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UN Sustainable Development Goal 7: clean energy – a holistic approach towards a sustainable future through hydrogen storage

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One of the UN Sustainability Development Goals 2030 (UNSDG) is Goal 7: “Ensure access to affordable and clean energy” – for every one of the eight billion inhabitants of our planet. According the UN, Goal 7 is defined as the “*key to the development of agriculture, business, communications, education, healthcare and transportation. The lack of access to energy hinders economic and human development.*”¹ Thus it is a key and a foundation for the majority of the other UNSDGs. Human history showed that many wars have been related to energy sources and, therefore, access to energy remains a potential reason for geopolitical disputes. Clean energy could potentially eliminate some of those conflicts when finally fossil energy sources become obsolete and substituted by clean energy sources. The current available energy mix and distribution is neither clean nor accessible and affordable for everyone. In 2022, the global energy consumption surpassed 160 000 TWh annually, and still about 140 000 TWh rely on conservative fossil sources like coal, oil and natural gas, and only the rest is based on renewable energies and nuclear power.^{2†} Depending on the regional

topography (*i.e.* seaside, mountains, countryside, metropolitan areas, deserts, *etc.*) and microclimate, it requires further decentralisation and diverse utilisation of renewable power sources to overcome the obstacles towards clean, accessible and affordable energy. Those renewable energy sources can decrease current greenhouse gas emissions (33 Gt CO₂ per year), and have a positive impact on climate change and air pollution by reducing the emissions of the electricity/heat production sector, industries, transportation, buildings and agriculture. The major concern about the volume of the annual anthropogenic CO₂ emissions is that it surpasses the annual amount which can be fixed biologically – terrestrial and marine – by several gigatons per year.³ Thus, the total anthropogenic carbon dioxide accumulated over the past decades sums up to a surplus of multibillion tons, which need to be extracted from the atmosphere again.

Related to clean energy, you probably will have readily in mind wind, solar and hydro power. And, after a short brainstorm, other technologies such as geothermal power, bioenergy, biofuels, e-fuels, biogas and green or white/natural hydrogen will be added to your list of clean energy. The latter one, natural hydrogen, is released from geological processes through serpentinisation (*Schikorr reaction*), however it is still a curiosity and not yet explored on a relevant larger scale. But have you ever wondered why wind turbines in wind power parks are standing still, even if they provide clean and cheap energy? The

simple answer is: practically, we cannot store large amounts of electricity in an easy manner with conventional electricity storage systems, like classical metal-based batteries or more specifically modern lithium batteries. For example, in 2022, the British national electricity grid operator spent £215M on wind generators to turn off turbines because of this surplus of electricity. In addition they spent £717M to turn on gas turbines to close a gap of 6% electricity. To build a better picture about this problem, we need to have a closer look at the generated energy, the energy storage capacities of batteries and the composition. A typical single onshore wind turbine (2.5–3 MW) is able to generate roughly 16 000 kWh per day (*ca.* 6M kWh per year)⁴ and would require a storage system consisting of 160 100-kWh-battery packs (weight: approx. 600 kg per pack), typically used for e-cars, with a total battery weight of 96 tons for a single wind turbine. More specifically, the minimum amount of lithium per kg cell is 72 g, or 43 kg per 100 kWh battery pack. However, in practice, the world's largest e-car manufacturer uses 62 kg of lithium for a 100 kWh pack, very likely to increase the total number of recharges and enhance the life time of the battery to 1500 battery charge cycles, since battery aging caused by chemical and mechanical degradation remains a major obstacle. Thus, a lithium battery based electricity storage system for a single wind turbine (2.5–3 MW) would consequently require about 7 to 10 tons of lithium with a limited number of

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† For accessibility without boundaries and towards inclusion, mainly open sources have been used and cited for this editorial. Depending on the used data source there is a variation in the values for the different cited parameters.

charge cycles. Albeit the weight of a stationary energy storage system does not play a role, the lithium content remains the limiting factor on a global scale. Currently, the world hosts wind power parks with a total capacity of 906 GW⁵ which would require about 3 million tons of lithium. This is approx. 5% of the world's total estimated lithium resources, or >20-times the current world's annual mining capacity of 130 kton in 2022.⁶ In other words, it would require more than 20 years to deliver the lithium just for the batteries of the wind parks, and other fields of applications of lithium batteries like common electronic mobile devices and the e-mobility sector would be excluded. To lower the quantities of raw materials, one may consider the use of much smaller batteries for wind turbines to store the surplus of electricity and stabilise the grid. Therefore, one bottleneck that avoids the storage of large amounts of electricity derived from renewable power is the limited annual production of raw materials for such systems. The constrained yearly output of feedstocks is due to technical reasons, but also related to limitations of workforce in the respective sectors. In addition, most of the available lithium resources are located in a small number of countries, which might become a geopolitical conflict in the future. A different approach for electricity storage under development is the sodium ion battery. It might become promising for stationary applications in wind farms, although the energy density of sodium batteries (140 Wh per kg) is lower than the energy density of lithium batteries (265 Wh per kg), thus the batteries would be bigger, but sodium is widely abundant globally and easier to extract and to produce.

To overcome the obstacles for the storage of large amounts of electricity, we need to rethink the idea of electrochemical energy storage for large power plants. A promising approach has been identified and uses renewable energies to feed water electrolyzers to produce hydrogen and release the stored chemical energy in a hydrogen battery. The high energy density of hydrogen (33.3 kWh per kg H₂) and the availability to generate hydrogen from plain water (hydrogen

content: 11 wt%) are major advantages for a global decentralised production and energy storage by using the already installed wind power parks. Furthermore, other industrial facilities with waste energy output like concrete production can supply energy from waste heat harvesting. Currently, still >95% of the world hydrogen production (total: 94 Mt in 2021) is based on fossil sources like natural gas and only 4% by electrolysis. Most of the hydrogen is not used for energy storage, and approximately 2/3 of H₂ is employed in Haber–Bosch processes to produce fertilizer for crops that feed eight billion inhabitants and many animals.⁷ No surprise that about 80%⁸ of nitrogen found in human beings is derived from the Haber–Bosch process, which further underlines the role of hydrogen for modern societies in the fight against hunger (Goal 2)⁹ and poverty (Goal 1). Since, most of the today's hydrogen is reserved to feed the world's population, by converting fossil sources into fertilizers for plants, it requires even more urgently the broad implementation of water electrolyzers driven by wind/solar/water power to realise the utilisation of hydrogen as fuel for the mobility sector and mobile electronic devices. In 2021, in the metropolitan area of Cologne (Germany), Europe's largest electrolyser with a capacity of 10 MW was installed; such an electrolyser could use the energy of 3–4 onshore wind turbines to store the wind energy in a hydrogen battery.¹⁰ Further 100 MW electrolyzers will be implemented in Europe and other countries within the next couple of years. For example, a 100 MW proton exchange membrane (PEM) electrolyser is capable of producing approx. 15 000 tons of green hydrogen per year using 100% renewable energies, and simultaneously reducing the CO₂ emissions by 188 000 tons CO₂ in comparison to classical natural gas reforming. Using these state of the art technologies for green hydrogen production on a global scale (94 Mt per year) requires the installation of about 6300 100-MW-electrolysers worldwide over the next couple of years. Again, this progress is limited and slowed down to a vast extent by the availability of a qualified workforce in the energy sector, and more precisely in the hydrogen sector for the

manufacture of catalysts, electrodes, whole cells and the required infrastructure. Noteworthy, these 94 Mt of H₂ are already reserved for the current needs in the chemical industry and for green ammonia production for fertilizers. Thus, to use hydrogen as fuel for the global transportation sector (incl. aviation and shipping), which is responsible for approx. 25% (*ca.* 40 000 TWh per year) of the global energy consumption,¹¹ it would require scaling up of the global hydrogen production to 1.2 Gt per year. Likewise it would require the installation of 80 000 100-MW-electrolysers worldwide to convert about 11 Gt (1.1 km³) of water into hydrogen annually to store 40 000 TWh of renewable energy in a small gaseous and volatile molecule. This amount would simultaneously nearly eliminate the annual CO₂ emissions of the transportation sector (8 Gt CO₂) which is *ca.* 24% of the global energy-related CO₂ emissions (33 Gt CO₂).^{12,13} In addition to the green hydrogen production, the installation of national hydrogen grids for the storage and distribution of the gas will be required. Ideally, the natural gas grids could be modified for this purpose. The hydrogen can be used to generate electricity by using fuel cell technologies with water as only by-product.

Low volumetric density at ambient pressure (0.09 g/L) and volatility of hydrogen are the major disadvantages in comparison to competitors such as conventional fuels like diesel (0.85 kg/L) or kerosene which are easier to store, handle and to transport in a tank. Therefore, it requires use of high pressure tanks, typically 700 bar, or cryogenic cooling to –253 °C to realise a higher energy density per weight (>5 wt% H₂) for the competitive utilisation in e-mobility, respectively hydrogen mobility with an electric engine driven by a direct hydrogen fuel cell which has a lower operating temperature and higher efficiency than a conventional combustion engine for fossil fuels. A different approach to overcome the obstacles of hydrogen and the related disadvantages, in particular low volumetric density, is the onboard generation of hydrogen from liquid organic hydrogen carrier (LOHC) molecules in the presence of a catalyst to feed a fuel cell with *in situ*



generated hydrogen. A promising example uses liquid methanol as fuel for a reforming methanol fuel cell, wherein catalytic methanol reforming provides the required hydrogen for the hydrogen fuel cell. The use of methanol as energy carrier has also been under investigation for several decades and it is possible to produce green methanol by reduction of CO₂ using renewable energies like geothermal power, which has been demonstrated in Iceland in an industrial environment. Thus, methanol production and reforming becomes CO₂ neutral for fuel utilisation.

Both types of fuel cell driven vehicles, including cars, buses, trains and aeroplanes, are currently in field tests in Europe and other parts of the world. The cars demonstrate independent ranges of 850 to 1200 km with a full tank which surpasses the ranges of e-cars, and a broader production of such vehicles is expected within the next few years. However, similarly to the current situation with e-cars, the real broad use of such vehicles is limited to the national infrastructure to recharge the vehicles with energy which delays the consolidation of more sustainable mobility since the gas stations must be equipped to provide hydrogen as fuel to the customers. This infrastructural boundary of the required national gas grid for hydrogen must be overcome and then also other sectors would benefit from the use of hydrogen instead of natural gas for heat production in industrial processes. Examples might be the production of building materials such as steel, aluminium, glass, concrete or cement. Likewise, these energy intensive industries with large CO₂ emissions could become hydrogen producers by taking the advantages of waste heat harvesting through a thermocouple (thermoelectric effect) to feed water electrolyzers. In addition, these CO₂ intensive industries also could apply carbon capture and storage (CCS) technologies to extract CO₂ from waste gas streams and produce methanol. This type of CCS might be interesting for cement production plants since larger amounts of CO₂ are formed during CaO formation from CaCO₃.

The monitoring of the conversion and storage of energy and electricity, likewise the distribution and use of energy

towards more efficiency and lower CO₂ emissions could be further optimised with support of the IT sector, use of big data, AI and machine learning for production processes, transportation, networks, grids and supply chains. Parameters derived from big data as used in this editorial – for energy consumption and emissions – are important on a global scale. And, the automated time-resolved monitoring, collection, storage, communication and accessibility of the data could be further optimised through decentralised IT technologies using the internet and decentralised networks consisting of thousands of nodes to store data which is then accessible for everyone. The data centres and networks together consume about 2–3% of the global electricity and are responsible for 1% of the greenhouse emissions, while the use of renewable energies are strongly increasing together with waste heat harvesting from data centres to heat buildings. Therefore, the collection of big data for emissions, energy consumption, production and distribution through this technology could be considered as an obvious and logical consequence. Interestingly, case studies – also funded by the EU – in this direction have been implemented for example in Spain also for the production and distribution of green hydrogen towards a transparent supply chain.

The above-mentioned exemplary opportunities to turn the global energy market clean and affordable still need many efforts. Examples to further develop the required technologies are: (i) improve the efficiency, (ii) substitute scarce and precious catalyst materials for electrolyzers and fuel cells containing platinum, iridium or palladium with more abundant metals like iron, manganese, cobalt, nickel or ruthenium, (iii) to manufacture all the required machinery on a large scale on assembly lines and (iv) build up the (inter)national infrastructure for a global hydrogen society. To realise all this, already the European demand is estimated to be that one million technicians, engineers, scientists and service providers specialized in the hydrogen sector are necessary to fill the needs of academia, governments, communities, NGOs, technology hubs, start-ups, SME

and big companies in industry. This said, we all must encourage the younger generation interested in sustainability to study the required subjects with a focus on hydrogen. Universities and engineering schools must recruit young students in fields such as physics, chemistry, chemical engineering, process engineering and mechanical engineering so that they become well prepared to establish clean and affordable energy for their very own future. If this does not happen, the clean energy sector will remain a future technology owing to the lack of clean energy storage. A future technology which is under development for over 200 years (*i.e.* Döbereiner Pt/H₂ lighter, 1823; Grove's H₂ fuel cell, 1842). About 150 years ago, in 1874, Jules Verne wrote about the role of water and hydrogen in his novel *Mysterious Island*:

"Yes, but water decomposed into its primitive elements[...] and decomposed doubtless, by electricity, which will then have become a powerful and manageable force, for all great discoveries, by some inexplicable law, appear to agree and become complete at the same time. Yes, my friends, I believe that water will one day be employed as fuel, that hydrogen and oxygen which constitute it, used singly or together, will furnish an inexhaustible source of heat and light, of an intensity of which coal is not capable. Some day the coal rooms of steamers and the tenders of locomotives will, instead of coal, be stored with these two condensed gases, which will burn in the furnaces with enormous calorific power. There is, therefore, nothing to fear. As long as the earth is inhabited it will supply the wants of its inhabitants, and there will be no want of either light or heat as long as the productions of the vegetable, mineral or animal kingdoms do not fail us. I believe, then, that when the deposits of coal are exhausted we shall heat and warm ourselves with water. Water will be the coal of the future!"

And, hopefully this will be realised soon.

The Goal 7 supported by Goal 4 (quality education) will set the foundation to enable the achievement of all other UNSD goals directly or indirectly.

A well-educated world population (Goal 4) will be more empathetic and able to provide clean energy (Goal 7)¹⁴ for the



production of affordable nutrition (Goal 2),⁹ and to create more efficient business models for everyone to escape poverty (Goal 1). These will lead to better health (Goal 3), improved equality within the population (Goals 5 and 10), a lower pollution of the whole environment, in particular air, water and soil (Goals 6, 11, 13,¹⁴ 14–15¹⁵), better and more efficient work conditions (Goals 8 and 9). And, this may lead to fewer geopolitical conflicts about resources, and peaceful, collaborative societies with guaranteed justice for all (Goals 16 and 17).

The obstacles to achieve the UNSDG 7 are also described as the *Energy Trilemma* which summarises the current situation of the three energy related objectives to be resolved: targeting security, equity and sustainability issues.¹⁶ And, to tackle those, we need a diverse set of solutions for energy generation, conversion and storage as described above in this article. Likewise, for an undefined period, we need to accept that we need to spend less energy to achieve the goals and sustain Nature.

Finally, the most precious and priceless parameter every single human being has, is time. It is non-renewable and limited to the very end, and therefore everyone needs to act wisely and sustainably with the person's very own time¹⁷ – it's about time and energy management. It requires flexible pauses during office hours, remote work, business travels, holidays or exercise, and general flexibility, likewise chronodiversity¹⁷ over the day, month, year and lifetime to enhance productivity and achieve the set goals most efficiently while maintaining wellbeing and health (Goal 3). To sustain one's energy for the journey and the travel range, safe energy to increase your range. Running a car at 180

km/h consumes much more fuel than at 130 km/h and lowers the range significantly through waste of energy. Same holds true for a sprint or marathon, and a lifetime is the latter one. Time runs like silver sands through your hands.

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