Energy storage, the new frontier

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Executive Summary

Energy storage is a crucial element of a functioning energy system and covers three main functions. Firstly, it addresses the mismatch between supply and demand. Secondly, it provides a buffer against energy supply disruption, contributing to energy security. A third driver for storage is commercial. Prices fluctuate and traders and operators buy fossil fuels when prices are low, store, and take advantage of price fluctuations.

Most energy is stored and transported as a molecule, amounting to 20.8% of all annual molecular energy demand in the world. 26.8% of oil, 20.6% of coal and 13% of annual natural gas demand is being stored, amounting to 28,541 TWh in storage. Electrochemical batteries and pumped hydro storage amount to 9.5TWh, a mere 0.03% of global energy storage.

We have analyzed several energy models projecting the make-up of a future clean energy system and conclude that most, if not all, underestimate the storage requirements to provide a functional energy system. Our future electricity system, which will cover half of all future energy use, cannot function based on the numbers provided in these models because there is insufficient consideration for flexibility provided by storage and transport of molecular energy in the system.

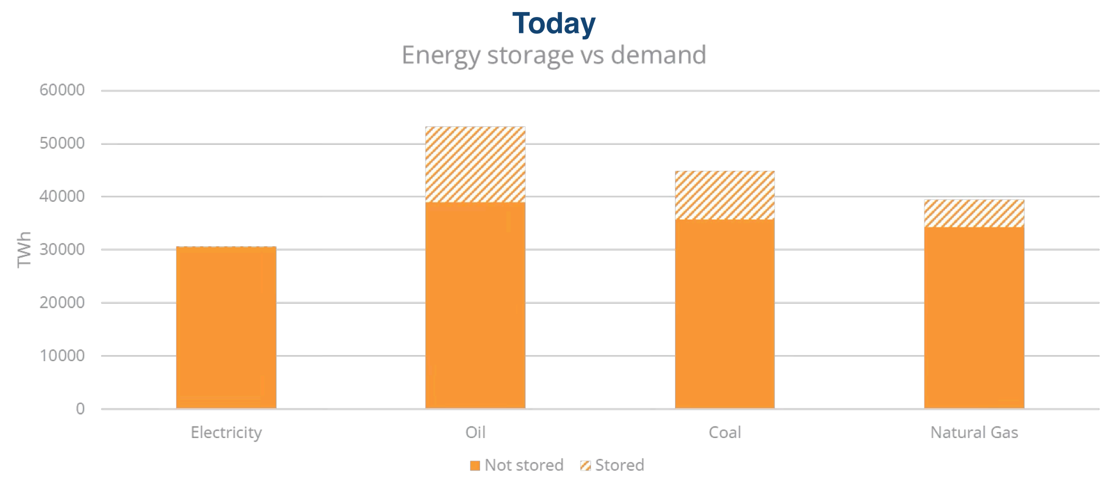
We have used IRENA's NetZero 1.5°C Pathway of their World Energy Transition Outlook 2023 but added additional hydrogen storage to create a functioning electricity system.

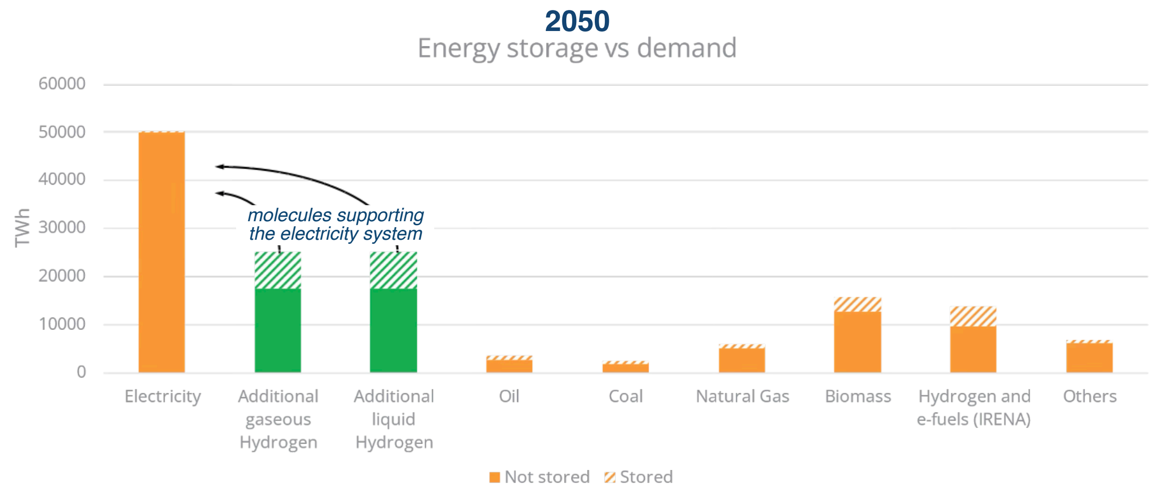
We estimate that 50% of all future clean electricity is derived from hydrogen and derivatives, down from the current 60% molecules used in the electricity system.

More quantitative analysis is required, but the role of hydrogen is much more important than most models predict.

The result of our analysis is that the overall storage amount decreases by 14% from 28,551 TWh now to 25,070 TWh in 2050. Although in our future energy system the percentage of storage hardly changes as share of annual demand, the capex cost of storage will increase 6-fold from $3 trillion today to $18 trillion by 2050.

In 2050, electricity storage in batteries and pumped hydro constitute a mere 0.05% of all stored energy but their associated capex of $2.4 trillion in 2050 represents 13% of all storage capex, a clear indication of how much cheaper storing molecules is compared to electricity storage.





Introduction

Our energy system runs on two main energy carriers, electricity and molecules. Electricity accounts for less than 30% of all final energy use in the world and in 2023 approximately 30% of that was renewable electricity[1,2]. More than 70% of all energy we use is in the form of molecules, and 90% of that comprises oil, natural gas and coal. Global supply chains of bulk transport, transmission and distribution of electricity and molecules link places where we extract fossil fuels or generate electricity with the final locations for their use.

Energy storage plays a vital role in maintaining a stable and efficient energy system. It covers three distinct aspects:

1. **Supply and demand balance:** Often, there is a mismatch between the constant production of fossil fuels and the seasonal variation in energy demand. For instance, in moderate climates, energy demand for heating and lighting increases during the winter. To manage this imbalance, energy is stored.
2. **Energy security:** Strategic energy reserves are essential for ensuring energy security and reducing price shocks. For example, IEA countries established requirements for strategic oil reserves 50 years ago, and the European Union has similar requirements for strategic gas reserves[3,4].
3. **Trade:** By purchasing fossil fuels when prices are low and storing them, traders and operators can sell them at higher prices later, thus capitalizing on price fluctuations.

The fundamentals of energy storage*

Energy can be stored in a variety of ways, using different storage technologies: in chemical energy (coal, wood, oil, natural gas, hydrogen, ammonia, methanol, etc.); in electrochemical energy (supercapacitor, batteries); in mechanical energy (flywheel, pumped hydro power, compressed air); in heat/cold (hot water, phase-change material (PCM), thermo-chemical storage); and in a few other forms. Energy storage in an energy system can be characterized by three metrics: energy content, power, and charge/ discharge timescale.

- **Energy content in kWh.** This metric is determined to a great extent by the energy density (kWh/l). The storage method or technology moreover determines how much volume and weight you need to add for the storage itself. For oil, all you need is a tank with a relatively thin wall; for gas under pressure, you need a tank with a thicker wall, which means its volume is greater and it is heavier.
- **Power in kW.** This quantity represents the amount of energy you can draw from the storage per unit of time. For a battery, this is determined by the power electronics around the battery, while for a tank it is a function of the pump capacity. The relationship between the storage volume and the storage power indicates how long the storage can supply energy when it is run at full power until depletion. For stationary batteries, a period of four hours (or a multiple of four hours) is often realized.
- **Charge/discharge timescale.** This is the time that you can store the energy without significant losses. Flywheels lose a few percent of their energy after an hour. The loss in the case of heat storage in tanks depends on the insulation, but it is generally on a timescale of days to weeks. Lithium-ion batteries lose 1-5% of their energy every month. When you store molecules in a tank, they generally undergo no losses over time. The storage can last months, even years, with no energy loss. During the storage of liquid gas or hydrogen, depending on the insulation, some of the liquid will evaporate, or "boil off", and return to a gaseous state. The boil-off rate of a stored liquid gas, such as liquid hydrogen, is 0.1-2% per day, depending on the insulation. But since no molecules are lost, this is, strictly speaking, not an energy loss. Indeed, the boil-off, which is still very cold, can be re-liquefied using very little energy.

* This paragraph is an abstract from "Green Energy for All – How hydrogen and electricity carry our future" – Ad van Wijk et al, October 2023, ISBN: 9789082763737

The different energy storage systems are often represented graphically with double logarithmic axes. This presents a misleading picture: it makes it look as though the energy content and the power of molecule storage are only a couple of times larger than those of battery storage. But this is not the case. If you use a graphic with linear axes to compare the same energy storage systems, it then appears that only chemical energy (molecules) can be stored on a large scale over longer periods. In a sustainable energy system this concerns energy in the form of hydrogen or hydrogen derived molecules and synthetic or biofuels.

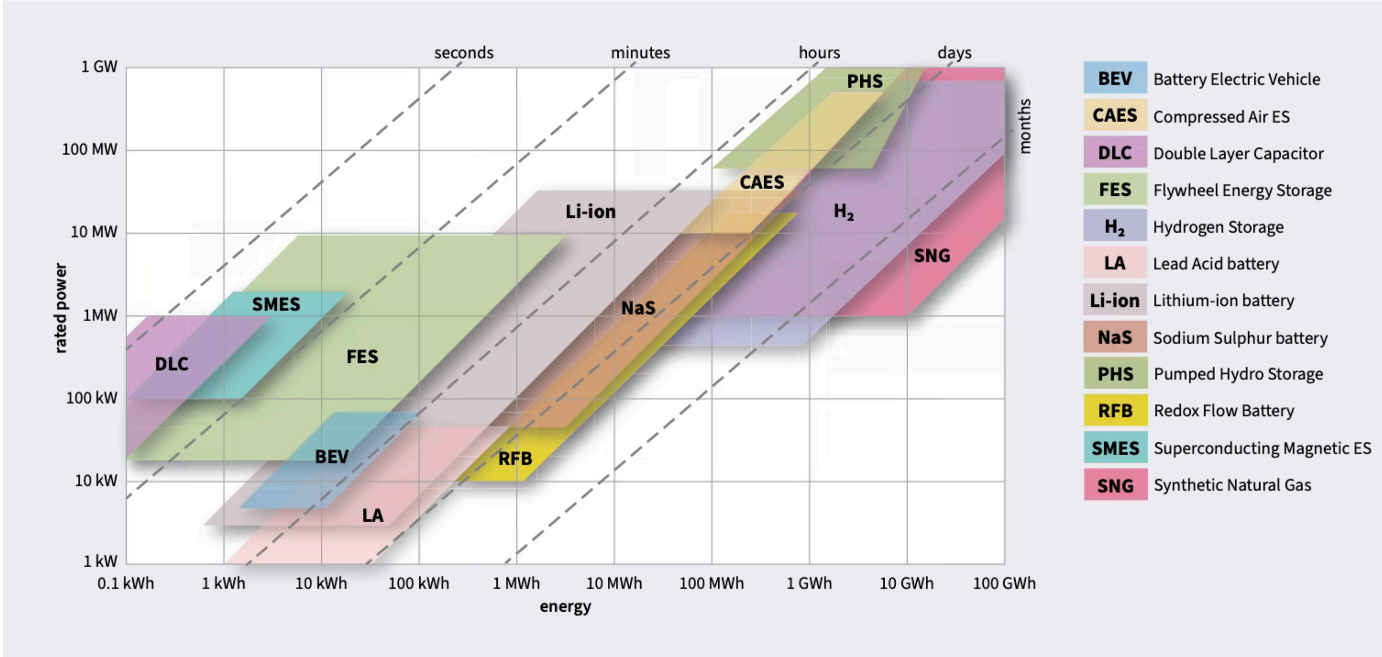


Figure 1. Energy content, power, charge/discharge timescale for different energy storage systems (logarithmic scale).

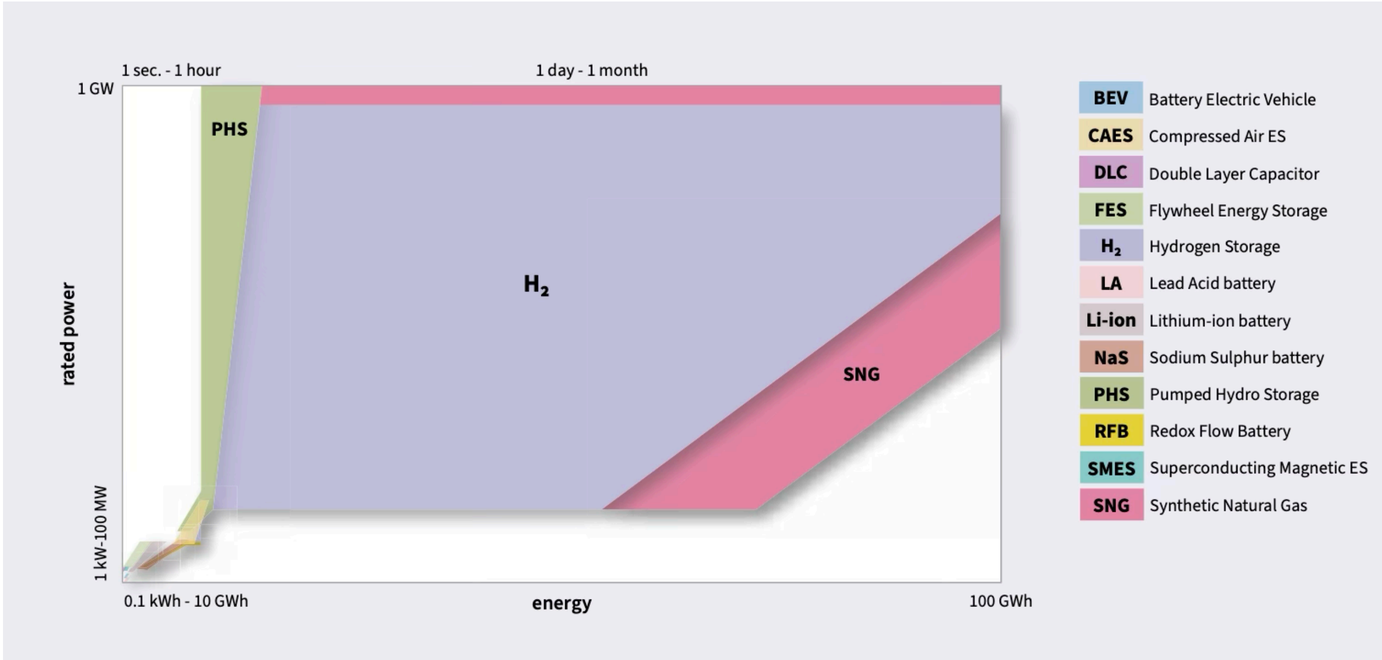


Figure 2. Energy content, power, charge/discharge timescale for different energy storage systems (linear scale)

Storage capacity today

Most energy is stored in molecules given their dominance in the energy system.

How do current storage volumes relate to annual consumption? According to the Energy Institute, in 2022 the global primary energy consumption added up to 167.9 PWh in 2022 (see Figure 3)[5]. Oil amounts to 32% of energy use, coal 27%, natural gas 24% and renewables and nuclear 17%.

The following sections analyze the different energy carriers.

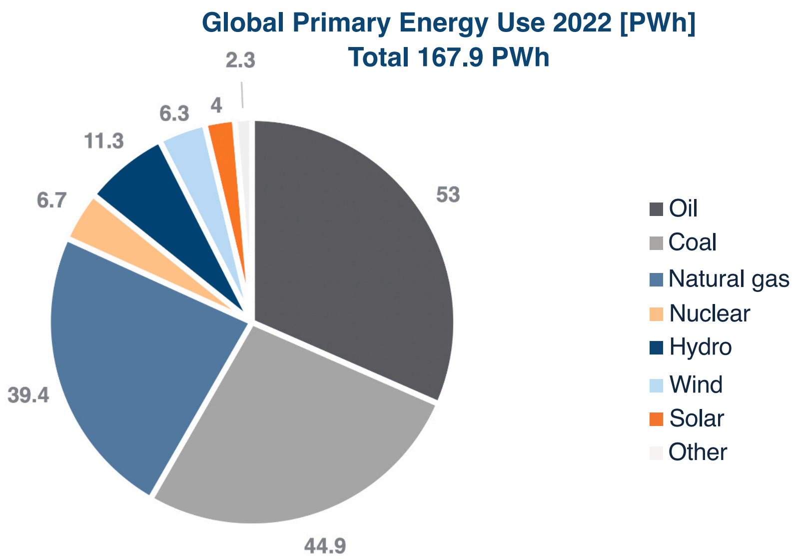


Figure 3. Global Primary Energy Use 2022

Storage of oil

Oil is a globally traded commodity, with a select few producers, exporting to a global market. The overall global onshore and floating offshore oil storage amounts to 7.2 billion barrels, which equates to 11,700 TWh[6]. Part of this, the strategic reserves held by IEA member countries, which is 90 days of net imports, currently amount to 1.2 billion barrels[7]. In addition, there are close to a million petrol stations in the world, storing about 150,000 liters each, adding another 1,500 TWh to the total[8,9,10]. With an additional estimated amount of at 1,000 TWh being transported in tanker trucks, barges and trains we have 14,200 TWh total oil storage (8.7 billion barrels), which amounts to **26.8% of annual global demand**[11]**.**

Please note that we have not included storage in fuel tanks of the estimated 2.4 billion cars, motorbikes, trucks, trains and other vehicles, nor the oil contained in pipelines.

Storage of coal

Coal is currently the dominant fuel in global power production. Despite the heavy CO^2 footprint and phasing down of coal use in the US and Europe, coal production continues to rise in China, Indonesia and India. In 2023, global coal production amounted to 8,741 Mt, with steam coal for power production accounting for 87% of demand[12].
So, 7,605 Mt of coal is produced for energy. Storage of coal is an important part of the value chain, providing security of electricity supply and balanced production costs, evening out price fluctuations.

China is the largest consumer of coal with 4,993 Mt in 2023, comprising 57% of global demand. Second comes India with 15%[13]. Coal storage near power plants is usually expressed in days of burn. Globally there are large variations in this metric, with the USA currently exhibiting an average of 130 days of burn according to the EIA[14]. This equates to 36% of annual demand. Beijing set a goal in 2021 to have coal reserves equivalent to 15% of its annual consumption stocked at mines, ports, power plants and some designated storage areas[15]. According to India's coal ministry, the current stockpile, which include those at thermal power plants, at pitheads (mines), and coal in transit, amounts to 147 Mt, which is 12% of annual demand in India[16].

A multiyear data analysis shows a global average of 75 days of burn, with 45 days at coal hubs and 30 days at plants, or **20.6% of annual global coal demand in storage**, amounting to 9,227 TWh[17,18]. In terms of weight, 20.6% of 7,605Mt equates to 1,563Mt coal in storage.

Storage of natural gas

Natural gas can be stored in saline aquifers, depleted gas fields, salt caverns, in pipeline networks or as a liquid in LNG tanks.

At the end of 2019, there were 661 underground gas storage facilities in operation in the world. The global working gas capacity reached 422 billion cubic meters (bcm). North America concentrates two thirds of the sites (441 facilities) and accounts for almost 40% of global working gas capacity (163 bcm). There are 141 facilities in Europe (108.6 bcm), 47 in the CIS (121 bcm), 28 in Asia-Oceania (22.4 bcm), and 3 in the Middle East (6.9 bcm)[19].

Storage in depleted fields dominates with 80% of global working gas volumes, but storage in salt caverns now accounts for 26% of global deliverability, a measure of the amount of gas that can be withdrawn (delivered) from a storage facility daily.

LNG is 600 times denser than natural gas. The global LNG storage tank capacity amounts to 64.2 million cubic meters[20]. In addition, there are more than 700 LNG carriers with an average size of 150,000 cubic meter, carrying a volume of 105 million cubic meter. These storage capacities combined sum up to 169.2 million cubic meters of LNG, which equates to 101.5 billion cubic meters of gaseous natural gas. This represents 19% of the globally stored natural gas.

The overall peak global natural gas storage of 523.5 bcm amounts to 5,114 TWh. It should be noted that there is a seasonal pattern in how the gas storage in moderate climates is used. The peak storage demand is **13% of annual demand**.

Storage of electricity

Flexibility in the electricity system is largely provided by storing molecules, especially to deal with weekly, monthly and seasonal variations. Apart from this, electricity storage downstream from generation always requires electrons to be converted into something else, e.g. electrochemical energy in batteries or gravity potential in pumped hydro storage systems. According to the IEA, pumped hydropower storage is still the most widely deployed storage technology, but grid-scale batteries are catching up[21]. The total installed capacity of pumped-storage hydropower stood at around 160 GW in 2021. Global capability was around 8,500 GWh in 2020, accounting for over 90% of total global electricity storage of approximately 9.5 TWh, which is 0.03% of global electricity demand. The world's largest capacity is found in the United States. Most plants in operation today are used to provide daily balancing.

Batteries, nowadays mostly lithium-ion, are typically employed for hourly and daily balancing. Total installed grid-scale battery storage capacity stood at close to 28 GW at the end of 2022, installations rose by more than 75% in 2022, as around 11 GW of storage capacity was added. On a global scale this is still insignificant.

To put that into perspective, oil storage amounts to 8.7 billion barrels, which equates to 14,200 TWh[6]. So, oil storage alone is more than a thousand times larger than all electricity storage capacity currently operational. And even with the ongoing exponential growth of batteries, their cumulative installed capacity will merely reach 4.4 TWh by 2035[22].

Overview of current storage

The following table provides an overview of stored energy globally. The cost elements involved in the actual storage infrastructure include land, tanks, caverns etc. Table 2 provides a cost overview.

This leads to the following assessment of current global storage capex for fossil fuels, expressed in Table 3.

Table 1. Stored energy as percentages of annual demand

	Stored energy (TWh)	Overall annual demand (TWh)	Percentage
Molecules			
Oil	14,200	53,000	26.8%
Coal	9,227	44,900	20.6%
Natural Gas	5,114	39,400	13.0%
SUM/AVERAGE Molecules	28,541	137,300	20.8%
Electrons			
Electricity (PHS)	9.5	30,600	0.03%
Molecules and Electricity	**28,551**	**167,900**	**17.0%**

Table 2. Specific capex cost of storage

	CAPEX $/kg	HHV kWh/kg	CAPEX $/kWh	CAPEX $/MWh	Notes
Crude Oil Tank Farm [23]	0.52	11.19	0.05	46	Complete tank farm
Coal (Bituminous) Open Yard	-	7.83	-	-	Cost negligible
Coal (Bituminous) Shed [24]	0.44	7.83	0.06	56	Includes enviro & safety protection systems
Natural Gas UGS Depleted Field [25]	0.96	11.90	0.08	80	Includes 50% Cushion Gas, cost @ $32/MWh*
Natural Gas UGS Aquifer [25]	3.06	11.90	0.26	257	Includes 80% Cushion Gas, cost @ $32/MWh*
Natural Gas UGS Salt Cavern [25]	2.42	11.90	0.20	203	Includes 30% Cushion Gas, cost @ $32/MWh*
Natural Gas LNG FSU Terminal [26]	1.85	12.28	0.15	151	Floating storage unit, 180k/m³
Natural Gas LNG FSRU Terminal [27]	6.17	12.28	0.50	485	Floating storage & regasification unit, 180k/m³
Pumped Hydro Storage (20h) [28]	N/A	N/A	99	99,000	According to USA DOE

Table 3. Global storage capex for fossil fuels and electricity

	CAPEX $/MWh	Share per type (oil, NG, LNG, coal)	Amount of consumed energy (TWh)	Percentage in storage	Amount of stored energy (TWh)	CAPEX ($ billion)
Crude Oil Tank Farm	46	100%	53,000	26.8%	14,200	654
Coal (Bituminous) Open Yard	-	50%	22,450	20.6%	4,614	-
Coal (Bituminous) Shed	56	50%	22,450	20.6%	4,614	257
Natural Gas UGS Depleted Field	80	80%	25,531	13%	3,314	444
Natural Gas UGS Aquifer	257	10%	3,191	13%	414	178
Natural Gas UGS Salt Cavern	203	10%	3,191	13%	414	140
Natural Gas LNG FSU Terminal	151	50%	3,743	13%	486	122
Natural Gas LNG FSRU Terminal	485	50%	3,743	13%	486	392
Pumped Hydro Storage (20h)	99,000	100%	30,600	0.03%	9.5	941
SUM			167,900		28,551	3,128

The above table shows that the storage capex of our current energy system represents a value of $3 trillion.

Storage in a future without emissions

Given rampant climate chaos as evidenced by rising global temperatures, warming oceans, shrinking ice sheets, and increasing frequency of extreme events, reducing emissions is a top priority[29]. The Paris Climate Agreement, a legally binding international treaty on climate change was adopted by 196 Parties at the UN Climate Change Conference (COP21) in Paris, France, on 12 December 2015. Its overarching goal is to hold "the increase in the global average temperature to well below 2°C above pre-industrial levels" and pursue efforts "to limit the temperature increase to 1.5°C above pre-industrial levels." Furthermore, the UN's Intergovernmental Panel on Climate Change indicates that crossing the 1.5°C threshold risks unleashing far more severe climate change impacts[30].

To limit global warming to 1.5°C, greenhouse gas emissions must peak before 2025 at the latest and decline 43% by 2030.

More and more countries are committing to a net zero energy system by 2050. Global scenarios developed by leading institutions and think tanks, including the IEA and IRENA, show what that could look like. Since we have developed low-cost solar and wind energy technologies, renewable electricity is now the cheapest option and will be the foundation of our future energy system. For many years now, most capacity additions in the electricity sector have been renewable, accounting for 83% in 2023[31].

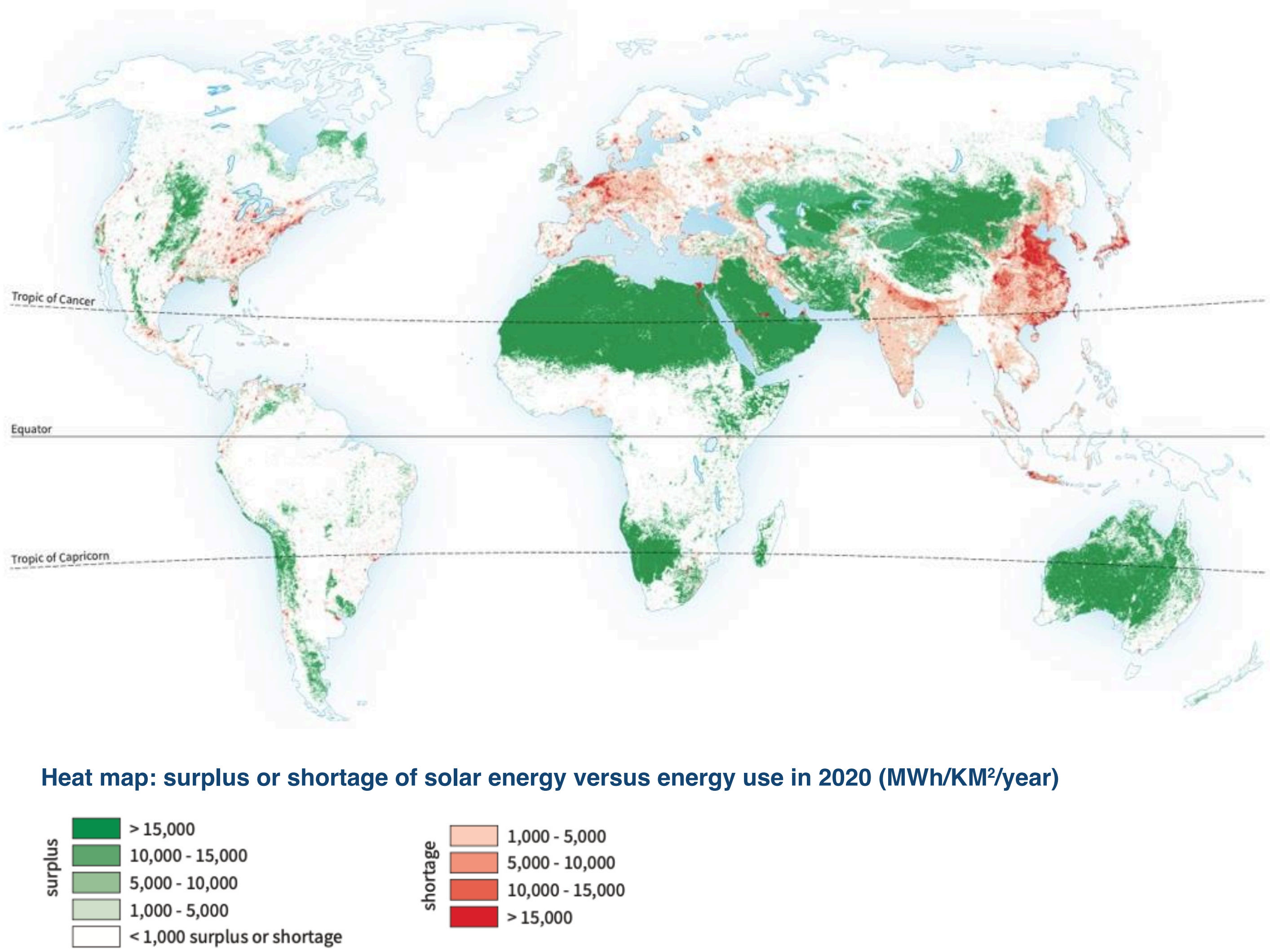


Figure 4. Solar energy heat map: surpluses and shortages per km2 (Source: Ad van Wijk[32])

Since renewable electricity is clean and cost-effective, electrification is the bedrock of the energy transition. Direct electrification with renewables will be pursued wherever possible, but there are limitations because transmission and storage of electricity is not cheap and there are more cost-effective options. Many densely populated areas lack the potential, especially for large industrial demand, and variable electricity sources require additional flexibility.

Figure 4 shows a solar energy heat map that indicates that areas with higher population density (Europe, USA's coastal areas) exhibit a solar energy potential deficit, whereas the Sahara Desert and Australia exhibit large surpluses. Our future energy system will therefore have large energy trade flows, much like our current energy system.

Global scenarios arrive at a natural ceiling of around 50% for end use electrification, with the remaining 50% being clean molecules by 2050. It should be noted that several regional scenarios for a 100% renewable electricity system indicate that up to 30% of this needs to be stored in the form of hydrogen[33].

IRENA's World Energy Transition Outlook 2023 contains a vision for a future global energy system compliant with the Paris Agreement's 1.5°C global warming by 2050[17]. We observe that IRENA's scenario doesn't adequately project future storage needs, which we will discuss below.

The energy storage required to make an electricity system covering 51% of all demand functional, requires an additional 50,009 TWh of clean molecules, which needs to be added to IRENA's 98,056 TWh. So, rather than IRENA's total green energy system requirement of 98,056 TWh (353 EJ), a functional system would amount to 148,066 TWh clean energy in 2050.

Figure 5 shows the total final energy consumption in the two scenarios, broken down by energy carrier.

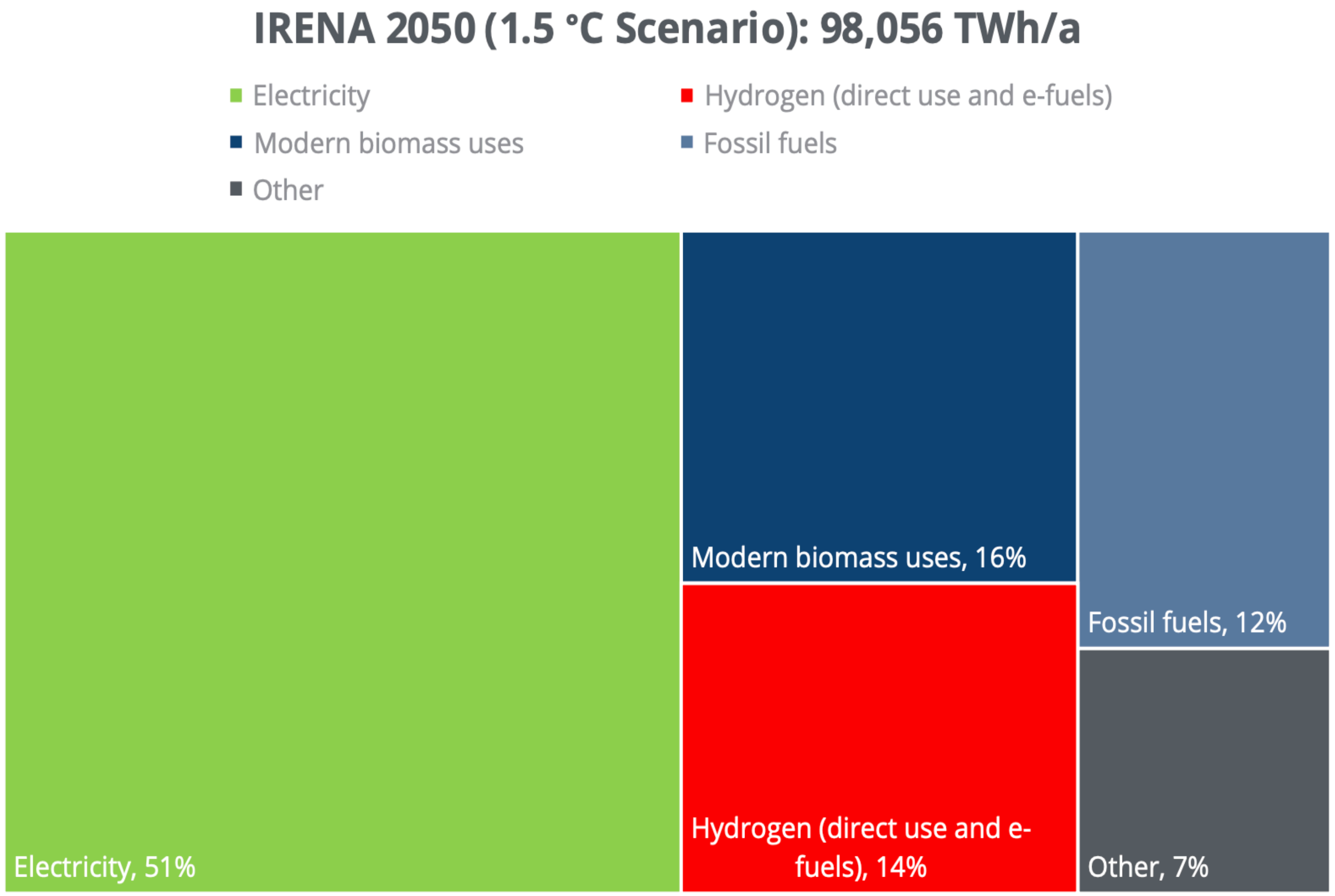
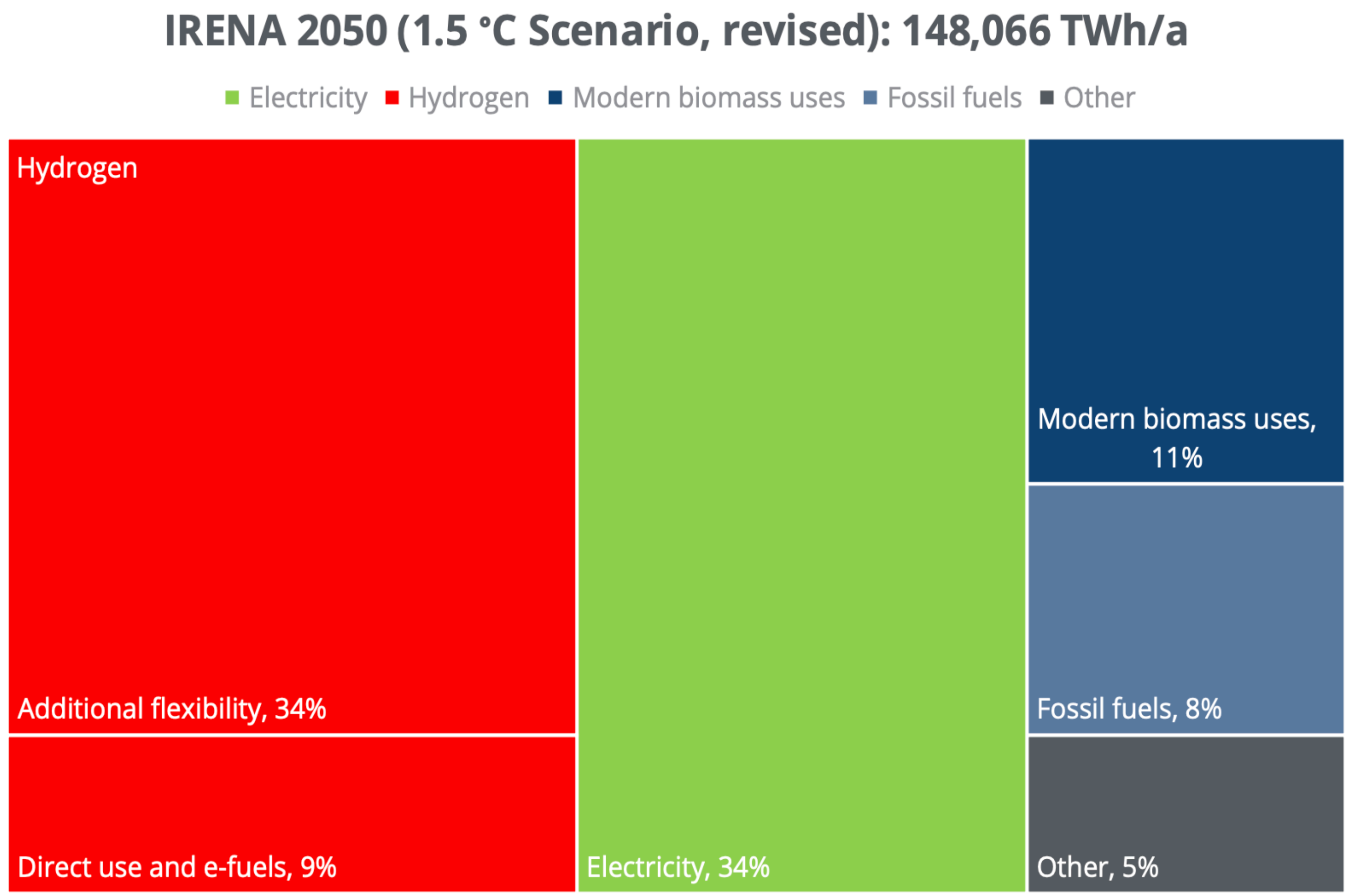


Figure 5. Breakdown of total final energy consumption by energy carrier in 2050 under the 1.5°C Scenario (above) and under its revised scenario (following page) that includes additional hydrogen required to provide flexibility to the electricity system.



What types of storage will we have?

Like today, when we think about how to store energy at scale in the future, we need to consider molecules first.

Storing green molecules is more expensive than fossil fuels. Oil can mostly be stored in simple atmospheric tanks and coal in low-cost sheds. Natural gas is mostly stored in depleted gas fields. Hydrogen and ammonia on the other hand require special considerations. Ammonia tanks need to be pressurized or cooled since ammonia is liquid either at 7 bar or minus 33 °C. And ammonia tanks need to be extra safe to avoid spills due to its toxicity. Underground storage in salt caverns or lined rock caverns is the preferred method for bulk storage of hydrogen as it mitigates challenges associated with its small molecular size. Although hydrogen can potentially be stored in depleted gas fields or underground saline aquifers, there is wide consensus that salt caverns are one of the most cost-effective, efficient and proven ways to store large volumes of hydrogen onshore[34].

Batteries are predicted to continue to grow exponentially, following a similar dynamic seen with solar PV: increased deployment encourages manufacturing at scale and innovation, which leads to lower cost, which in turn increases deployment. Following this logic, the IEA predicts in their net zero energy scenario an installed base of 5 TW by 2050, with an average global duration of 3.4 hours[35]. These 17 TWh make batteries larger than pumped hydro and are a huge increase compared to the current installed base. Pumped hydropower storage is currently responsible for 90% of all electricity grid storage globally and is expected to double by 2050 in a net zero scenario[36]. That would take pumped hydropower storage to 450 GW, which equates to 9.5TWh, assuming a global average duration of 20 hours. So, by 2050, batteries and pumped hydro combined account for 26.5 TWh, which is a mere 0.02% of global final energy demand of 148,066 TWh, comprised of 98,056 TWh as per IRENA's 1.5°C Pathway scenario plus an additional 50,009 TWh hydrogen[17].

Please note that we have not included batteries in EVs, because we excluded fuels in fuel tanks of cars, trucks and trains. But even if all 1.5 billion cars would be 100% electric with 100 kWh batteries each, it would add 150 TWh to the total amount of battery storage, which is 0.1% of projected energy consumption in 2050. And even if we account for the IEA's notorious underestimation of clean technologies, it is a stretch to see batteries covering more than a fraction of 1% of global energy consumption[37].

Location of storage

In a fossil energy system, the production of coal, oil and gas is more or less constant or can be matched with demand. But renewable energy production, especially from solar and wind, is fluctuating depending on the weather conditions and time of day. To deal with renewable production fluctuations, storage capacity is required.

In the case of large-scale renewable energy production, storage capacity close to the production allows for a constant flow of renewable energy to the load centers, which reduces the transmission costs due to more efficient use of infrastructure.

Close to energy demand, storage is required to deal with demand fluctuations. The storage volume and duration required at the energy demand is more or less the same as in the present fossil energy system.

Batteries and tubes/tanks for hydrogen and hydrogen derivatives can deal with production and demand fluctuations on short time scales and modest storage volumes. As explained above, renewable molecules such as hydrogen and hydrogen derivatives are also required for long duration and large volumes of energy storage.

Hydrogen storage is therefore required to manage fluctuations in both renewable hydrogen production and demand.

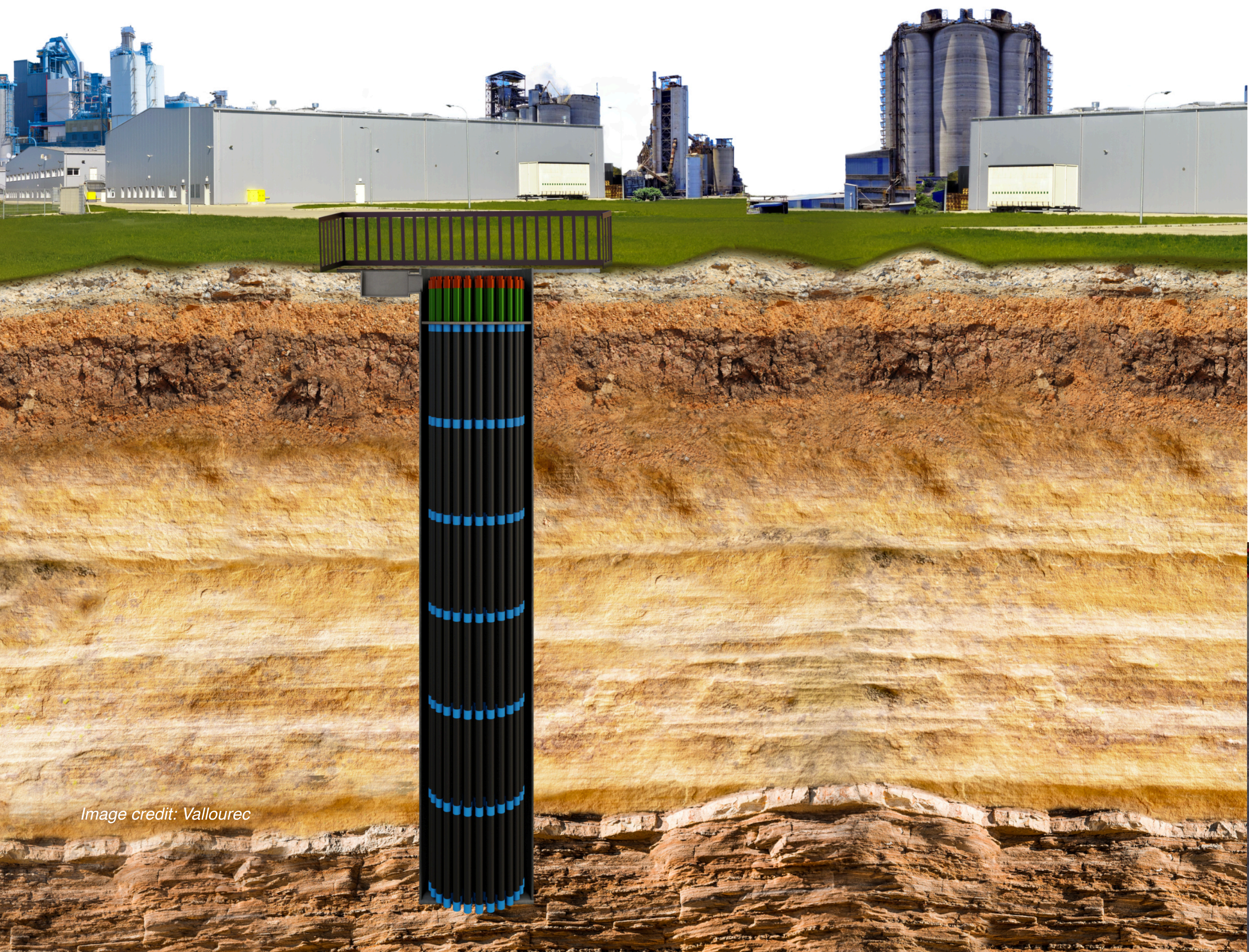
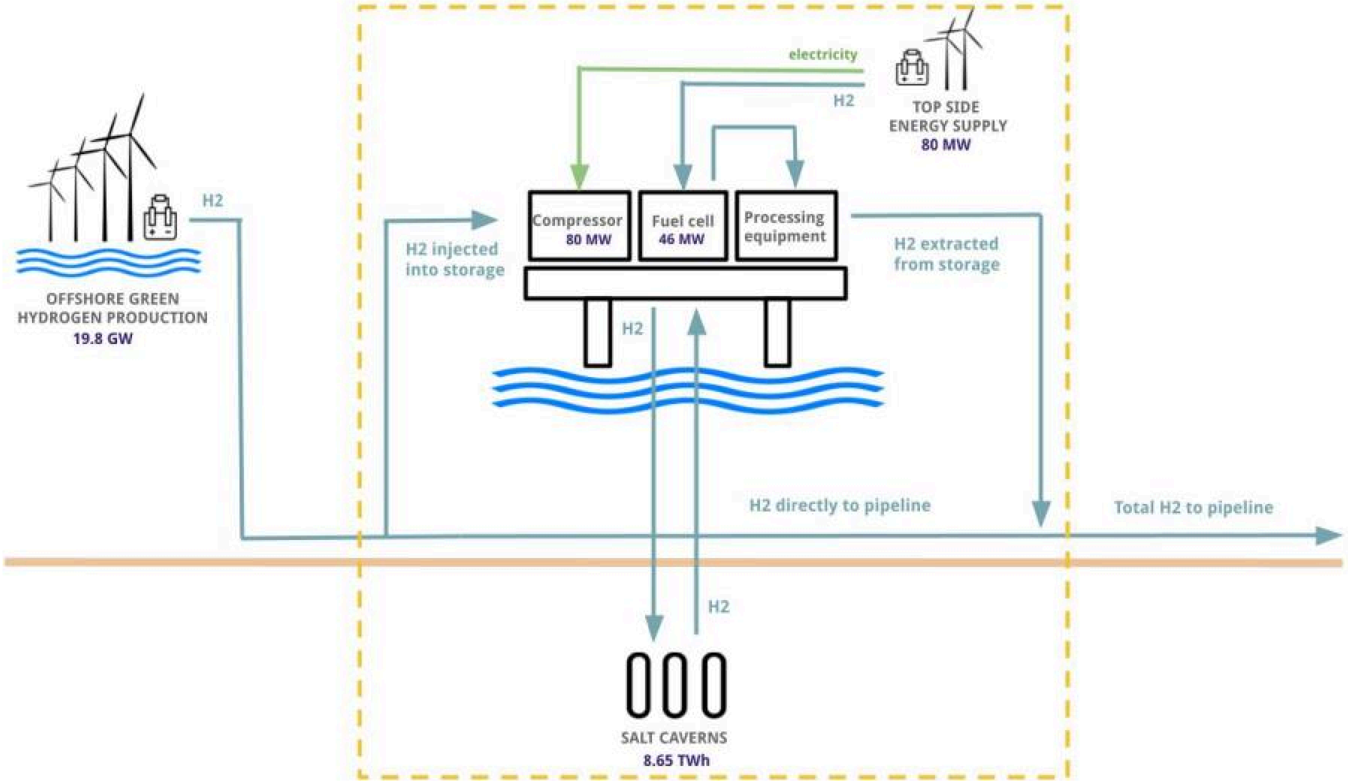


Image credit: Vallourec

A simulation study was conducted to investigate how much storage capacity is required to deliver base load hydrogen from an offshore wind hydrogen production plant at the North Sea. The simulations reveal that a 19.8 GW wind park in combination with an 8.65 TWh salt cavern storage system would be sufficient to provide a constant hydrogen supply to a 10 GW pipeline. The total yearly hydrogen production by the system amounted to 85.8 TWh (2.18 Mt), of which 23.3 TWh (0.59 Mt) was injected into the storage system and 62.5 TWh (1.59 Mt) was injected directly into the pipeline.



D.S. Eradus; The techno-economic feasibility of green hydrogen storage in salt caverns in the Dutch North Sea, Master thesis - Sustainable Energy Technology, TU Delft, January 2022

As can be seen from the above simulation, 27% of annual hydrogen production is being stored in a production system that produces baseload hydrogen. Allowing for some additional storage close to the demand, our working assumption here is that **approximately 30% of annual hydrogen demand will be stored.**

Bulk storage of hydrogen is currently done in salt caverns. Salt caverns storing hydrogen have been operational for decades in the US, UK, Germany and Russia and the technical potential in Europe alone is estimated to amount to 85,000 TWh, more than 85% of IRENA's projected final energy demand by 2050[38]. However, salt caverns are not available everywhere. In Europe for example, salt caverns are prevalent in Northwestern Europe, most notably in Germany and the Netherlands, both onshore and offshore.

This means that hydrogen storage on a system level requires a well-designed hydrogen gas transmission pipeline network. Like the current European electricity system, storage in pumped hydro is concentrated in Norway and the Alps, with a strong grid making this storage available to other countries.

Image credit: Vallourec

Costs of future storage

Table 4 contains an overview of the specific storage costs in our future energy system.

Table 4. Specific costs of new energy storage

Commodity & Type	CAPEX $/kg	HHV kWh/kg	CAPEX $/MWh	Notes
Battery Energy Storage BESS 8 Hours	N/A	N/A	87,500	50% of current LFP battery pack cost @ $75/kWh
Pumped Hydro Storage 20 Hours	N/A	N/A	100,000	According to USA DOE
Hydrogen UGS Lined Rock Cavern 150 Bar	82.8	39.4	2,102	Includes 10% Cushion Gas, cost @ $2.5/Kg
Hydrogen UGS Pipeline 100 Bar	593.4	39.4	15,061	Working pressure 8 to 100 bar
Hydrogen Salt Cavern 200 Bar	43.7	39.4	1,109	Includes 30% Cushion Gas, cost @ $2.5/Kg
Hydrogen Tank Liquid -253°C	103.7	39.4	2,631	Cost for import/export terminal
Ammonia Tank Liquid -33°C	1.0	6.3	157	Includes liquefaction & storage tank
Methanol Tank Liquid Ambient T-P	0.2	6.3	26	Fraunhofer ISE/H2Global data
Kerosene Tank Liquid Ambient T-P	0.4	12.8	28	Fraunhofer ISE/H2Global data

Table 5 contains an overview of the capex storage costs in the IRENA NetZero 1.5°C pathway. We have assumed 17 TWh of battery capacity, and 9.5 TWh of pumped hydro storage to support the electricity system.

Additional storage for electricity is in the form of hydrogen, since the UK government calculated that the largest savings in net zero system costs arise when electricity flexibility is met through hydrogen storage and hydrogen Combined Cycle Gas Turbines (CCGTs)[39]. We have assumed specific storage costs of solid, liquid and gaseous biomass like the costs for fossil fuel storage. For hydrogen and hydrogen derivatives we have assumed 30% accounting for storage at the point of production and where the hydrogen or derivatives will be used. In addition, and like today, countries and regions will keep strategic reserves to guarantee supply and avoid price spikes and traders will use storage to profit from arbitrage.

It should be noted that long term global energy scenarios such as IRENA's World Energy Transition Outlook and other scenarios usually start from a prediction of demand and then use cost optimization algorithms to calculate a mix of energy supply options to cover that predicted demand in the future. Where these scenarios fall short in detail is how the energy system then is supposed to function. They are basically energy balancing tools without sufficient detail, most notably from a transmission or storage perspective. If we project a future system consisting of 50% electricity end use combined with 50% clean molecules, these scenarios underestimate the requirements regarding supporting infrastructure for that electricity system.

Current and future global demand centers are densely populated and often don't have the best renewable energy resource nor the space available to generate all the electricity close by, as can be seen in Figure 4. And most moderate climates require seasonal storage of energy, which requires molecules. Places with the best conditions for bulk production of clean energy are often far away from such load centers, and we don't expect that many Europeans will move to Mauritania because energy is cheap there.

A large share of future energy for our electricity system will need to be molecules, which is cost-effective because molecules can be stored easily and cost-effectively, and the bulk transport of molecules is five to ten times cheaper than electricity grids[32]. It should be noted that our current energy system functions in much the same way, with many power plants running on fuels that are shipped from abroad, with a supply chain that contains storage. **More than 60% of all electricity is currently generated by burning fossil fuels**, providing a reliable and cost-effective year-round 24/7 electricity system in most countries[40].

We estimate that a future scenario in which 50% of all final energy use is electricity, an estimated 50% of that electricity will come from hydrogen or derivatives, produced elsewhere and partly stored. This is included in the table in red and labelled "additional gaseous hydrogen" and "additional liquid hydrogen derivatives". Given the conversion loss of roughly 50%, the required volume of additional hydrogen in such a system amounts to 100% of all direct use of electricity. This hydrogen would then come on top of the volumes that are calculated in IRENA's energy balance scenario.

For a more accurate assessment, an analysis to a much more granular level would be required. However, such analyses to project a global clean energy system with sufficient geographical and temporal resolution to include all production, demand, and transmission and storage infrastructure require massive computing power.

Table 5. Projected capex storage costs by 2050 in NetZero 1.5° pathway

Global Final Energy Use by Fuel	IRENA NetZero 1.5° Pathway 2050 Consumption in TWh p.a.	Share	Specific Amount of fossil, biomass and hydrogen fuel in TWh p.a.	Storage percentage of annual demand	Storage amount in TWh p.a.	CAPEX $/MWh	Overall CAPEX ($bn)
Fossil Fuel (subtotal)	11,767						
Oil	-	30%	3,530	26.8%	946	43	41
Coal	-	20%	2,353	20.6%	484	54	26
Natural Gas	-	50%	5,884	13%	764	217	166
Electricity (direct use)	50,009				-		
Additional gaseous hydrogen*	25,005		25,005	30%	7,501	1,311	9,835
Additional liquid hydrogen derivatives**	25,005		25,005	30%	7,501	190	1,427
Pumped hydro storage				0.02%	9.5	100,000	950
Battery storage (2050)				0.03%	17	87,500	1,488
Biomass (subtotal)	15,689				-		
Liquid biomass	-	30%	4,707	26.8%	1,261	43	55
Solid biomass	-	30%	4,707	20.6%	967	54	52
Gaseous biomass	-	40%	6,276	13%	815	217	177
Hydrogen and e-fuel derivatives as per IRENA	13,728				-		-
Gaseous hydrogen	-	65%	8,923	30%	2,677	1,311	3,510
Liquid hydrogen derivatives	-	35%	4,805	30%	1,441	190	274
Others (district heat and other renewables)	6,864		6,864	10%	686	250	172
SUM	**148,066**				**25,070**		**18,173**

**We assume that salt caverns comprise the average price point for bulk gaseous hydrogen storage*
*** We have assumed that ammonia represents the average price point for bulk liquid hydrogen derivative storage*

As can be seen from Table 5, the overall storage amount decreases by 14% from 28,551 TWh in 2024 to 25,070 TWh in 2050.

Table 6 compares the amount of storage in our energy system and the associated capex in 2024 with a projection in 2050. The amount of storage as a percentage of annual demand remains approximately the same, but the capex cost increases 6-fold from $3 trillion today to $18 trillion by 2050.

Electricity storage in batteries and pumped hydro constitute a mere 0.05% of all stored energy but their associated capex of $2.4 trillion in 2050 amounts to 13% of all storage capex.

Table 6. A comparison of storage metrics now and in 2050

	Stored energy (TWh)	Overall annual demand (TWh)	Percentage	CAPEX ($ billion)
Storage in our current energy system				
Molecules				
Oil	14,200	53,000	26.8%	654
Coal	9,227	44,900	20.6%	257
Natural Gas	5,114	39,400	13.0%	1,277
SUM/AVERAGE Molecules	28,541	137,300	20.8%	2,188
Electrons				
Electricity	9.5	30,600	0.03%	941
Molecules and electrons	28,551	167,900	17.0%	3,128
Storage in our future energy system				
Molecules				
Fossil fuels	2,193	11,767	20.80%	233
Biomass	3,043	15,689	18.50%	284
Hydrogen and derivatives	19,121	63,737	30.00%	15,046
Other	686	6,864	10.00%	172
SUM/AVERAGE Molecules	25,043	98,057	25.5%	15,735
Electrons				
Electricity	26.5	50,009	0.05%	2,438
Molecules and electrons	25,070	148,066	16.9%	18,173

Conclusion

Energy storage is and will remain a crucial element of a functioning energy system. Today, most energy is stored and transported as a molecule, amounting to 17% of all annual energy demand in the world. 26.8% of annual oil demand is in storage, 20.6% of coal and 13% of natural gas is being stored, as well as 0.03% in pumped hydro, amounting to 28,551 TWh in storage overall. Electrochemical batteries are not yet significant.

We have analyzed several energy models projecting the make-up of a future clean energy system and conclude that most, if not all, underestimate the storage requirements to provide a functional energy system, in particular the electricity system that will be of growing significance in the future, covering half of all energy use.

We have used IRENA's NetZero 1.5°C Pathway of their World Energy Transition Outlook 2023 but added additional hydrogen storage to create a functioning electricity system. More quantitative analysis with a granular temporal and geographic view is required.

The result of our analysis is that the overall storage amount decreases by 14% from 28,551 TWh now to 25,070 TWh in 2050. Although in our future energy system the percentage of storage as share of annual demand stay the same, the capex cost of storage will increase 6-fold from $3 trillion today to $18 trillion by 2050.

Electricity storage in batteries and pumped hydro constitute a mere 0.05% of all stored energy but their associated capex of $2.4 trillion in 2050 amounts to 13% of all storage capex, a clear indication of how much cheaper storing molecules is compared to electricity storage.

	NOW	2050
Overall demand	167,900 TWh/a	148,066 TWh/a
Overall storage	17%	16.9%
Percentage of electricity storage	0.03%	0.05%
Overall storage capex	$3 trillion	$18 trillion

Acronyms

bcm	Billion cubic meters
capex	Capital expenditure
CCGT	Combined cycle gas turbine
CIS	Commonwealth of Independent States
EHB	European Hydrogen Bank
EIA	Energy Information Administration
FID	Final Investment Decision
FSRU	Floating Storage and Regasification Unit
FSU	Floating Storage Unit
GWh	Gigawatt-hour
IEA	International Energy Agency
IRENA	International Renewable Energy Agency
LNG	Liquified natural gas
Mt	Million tonne
MWh	Megawatt-hour
NG	Natural gas
PHS	Pumped Hydro Storage
PWh	Petawatt-hour
toe	Tonne of oil equivalent
TWh	Terawatt-hour
UGS	Underground Gas Storage

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