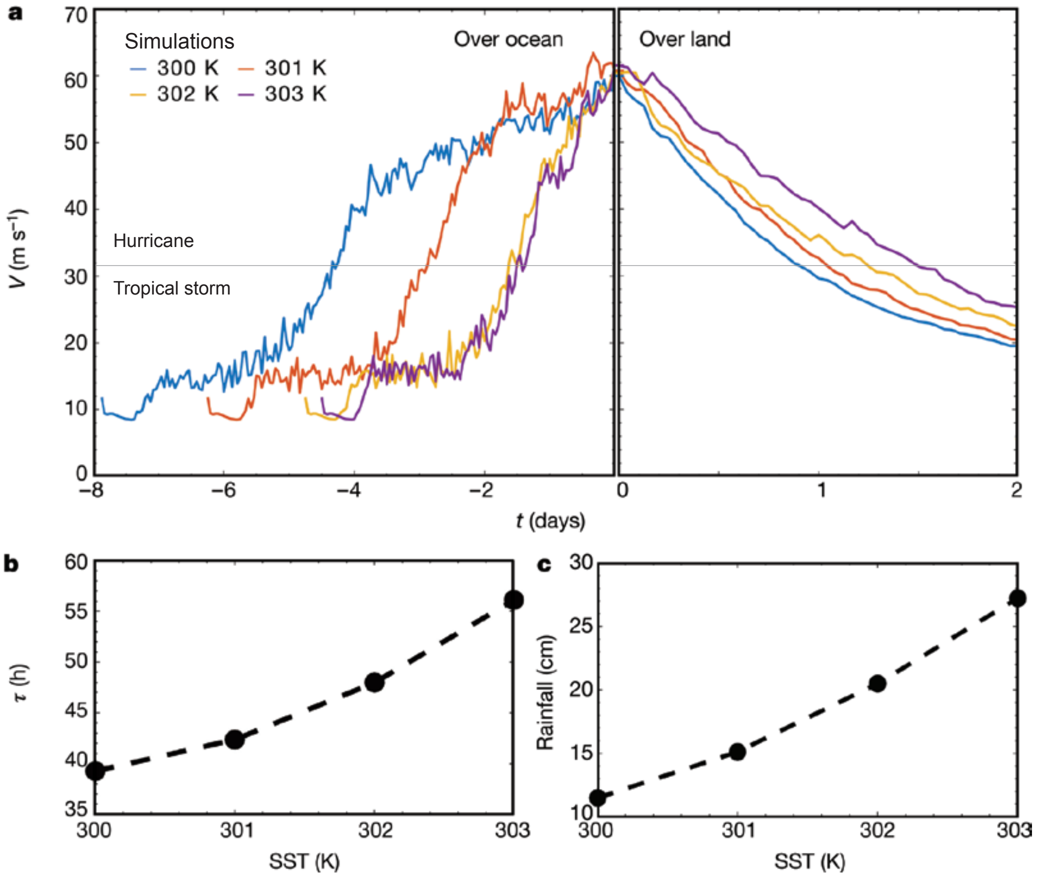


Figure 8: Effect of sea surface temperature (SST) on the decay of simulated landfalling hurricanes. A) Velocity = Intensity (V) versus time (t). t < 0, the hurricanes develop over warm oceans. Different colours represent different SST. At t = 0, the hurricanes make landfall with V≈ 60 m/s. B) Decay time (τ) versus SST. C) Rainfall versus SST. This is the total rainfall accumulated inside a radius of 100 km and over the first two days past landfall.[33]

(τ) – due to the higher moisture content which serves as energy source. That echoes the field observations (Figure 8 b) but in contrast to these, in the model the increase in τ is solely dependent of the SST. As the enhanced storm moisture eventually precipitates as rain, the rainfall from hurricanes increases approximately 2.5 fold when the SST increases by 4 C (Figure 8 c).[34]

The effect of precipitation is not included as a parameter in the Saffir – Simpson scale. In the past, inland rainfall was often heavy, but not as devastating as it is now and will be in the future. This development was demonstrated by Hurricane Harvey which hit the Caribbean and the US states of Texas and Louisiana in August 2017. This Category 4 storm brought to up to 125 cm of rain (1 250 l/m²) during its lifetime. The resulting floods caused power outages for 300 000 households in Texas with cascading and devastating effects on critical infrastructure. Eleven percent of the US oil refining capacity and a quarter of the oil production from the US Gulf of Mexico were shut down. Actual and anticipated gasoline shortage caused regional and national price spikes.[35]

THE FUTURE OF NAVAL BASES

In risk assessment studies, inundations are dealt with as an entity, regardless of the cause. Hurri-

Figure 9: Flooding caused by hurricane Harvey in Port Arthur Texas (USA), on 31st of August in 2017, six days after Hurricane Harvey made landfall along the Gulf Coast.[36]

canes are only one of many contributors. Others are spring tides or extreme rainfall floods. Globally the US Navy maintains 111 000 buildings and facilities on 890 000 hectares of land. A total new construction of all facilities would cost at least 220 * 10^9 US$. A sea water rise of 90 cm would put 55 Navy bases (worth 100 * 10^9 US$) at risk.

Some bases may have to be abandoned. The most prone is the US Navy base in Yokosuka (Bay of Tokio, Japan) which serves as the headquarter of the Seventh fleet and the base on Diego Garcia, an atoll in the Indian Ocean, an important logistic hub for missions in the Middle East and the Mediterranean Sea.

Bases to be operated in the future, have to be adapted to the coming challenges. For example, the Norfolk Naval base is currently inundated at least once a month during spring tides and heavy rainfall events. When it was built in 1917, the sea level was 46 cm lower than today. The landing bridges are often affected, impeding the maintenance schedules and the supply of power, water and steam to the ships. Currently, the landing bridges are renewed for US$ 100 x 10^6 each. These efforts are severely impeded by the ongoing inundations. The new supply lines are installed above the water line.[37]

ADAPTION TO AND MITIGATION OF STRONGER HURRICANES

Adaption means the introduction of measures to cope with new environmental conditions. In 2014, the US Department of Defence issued a roadmap for the most pressing goals and lines of works with general descriptions of the expected tasks.[38] The implementation of adaption measures is normally done on a short- and/or mid-term time frame compared with mitigation strategies, which normally are long-term and which aim to reduce the negative effects of new environmental conditions. Sometimes measures show characteristics of both adaptation and mitigation.

The current infrastructure of coastal protections and buildings is generally not well adapted to cope with the increasing threats of stronger hurricanes. Upgrading is very difficult and costly and in many cases impossible. This is due to a) the sheer size of the involved natural forces, b) the vast areas affected, c) the population density in these areas, d) the millions of buildings and installations in these areas and e) the lack of appropriate funding. Therefore, measures to protect people and infrastructure only seem feasible in a limited number of cases.

For example, the Indonesian capital city of Jakarta suffers from regular and severe floods caused by a combination of rainstorms, subsiding grounds and rising sea levels. Therefore, in 2019, the government decided to relocate the capital with its approximately 30 million citizens to the island of Borneo within 10 years at an estimated cost of more than 30 billion US$.[39]

Climate change mitigation strategies are generally centred on the containment of the rising global average temperature. Global warming is influenced by many factors, such as the release and fixation of greenhouse gases (GHG), ozone, aerosols, clouds, surface albedo (absorption of heat due to the colour of a surfaces), contrails, volcanic activity and many more.[40] Only a few of these factors can be managed by humans and still fewer can be influenced by large companies, organisations or even individuals.[41] It seems prudent, that civil societies and also the military figures out, in which field the impact caused by their mitigation efforts will be most pronounced and efficient.

Adaption and mitigation may be achieved by technical solutions or by natural processes. Short-, mid- and long-term measures are available for both measures. Some selected examples – with special focus on the military – are described below.

Technical Adaption

BARRAGES

Typical adaptation strategies for infrastructure are building codes.[42] They can only be applied to new buildings, leaving the existing infrastructure at risk. To abandon this infrastructure is generally no option. Protective installations from storm surges in coastal regions and flooding from rivers or both – as in estuaries – were erected for many centuries, as these regions are historically densely populated because of their resourcefulness and trading possibilities. A selection of the most effective ones is given below.

Stationary dikes and levees to protect coastal regions have been used for several hundred years and are aimed to last for several decades. They do prevent flooding of coasts and riverbanks but cannot protect estuaries or bays. The Netherlands are most famous for their dikes as huge parts of its lands lie below sea level.

The building of mobile protective barrages is technically possible. They are operational at rivers, bays and lagoons, some for several decades now (see box below). Mobile barrages protect human settlements, allow shipping and freshwater management. Rising sea levels must be integrated into the planning or otherwise the barrier will soon be overwhelmed.

OPERATIONAL MOBILE BARRAGES FOR RIVERS, BAYS AND LAGOONS

The Thames Barrier in East London is 520 m wide and operational since 1984. It was established as a consequence to the so called “North Sea Flood” from 1953, which caused 307 fatalities in the UK alone. Plans to build a new barrier are in preparation downstream of the existing barrier as a) rising sea levels will overwhelm the established barrier in the foreseeable future and b) greater parts of London should be protected from future flooding.[43]

The Marina Bay in Singapore is often flooded by the sea leading to inundation in Singapore itself. In an effort to increase its self-sufficiency, the Singaporean government wants to use the bay as freshwater reservoir. Sea water intrusions thwart theses plans. The Marina Barrage is 350 m wide and includes powerful pumps which are able to regulate the water level inside the

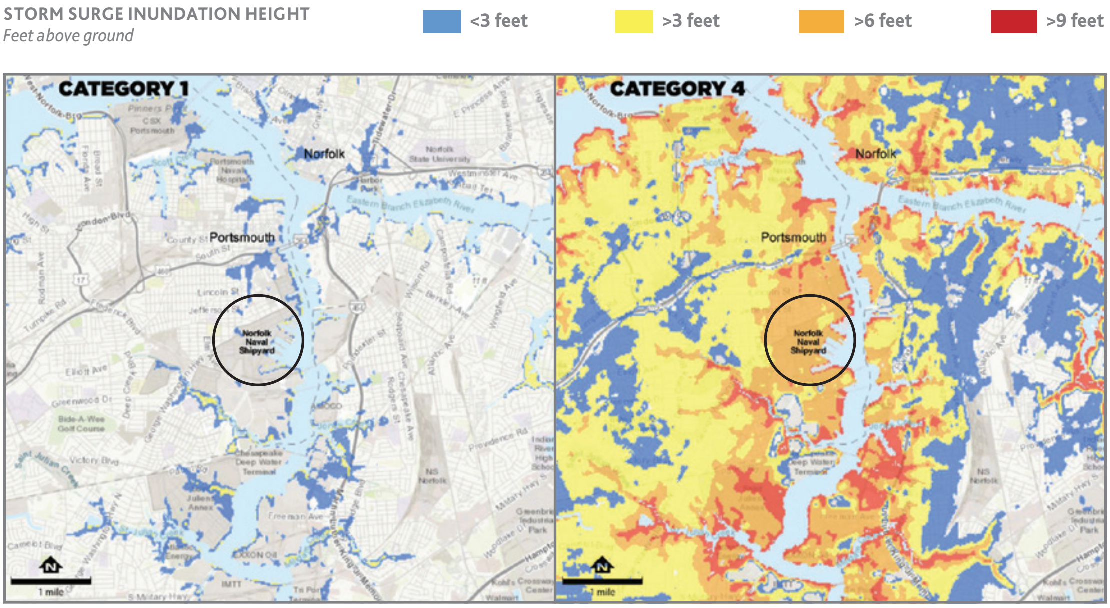


Figure 10: Simulation of inundation effects of a hurricane Category 1 and a hurricane Category 4 making landfall at or near Norfolk (Virginia, USA) on the Naval Ship Yard of the US Navy (indicated by a circle). 3 feet = 91 cm. 6 feet = 182 cm. 9 feet = 273 cm.[48]

bay when the barrage is closed. It is operational since 2010.[44]

Venice in Italy - which is built on sinking ground and is often inundated - has built in 2020 the massive 1 600 m wide barrier MOSE, which now successfully protects the historical heritage of the city.[45]

The Norfolk Naval base is located at the estuary of the James River. The Norfolk Naval Ship Yard is located a few miles upstream the river. If no further action will be taken, stronger hurricanes will lead to severe flooding of the entire naval base and shipyard. A simulation of inundations caused by a Category 1 and a Category 4 hurricane is shown in Figure 10 for the Naval Ship Yard. Damage to military infrastructure would be disastrous and severely hamper the Navy's combat readiness. Between the southern coast at Willoughby Bay and the northern coast of Fort Monroe the estuary is approximately 3 km wide and is already spanned by the Route 64 in a combination of bridges and tunnels.[46] None of the already existing barriers is built to resist a storm surge of a Category 4 hurricane, which may result in a coastal storm surge as high as 540 cm (17.7 feet).[47]

Technical Adaption and Mitigation

BUILDING CODES

Generally building codes may define a) the areas in which building is allowed, b) the technical details of walls, roofs etc. and c) the materials to be used. Points a) and b) are important for adaptation to new environmental conditions such as increased danger of inundation. Point c) may play a role in mitigation, when carbon neutral materials were compulsory for construction e. g. wood.

The US Navy requests now a special permission for each building which is to be erected below the future predicted sea level line (2 m above present).[49]

Technical Mitigation

COOLANTS

The GHG class of halocarbons – also known as Frigene – are used in cooling devices. They work as GHG in the lower parts of the atmosphere and they also deplete the ozone in the stratosphere in the polar regions during winter.[50] They are very stable in the environment and generally are released during the life cycle of a cooling device. Non halogenated substitutes are known and have been in use for many decades but they are more expensive. The routine replacement of cooling devices or coolants with non-halocarbons could be started now and have an immediate effect.

ENHANCING ALBEDO

Light coloured surfaces do reflect radiant heat from the sun back into space (albedo) and, therefore, do not contribute to the heating of the globe. Painting surfaces in light colours would reduce the amount of heat absorbed on earth. Each surface is suitable e.g., walls, roofs, streets, sidewalks, car tyres etc. Light coloured versions may be installed during maintenance or replacement work. Light coloured buildings do also reduce the needed energy for ventilation and cooling of these buildings.[51]

Biological Mitigation

MANGROVES

An interesting and ecologically important option to mitigate hurricane storm surges and, at the same time improve carbon capture and long term sequestration, involves the restauration of mangrove forests. They are well known to protect people and property in coastal areas in the tropics from storm surges.[52] They grow in the tropical and subtropical coastal regions of the world with a nice overlap with the tropical storm regions (Figure 4, Figure 11).

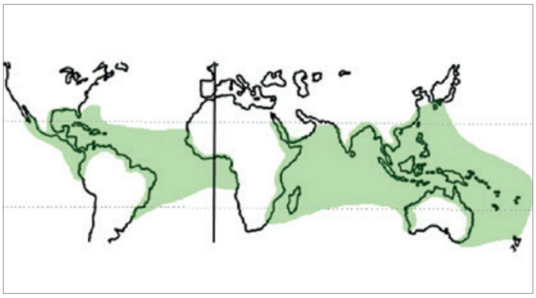


Figure 11: Global distribution of mangroves. Dotted lines = Tropical zone (30 degree north and south of the equator). Solid line = Greenwich meridian.[53]

Observations and simulations indicate that the 6 to 30 km wide mangrove forest along the Gulf Coast of South Florida effectively attenuate storm surges from a Category 3 hurricane. The surge amplitude decreases at a rate of 40 – 50 cm/km across the mangrove forest and at a rate of 20 cm/km across the areas with a mixture of mangrove islands with open water. In contrast, the amplitudes of storm surges at the front of the mangrove zone increase by about 10 – 30 % because of the blockage of mangroves to surge water. This effect may cause greater impacts on structures at the front of mangroves than the case without mangroves.[54] These effects do apply to all forms of surges. The effects of a tsunami caused surge on mangroves and artificial infrastructures is shown in Figure 12. The human infrastructure

Figure 12: Boat jetty in the Vellar estuary (south-east cost of India) broken into pieces by a tsunami induced surge on the 26th of December 2004 in the background. The foreground shows an artificially established intact mangrove forest.[56]

Table 2: Net primary production (NPP) and carbon sequestration (so-called burial rates) for typical ecosystems.[60] The burial rate describes the amount of carbon which is removed from the carbon cycle for many thousand years.

Ecosystem	NPP [kg dry matter m-2 y-1]	Carbon sequestration [g C m-2 y-1]
Tropical forests	1.0 – 3.5	4.0 ± 0.5
Boreal forests	0.2 – 1.5	4.6 ± 2.1
Temperate forests	1.0 – 2.5	5.11 ± 1.0
Seagrasses	1.0 – 6.0	138.0 ± 38.0
Salt marches		218.0 ± 24.0
Mangrove forests		226.0 ± 39.0

is destroyed, while the juvenile mangroves are still intact.[55]

On a global scale, the area covered with mangrove forests has profoundly declined in recent years. Globally – and in comparison to other forest ecosystems – its area is small. They are cleared most often for agriculture and shrimp farming.[57] Mangrove forests have one of the highest biomass production and carbon sequestration – the so called burial rates – of the known forest ecosystems (Table 2).[58] These processes remove carbon dioxide (CO_2) from the atmosphere and, therefore, reduce the effects of global warming.[59]

Afforestation and reforestation of tropical and subtropical coastal regions and estuaries can therefore serve two purposes a) the mitigation of storm surges from tropical storms by reducing the amplitude of the storm surge and b) the mitigation of tropical storms by reducing global warming and therefore reducing SST in the long run. In the US Department's of Defence Adaption Roadmap for Climate Change the need for "partnerships with external, non-federal government land and resource stewardship organizations" is pointed out.[61] Mangrove management could be a much valued issue for all involved stakeholders.

The afforestation of small patches of land can have immediate effects on the adjacent surrounding in terms of the microclimate (e.g. cooling, shade etc.), living quality and biodiversity. The movement of "tiny forests" install forests on areas as small as a tennis court. The concept promotes rapid growth of the used local tree species.[62]

Long term mitigation

REDUCTION OF CARBON DIOXIDE EMISSIONS

Carbon dioxide is the most important GHG in terms of the emitted amount and one of the most difficult to reduce, due to lacking alternative fuels and technologies. The military itself emits millions of tonnes of CO_2. The US military for example emits in a typical year without major warfare and conflicts more than 55 million tons of CO_2-equivalents (Figure 13). The relative parts from combat related and non-combat related activities approximately equal each other and the absolute amount was declining considerably during the years between 2000 and 2018.[63]

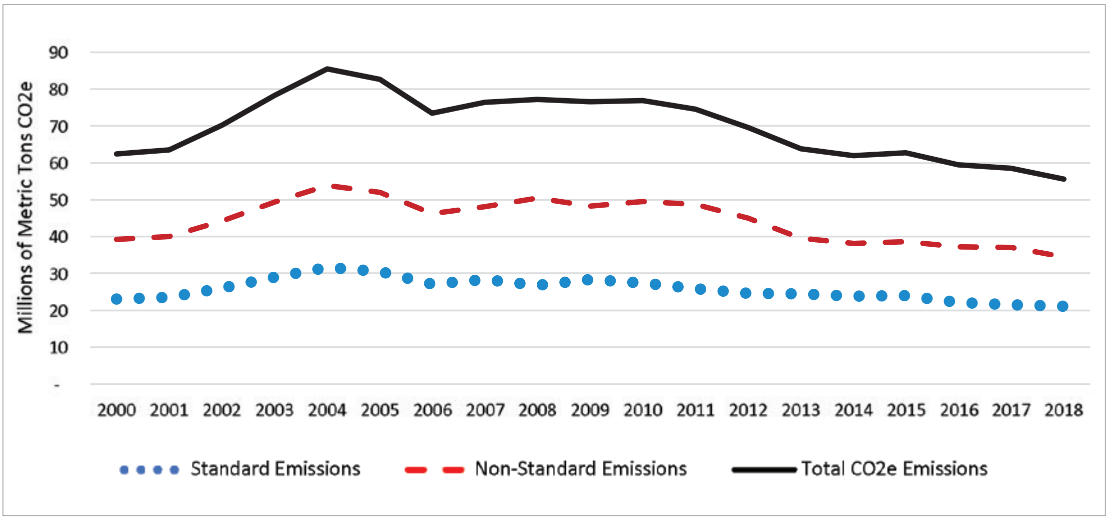


Figure 13: Estimate greenhouse gas emissions of the US Department of Defence (expressed as carbon dioxide equivalents CO$_2$e) for the fiscal years 2000-2018. Metric tons = 1 000 kg = 1 ton. Blue dotted line = standard emissions. Red broken line = Non-Standard emissions. Black line = Total Emissions. Non-Standard emissions are defined by the US Department of Energy as "vehicles, vessels, aircraft and other equipment used by Federal Government agencies in combat support, combat service support, tactical or relief operations, training for such operations, law enforcement, emergency response, or spaceflight (including associated ground-support equipment)". Standard Emissions are defined by the same body as "everything else, that the Department of Defence does to accomplice its functions, roles and missions"[65]

CO$_2$-Equivalent

A CO$_2$-equivalent is the GHG potential of a specific gas with the CO$_2$ GHG potential used as a reference. CO$_2$ was selected, as it is the most important GHG with respect to abundancy and production. Potent GHG emitted from military activities are for example nitrogen oxides (289 times 100-year global warming potential of CO$_2$) from combustion processes and fluorinated hydrocarbons (14 800 times 100-year global warming potential of CO$_2$) from cooling facilities.[64]

Jet fuel consumption is the largest single position of the US military energy consumption and the largest single expense of the US government in terms of energy demand (Figure 14).[66] Diesel and electricity usage were the second and third largest single positions of US military energy consumption, each approximately a quarter of the jet fuel consumption.[67] Diesel is used in ships, land-based mobility and mobile installations. Improvements in energy efficiency and low or carbon neutral fuels may have a huge impact

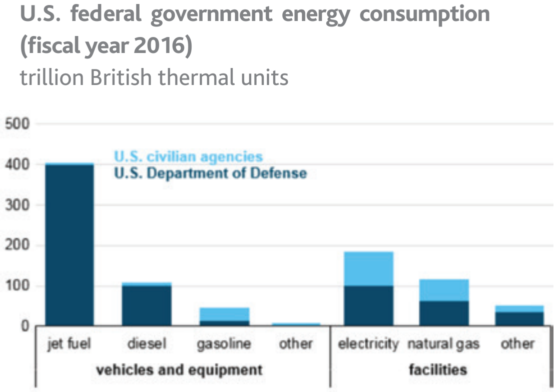


Figure 14: Categories of energy consumed by the US Government and the Department of Defence in 2016. Dark blue = US Department of Defence. Cyan = US civilian agencies.1 * 1 012 BTU = 296 kWh.[69]

on CO_2 emissions. The biggest impact of these improvements would be on airborne activities. Research and development on alternative fuels and engine technologies has intensified during the last years. An overview of the military aspects of fuel cells on military applications is given by several authors.[68] Efforts to reduce the weight of aircrafts include e.g. pilotless air fighters and drones.

The reduction of the CO_2 emissions would be an important long-term contribution to a net carbon dioxide neutral society and therefore the mitigation of global warming. A lesser need to transport fuel to military zones could also reduce human casualties.[70]

The transported fuels are currently kerosene and diesel fuels, which are used to operate aircraft, helicopters, vehicles, heaters and electric generators. The US Marine Corps started solar panel generated electricity supply as early as 2012 for combat outposts in Afghanistan (Figure 15).[71] Electricity for facilities can be produced from renewable sources. It may be procured from respective sources or produced within the compounds of military facilities itself. Field camps of several nations are currently being equipped with large solar panel arrays for reducing the need for liquid fossil fuel supply.

Figure 15: US Marine Corps troops installing solar panels on a combat outpost in Afghanistan (November 2012) to provide power to radios, laptops and computers.[72]

CONCLUSIONS

The majority of the international community accepts the need to reduce the impacts of global warming and global change. In the "Paris Agreement on climate change mitigation, adaptation and finance" the signing nations – currently 190 UN member states - committed themselves to the goal of keeping the increase in global average temperature well below 2 °C above pre-industrial levels and to pursue efforts to limit the increase to 1.5 °C.[73] Achieving this goal would substantially reduce the risks and impacts of climate change but may not be reached without immediate decisive action. The aim is to establish a net carbon free economy as soon as possible.[74] The 2 °C goal – as it is generally named – can only be reached by active mitigation strategies. Even if it is achieved, which is not certain at the moment, further adaptation strategies are needed to protect existing infrastructure from the consequences of a 2 °C global warming.

WHAT ADAPTION AND MITIGATION STRATEGIES MAY FIT THE MILITARY MISSION?

Measures to combat global warming and its effects may be a mixture of adaptation and mitigation and may have effects on different time scales. In this publication we define short-term as < 2 years, mid-term as 3 – 5 years and long-term as > 5 years. During these time spans the first effects of mitigation projects will be measurable. Table 3 shows the time between inception and expected results for adaption and mitigation measures.

SO, WHAT CAN BE DONE WITHIN THE MILITARY ENVIRONMENT?

Building codes for fixed installations are technical measures, which can be implemented quickly. When e.g. timber becomes mandatory for regular construction, long-term CO_2 fixation is possible. The construction of dikes, levees and barrages generally took several decades from planning to completion. The Thames Barrier was completed approximately 30 years after the flood, which triggered its construction. The replacement of Frigene coolants with environmentally friendly variants

Table 3: Selection of measures for adaption and mitigation of the effects of climate change with emphasis of the military. Measures are categorised a) into technical and biological and b) on their time scale. Short-term < 2 years. Mid-term = 2 – 5 years. Long-term > 5 years.

Measure		Adaption			Mitigation		
		Short-term	Mid-term	Long-term	Short-term	Mid-term	Long-term
Building codes	Technical Biological	x					x
Dikes, levees, barrages	Technical			x			
Coolants	Technical				x		x
Light coloured surfaces	Technical				x		
Mangrove forests	Biological		x				x
Tiny forests	Biological		x				x
Alternative fuels	Technical					x	
Renewable power supply	Technical				x		

could be started immediately and the positive effect in the lower atmosphere would be immediate while the effects in the stratosphere would have a time delay of several years. Afforestation of mangrove forests in coastal areas develops its protective effects on a mid-term time period. The sequestration of carbon by reforestation or newly afforested areas is a long term process. The development and rollout of alternative fuels will shows its impact at best in a mid-term time scale because the development of engines and technologies as well as the building of infrastructure is a long-term effort. The usage of renewable power production technologies can be started immediately, as the technology is already mature enough.

Many opportunities for climate change adaption and mitigation exist for the military. In many cases they are compatible with and in some cases even favourable for the missions of the military. As the military plays a significant role in our society, its actions have the potential to spearhead social change for the better.

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Notes

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