EXECUTIVE SUMMARY

The energy transition for defence needs progress in several areas. Energy sources, energy carriers (i.e. fuels/storage), energy efficiency/savings, and smart energy applications and design. Naturally all of this should be clean and sustainable, or at least better than the ones they replace. The most effective climate impact policy by far is innovation and hence should be invested in the most [1] (Galiana and Green, 2010).

The classic renewable sources i.e. wind and solar, require a lot of space, critical materials as well as storage and backup due to the intermittent nature. The unfortunate fact that these sources suffer from a poor energy return on investment EROI make these not very attractive choices [2] (Rhebergen, 2022). They are however an essential driver of clean technology and have niche applications where they are hard to beat at.

Especially for defence applications a concentrated form of storable and quickly transportable[1] energy is required. Currently this is fossil fuel. In the future this could be battery storage of electricity from sustainable sources or synthetic/biofuels/efuels or even hybrid combinations. Hydrogen could also fulfil this role but storage and transportation is inefficient and generally problematic, hence it should be reserved for niche areas where there is no viable alternative [3] (Liebreich, 2021).

Saving energy and improving the efficiency of systems is always a good idea and also makes economic sense. However the gains are offset by an overall increase in energy use, the so called "Jevon's paradox" [4] (WikiPedia - Jevon's Paradox, n.d.). Energy conservation alone, though useful, will not be a decisive factor in the energy transition for defence. The gains are just too small but nevertheless should be pursued.

The smart application of energy for the purpose(s) intended/needed, means an optimal match of energy sources, technology and design decisions. An example could be increased use of smaller (expendable) unmanned systems needing less or no armour, no space nor life-support for crewmembers needed, thus less, or different/smaller energy sources required. Another example could be a clever hybrid combination where shortcomings in one area are compensated for by strength of other technologies.

In the near and short term civilian expansion of classic renewable sources will continue. The scarcity of clean energy though makes it irresponsible to waste this by employing inefficient technology or applications. The continued improvement and adoption of solar and wind will (indirectly) contribute to the energy transition for defence by driving defence specific R&D. In many respects the military can follow civilian technology albeit selectively and with an emphasis on robustness and safety especially with regards to storage and transport.

Most of the shortcomings and gaps in the energy transition can be eclipsed when it becomes possible to generate large (scalable) amounts of clean energy independently and in a concentrated fashion. This is only possible through the use of nuclear technology [5] (United Nations Economic Commission for Europe, 2021). We see possibilities for small modular reactors (SMR) close to in-country military bases. These could be used to not just generate heat and electricity but could also play an important role in the production of hydrogen and synthetic fuels. Commercial efforts along these lines are already underway and will come online in 2027 [6] (Kryssare and Vattenfall, 2021).

[1] Logistics friendly

For smaller bases and remote applications there is a big role for so-called micro reactors (XSMR) These deliver heat and electricity ranging from several MWe to a dozen or more MWe. They are very robust and consist of just a few standardised freight containers which can run for years without ”refuelling” [7] (U.S. Department of Defense, 2022). Units could be coupled with other modules that are specifically designed for synthetic fuel production [8] (Karlsruher Institut für Technologie, 2022) or water purification. The fact that so much dispatchable clean energy is on tap makes this a must have asset for any military. Development is already underway and several demonstrations are slated for 2025/2027 (see ANNEX D).

Summarising, we can state that while classic renewable sources are gaining ground, their dependency upon critical materials, whose extraction and processing is dominated by geopolitical adversaries, is problematic. The world wide scramble for these materials will drive up the price, while the western buying power will edge out developing nations. Paradoxically these countries could benefit the most from these technologies. Furthermore the ecological impact is not to be underestimated [9] (Maughan, British Broadcasting Corporation / BBC, 2015) as these resources are frequently located in sensitive natural ecosystems. A clean technology which has the smallest ecological footprint is therefore preferable [10] (Gladek and Van Exter). This clearly is nuclear.

Finally a combination of technological improvements and innovations will deliver the best overall results. Phasing the technology and investment well is essential. Short term gains should not impede long term needs. Pareto’s principle tells us that for many outcomes, roughly 80% of consequences come from 20% of causes [11] (WikiPedia - Pareto, n.d.), [12] (TechTarget, n.d.). This is why the EROI metric is so important (and logical) and why innovation matters so much.

INTRODUCTION

While maintaining the required operational effectiveness, a successful energy transition for defence needs to:

- take into account short and long term solutions (i.e. 2030, 2050 and beyond)
- invest in innovation because this offers the best return by far (up to 11 times better when compared to other climate policies)
- drive technological downstream developments (improve efficiency, discover new methods)
- promote fundamental and abundant energy availability (e.g. energy security)
- develop non fossil powered weapon systems keeping energy autarky, logistic compatibility and quick deployability in mind.

We investigated along the following lines:

- efficiency and energy conservation
- role of hydrogen and synthetic e-fuels
- application of small and medium scale nuclear energy technology
- smart defence application, integration and design

MAIN CONCLUSIONS

Comparing climate impact policies, innovation offers by far the biggest return and hence should attract most investment and effort.

Small unmanned systems like UAVs, need less armour nor space and life-support for crewmembers and thus less energy. These could complement or perhaps even replace larger traditional manned systems. Energy storage, either electrical in batteries, e-fuels, hydrogen tanks or another medium such as iron powder, needs to be made efficient, rugged, safe and reliable for military use. Modular design of energy systems will enable swapping in/out new/old tech as it becomes available thus making it future proof.

Existing fossil technology needs to be improved through cleaner combustion technology (DFI[2]) and cleaner fuels (DWE[3], OME[4]). Retrofitting existing systems makes quick results possible. A hybrid combination of a methanol fuel-cell, a battery, and a methanol engine or generator, can result in an electric vehicle that has endurance and can be quickly charged or refilled. All the technology needed already exists but needs to be integrated. Ammonia can be a viable energy carrier for maritime application but some development is still needed.

The ultimate source of clean, reliable and dispatchable heat and electricity is nuclear. For military applications the development of freight-container sized micro-reactors is of critical importance. The US is pursuing this and so should the EU.

Synthetic fuels can be produced by pairing nuclear reactors with chemical installations. Nuclear can deliver the heat and electricity for the process itself but also to produce the feedstock needed. This needs to happen on both a small scale and large scale.

[2] Ducted Fuel Injection
[3] Diesel Water Emulsion
[4] Polyoxymethylene dimethyl ether

For many industrial processes high temperature heat is required which enables different processes and improves efficiency considerably. Therefore the development of high temperature molten salt or gas cooled nuclear reactors is essential in the long term. This technology has already been demonstrated in the 50's in Germany and more recently in China on a substantial scale.

In the short term, current (fossil) systems can be made cleaner and more efficient while simultaneously developing clean and lean alternatives to replace them. In the long term CO_2 neutral or even CO_2 negative solutions will need to become available. To achieve this, at the elevated scale needed, the most efficient solution by far is nuclear energy. On top of that it satisfies geopolitical concerns about supply chain security and spares the natural environment.

The current deployment of classic renewable energy sources is driving the ever improving technological solutions and the need to conserve energy. This will continue but will not be sufficient in the long run. This is due to the fundamental problem that, in order to obtain the energy from renewable sources, we are fighting an uphill battle against entropy i.e. the 2nd law of thermodynamics [2] (Rhebergen, 2022). The same is to some extent also true for nuclear energy but here the return on energy invested is orders of magnitude larger.

Large scale adoption of nuclear energy will inevitably be needed [5] (United Nations Economic Commission for Europe, 2021). Hence development and deployment of nuclear energy technology at both small and medium scale needs to be accelerated. This means that the defence domain should consider the availability of nuclear energy as a core strategic asset both at home and during operations. Just like investments for frigates and submarines, substantial billion-Euro order of magnitude budgets are reasonable and necessary here.

PROPOSALS/RECOMMENDATIONS

Below are some potential projects that could be supported by the European Commission. In particular when commercial developments are lacking or will not be available soon enough. Additionally some recommendations are listed which will also support the energy transition for defence.

PROPOSED PROJECTS

Energy storage,[*)] be it through storage of electricity in batteries or hydrogen in tanks (or another medium) needs to be made rugged, safe and reliable for military use.

Improving current fossil based systems[*)] by reducing emission and improving efficiency, could be achieved by ducted fuel injections (DFI) and diesel/water-emulsion (DWE) technology. These could potentially be retrofitted on existing engines and thus have an immediate effect in the short term. Specially engineered oxymethylene ethers (OME) based fuels offer an extremely clean burning alternative to diesel, especially when these can be produced using clean and sustainable sources and feed-stocks.

Hybrid technology[*)] such as a combination of a methanol fuel cell, battery, and a methanol engine, could result in an electric vehicle that can be charged using clean sustainable electricity but also has endurance due to the methanol fuel cell and combustion engine.

Methanol and ammonia[**)] are potentially clean fuels if produced sustainably. The use of ammonia is especially suited for maritime applications but needs to be developed further (i.e. technology and supply chain).

Micro nuclear reactors[**)] will be a reliable source of clean sustainable power that can supply heat and electricity independently and for prolonged periods when other sources cannot fill the gap.

Europe will need its own micro reactor specifically designed for military use, i.e rugged, trans-portable, low maintenance, etc.

Sustainable synthetic fuels[5**)] are intended to replace traditional fossil fuels as a drop in replacement[6]. These need to be produced at a substantial scale using sustainable energy sources and feed-stocks. Efficient large scale production can best be achieved using a small modular nuclear reactor (SMR) paired with a chemical/industrial plant. Small scale containerised versions of these power-liquid installations, paired with micro nuclear power plants (XSMR), could provide an independent onsite fuel supply during operations.

Advanced high temperature reactors,[***)] be it molten salt or gas cooled, will enable a substantial jump in efficiency and unlock processes that rely on, or profit from, high temperatures (e.g. hydrogen production). These designs are also interesting from a safety perspective due to low pressure operation.

***) = long term, 10-20 year, **) = medium term, 5-10 years, *)= short term, 0-5 years.

OTHER RECOMMENDATIONS

In addition to the projects mentioned above, improvements on current technology is possible and will make short and intermediate term gains attainable.

- Apply modularity in design such that especially energy related platform elements can be replaced when better/cleaner alternatives become available (specially true for ships though not exclusively).
- Expand and complement use of UAVs to complement regular (traditional) platforms. Many tasks could potentially be assisted by (or even taken over by) UAVs or comparable technology.
- Complement and extend use of smaller, lighter and more agile unmanned systems that need not be heavily armoured as this saves fuel/energy.
- High energy laser systems and rail-guns are essential to counter future (or even present) threats. Where they will save on regular ammunition and related logistics. Suitable (pulsed) power sources for these systems need to be developed.
- Invest in digitisation of general replacement parts such that they can be 3D printed on demand instead of stored and shipped in thus relieving logistical pressure and energy use.
- Build small modular nuclear reactors (≈300 MWe) to supply electricity and heat to large military bases. These could be built on or near the bases and paired with industrial chemical plants producing fuels from sustainable feed-stock and supplying heat to the communities in the neighbourhood.

[5] Including e-fuels
[6] This enables prolonged use of already existing infrastructure thus saving time and CO_2 emissions.

ANNEXES

A. General overview and discussion
B. Synthetic fuels production
C. Hydrogen generation and application
D. Nuclear power applications and development

ANNEX A: GENERAL OVERVIEW AND DISCUSSION

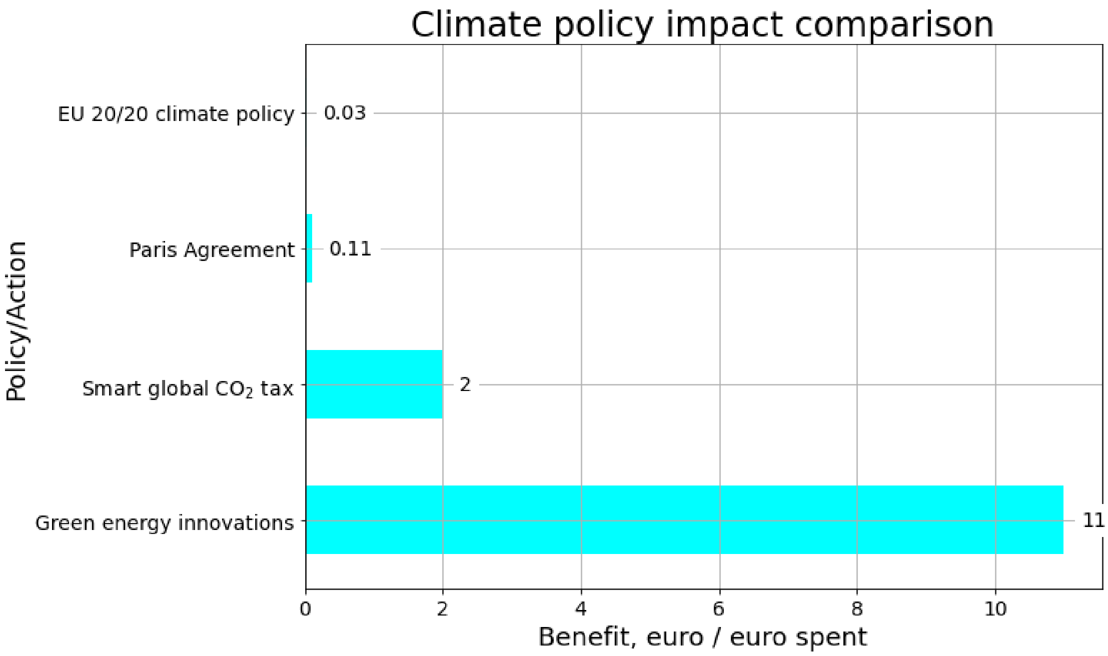
The energy transition is currently one of the most important topics in national and European policies, governments and society. The European Green Deal is a top priority. Billions of euros are being allocated and spent on research, development and implementation of new technologies.

However, all these policies are primarily directed to civilian applications in society. On one end we see huge (liquified) hydrogen factories and nuclear power plants at fixed locations and on the other end of the spectrum, we see small applications for individual private use. The military will also need small, high-density, reliable, mobile and rugged systems for power generation and invulnerable assets with a small logistic footprint for use during operations. If possible, energy should be generated and stored locally to quickly replenish electric charge or fuel levels of vehicles and equipment. Since energy usage is likely to increase exponentially over the next few decades, energy delivery and management will remain a continuing challenge. These are not necessarily a priority in the Green Deal.

In addition to this, and as a consequence of the recent conflict in Ukraine, discussions on autonomy and self-sufficiency of energy are increasing. Energy dependencies on other countries will in future conflicts be increasingly used as means of pressure (i.e. "weaponizing energy"). The European Union and individual Nations must find solutions to have sufficiently suitable energy supplies available for all levels of a conflict. For military use, dependencies and risks should be analysed to determine necessary investments.

Most Ministries of Defence do not intend to spend their funds on R&D for energy transition but follow the developments in civilian technology. Consequently, new military capabilities will likely be equipped with current power generation and propulsion systems. Because these capabilities are being designed to be used for a 30-40 year life span, the 2050 sustainability goals may not necessarily be met. Worse, these capabilities could become useless if the availability of fossil fuels declines in the next decades or even earlier, which is a geopolitical vulnerability and has direct operational impact. Therefore energy security, suitably matched by energy transition should be a top priority.

While the Green Deal initiative is progressing, it is important to discuss options to overcome the sustainable technology gap for Defence, and implement policies to increase the availability of specific energy transition technology for military capabilities. It has been shown that historically innovation offers the most "bang for the buck". Hence, a specific course for Defence energy innovation needs to be plotted. See *"An Analysis of a Technology-led Climate Policy as a Response to Climate Change"* by Isabel Galiana & Christopher Green for the Copenhagen Consensus Center [1] (Galiana and Green, 2010). Note that this result depends on the chosen model(s) and other parameters like discount rate etc.



Several of the issues described in the introduction will be discussed in the next paragraphs:

- Major defence systems, planned to be used long past the 2050 goal.
- Defence systems with a short(er) life span,
- Specific sustainable energy technologies and/or alternative solutions/approaches,
- Limitations of options.

MAJOR CAPABILITIES WITH A LONG LIFESPAN

Major military capabilities planned to be built in the near future with an intended lifespan of 30 years or more will use their power systems long past the 2050 goal. When using traditional power systems these may not be able to operate beyond 2050 or only at a very high cost from unreliable sources. Hence, in the design and construction phase, this needs to be considered, e.g. modular energy and propulsion systems that could potentially be upgraded or swapped with newer and alternate technologies.

Examples are:

A. Naval ships

In general: when using X-electric propulsion the unit generating electricity should be exchangeable in the future. X could currently be diesel and swapped to be fuel-cell, ICE running on synthetic fuels or methanol etc.

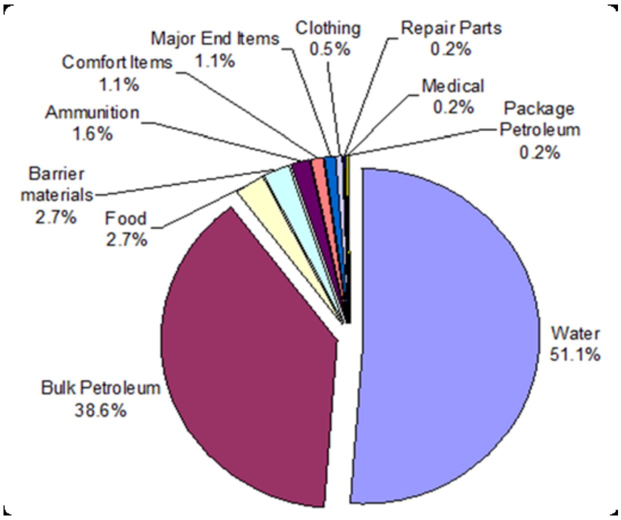
a. Combatants. Large combatants (cruisers, aircraft carriers, submarines) can use nuclear energy. However, a joint effort is needed to overcome technical and financial hurdles. Smaller combatants best focus on diesel-electric propulsion with drop-in fuel replacement potential (synthetic, methanol, ammonia, etc.).
b. Non-combatants best follow commercial shipping innovation: emerging technologies and alternative fuels, complemented by wind-solar power if possible/suitable.
c. Autonomous and small vessels.
Focus on fuel cell technology, hydrogen storage and battery electric packs.

B. Aircraft
   a. Large transporters and surveillance aircraft can make use of commercial technology, like Sustainable Aviation Fuels (SAF) or perhaps hydrogen.
   b. Unless Adaptive Engine Technology can provide a breakthrough, fighter aircraft could be complemented or perhaps even replaced by armed UAVs.
   c. Besides maturing battery technology, smaller UAVs can make use of fuel cell technology and perhaps some form of stored hydrogen.
   d. Missiles use fuel only once. The relevance of adaptation to meet energy transition criteria is low.

C. Land vehicles and fixed systems

General: If possible, in operational areas energy should be generated and stored locally to quickly replenish electric charge or fuel levels of vehicles and equipment. New applications could be exchangeable compact alternative power sources (batteries, stored hydrogen,synthetic fuel, etc…) .
   a. Supplying large armoured vehicles with fuel in a hostile environment is already challenging. Currently no credible alternative power technology can overcome logistics and weight/space constraints. Some weight reduction can be achieved by replacing armour with composites. Potentially, the best way ahead is to make protection less important by operating systems remotely. Replace current systems with unmanned, smaller, lighter and more agile systems including alternatives for quick fuel/power replenishment..
   b. Armoured systems that inherently need mass to be effective like artillery, break-through and bridge-laying systems inevitably do need drop-in synthetic fuels to replace fossil energy.
   c. Fixed military sites. Use commercially available systems. If necessary reinforced and protected to meet military requirements. Potentially, this could also lead to dual-use solutions relevant for commercial applications.
   d. A combination of existing technology could alleviate drawbacks of one component with advantages of another. Hybrid applications that include a battery, a methanol fuel-cell and a conventional methanol combustion engine could result in a sustainable electrically powered vehicle that also has endurance while also using alternate sources of propulsion energy.

D. Miscellaneous
   a. High-energy laser (HEL) systems and railguns need very high-energy pulses. These pulses can not always be provided with commercially available power sources. In these cases, technology must be developed for these specific purposes only.
   b. A considerable amount of fuel and operational assets are used to ship-in fuel, drinking water, supplies and spare parts. Additive manufacturing (3D printing) and drinking water production on-site by desalination and purification could reduce this burden on logistics.



Logistic requirements for out-of-area operations

CAPABILITIES WITH A SHORTER LIFESPAN

Often smaller capabilities used for deployment in combat cannot use civil energy transition technologies due to safety concerns. These may even be unable to meet the 2030 deadline of the sustainability goals. That means solutions have to be provided in the next decade.

Examples are:

A. Smaller vehicles.
Permitting weight and size constraints, smaller combat and transport vehicles may need to follow the commercial market and adopt electrification. It allows for better use of available power and (additional) recharging by nuclear, solar and wind power during downtime.

B. Out-of area operation
Armed Forces could reduce their fossil fuel dependency by procuring commercially available technology for accommodation, sanitation and non-operational transportation. However, a comprehensive plan and a budget are necessary.

TECHNOLOGIES

Specific sustainable energy technologies that could resolve the issues mentioned above are described in this chapter. Including current status and specific needs for Research and Development to make these technologies available for military use on time to reach the 2030 and 2050 sustainability goals.

A. Alternative (synthetic) fuels
Alternative fuels will impact the design of weapon systems, may be dangerous or toxic, difficult to handle logistically and/or less readily available worldwide. Of all potential options, drop-in (synthetic) fuels seem to be the most feasible. Good candidates are ammonia and methanol. Specifically engineered (synthetic) fuels may also be needed. ANNEX B delves deeper into this topic.

B. Hydrogen
Is a clean energy carrier which, once it is available, has some great advantages. However, producing hydrogen is energy intensive and quite inefficient (see article in references). When transport and

storage of hydrogen is also needed the efficiency drops even more. This means that hydrogen, by preference, should be used when and where it is needed and there are not viable alternatives. In fact hydrogen production may even result in higher CO2 emissions. ANNEX C addresses these issues and explores possible ways to mitigate the aforementioned problems. Hydrogen production is also an important feedstock for synthetic fuels. Inefficiency in hydrogen production can be negated by plentiful availability of energy. This makes nuclear energy a good fit.

C. Nuclear energy
As nuclear energy regains interest as an indispensable technology to combat climate change, the military must seize the opportunity to implement this technology, especially for larger (maritime) combatants, but also for land-based transportable nuclear power generation. Promising developments in the area of microreactors are on the cusp of being realised and will make a meaningful contribution to many (military) aspects like on-site heat, electricity, synthetic (jet) fuel and hydrogen production as well as water desalination and purification. ANNEX C analyses the current developments and potential of small modular reactors, micro reactors and high temperature (molten salt) reactors. The latter will be an important source of process heat needed in chemical reactions for the production of hydrogen and synthetic fuels

D. Electrification
Electrification is essential for both the market and the military. Not only because it makes optimal use of available energy (i.e. more efficient) but it also allows for a variety of sustainable origins (i.e. wind, solar and nuclear). Also important for military applications, electricity can be generated on site and can be used directly or indirectly to propel vessels and vehicles. Various generation and storage systems can be used when vehicles are driven electrically. These could be exchanged in the future when more advanced generation and storage become available.

E. Robotics
Weapon systems are designed to deliver impact and to allow for a safe return of the crew. A breakdown of weight, speed and manoeuvrability often reveals that more weight is used for survival than for impact. An unmanned weapon system may be more vulnerable in combat but that often pays off against lower costs for both production and operation (e.g. fuel costs).

F. Digitalisation rather than transportation
Transportation requires a substantial share of operational energy. Introducing new digital tools to reduce transportation (3D printing, remote surgery, technical assistance etc.) can reduce the costly transportation of people, tools and supplies.

LIMITATIONS

A. No credible scenario or emerging technology will completely cover the phasing-out of fossil fuels. This is true unless synthetic fuels become economical to produce which will only be the case when there is an abundance of energy available. In the short to medium term the armed force's best chance to tackle this challenge is to develop new weapon systems that inherently use less fuel than the systems they replace.

B. The defence industry and engineers, albeit essential for the energy transition of the military, must avoid the impression that they alone can ensure that the military will meet the 2050 goals and vice versa. After all, everyone is restricted by the laws of physics and engineering principles such as the

Carnot cycle. It is up to the military to develop strategies, tactics and operating procedures that will allow for new weapon systems as indicated in the previous paragraphs.

CONCLUSIONS

Preparing the military for the energy transition requires a Herculean effort. We suggest the European Commission and national MoDs to address the topics mentioned below (in no particular order):

1. Reduce the need for energy by developing weapon systems that inherently (size, weight, speed) use less fuel than the ones they replace. Unmanned, remotely controlled or autonomous. If onboard personnel is not necessary anymore, all requirements for humans can be removed. Space, protection (armour), air conditioning and heating, food, water and more. This will save quite some weight and space and reduce the need for energy.
2. Energy usage is likely to increase exponentially over the next few decades. For this reason, energy for military purposes should be generated and stored locally. During operations, the military will need small, high-density, reliable, mobile and rugged systems for power generation and invulnerable assets with a small logistic footprint and quick refuelling/recharging..
3. When size and space restrictions permit, change to X-electric, where X currently could be diesel, to be replaced by non-fossil synthetic fuels once these become available. Small unmanned systems can make use of battery or fuel-cell-powered electric systems.
4. If downsizing is unrealistic, change to unmanned systems/loitering ammunition (land, air, sea). Compensate for a potential loss of operational impact by providing the military with larger quantities of systems.
5. For non-combatant capabilities, armed forces should follow market innovation and adopt alternative fuels. Current and near future combatants are bound to drop-in fossil fuel replacements. In order to guarantee the availability of drop-in (synthetic) fuels, the European Commission and national MoDs should encourage R&D and promote drop-in replacement synthetic fuels to mature and reach the market.
6. Energy storage, be it through storage of electricity in batteries or hydrogen in tanks (or another medium) needs to be made rugged, safe and reliable for military use.
7. For the medium to long term, the European Commission and national MoDs should Invest in new high-density and high-availability energy sources as well, with the considerations of required autarky and self-sufficiency during all levels of a crisis. Substantial scaling up of nuclear energy and hydrogen feed-stock production have strong cards and will also benefit society as a whole.
   As long as development of large scale alternative fuel infrastructure is unlikely to be introduced any time soon, MoDs could invest in small nuclear power stations (200-400 MW) at several military locations that could also be used to produce synthetic fuels, (compressed) hydrogen and supply heat. The annexes on hydrogen, synthetic fuel and nuclear technology expand on this topic.

ANNEX B: SYNTHETIC FUELS / EFUELS

This annex offers a non-exhaustive overview of synthetic-fuel(s) related issues. It has been compiled with some boundary conditions in mind:

- availability of enough clean/sustainable energy
- current status quo and nascent technological pathways
- need and potential for defence applications
- medium to long term horizons

An e-fuel, or a synthetic fuel (synfuel), is created using sustainable or renewable energy sources and non-fossil feed-stock, turning them into a fuel similar to actual fossil fuels. The main kind of feed-stocks employed are hydrogen and carbon-(dioxide). To achieve a true net zero CO_2 effect, not only the energy but also the required feed-stock has to be sourced from non-fossil origins. In this way an artificial fuel can be produced that can replace traditional fossil fuel(s) as a drop-in replacement(s). The main advantage here is that there is no need for a change in handling or completely different infrastructure requirements.

Instead of employing carbon-(dioxide) it is also possible to use nitrogen which leads to the production of ammonia as an alternative fuel or a secondary feed-stock for other downstream products e.g. fertiliser. Ammonia could be labelled a synthetic fuel but usually is regarded as a method for storing hydrogen [13] (United States Department of Energy, Office of Energy Efficiency & Renewable Energy, n.d.) An example of the use as a maritime fuel for sustainable shipping can be found in the proceedings of the 18th annual Ammonia Energy Conference in a presentation by LucidCatalyst director Eric Ingersoll [14] (LucidCatalyst) (Ingersoll, LucidCatalyst, 2021)

Specifically engineered (non)drop-in[7] replacement synthetic fuels may be interesting due to cleaner combustion and upstream advantages such as less complicated manufacturing or less energy intensive production methods. This however is not a given.

With all energy sources one should consider the following aspects:

1. energy density (how much is available per mass or volume unit)
2. energy transfer (how quickly it can be handled/transported)
3. energy efficiency (how much of the initial energy remains from source to endpoint after conversion losses)

[7] These may or may-not be drop-in replacements

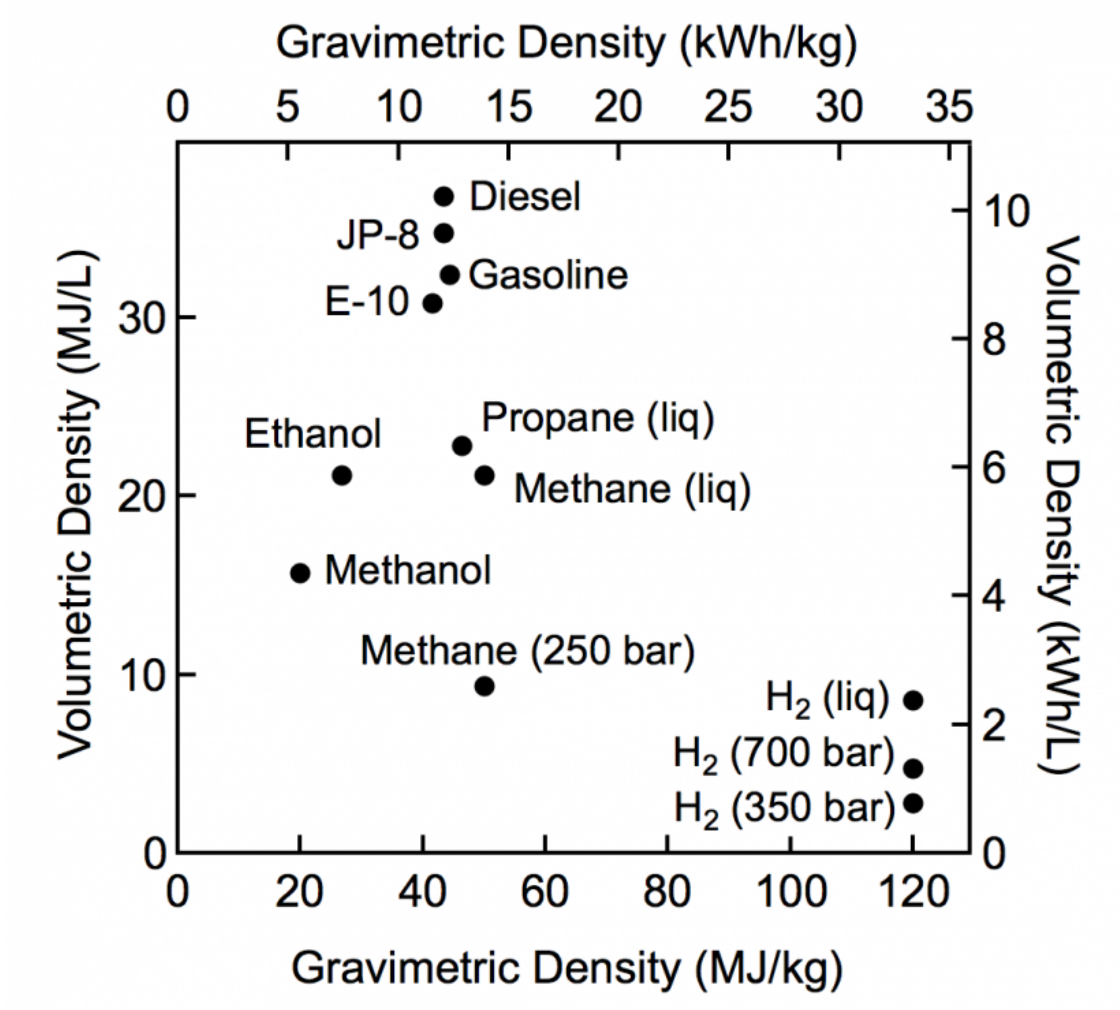


Image credit: [13] (United States Department of Energy, Office of Energy Efficiency & Renewable Energy, n.d.)

GENERAL NOTES ON FUELS

- Any fuel is a form of safely stored (chemical) energy that can be released in a very short amount of time
- Fossil fuel can be considered a very old bio-fuel that has been subjected to a pyrolysis process in the Earth and it now exists in a different chemical composition but is essentially still a biofuel.
- A synthetic fuel[8] is a human made fuel (engineered according to our needs, i.e. easily stored and released) potentially using other raw materials[9] which can but need not be biofuel.
- The most obvious synthetic fuel candidate is methanol for various reasons:
  - Simplest form of alcohol (1 C, 3H and 1 OH group)
  - The Sabatier process can produce methane or methanol depending on conditions/mix/components.
  - Methanol is not a greenhouse gas unlike methane.
  - Although toxic to humans it is biodegradable (a spill can simply be diluted/dissolved with water and environmental damage is very local and temporal limited) eventually it will be

[8] We include e-fuels which are synthetic fuels that are produced using electricity.
[9] Potentially recycled.

broken down by biological organisms when the concentration is below a certain threshold (unlike a petrol or diesel spill).
  - Unlike methane it is a liquid at and around room temperature which makes it easy to handle (pump/pour/transport/store).
  - Great fuel for an Otto-cycle engine, high octane rating. The single carbon atom per molecule means you can easily disperse/mix it to create any desired fuel/air rat to.
  - Burns cleanly and Otto-cycle engines can reach high compression ratios running on methanol.
  - There is already an industry that produces and uses methanol for many applications.
- A switch from heavy (bunker) fuel to methanol fuel would clean up the maritime industry enormously.
- Maersk shipping is in the process of switching their ships to methanol. This will have a tremendous positive impact on air quality.
- MAN will have heavy engines available (maritime applications?) that run on methanol or or can be easily adapted to run on methanol by 2024.
- Hydrogen is necessary as feed-stock for many products but hyped too much. Serious issues remain if hydrogen is used as a fuel just as it is although this may change.
- H_2 has high energy density per mass but low energy density per volume (even if compressed or liquefied) This makes storing and transporting it very difficult and energy intensive. On top of that it embrittles steel. This makes the best material to use (e.g. for transport and storage) unfit for hydrogen applications.
- H_2 cannot easily replace methane infrastructure (e.g turbines or burning/combustion) It can be blended (dissolved) with methane up to about 10% maximum.
- Methanol can be mixed with petrol in any ratio and Otto-cycle engines can simply be modified (retrofitted) to adapt to this mixture.
- Hydrogen has only been used as a real (combustible) fuel in the space industry which proved difficult to master and still is quite problematic due to H_2 properties. Currently other rocket fuels are preferred because of the many drawbacks of H_2 (despite its advantages). Space-X uses kerosene or methane both with liquid oxygen. Others like Blue Origin follow the same path and have not adopted hydrogen for similar reasons. This despite deep pockets (budgets) and huge manpower available in the space industry to “babysit” the (hydrogen) fuel. Fossil fuels (or drop-in compatibles) are far less problematic in this respect. Countries have strategic supplies of fossil fuels that can last for months (or even much longer) without the need to “babysit” this facility. This is very problematic with hydrogen! (it has a tendency to leak easily).
- Four viable methods to produce hydrogen:
  1. Geo-thermal energy
  2. Hydro-electric power
  3. Nuclear energy (both heat and electricity)
  4. Methane pyrolysis (use heat in an inert environment to decompose methane into hydrogen and solid carbon which can be easily stored).
- Using steam methane reforming (current industrial default method) [15] (Rhebergen and Sikkema, 2022) one cannot really catch all the CO_2 and neither will one be able to store all that one can capture. Additionally there are concerns about the longevity of the proposed storage methods. This is not the case when using pyrolysis.
- Though there might (always) be some methane leakage it will decompose in the atmosphere unlike CO_2 which lingers in the atmosphere virtually indefinitely.
- To counter the greenhouse effect it is therefore sufficient to limit or slightly decrease the total methane emissions despite its larger effect.

- Carbon capture is making some progress although still expensive it is not as crippling for the energy transition as initially thought. Biogenic capture is (still) hotly disputed as a carbon sequestering method and indeed it must be carefully weighed when applied whether used as a source of energy or a source of carbon.
- Carbon removal from surface (sea) water is slanted to be more efficient due to the higher concentration compared to ambient air. Carbon removed from the ocean will be replenished due to a tendency to maintain an equilibrium with the rest of the environment (i.e. atmosphere).
- The cooling towers of nuclear power plants can be used as huge carbon capture devices by dissolving a base to the cooling water making it alkaline. When the water is then sprayed in the cooling tower the naturally up-drafted air will mix with the alkaline water and carbonate salts will be formed binding the ambient CO_2. Hence besides quickly cooling (evaporation entropy of water is very high, i.e. one only need to evaporate little water to absorb a lot of heat) it also removes carbon thus a nuclear power plant can in fact become carbon negative. The salt can be collected at the bottom of the cooling tower and in a further process step be decomposed (separated) into the alkaline solution and captured CO_2 again [16] (World Nuclear News, 2022).
- Nuclear power plants (NPP's) that use sea water for cooling can use a similar process to decarbonise the sea water.

NOTABLE DEVELOPMENTS

Methanol [17] (The Methanol Institute, 2021) can be made from natural gas, from coal, from any organic wastes, from algae, etc. It can also be made from hydrogen and carbon-dioxide. If methanol is chosen as a synthetic fossil fuel replacement there are some interesting developments [18] (Myers and Rhoda, 2021) that deserve attention. Naturally we still want the source of carbon to be non-fossil. The next sections outline some developments that could be of interest.

METHANOL FUEL CELL DEVELOPMENTS

Application of these fuel cells for mobility applications have been investigated by e.g. Mercedes and Audi in the past. Currently there is some renewed interest due to the efforts of mr. Roland Gumpert from Ingolstadt Germany who has integrated a methanol fuel cell, together with a battery acting as a buffer and an electric motor into a high performance car. This results in an electric vehicle with desirable characteristics of both an extended range and fast reloading (not charging) by tanking methanol in a matter of a few minutes [19] (GUMPERT AIWAYS AUTOMOBILE GmbH, n.d.). However closer inspection uncovers some caveats. The methanol fuel cell has a limited capacity not really delivering enough power for sustained high speeds. The (smaller) battery is charged by the methanol fuel cell when the car is parked and thus it could be viewed as a kind of range extender. This in itself may be an interesting application. Under certain conditions methanol fuel cell emissions may also consist of carbon monoxide. If not solved or prevented this of course is quite problematic. The Danish company [20] (Blue World Technologies - Automotive, n.d.), supplies the used methanol fuel cell and claims clean emission. The fact that methanol is less energy dense thus needing a bigger tank is offset by the need for a smaller/lighter battery. It is also claimed that the fuel cell efficiency partly makes up for this reduced energy density.

The technology may be not quite cheap enough for mass production and technically a bit more/too involved, but it makes for an interesting military use case. It is thus possible to make an electric vehicle (or hybrid) that can be charged via a plug/outlet like other EV's but the combination of a methanol fuel cell solves a couple of problems. For instance if the vehicle's battery is depleted and the fuel tank empty you can just take on additional methanol which will produce a modest amount of power which can be enough to move the vehicle although not at maximum specifications (i.e. back to base or out of harm's way). As methanol can be used in Otto-cycle engines the combination mentioned above can be complemented by a regular internal combustion engine turning it into an interesting hybrid concept. This does not exist yet and is a worthwhile development to pursue as the individual components are already proven technology.

CLEAN (BIO)DIESEL ENGINE TECHNOLOGY

Ducted Fuel Injection (DFI) [21](Charles Mueller, Combustion Research Facility, Sandia National Laboratories, 2019) is a high potential technology that can cut particulate matter output by between 50% and 100% depending on circumstances [22] (Ashley, Scientific American, 2019).

Its principle of operation is akin to the venerable Bunsen burner. This common piece of lab equipment has a tube that (con)ducts the gas upwards while drawing in air from below, burning cleanly with a small bluish flame. Remove the tube and the flame will become orange/yellowish due to the glowing carbon (soot) particles. Similarly the DFI achieves a far superior clean combustion of fuel, compared to traditional piëzo electric or solenoid operated fuel injectors.

The DFI injectors reduce the amount of fuel used by a factor of between 2 and 10 thus increasing the overall efficiency. The excess fuel in traditional injectors tends to generate correspondingly increased amounts of carbon particles/soot.

The fact that carbon particulates are virtually removed means that other problematic emissions can also be reduced for instance by increasing the exhaust gas recirculation [23] (WikiPedia - EGR, n.d.) which in turn will substantially decrease NO_x output. Because there will be no carbon deposits in the EGR system (valves) this will have a positive effect on the reliability of this system as a whole as well.

It appears that older engines may be retrofitted with these types of DFI components while earlier less effective emission control measures previously introduced are superfluous and can be removed increasing reliability and decreasing maintenance cost.

Not having to build new vehicles but cleaning up older ones, extending their operational lifetime while improving reliability is of course also a gain for the energy transition and environment. After all, building a new truck/engine costs CO_2 and needs to be offset or compensated during its operational lifetime.

ULTRA CLEAN SYNTHETIC FUEL TECHNOLOGY

Poly(oxymethylene) dimethyl ether is a collective term that contains a number of CH_2-O units (usually between 1 and 8). Oxymethylene Ethers (OME) engineered fuels are extremely clean burning and a potential alternative to regular fossil based diesel fuel. Currently several synthesis routes are researched to determine most efficient options.

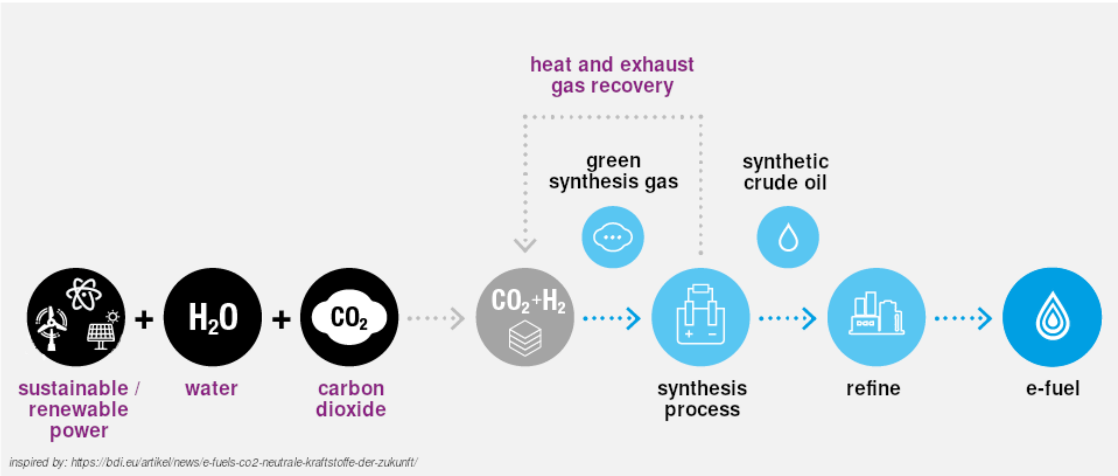
The composition varies from OME2 to OME6 or from OME3 to OME5. These mixtures have the advantage that they are close to diesel standards and can be produced by various synthesis routes. The actual technical challenges consist of optimising the process yields of existing synthesis routes as well as using renewable resources like biomass, residues, and wastes.

[24] (Härtl, n.d.) et al. investigated various oxygenated fuels and identified OME as the most effective for soot reduction. Storage stability and material compatibility of Polyoxymethylene dimethyl ether diesel like fuel (OME) are favourable and comparable [25] (Bongartz, Burre, and Mitsos, 2019). If biomass is used as carbon feed-stock studies show that it is possible to produce 277.3 tonnes/day of wet woody biomass can produce 9.02 tonnes/day of OMEs 3–5 through the gasification process [26] (Zhang et al. 2016) and [27] (Drexler et al. 2021).

POWER-TO-X (LIQUID) EFUEL/SYNFUEL PRODUCTION

So called "power-to-x" are process chains that use electrical (and/or heat) power in a multi-step procedure to turn CO_2 (from ambient air) and energy from sustainable sources into synthetic fuels. The steps can be summarised as listed below:

- Carbon-dioxide extraction from ambient air via direct air capture
- Simultaneous high temperature electrolysis of H_2O and CO_2
- Fischer-Tropsch synthesis in micro-structured reactors
- Processing of the product (e.g. hydro-cracking and isomerisation) for the production of conventional fuels



A completely integrated small modular system about the size of a standard cargo container has been demonstrated by "Karlsruher Institut für Technologien" (KIT), could be optimised and scaled up [28] (Karlsruher Institut für Technologie, 2022).

Shell, Vattenfall and Lanzatech companies agreed to investigate starting a facility that could provide SAS (airlines) with a quarter of its demand for sustainable aviation fuel by the 2030s. This process is quite similar to the one described above. The potential site for the plant is near the Forsmark nuclear power plant. It could be commissioned between 2026 and 2027, with the site able to produce up to 50.000 tons of synthetic jet fuel a year [6] (Kryssare and Vattenfall, 2021).

OUTLOOK AND RECOMMENDATIONS

As mentioned above the production of synthetic fuels depends on:

a) CO_2 free energy availability
b) non-fossil sources of carbon

For both there are some options available. Clean energy is currently in small supply and so are clean sources of carbon, making the production of synthetic fuels very expensive. On top of this, whatever the process and sources, it needs to scale up to truly incredible/ludicrous quantities given the current use of fossil fuels that we want to replace.

SHORT TERM

It is therefore advantageous to concentrate (in the short term) on areas where there is no true/realistic substitute (e.g. intercontinental air travel i.e. jet fuel). Sources of carbon feed-stock such as biomass can be regarded as problematic due to competition with food production and arable land which of course is undesirable. Apart from CO_2 free clean energy, there is also a similar need to obtain the required feed-stock(s) in a sustainable fashion. Hence capturing carbon needs to be made efficient and scale-able. Capture at the source and from the ambient environment (air/water) should both be investigated and invested in. Any process that will accelerate this is worthwhile exploiting/exploring further. Nitrogen based fuels could be investigated although perhaps less desirable due to toxicity and safety concerns. This research and development in carbon capture (and/or recycling) processes should be promoted while keeping previously mentioned boundary conditions in mind. Perhaps it would be a good idea to engage in a public private partnership to pursue these goals.

When deciding to investigate the application of synthetic fuels (e.g. for defence) it is advantageous to look at the complete picture for a particular application to decide which way to go (e.g. source of energy and feed-stock). Many factors and scenarios are to be taken into account depending on the requirements. It is therefore worthwhile to keep an up to date technological overview of the current state of art. In fact such an overview should be a dynamic software based system that can be interrogated to supply answers to a specific set of questions/conditions. Such an expert system could be maintained for the benefit of many potential stakeholders and would be a great asset to have.

MEDIUM TO LONG TERM

In the long run The only answer to sustainable procurement of clean energy and feed-stock is to generate an abundance of this energy. If all of this has to be achieved using technology currently used to harvest renewable energy it will not be sustainable due to the enormous need for critical/strategic metals and minerals. This will have a detrimental effect on the eco-sphere. On top of that competition for these materials will shape the geo-political landscape for decades to come. It is therefore of utmost importance to invest in nuclear energy generation. In the medium term building current state of the art nuclear power plants (NPP's) has to suffice but in the longer run we need advanced reactors such as molten salt reactors and helium gas cooled high temperature reactors which are already being tested. They will supply valuable high temperature heat energy that can be applied efficiently in industrial processes which can produce the required feed-stocks and synthetic fuels at scale, not to mention electricity and 'waste' heat.

These initiatives come to mind:

1. **Japan HTGR** - Helium gas cooled high temperature reactor (1000°C) capable to drive iodine-sulphur cycle to produce hydrogen, without needing to produce electricity and hence much more efficient [29] (Japan Atomic Energy Agency, HTGR Research and Development Center, n.d.), [30] (Japan Atomic Energy Agency, Oarai Research & Development Institute, n.d.), [31] (The Sankei Shimbun, Editorial Board, 2022).
2. **Thorizon** - A company based in The Netherlands which aims to develop a Thorium molten salt reactor [32] (World Nuclear News, 2022), [33] (Thorizon, 2022) that will produce high temperature steam of 550°C suitable to drive industrial chemical processes to generate hydrogen such as the copper-chlorine 4 step cycle [34] (WikiPedia - Cu/Cl cycle, n.d.) or the 2 step hydrogen-chloride (HCl) cycle [35] (Bicer, The 2nd International Symposium on Hydrogen Energy and Energy Technologies (HEET-2018), 2019).
3. **Terrestrial Energy** - Integral Molten Salt Reactor (IMSR) producing close to 600°C heat. This makes it very suitable to drive industrial processes needed to produce hydrogen similar to the one described above [36] (Terrestrial Energy, n.d.) [37] (Irish, Terrestrial Energy, 2022).

ANNEX C: HYDROGEN GENERATION AND APPLICATION

The reason hydrogen could play a role in the energy transition for Defence is the fact that, if generated from clean energy sources, it is an energy carrier that could be employed in various ways while not polluting the environment. Currently however, the bulk of all the hydrogen produced is from non-sustainable sources. Unfortunately there is very little hydrogen available produced in a sustainable fashion. Because of this tiny supply, a displacement effect occurs, paradoxically resulting in more CO_2 emissions during the production of hydrogen from (renewable) electricity than during the production of hydrogen from natural gas or coal. Unless some major obstacles are cleared, there currently is no gain for the environment/climate by producing hydrogen in this way. Only when there is a veritable glut of cheap plentiful sustainable CO_2 free energy, does it make sense to produce hydrogen. This is all explained in an accompanying article with references [15] (Rhebergen and Sikkema, 2022).

Transport and storage of hydrogen is also problematic. It has to be either cryogenic cooled to -253°C or pressurised to 300-700 bar. Both modes require an extraordinary amount of energy. Normally the best material to construct pipelines and storage tanks is steel. Unfortunately hydrogen has a tendency to embrittle steel which makes the application of steel for transport and storage problematic. Fortunately because hydrogen is an important feed-stock in the chemical industry there is experience in handling and producing hydrogen albeit not sustainable.

Once hydrogen is produced and pressurised, it is an attractive clean burning energy carrier. The graph included in ANNEX B about synthetic fuels, shows it has a very high gravimetric energy density. This (favourable) characteristics of hydrogen, its generation, storage and transportation more or less dictate the way it should be used. Preferably it should be produced where and when needed. To effectively deploy hydrogen one can choose one of several pathways (apart from pressurising) depending on the application.

As it is, plain hydrogen can be burned to generate heat however this is a bad idea. Heating with hydrogen from renewable energy is six times less efficient than using the same electricity in a heat pump. No serious energy analyst, not affiliated with the fossil gas industry, will promote hydrogen for heating. Hydrogen can also be employed to generate electricity in a fuel cell at about 60% efficiency. This fact shows that careful consideration of hydrogen use and alternatives are always a prudent approach.

HYDROGEN PACKAGED IN OTHER SUBSTANCES (MOLECULES)

There are several alternatives to the cryogenic or high pressure storage approach. To name but a few:

- Sodium borohydride ($NaBH_4$)
- Formic acid (HCOOH)
- Ammonia (NH_3)
- Hydrazine (N_2H_4) or hydrazone compounds
- Liquid organic hydrogen carriers (LOHC) ⟵(also nascent fuel cell technology) [38] (WikiPedia - LOHC, n.d.), [39] (DENS, n.d.)

These compounds all aim to store the energy that hydrogen can release (almost like a fuel). However the typical process to create ammonia (Haber-Bosch) is very energy intensive. When ammonia is used it releases nitrogen which may not be desirable. On top of that, ammonia is toxic. Similarly formic acid will release carbon-dioxide when employed as fuel. If this can be captured upon releasing hydrogen or added when producing formic acid we have a circular net-zero CO_2 system especially if the processing energy needed is also generated without causing CO_2 emissions.

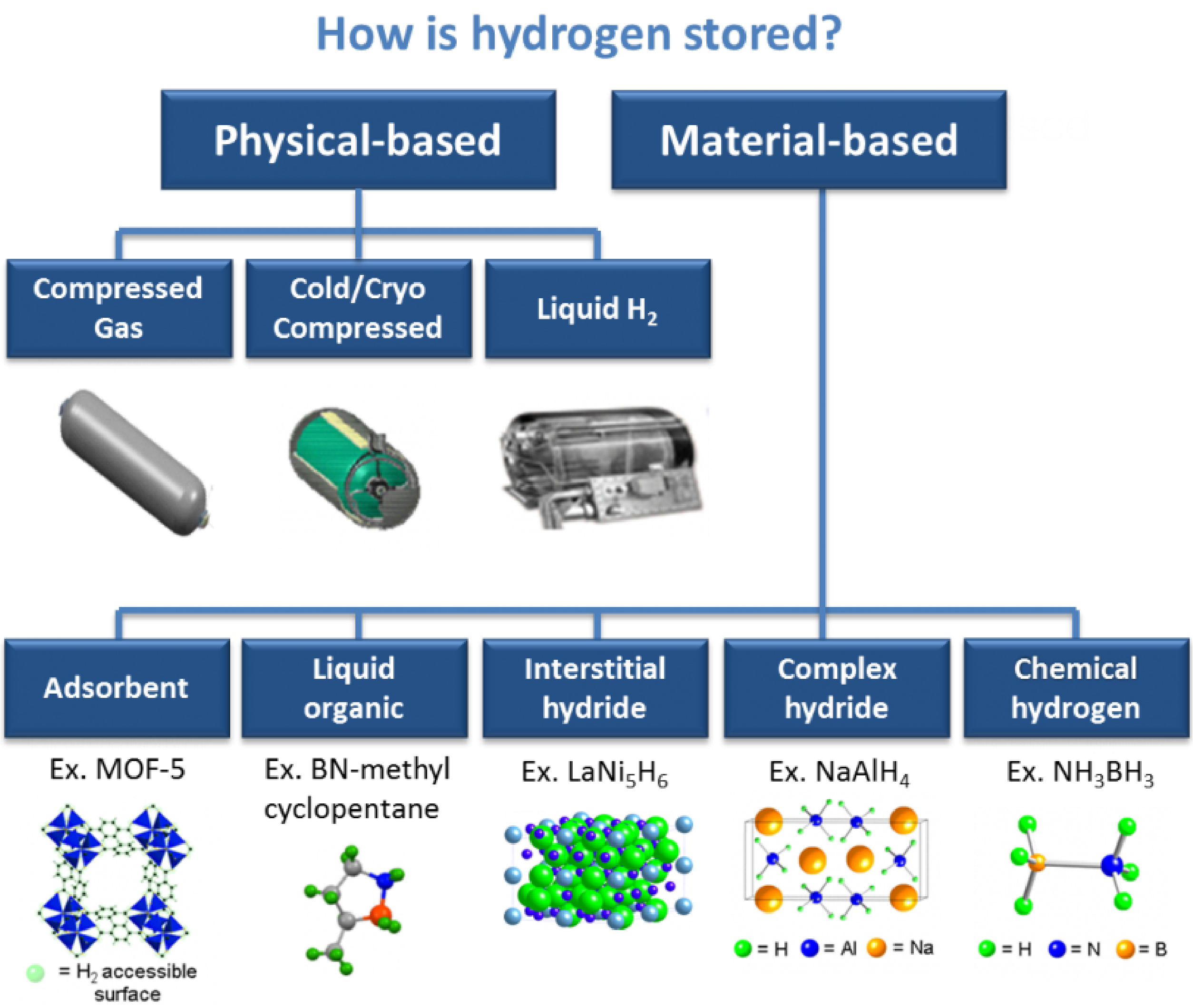


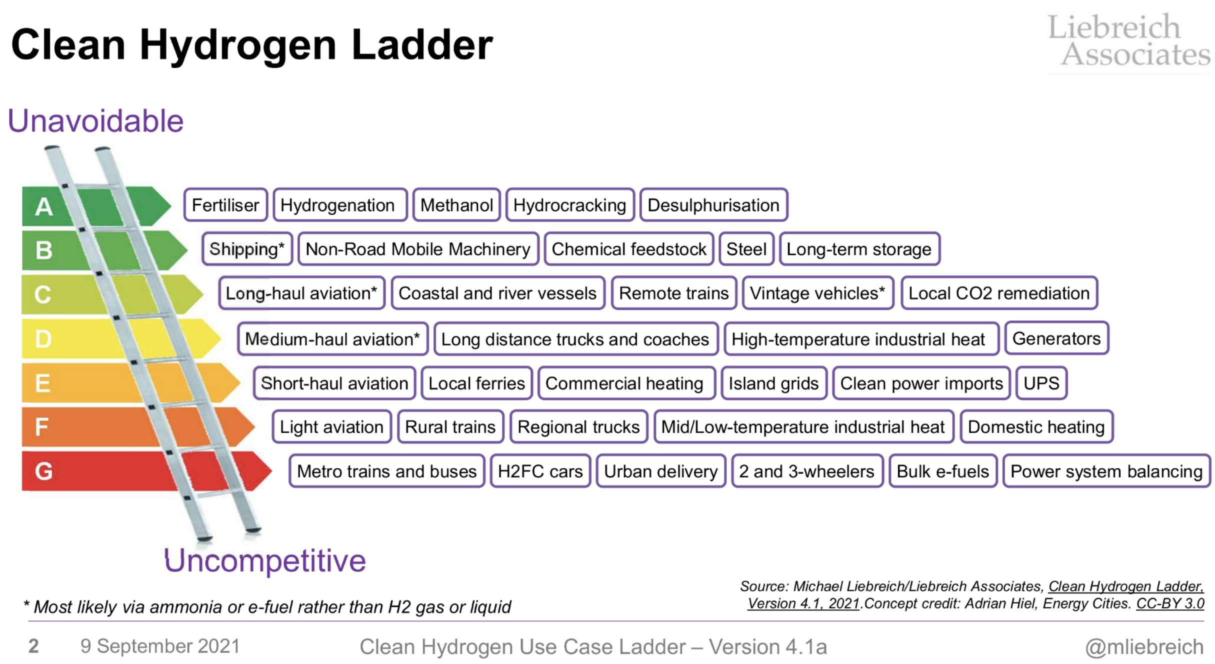
Image credit: [[13] (United States Department of Energy, Office of Energy Efficiency & Renewable Energy, n.d.)]

The sodium borohydride once it has reacted, and has produced hydrogen, has turned into sodium metaborate (borax) which can be regenerated virtually indefinitely (i.e turned into sodium borohydride again). The caveat here, like before, is that it needs copious amounts of energy to accomplish this.

So basically all the substances listed above are more or less efficient methods to store the hydrogen potential energy. Depending on the application these may be worthwhile investigating further. Typical questions that need to be addressed to determine the match with a potential application:

- mass energy density
- volumetric energy density
- net energy needed to produce or regenerate
- rate of energy release (or equivalent)
- how is the energy released, i.e.~heat, electricity? (both)
- conversion efficiency
- depletion and wear (it applicable)
- safety/security

Energy guru Michael Liebreich has released a convenient graphic [3](Liebreich, 2021) that makes sense of the above criteria in one simple picture (below). The graphic is included again at the end of this annex highlighting various areas/domains of application.



The sodium borohydride hydrogen fuel cell finds application in the maritime domain due to the need for water which of course is plentiful at sea. Development work for various technical solutions such as better reactors are pursued by companies and universities. Delft University of Technology has supported several master degree studies [40] (Lensing, 2020), [41] (van Nievelt, 2019), that have looked into the application of this technology. The reports contain a collection of extremely useful background information which may also help to determine sensible use scenarios.

OUTLOOK CONCLUSION & RECOMMENDATIONS

SHORT TERM

Technological developments in the areas of generation, storage and transport are edging along but not at breakneck speed. Matching the proper hydrogen technology to the desired application and comparing it to alternatives is an important step. It seems like the market will sort out what solutions will prevail. Due to its specific requirements it is possible that solutions relevant to the defence domain might be neglected if it is left solely to market forces. Identifying critical technical bottlenecks which might affect defence applications is therefore an important task and subsequently technology to alleviate these bottlenecks should be promoted.

For the defence domain important use cases are the use of hydrogen as a feed-stock for synthetic fuels and fossil replacements in general. Hence the short term focus should be to promote research and technological developments that advances specific application or generation of hydrogen. A good starting point could be an appraisal of the five examples mentioned at the start of this annex for specific defence relevant applications. The ammonia could be a potent shipping fuel (long haul) and formic acid a good fit as a replacement for on site electric generators. Liquid organic hydrogen carriers may be a good fit for transportation and storage of hydrogen.

Secondly, a dynamic knowledge base (expert system) that is kept up to date for project initiators to consult when engaging in sustainable hydrogen related projects is advantageous. The U.S. Department of Energy

Hydrogen Program in the past has compiled a document called "Go/No-Go Recommendation for Sodium Borohydride for On-Board Vehicular Hydrogen Storage''. This concept can be copied and reproduced as a digital service, not just for sodium borohydride, but also the other substances mentioned above. It also need not be limited to hydrogen but could be expanded as a more general dynamic knowledge base (we also mention this elsewhere in this document). To properly execute and implement a digital platform as suggested here, is certainly not a small task and will require substantial commitment and involvement of many stakeholders and key players. It will be a very valuable instrument to guide decision makers, project managers and guide healthy policy development.

MEDIUM AND LONG TERM

Solving technical application problems and efficiency improvements will take place in due course as a result of market pressures. However this does not solve the one basic boundary condition which is the plentiful availability of sustainable energy. Energy from renewable sources sadly cannot contribute nearly enough but will have to do so in the short term alongside fossil sources. The issue is that large scale deployment of traditional renewables (wind and solar) will result in a run on critical/strategic materials which are in short supply and extracted in locations that are problematic from an geopolitical point of view. The vast amount of these metals/minerals needed will have a tremendous negative effect on natural ecosystems of the countries where these materials are mined. The data and reasoning behind these statements are discussed in an upcoming paper [42] (Rhebergen, 2022).

There is a false notion that surplus renewables derived energy will drive a hydrogen economy. This is not likely to happen because:

1. there are costs associated with harvesting curtailed power; and
2. no investor will put money into an electrolyser operating only at times of curtailment.

An analysis by Michael Liebreich [43](Liebreich 2020), [44] (Liebreich 2020) on the EU policies with respect to hydrogen is definitely worth reading.

Fortunately there is a solution which requires far less mineral resources and space and is virtually independent of strategic materials. This solution is the deployment of nuclear energy at scale. Regular nuclear power plants that are available "off the shelf", e.g. EPR's and AP1000's (or others) will do for now i.e. medium term. Eventually emerging high temperature nuclear reactors (i.e.HTGR) will play an important role in efficiently scaling up production of hydrogen. See the diagram below.

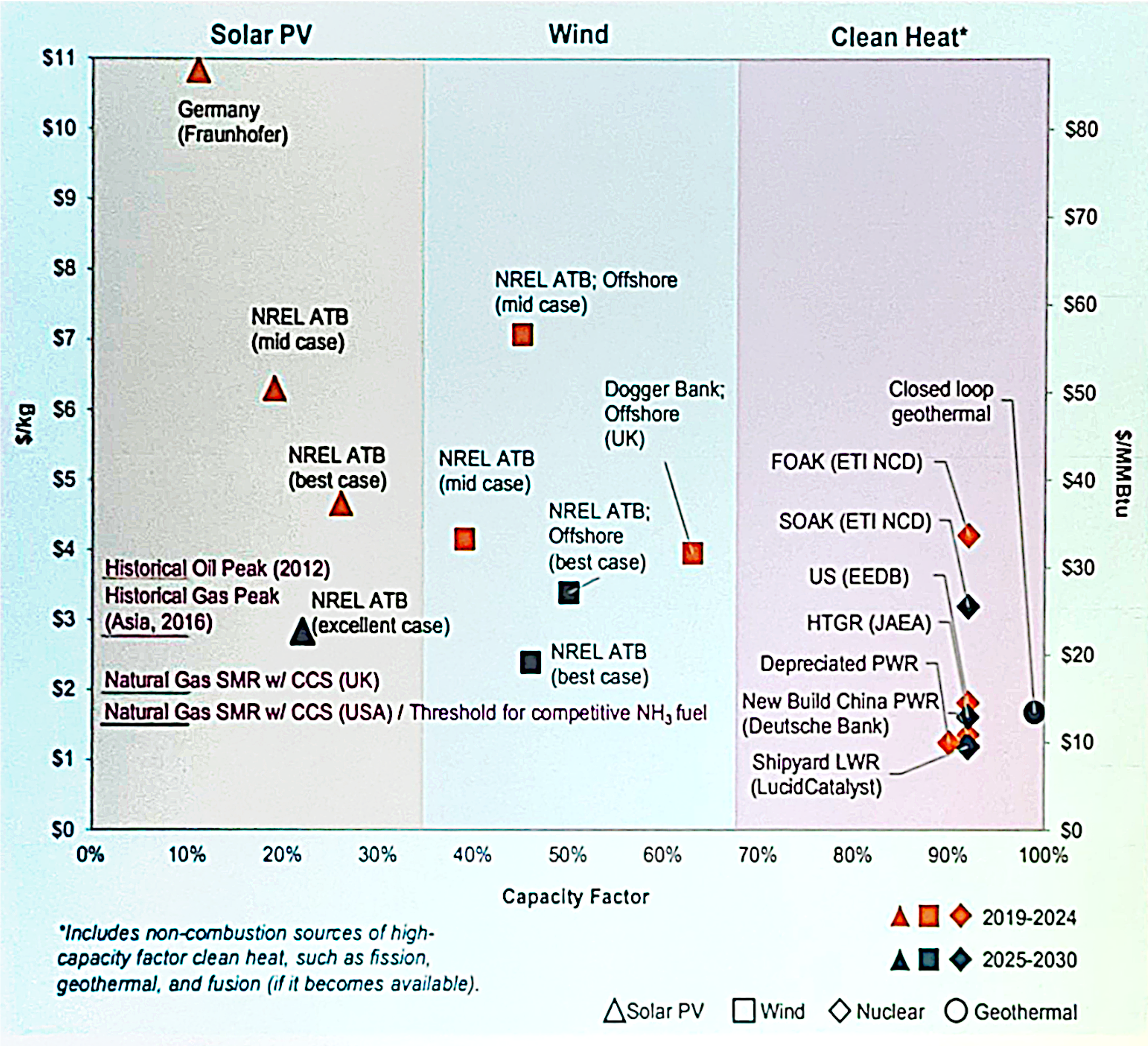


image credit: Nuclear Energy Institute, 2021

Examples of this are also mentioned in ANNEX B on synthetic fuels. They are:

1. **Japan HTGR** - Helium gas cooled high temperature reactor (1000°C) capable to drive iodine-sulphur cycle to produce hydrogen, without needing to produce electricity first and hence much more efficient [29] (Japan Atomic Energy Agency, HTGR Research and Development Center, n.d.), [30] (Japan Atomic Energy Agency, Oarai Research & Development Institute, n.d.), [31] (The Sankei Shimbun, Editorial Board, 2022).
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3. **Terrestrial Energy** - Integral Molten Salt Reactor (IMSR) producing close to 600°C heat. This makes it very suitable to drive industrial processes needed to produce hydrogen [36] (Terrestrial Energy, n.d.) [37] (Irish, Terrestrial Energy, 2022).

Terrestrial Energy has been working on a design for the past 9 years which should be finalising the regulatory approval process by the end of 2022. The Japan HTGR was restarted last year after a 10 year pause due to the Sendai tsunami and earthquake. In fact the Japanese government has released a strategic plan and road-map last year that includes nuclear generation of hydrogen [45] (Ministry of Economy, Trade and Industry, JAPAN 2022). The document shows a clear commitment of the Japanese government towards extensive use of nuclear energy and invests heavily in hydrogen and ammonia production. Unfortunately the language barrier makes it hard to give a good appraisal of the policy paper. The formal English web-page [46] (Ministry of Economy, Trade and Industry, JAPAN 2022) is limited to the mere essential information. Meanwhile it is significant to note that Poland has signed an Implementing Arrangement regarding the cooperation in research and development in the field of high-temperature gas-cooled reactors technology [47] (Progressive Media International, 2022).

ANNEX D: NUCLEAR POWER APPLICATIONS AND DEVELOPMENT

Nuclear technology is set to retake an important role in the civil domain and is likewise suited to do the same in the energy transition for defence. It should be regarded as part of defence critical infrastructure just like for instance the defence pipeline organisation. Therefore it deserves appropriate attention and funding in the same order of magnitude as for instance large naval platforms. This annex describes possible matches and applications should by no means be considered to be exhaustive but rather food for thought.

SMALL MODULAR REACTORS (SMR)

These kinds of nuclear reactors, though called “small” are still sizeable constructions. The “modular” concept is to avoid having to manufacture components on site, but rather on factory production lines under controlled conditions, helping to ensure constant quality. Serial production is expected to increase learning rates and improve productivity. Another benefit often found in small reactors is the passive cooling ability, i.e. not requiring mechanical[10] cooling after shutdown. This further improves already stellar safety standards while reducing complexity and cost.

Drawbacks tend to include lower “fuel” efficiency and higher specific operational cost, but these are expected to be compensated for by shorter construction time and thus lower specific capital cost. The idea is to seek economies-of-numbers rather than economies-of-scale.

Definition: **Small modular reactors (SMR)** are nuclear fission reactors that are smaller than conventional nuclear reactors and typically have an electrical power output of less than 300MWe[11] or a thermal power output of less than 1000MWth, although some designs appear to be somewhat more powerful.

SOME EXAMPLES

We limit the examples to a few that are already built or projected to be in the short to medium term.

- GE Hitachi BWRX-300 (USA/Japan, 300 MWe)
- Linglong 1 (China, 100 MWe)
- Nuscale (USA, 77 MWe)
- Nuward (France, 2 x 170 MWe)
- RITM (Russia, 55 MWe)
- Rolls Royce SMR (UK, 470MWe)

These are light water reactors, conceptually similar to traditional “large” reactors. There are also gas, liquid metal or salt cooled SMRs in various stages of development.

As an example of a molten salt SMR, Thorizon (Netherlands) has completed the conceptual design of an innovative molten salt reactor in which the core and primary loop form integrated hermetically sealed removable and disposable (recyclable) modules. This allows simplification of the balance of the system, and avoids the need for long lived core components. Thorizon aims to use long-lived waste combined with Thorium in the first systems. The technology basis is generic, and allows further development towards closed fuel cycles, for which the first commercially viable systems can serve as proof and support. Maximum size is 300Wth, with 120MWe assuming a 550°C steam cycle for electricity production (42% efficiency on average, but can be higher). Thorizon is exploring making the system smaller, to increase

[10] No forced or active cooling.
[11] https://en.wikipedia.org/wiki/Watt#MWe

margins for managing (unknown) development risks, and for a potential market for smaller sizes, one of which is maritime/naval applications.

MICRO SMALL MODULAR REACTORS (XSMR)

Nuclear micro reactors sometimes referred to as XSMR (extremely small modular reactors) are an interesting proposition for Defence applications be it for peace time civil use or during operations.

We have identified the following initiatives in this field (so far):

- Radiant energy, [48] (Radiant, n.d.)
- Project PELE, [49] (U.S. Department of Defense, 2022)
- U-Battery, [50] (U-Battery Consortium, 2022)
- Westinghouse project eVinci, [51] (Westinghouse Nuclear, n.d.)
- Mitsubishi Heavy Industries, [52] (OSHIKIRI, 2022)
- NAAREA, [53] (Maurice-Cacciaguerra and NEERAE, n.d.)
- JIMMY, [54] (Jimmy, n.d.)
- USNC MMR, [55] (Ultra Safe Nuclear Corporation, n.d.)

Interesting to note that about all seem to employ the extremely sturdy and accident proof TRISO “fuel” pellets/grains [56] (WikiPedia - TRISO, n.d.). On the down side is the high cost of this type of “fuel” [57] (BWX Technologies, Inc., n.d.). The cost aspect however may not be overly problematic for a defence application. From a safety and robustness [58] (Office of Nuclear Energy, 2019) point of view high temperature gas cooled systems need to be pressurised to be efficient enough. A lower pressure is possible but will have its consequences. It thus depends on design decisions to determine what purpose/task these micro reactors are best suited for. Liquid metal or molten salt systems may be better suited because they mostly operate at near atmospheric pressure.

APPLICATION(S)

The SMR (or XSMR) case may be just the right form factor for deployment at a large navy or air-force base. The smaller ones such as the Nuscale or RITM reactors can be installed on ships or barges. The role of a land based (X)SMR could be to produce electricity and heat in conjunction with the production of synthetic fuels. This might potentially happen in a public private partnership.

Micro reactors could fulfil a key role in energy reliability and dependability not just in remote areas and forward bases. In peacetime operation they can be used to ensure an independent and clean energy supply for a (small) base, reducing the consumption of diesel for running base equipment and space heating/cooling.

Due to the employed TRISO “fuel” these reactors are very robust and safe to operate even when handled roughly or inappropriately. If installed underground (even partially) with sufficient armour, little or no radioactivity is likely to ever be released from TRISO fuelled reactors even if the facility comes under attack.

Thought experiment

A partner like Shell (or comparable) may be interested to cooperate in a public/private partnership for the production of synthetic fuels. Shell is currently involved in a Swedish pilot project that is set to produce synthetic fuels for aviation [6] (Kryssare and Vattenfall, 2021). The energy needed originates from a Swedish nuclear reactor. Similarly this could be applied for defence application(s) e.g. on a major military base with the right infrastructure and good location.

A large navy base like Den Helder in the north of The Netherlands is a good location for various reasons. An SMR could produce electricity and heat for local use, either on base or for the civil community of the city of Den Helder and surroundings. Similarly a concept like this could be realised close to a major air base.

OUTLOOK & RECOMMENDATIONS

The advantages of factory built components and limited size make these reactors an attractive proposition. This despite the fact that bigger units may in the long term be more cost effective although they have a higher upfront financing need. SMR's are projected to be built much faster (and cheaper) than "regular" ones. These characteristics make an SMR a good candidate to supply energy to a large military base producing not only electricity but also, hydrogen, synthetic fuels and heat for the base and neighbouring communities.

Hydrogen production for the purpose of producing synthetic fuel(s) unfortunately is rather energy inefficient [15] (Rhebergen and Sikkema, 2022). Electricity (and heat) from a nuclear power plant can be used in electrolyser to produce hydrogen[12]. To substantially increase energy efficiency, high temperature nuclear reactors are in development. This can be achieved via two routes:

1. Molten salt reactors (MSR) or liquid metal cooled reactors (LMR)
2. High temperature gas-cooled reactors.

The latter is able to provide heat at 750°C or higher. A reactor like this could drive the Iodine-Sulphur cycle to efficiently produce hydrogen. This is ongoing research in Japan and China.

The development of micro reactors is progressing worldwide. Some models may become available commercially in the late 20's or early 30's. A lot of the scientific of technical boundary conditions are already satisfied (e.g. TRISO has been available for decades). This means that the further development is predominantly an engineering exercise. This development should be encouraged and channelled to deliver a product that is optimised for various defence applications. For instance characteristics like robustness, effectiveness, transportability, simplified operation, maintenance and deployment should be leading. Europe should definitely collaborate to obtain/cement the knowledge and gain the technological edge in this field (not to mention that civil spin-offs might be a valuable outcome).

The military application of nuclear energy technology should be considered similar in vulnerability and protective (mitigating) measures as would be appropriate for ammunition dumps or fuel depots. The robust designs currently under consideration however show that the risk is far less than the aforementioned examples.[13]

Europe should pursue its own technological and industrial development program in this field. The future cost effective provisioning of synthetic drop-in fuels may well depend on mastering nuclear power and heat. Moving from dependence on imports of liquid fossil fuels to imports of liquid synthetic fuels would not improve European energy security.

As already mentioned in the annexes on hydrogen production and synthetic fuel, high temperature industrial heat is needed for many critical processes. As renewable sources are not able to supply this high temperature heat, nuclear energy is the best option to decarbonise heavy and chemical industries. These industries are essential for the production of green-steel for armour and synthetic fuel for transport and mobile defence applications. It is not surprising that Poland has signed an "Implementing Arrangement" regarding the cooperation in research and development in the field of high-temperature gas-cooled reactors technology [47] (Progressive Media International, 2022).

[12] High temperature heat (>500°C) can also be used to improve electrolyser performance, thereby increasing overall energetic efficiency.
[13] Details are classified and cannot be shared here.

1. **Japan HTGR** - Helium gas cooled high temperature reactor (1000°C) capable to drive iodine-sulphur cycle to produce hydrogen, without needing to produce electricity and hence much more efficient [29] (Japan Atomic Energy Agency, HTGR Research and Development Center, n.d.), [30] (Japan Atomic Energy Agency, Oarai Research & Development Institute, n.d.), [31] (The Sankei Shimbun, Editorial Board, 2022).
2. **Thorizon** - A company based in The Netherlands which aims to develop a Thorium molten salt reactor [32] (World Nuclear News, 2022), [33] (Thorizon, 2022) that will produce high temperature steam of 550°C suitable to drive industrial chemical processes to generate hydrogen such as the copper-chlorine 4 step cycle [34] (WikiPedia - Cu/Cl cycle, n.d.) or the 2 step hydrogen-chloride (HCl) cycle [35] (Bicer, The 2nd International Symposium on Hydrogen Energy and Energy Technologies (HEET-2018), 2019).
3. **Terrestrial Energy** - Integral Molten Salt Reactor (IMSR) producing close to 600°C heat. This makes it very suitable to drive industrial processes needed to produce hydrogen similar to the one described above [36] (Terrestrial Energy, n.d.) [37] (Irish, Terrestrial Energy, 2022).

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