Danfoss Impact
Issue no. 5

# Green hydrogen:
# A critical balancing act

# Scaling hydrogen without breaking the bank or the grid

*Foreword by Mika Kulju*
*President, Danfoss Power Electronics & Drives*

In the global discourse on climate change, hydrogen emerges as a highly contested energy carrier, igniting heated debates and capturing headlines worldwide. While some fervently tout it as a "miracle fuel," others raise caution flags, branding it as a costly double-edged sword intertwined with the fossil-fuel industry.

Amid the urgency and complexity of finding sustainable solutions to combat climate change, it is easy to understand why advocates are looking for a silver bullet. Similarly, it is easy to understand why disputes around the efficacy of hydrogen are making it one of the most hotly debated topics of the green transition.

But **silver-bullet thinking and polarizing debates won't get us to net zero. Green hydrogen *will* play a critical role in the transition away from fossil fuels.** Currently, hydrogen remains concentrated in traditional applications, and we need to see a rapid upscale in hard-to-abate sectors like heavy industry and long-distance transport. **The good news is that we already have the necessary technologies to lower the cost of green hydrogen production.**

To keep global average temperature increases under 1.5°C, we must replace fossil-fuel technologies with ones powered by renewable electricity – as we addressed in Danfoss Impact No. 4. After years of debate, stalling, and inaction, this reality was finally recognized at COP28 in Dubai, UAE, where 198 Parties agreed to "transition away from all fossil fuels to enable the world to reach net zero by 2050."[1]

Crucially, this historic transition away from fossil fuels means **we must abandon legacy technologies and systems in favor of a fully electrified energy system.**

While the news from COP28 represents a welcome development, energy efficiency, electrification, and renewables will only get us part of the way to net zero – albeit a large part. To plug the final piece in the energy transition jigsaw, we will rely on alternative low-emission fuels to decarbonize the most hard-to-abate sectors. Here, the key solution will be hydrogen.

Low-emissions hydrogen is a versatile lever of decarbonization. It can be used as a means of storing excess renewable electricity in periods where supply outstrips demand. Similarly, when produced using renewable electricity, hydrogen can enable us to indirectly electrify sectors that otherwise may take decades to electrify, such as agriculture, aviation, shipping, and heavy industry.

However, while the use cases of green hydrogen are vast, so is its demand for renewable energy. In fact, by 2050, hydrogen production will require more than half of today's total electricity demand.[2,3,4,5]

As such, **we must produce hydrogen efficiently and use it wisely if we are to maximize its benefits without breaking the bank or our energy grid.** This includes repurposing existing grey hydrogen production facilities to green hydrogen.

In this paper, we present a balanced and systemic approach to hydrogen. We put forward a set of principles that will enable politicians and other key decision makers to **efficiently scale hydrogen production without putting an unmanageable strain on renewable energy production or financial resources.** By reducing overall energy demand, producing hydrogen efficiently, and using it wisely, we can effectively decarbonize the sectors and processes that currently contribute an outsized proportion of global greenhouse gas emissions.

Hydrogen is no silver bullet, and as with all other climate technologies, we need a holistic and cost-efficient approach. However, there is no doubt that it will play a crucial part in the green transition. We already have the technologies available for a rapid, cost-efficient, and sustainable build out of hydrogen. All we need now is to stop dealing in absolutes and start embracing the opportunities ahead.

> **"Green hydrogen will play a critical role in the transition away from fossil fuels. The good news is that we already have the necessary technologies to lower the cost of green hydrogen production."**

Drawing on empirical evidence and data from credible sources, Danfoss Impact Issue No. 5 maps out the role of hydrogen in the future energy system.

The terminology used when discussing hydrogen and hydrogen production in this paper follows no international agreements or regulations. Currently, hydrogen produced via electrolysis might be perceived as 'green' even if it does not consider the grid electricity's origin. The terminology of hydrogen produced via electrolysis using renewable electricity varies, but in this issue, hydrogen produced via electrolysis using renewable electricity is referred to as 'green hydrogen' and has a carbon intensity of close to zero. This issue will at times refer to 'low-emission hydrogen', adopting IEA[6,7] and EU[8] definitions of hydrogen produced via renewable electricity-based electrolysis and fossil fuels (natural gas and coal gasification) with carbon capture and storage (CCS). This term covers 'blue hydrogen' and 'green hydrogen', which is widely used across the literature, but with no standard definition.

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The views expressed in this paper are those of Danfoss. Their completeness and accuracy should not be attributed to any external reviewers or entities.

Danfoss Impact Issue No. 5 was prepared by Group Analysis in Group Communication & Public Affairs at Danfoss.

Comments or questions may be directed to Head of Analysis & Strategic Communication, Sara Vad Sørensen at sara.sorensen@danfoss.com

# Only got 2 minutes?

## *These are the key takeaways*

### Electrify and reduce demand first

Green hydrogen production is energy-intensive and expensive, and the renewables needed to produce it are not a free resource. Before deploying hydrogen, we must implement all available electrification and energy efficiency measures. **Energy efficiency is the most cost-efficient way to reach net zero.**

### Produce hydrogen efficiently

**By 2050, hydrogen production will require more than half of today's total electricity demand,**[9,10,11,12] so how efficiently we convert electricity into hydrogen is critical if we are to limit energy waste. Similarly, timing matters. Producing hydrogen when there is excess (and cheap) renewable energy in the grid can reduce costs and stress on our electricity grids. Finally, *where* we produce it also matters; by placing electrolysis plants near existing or planned district energy systems, we can repurpose excess heat to heat water, homes, and other buildings instead of just wasting free energy. We must also plan for proximity to clean water without jeopardizing water use for other purposes, such as drinking and agriculture.

### Use hydrogen wisely

Despite projections for major increases in the future hydrogen supply, its energy-intensive production process means it will still be a scarce and expensive resource. Therefore, **we must use hydrogen wisely and judiciously.** When machinery and processes can be directly electrified, they should be. Hydrogen currently remains concentrated in traditional applications, and we need to see a rapid upscaling in hard-to-abate sectors like heavy industry and long-distance transport.

# Hydrogen explained

## What is hydrogen?

Hydrogen is the most common chemical element in our universe. Despite being completely odorless, tasteless, and colorless, it is a foundational component of nearly everything that sustains human life, including the water we drink, the sun that warms us, and even our very anatomy itself. However, despite often being referred to as "the essential building block of the universe", it is rarely found in its free (gaseous) state. But actually, in this state, it has the power to deeply decarbonize our energy system.

## Why do we need it?

Beyond its cosmic implications, hydrogen has some very real, very critical functions here on Earth. For one, it is a very effective energy carrier, meaning it can serve as a means of storing energy. Similarly, hydrogen can be burned or converted into e-fuels, which are synthetic fuels produced without fossil sources that can serve as a low-emissions alternative for traditional fossil fuels such as methanol or kerosene. If produced and consumed wisely, they can have very little environmental impact, meaning their potential as a driver of the green transition is quite remarkable.

Many sectors of our economy require highly energy-intensive processes. Think of cement and steel production, or long-haul aviation. Fully electrifying these sectors and powering them with renewable energy is still a way out, and with the urgency of the climate crisis, we must explore all possible opportunities. Indirect electrification through green hydrogen is a good catalyst to jump start the decarbonization journey while direct electrification technologies for heavy and high-temperature applications are being developed. Hydrogen is a very viable alternative to the fossil fuels commonly used in these processes – an alternative that emits no greenhouse gases when burned. As such, when used strategically and sparingly, it can be one of the key enablers of decarbonization in these sectors.

If hydrogen is produced with renewable electricity – also known as green hydrogen – it can also serve as a key tool for stabilizing the future renewable electricity grid. Renewable energy production and demand come in waves, and oftentimes these waves do not align with one another. If the sun is shining or the wind is blowing but our lights and ovens are switched off, governments often pay energy suppliers to shut down production, which can cost exorbitant amounts of money (learn more in "Energy system flexibility in the EU and UK" case on page 15). But if we instead use this excess energy to produce hydrogen – either for storage or direct use as a fuel – we can avoid curtailment costs and grid disruptions while stimulating a profitable and efficient hydrogen economy.

Like we have seen, hydrogen has many benefits. But it is a false hope to believe that hydrogen is a silver bullet to the climate crisis. As we will see in the following chapters, energy efficiency, direct electrification, and a cost-efficient upscaling of green hydrogen will all be critical to meet global climate goals.

## All hydrogen is not created equal

There are many ways to produce hydrogen. However, there are no global agreements defining the different types of hydrogen produced, making it difficult to assign a specific level of emission to each means of production. In the figure below, we describe the four most prevalent types of production. Other forms of hydrogen production such as white, turquoise, or purple are less common or are still in early stages of development and are therefore omitted from the discussion.

### $H_2$ Green Hydrogen

Produced through a process called water electrolysis, where electricity splits water into hydrogen and oxygen. In order for hydrogen to be called "green", the power supply must stem from renewable sources.[13] Green hydrogen can have a carbon footprint from 0.5 to 6.6 kg of $CO_2$e per kg of $H_2$[14,15] and is one of the most promising options to supply low-emission hydrogen in the future.

### $H_2$ Grey Hydrogen

Produced with fossil fuels such as natural gas or coal. Usually, grey hydrogen is produced through processes called steam methane reforming or coal gasification. Producing grey hydrogen emits vast amounts of $CO_2$, and accounts for 95% of the global hydrogen production today. Emitting 10-26 kg of $CO_2$e per kg $H_2$,[16] this is not a suitable option for the green transition.[17]

### $H_2$ Blue Hydrogen

Produced in the same way as grey hydrogen but the carbon emissions are captured and stored. At best, 85-95% of the carbon can be captured, which means that 5-15% is still emitted.[18] Blue hydrogen is considered a low-emission hydrogen, but emitting 1.5-6.3 kg of $CO_2$e per kg $H_2$,[19] it is not the cleanest option.

### $H_2$ Pink Hydrogen

Produced via water electrolysis like green hydrogen, but with electricity from nuclear power plants. Emissions from pink hydrogen can be as little as 0.1-0.3 kg $CO_2$e per kg $H_2$.[20] However, nuclear power is a heavily debated issue and brings with it a host of political considerations.

# Water electrolysis: the pathway to green hydrogen

Conventional methods for producing hydrogen – almost all of which use fossil fuels – leave massive footprints. Today, these account for nearly all of the global hydrogen production. However, there are other ways to produce hydrogen that will only leave a small footprint, but which right now account for only 0.1% of global production.[21] The most viable low-emissions process is called water electrolysis.

Water electrolysis – oftentimes referred to simply as "electrolysis" – is a process where electricity is used to split water ($H_2O$) into its base molecules, hydrogen ($H_2$) and oxygen ($O_2$). While the oxygen can be released into the air or captured to reuse for other purposes, the hydrogen can be stored and used for many functions, such as in industrial processes or the production of fertilizer, fuels, thermal energy, and electricity. In cases where the hydrogen is produced via electrolysis run by renewable electricity (i.e., green hydrogen), the end-use product can be used to decarbonize processes where hydrogen can be implemented as an alternative fuel.

Hydrogen is a key element in many countries' climate strategies. To realize the goals set by the Paris Agreement, electrolysis capacity must reach more than 550 GW by 2030. However, planned projects will currently bring the capacity to 170-365 GW in 2030.[22] This means we must either radically ramp up hydrogen production, or look at energy efficiency measures to lower the demand. **Given the sheer cost and resource intensity of hydrogen production, the most cost-efficient strategy is to first implement all possible electrification and energy efficiency measures, then meet the remaining (lower) demand with hydrogen.**

While electrolysis is currently quite expensive, the International Renewable Energy Agency suggests that reducing the cost of electrolyzers can reduce the long-term investment costs by up to 80%.[23] As such, making early investments in efficient electrolysis can help to lower the lifetime cost. In the next chapter, we will explore how we already have the necessary technology available to lower the cost of green hydrogen production.

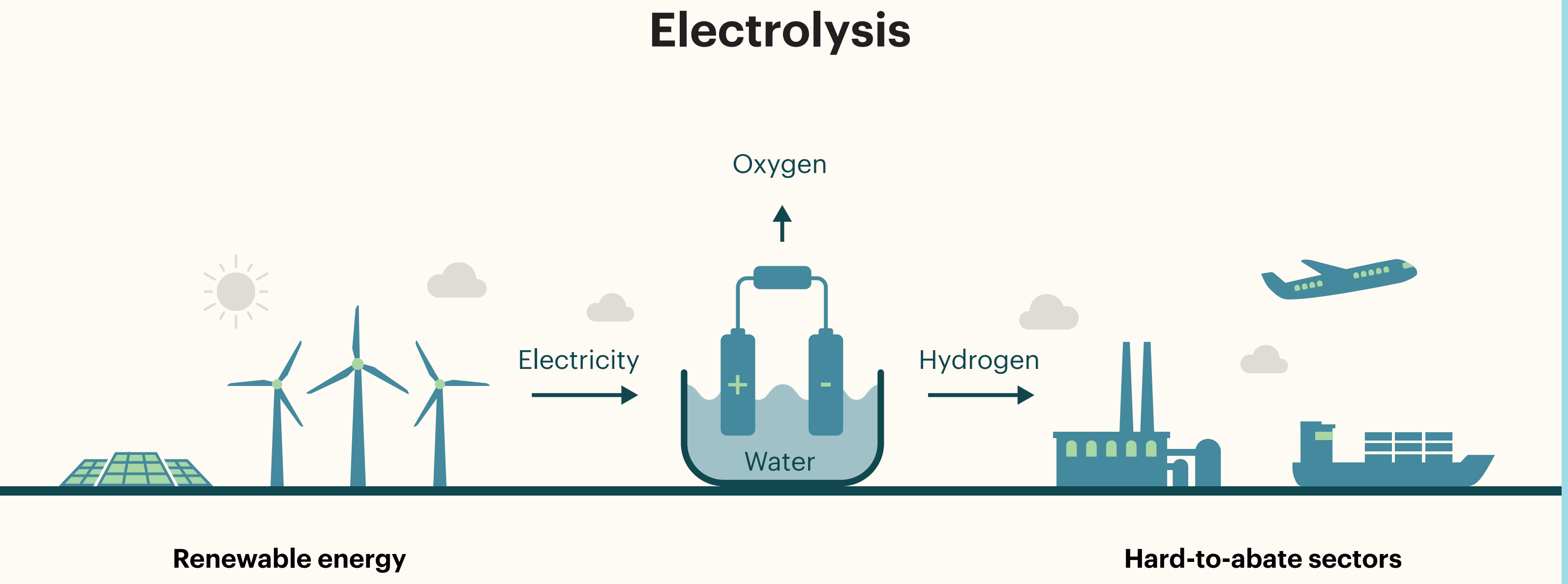


Figure 1: Converting renewable electricity to hydrogen through electrolysis

**We already have the necessary technology available to lower the cost of green hydrogen production.**

# Produce hydrogen efficiently

The IEA estimates that the global electricity demand for electrolysis in a net zero scenario will be 14,800 TWh by 2050.[24] This will be largely driven by ambitious strategies from some of the world's largest energy consumers, such as the US, China, and the EU.[25,26,27] So, even if we successfully reduce the overall demand for hydrogen by maximizing the energy efficiency of all elements across our energy system, we will still need incredible amounts of electricity to produce enough hydrogen to meet our net zero goals.

Which steps can we take to produce hydrogen in a way that does not cripple our energy system through excessive demand on renewable energy production? First and foremost, we must consider if there are other, cheaper alternatives than hydrogen, such as direct electrification or lowering overall energy demand. Then we must maximize the energy efficiency of the electrolysis process. This means minimizing the input of renewable electricity and water for electrolysis, both of which are critical – and in many places, *scarce* – resources for use beyond hydrogen production.

## Convert efficiently

Energy conversion is both very simple and astonishingly complex. Put simply, it means changing one form of energy to another. For example, this could be wind to electricity, electricity to hydrogen, or natural gas to heat. However, in practice, successfully converting energy requires incredible feats of engineering. Mastering the science and implementation of energy conversion will be fundamental if we are to decarbonize our energy system.

Every time energy is converted from one form into another, some of it is lost in the process. Most often, this energy loss comes in the form of heat (see section "Leverage excess heat from hydrogen production" on page 17). This heat loss can often be attributed to inefficient conversion machinery. For example, to propel a car down the street, one form of energy (e.g., electricity or gasoline) must be converted into another (e.g., movement). But partly because gasoline engines create more excess heat, they have a lower energy efficiency. In fact, gasoline engines lose on average 64-75% of energy, compared to only 15-20% for electric vehicles.[28]

In this case, the electric vehicle is converting energy more efficiently, thereby using less to achieve the same result.

These basic rules of thermodynamics also apply to hydrogen production. Indeed, there are more and less efficient ways of producing it, and minimizing energy loss by maximizing conversion efficiency will be critical as we continue to rapidly scale hydrogen production globally. Currently, **conversion of electricity to hydrogen creates an energy loss of roughly 30%.**[29] **But there are critical steps we can take with technology that already exists today to minimize this energy loss.** There is an entire ecosystem of technologies around producing hydrogen, for instance for cooling and pumping. Prioritizing energy efficiency during all steps can have a great impact and make the green transition both quicker and cheaper.

The efficiency of electrolyzers is essential in lowering production costs and optimizing the output. A new type of electrolyzer design can significantly increase efficiency through internalizing cooling - a design inspired by the proven and widely applied heat exchanger technology. In order for hydrogen to be used, it must be pressurized. This is another production process which requires large amounts of energy. Implementing pressurization into the electrolysis process, instead of having it as an extra step after it leaves the electrolyzer, is an essential measure to implement efficient green hydrogen production. By using efficient high-pressure pumps to pressurize the core of the electrolyzer – or the "stack", where the water is split – the pressurization can significantly increase the efficiency of electrolysis.

Another critical step for improving conversion efficiency is explored in detail in the case entitled "Efficient and stable conversion" on page 11.

## Water usage in production

Producing hydrogen requires significant amounts of water. In areas that face challenges with water scarcity, hydrogen can add additional stress to the system if not planned properly.[30]

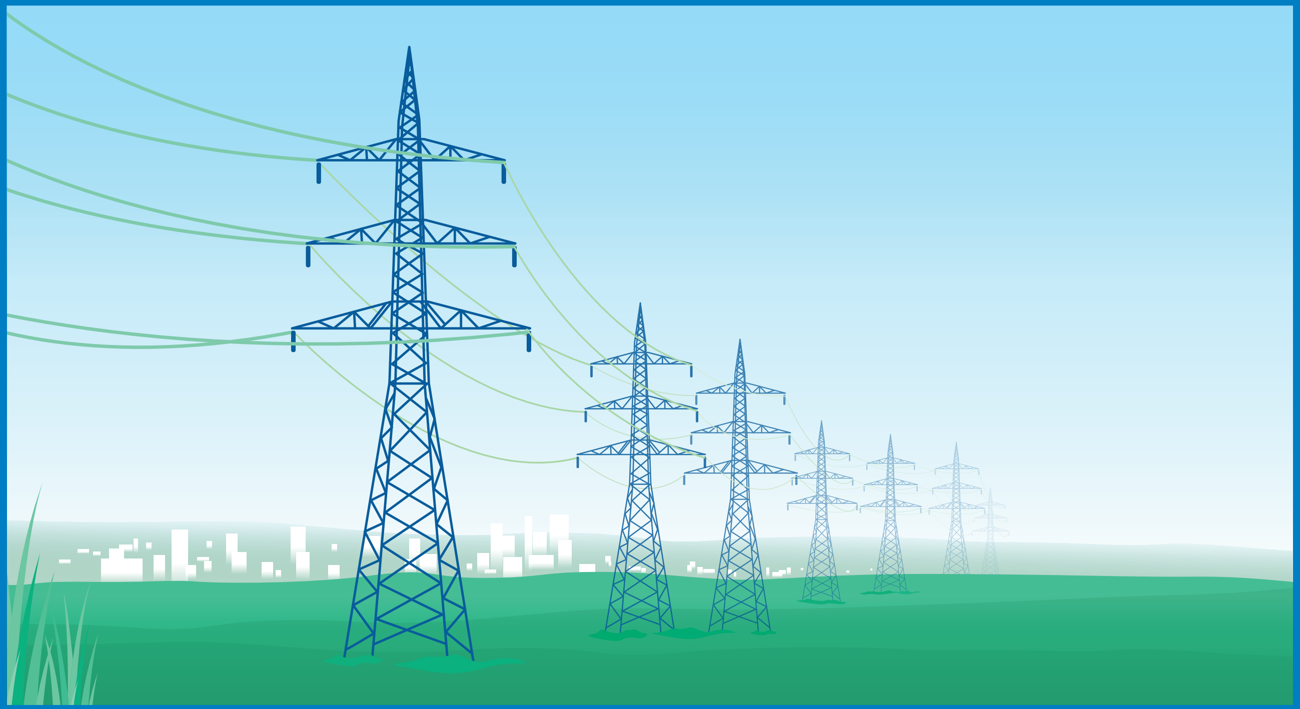
Grey hydrogen production requires water for processes such as steam generation and cooling, and blue hydrogen production needs additional cooling water for carbon capture and storage (CCS). Green hydrogen production splits water into hydrogen and oxygen, while the cooling demand is also substantial. And while all hydrogen production requires some amount of water, **green hydrogen consumes less water than blue hydrogen, and oftentimes less than grey hydrogen.** Actually, blue hydrogen consumes 24-49 liters of water per kilogram of hydrogen, compared to 18-31 liters for grey hydrogen and 18-22 liters for green hydrogen.[31]

Although electrolytic hydrogen production will require less water than other forms of hydrogen production, local water scarcity is a real issue. This is especially relevant in regions hit by recurring droughts and with limited access to fresh water. As cooling of the electrolyzer can have a significant pull on local water resources, the planning of hydrogen production must always consider local needs and resource availability. However, certain cooling technologies, such as dry cooling, can serve as another method of driving down water consumption in hydrogen production.

Careful planning of green hydrogen production and use of state-of-the-art technology can address the concerns and reduce the impact of green hydrogen's water footprint. For example, production can be coupled with desalination and wastewater facilities and provide water for domestic use. Desalination of water requires energy, and with the vast amounts of electrolytic hydrogen in the future, the energy demand for desalination is not a trivial concern. There are many ways to purify water, but using highly efficient high-pressure pumps will save huge amounts of energy.

Minimizing the cost, energy loss, and energy demand of green hydrogen production means we must look for ways to maximize efficiency of each of the links in the hydrogen chain.

# **Case:** Efficient and stable conversion



Hydrogen production will have a massive pull on the electricity grid in the future. As such, we must make sure to produce hydrogen as efficiently as possible and to avoid unnecessary disturbances in the grid. Green hydrogen is produced by an electrolyzer that splits water into oxygen and hydrogen using electricity. All electrolyzers use direct current (DC), while the electricity grid is powered by alternating current (AC). DC is found in regular AAA batteries, and the current always flows in one direction, whereas the AC in the grid periodically changes direction. This means that there is a need to convert the electricity from AC to DC to produce hydrogen. A low-quality AC/DC converter will disturb the AC on the grid, and costly compensation equipment will be needed to restore power quality.

Such disturbances in the grid from inefficient converters are a growing concern when discussing hydrogen production. Similarly, inefficient converters will deliver a low-quality DC to the electrolysis plant. However, there are already better converters on the market now. These create next-to-no disturbance in the grid, rendering compensation equipment obsolete, while delivering cleaner DC supply to the electrolysis plant. The cleaner DC supply can increase the overall efficiency of the production by roughly 1%.[32] And while this may not sound like much, **1% of the future electricity demand for hydrogen is actually enough to power London for almost four years.**[33] Additionally, some of the cost of higher-quality converters can be balanced out by the reduced need for compensation equipment and the maintenance that follows. Sometimes better equipment can simplify a system and also improve grid resilience.

**Mastering the science and implementation of energy conversion will be fundamental if we are to decarbonize our energy system.**

# Flexible hydrogen saves emissions and money

Efficient hydrogen production is not just about how we produce it, but also when we produce it. Let's imagine a future where we produce hydrogen when renewable electricity is plentiful, so we can deliver energy back to the grid when it is scarce. This is far from a sci-fi scenario: the solutions to use hydrogen production as a lever for creating a more flexible energy system already exist and are ready to be implemented today.

The way we use energy throughout the course of a day is dictated by our behavior as humans. In the hours of the very early morning, most of us are fast asleep. But as we wake up to start our day, water flows to buildings, gas to stoves, and electricity to homes. After a midday dip in energy demand, school and work finally let out and families return home. This is when we become hungry for energy. Dinners are prepared, laundry is washed, movies are watched, and lights switch on as day turns to night. After a normal evening at home, it is time for us, and our energy system, to rest for the night.

This is an example of how the energy demand cycles over the course of a normal weekday in a relatively developed energy grid. In a future energy system run on renewable energy sources, however, there will be peaks and valleys in the generation of energy as well (see Figure 2). The sharp peak in energy consumption that the grid experiences when people wake up or get home after a long day at work does not always align perfectly with periods of bright sunshine or intense winds.

This misalignment represents one of the major challenges of our future energy system. Currently, even in countries with a high share of renewables in the energy mix, fossil fuels are still used as residual energy sources in peak hours, meaning we release far more $CO_2$ than necessary during these periods. Similarly, we pay renewable energy producers hundreds of millions per year to shut down production in periods with too much wind or sun.[34] However, flexibility can reduce this curtailment by 25% already by 2030[35] and hydrogen production has a major role to play in this.

## Hydrogen as a critical lever of flexibility

In a world where we can neither fire up fossil-fuel power plants to meet peaks in demand nor pay renewable energy producers to shut down production, we must find new ways to manage energy more flexibly. Aligning green hydrogen production with periods of excess renewable electricity is one of our best tools for achieving this.

We must produce hydrogen when renewable energy supply is higher than demand. On a daily basis, this represents the periods in the middle of the day when the sun is at its highest but when we consume a relatively low amount. To balance out the curve and to avoid curtailment, this excess renewable electricity can be directed towards electrolysis plants. Similarly, if electricity demand goes up more than predicted, electrolyzer plants can react with incredible speed and temporarily turn down or shut off their operations. Additionally, on a seasonal basis, we use more electricity during the winter, despite producing more renewables in the summer. We can, however, store unused renewable electricity generated during the summer months in the form of hydrogen. This stockpile can then be converted back into electricity, should demand outstrip supply throughout the winter months. However, because power-$H_2$-power conversion has a total round-trip efficiency of 18-42%,[36] we should not use hydrogen as a standard fuel for electricity generation.

The timing of when we produce hydrogen can indeed make or break our ability to rapidly scale it in a sustainable way that does not put unnecessary strain on renewable energy production.

## The great misalignment of energy supply and demand

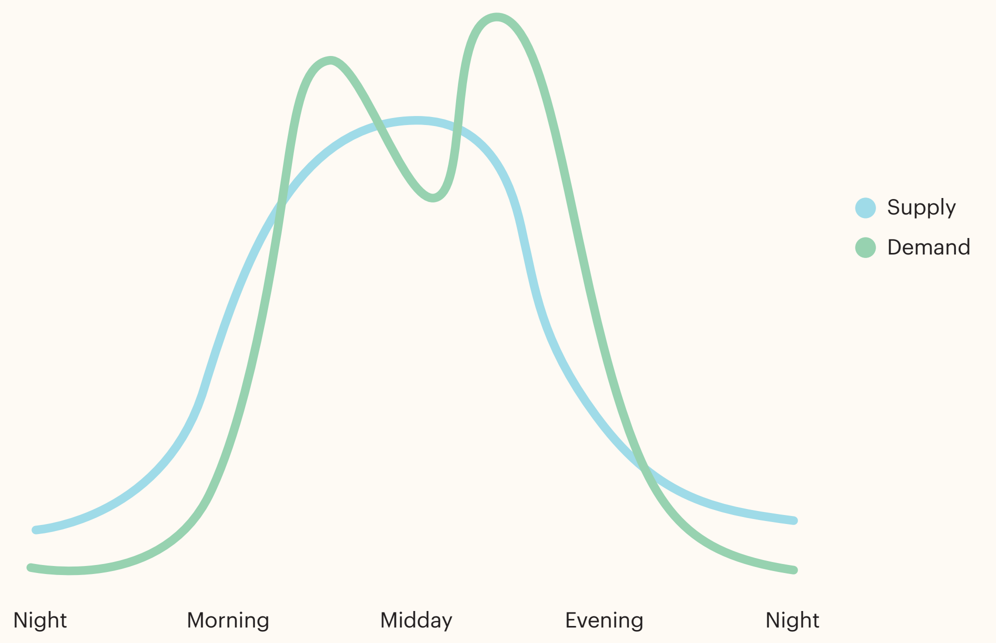
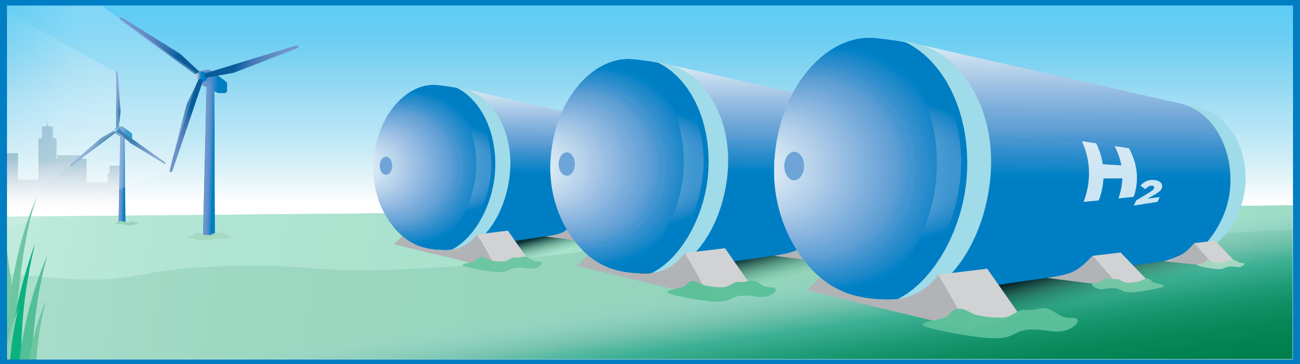


Figure 2: By producing green hydrogen in periods where renewable supply outstrips demand, such as late at night and around midday, we can avoid curtailment costs and can even use hydrogen as a low-emission alternative fuel during peak demand periods.

# **Case:** Energy system flexibility in the EU and UK



An analysis commissioned by Danfoss examines the potential of demand-side flexibility in the EU and UK wholesale energy market.[37] It finds that an **ambitious but realistic rollout will lead to substantial societal and environmental benefits, as well as lower energy bills for consumers.** The real potential is possibly greater, as this analysis does not consider savings in investments in the distribution grid and the internal transmission grid, and possible revenues from selling ancillary services to the system operators.

In the analysis, **hydrogen production proved to be the greatest lever towards a flexible and stable energy system in the EU and UK.** When the supply of renewable electricity surpasses demand, both wasting essential resources and risking destabilizing the grid, hydrogen production can be turned on. This both stores renewable electricity in the form of hydrogen and helps stabilize infrequencies in the grid.

During the very recent energy crisis, the UK earmarked €103 billion for the energy crisis, and the EU countries earmarked €681 billion.[38] There is another solution to become more resilient towards energy crises: The entire EU and UK can roll out demand-side flexibility measures. This can greatly reduce the need for government subsidies at this scale, as well as save money at both a societal and consumer level. Across the EU and UK, **the average consumer can save 7% on their electricity bill by 2030 and 10% by 2050.**

Flexibility is also an important tool to phase out fossil fuels from our electricity generation. Already by 2030, the annual electricity generation from natural gas can be drastically reduced by 106 TWh, or about one-fifth of the EU's natural gas consumption for electricity generation in 2022.[39] Similarly, **the EU and UK can save 40 million tons of $CO_2$ emissions annually by 2030,** more than Denmark's domestic climate footprint in 2021.[40] Alongside this, **the EU and UK can achieve annual societal cost savings of €10.5 billion by 2030 and €15.5 billion by 2050,** and this includes a significant part of the establishment cost of demand-side flexibility. Part of these savings in 2050 comes from a 21% decrease in investments in power lines.

The analysis is based on leveraging demand-side flexibility solutions in different scenarios and degrees of flexibility in the EU and UK. You can read more about demand-side flexibility in Danfoss Impact No. 4, "Energy Efficiency 2.0: Engineering the Future Energy System".[41]

# **Case:** Hydrogen as seasonal storage

Just as there are daily peaks in electricity production, there are also seasonal variations. At higher latitudes, it is necessary to heat the homes during winter, while mid- to low-latitude countries will have a higher demand for cooling during summer. Similarly, for the higher latitudes, there will be a gap between producing more renewable electricity in the summer while having the greatest need for electricity during the winter.

To fill out this gap, we must look at long-term storage options. Due to cost and capacity depletion over time, batteries are an ineffective solution for this. Hydrogen can prove a much better option for long-term storage since it can hold large amounts of energy with only a very little energy loss over time at a low cost per MWh.

Energy can be stored as hydrogen by converting low-emissions electricity into hydrogen. **There are several viable ways to store hydrogen on a large scale, from salt caverns to tanks.**[42] **This makes it ideal for seasonal energy balancing.**[43] In order to store hydrogen in salt caverns, they must be drained from salt water. While draining the caverns, we can take advantage of the high salt concentrations to generate electricity through a process called reverse osmosis. This can help to increase the efficiency of all the links related to hydrogen.

Moreover, the current pipelines for natural gas can be converted to transport hydrogen.[44] This way it is possible to use excess low-emissions electricity at one place to supply another region far away with energy – essentially creating a hydrogen market similar to the current natural gas market. Hydrogen storage has many potential uses but is not as efficient for short-term storage as other forms such as batteries.

Hydrogen can be an economic and sustainable choice for peak power periods, as very small volumes will be needed to serve these few peak hours a year.[45,46] For now, it is expensive to store energy as hydrogen, but the price is expected to decrease in the future with technological developments.[47,48]

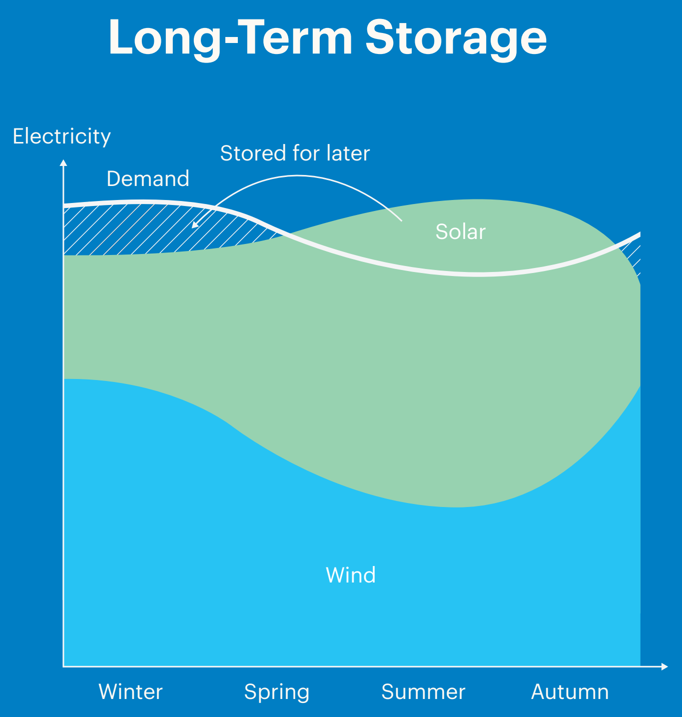


Figure 3: Hydrogen as a lever for seasonal energy storage

# Leverage excess heat from hydrogen production

> **"Everywhere in our energy system, energy is wasted into the atmosphere as heat. This excess heat is a sleeping giant of energy efficiency."**

Renewable energy is not an inexhaustible resource. However, in a fully electrified energy system, the demand for renewable electricity will be enormous. Therefore, we need to fully utilize all available energy sources across sectors – not least excess heat. Everywhere in our energy system, energy is wasted into the atmosphere as heat. This **excess heat is a sleeping giant of energy efficiency;** when strategically captured and deployed as energy, it has incredible potential to replace significant amounts of valuable energy sources such as fossil fuels and electricity, thereby saving both money and reducing GHG emissions.

Excess heat is most effective when planned through strategic sector integration. Sector integration is about combining different sectors to work together more efficiently and sustainably. Instead of treating each sector separately, sector integration aims to find ways to make them cooperate, reducing waste and improving overall system effectiveness. It also helps to reduce pressure on the energy grid by enabling greater exploitation of alternative energy sources such as excess heat.

Whether green, blue, or grey, large-scale hydrogen production creates incredible amounts of excess heat (see case "Excess heat from hydrogen production" on page 19 for analysis). In this section, we explore regional and global emissions-saving potentials of excess heat both from hydrogen and other major sources.

## Global potential of excess heat

Every time a machine runs, heat is generated. Just think of the warmth behind your fridge. The same is true on a larger scale with supermarkets, data centers, wastewater plants, metro stations, and water electrolysis facilities found in cities across the globe. **By 2030, up to 53% of the global energy input will be wasted as excess heat.**[49] Furthermore, the climate can benefit greatly if we recover excess heat. In fact, we can reduce global emissions by 10-19% if we recover the full theoretical potential of excess heat.[50]

Heating is one of the largest energy consumers in the energy system. In Europe, heating accounts for over 50% of the annual final energy consumption, and most European heat is still generated using fossil fuel-based sources, almost half of which is natural gas.[51] At the same time, all urban areas in Europe have access to numerous excess heat resources. There are about 2,860 TWh per year of waste heat accessible in the EU, much of which could be reused.[52] To put this number into perspective, it almost corresponds to the EU's total energy demand for heat and hot water in residential and service sector buildings, which is approximately 3,180 TWh per year in the EU27+UK.[53]

In some countries, the excess heat potential even matches the total heat demand.[54] In the Netherlands, for instance, excess heat amounts to 156 TWh per year,[55] while the water and space heating demand is only 152 TWh per year.[56] The picture is similar across the rest of the world as well. For instance, looking at the industrial sector in Northern China, there is around 813 TWh of excess heat during heating season alone.[57] Just imagine what the total amount of excess heat across all sectors in the whole of China looks like!

## Beyond excess heat

Just as we can use the heat and water (see page 10) from green hydrogen production, the excess oxygen created during the electrolysis process can also be repurposed. For example, through strategic planning and sector integration, the oxygen can be used in wastewater treatment facilities, for medical purposes, or in industries to boost energy efficiency in furnaces and combustion processes. This way we get the most out of the energy input for hydrogen production while limiting the waste of valuable resources.

# **Case:** Excess heat from hydrogen production

Over the coming years, the power demand for hydrogen production will be substantial and will only continue to increase (see Figure 4), driven largely by electrolysis. However, electrolysis wastes a lot of heat, and we can either let this disappear into the atmosphere, or leverage it to heat our homes, offices, and hot water supply.

This heat potential can only be utilized if we plan our hydrogen production wisely. For example, electrolysis plants must be constructed near infrastructure linking them to heat consumers, such as district energy networks or industrial clusters. In fact, this can already be done today. Several projects are underway and can soon distribute the excess heat from electrolysis plants through district energy systems to heat homes.[58,59]

Several factors influence how much of the excess heat can actually be put to use. For instance, using the full potential would require a large build out of district energy. Additionally, while all regions have some demand for heat, not all regions have the same demand for heat. However, the theoretical potential of recovering excess heat from electrolysis is so enormous that it would be a severe policy mistake not to consider it when planning future energy infrastructure around the globe.

On a global scale, we can theoretically recover 1,917 TWh of heat from hydrogen electrolysis in 2050 and redistribute it as district heat if the hydrogen production facilities are located near a suitable district energy system. **To put this into perspective, 1,917 TWh of heat is equivalent to more than 80% of today's global heat generation from coal, the largest source of heat.** In the EU alone, about 114 TWh can be recovered already by 2030, enough to cover Germany's current domestic heating more than two times. In China, 440-636 TWh can be recovered in 2060, between 27% and 39% of China's current heat generation in 2021.[60]

Latin America's electrolytic hydrogen production can reach six million tons in 2030, with 45% produced in Chile. Chile needs 142 TWh for electrolytic hydrogen production and can recover 31 TWh of excess heat from this. Chile has already included district energy in its future planning, and one roadmap suggests that in 2050, 40% of Chile's heat demand can be covered through district heating and that excess heat should be integrated in this.[61]

Of course, these potentials are theoretical. The actual potential depends on several factors such as local heat demand, vicinity to district energy, and how efficient electrolysis will be in the future. However, they demonstrate that if district energy and excess heat are considered in long-term energy system planning, it can be a key contributor to reaching the 1.5°C target.

## Hydrogen will be the single largest source of electricity demand in 2050

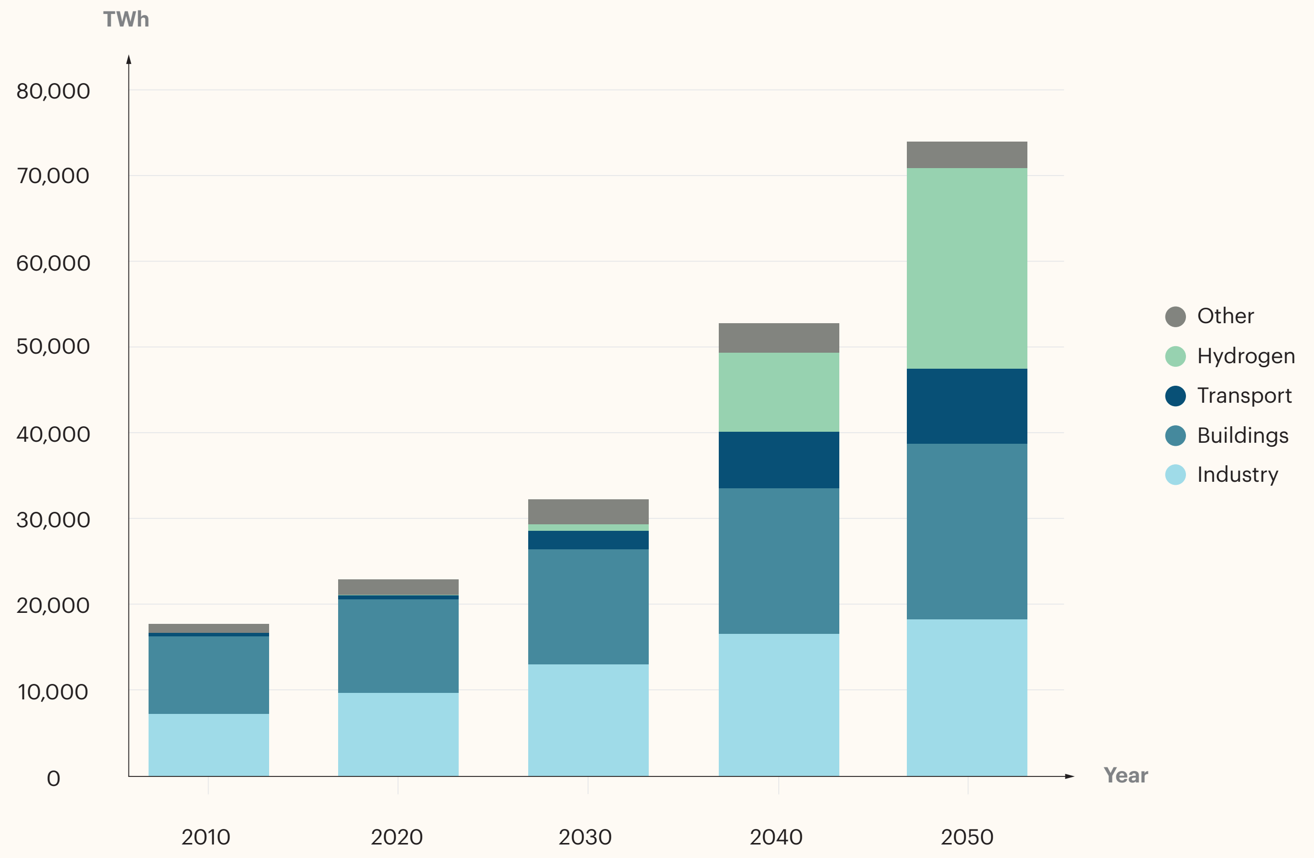


Figure 4: Sources of global power demand in BloombergNEF's Net Zero Scenario.[62]

# **Case:** Will the US push for "clean hydrogen" become a wasted opportunity?

In October 2023, the Biden-Harris Administration announced a $7 billion public investment in seven "regional clean hydrogen hubs [...] to accelerate the domestic market for low-cost, clean hydrogen."[63] Part of a larger $1.2 trillion bill to invest in infrastructure across the United States, the purpose of the hubs is to reduce emissions across particularly hard-to-decarbonize sectors and industrial processes – namely, heavy-duty transportation and chemical, steel, and cement manufacturing. The US Department of Energy claims that the hubs will eliminate nearly 25 million metric tons of $CO_2$ emissions from end uses annually.[64]

Together, the seven hubs will produce nearly three million metric tons of "clean hydrogen" per year, which the White House defines as hydrogen stemming from renewables, nuclear, biomass, or natural gas, leveraging carbon capture and storage for any associated carbon emissions.[65] Of the $7 billion allocated to the hubs, roughly two-thirds are associated with electrolysis-based production, while the remaining one-third will support other forms of hydrogen production.

Assuming that two-thirds of the hydrogen will be electrolytic, the US will need 111 TWh of electricity per year for splitting water. Vast amounts of heat will be wasted, and actually, 24 TWh of excess heat can be reused in district energy systems – something we can already do today. In 2022, the US used 106 TWh of coal, oil, and gas to generate heat. This means that the theoretical potential for recoverable **excess heat from electrolysis corresponds to more than 20% of the heat generated from fossil fuels in the US.**[66]

There is incredible potential for excess heat to be integrated into the energy system. For example, district heating networks and industrial clusters are great candidates for the reuse of excess heat, so long as the construction of electrolysis plants and greater hydrogen networks are planned strategically. In fact, there is a large overlap between residential and commercial low-temperature heating demand[67] and the regions where the hubs are to be constructed. This is especially true in states such as California, Pennsylvania, Illinois, Minnesota, Ohio, and Michigan, where expansive district energy networks serve some of the country's largest and most energy-intensive cities, such as Chicago and Detroit.

While heating is not in high demand all year round all across the country, the contribution of excess heat to year-long hot water supply and seasonal space heating through district energy networks can enable substantial reductions in the use of fossil fuels for heat generation. Additionally, it will not only reduce emissions: **reusing excess heat can also cut costs.** Every unit of excess heat integrated into district heating networks is one less unit that network owners need to purchase from fossil-derived energy sources. In other words, with excess heat, the energy has already been purchased, but we are currently just letting it (and dollar bills) evaporate into thin air.

Of course, the potential to reuse excess heat from the proposed regional clean hydrogen hubs can only be realized if strategic energy planning prioritizes proximity to district energy networks and other significant sources of heat consumption, such as industrial clusters. To avoid a becoming a wasted opportunity to reduce emissions and save money, it is critical that politicians and other key decision makers put excess heat at the center of the clean hydrogen revolution, both in the United States and beyond.

## US Clean Hydrogen Hubs

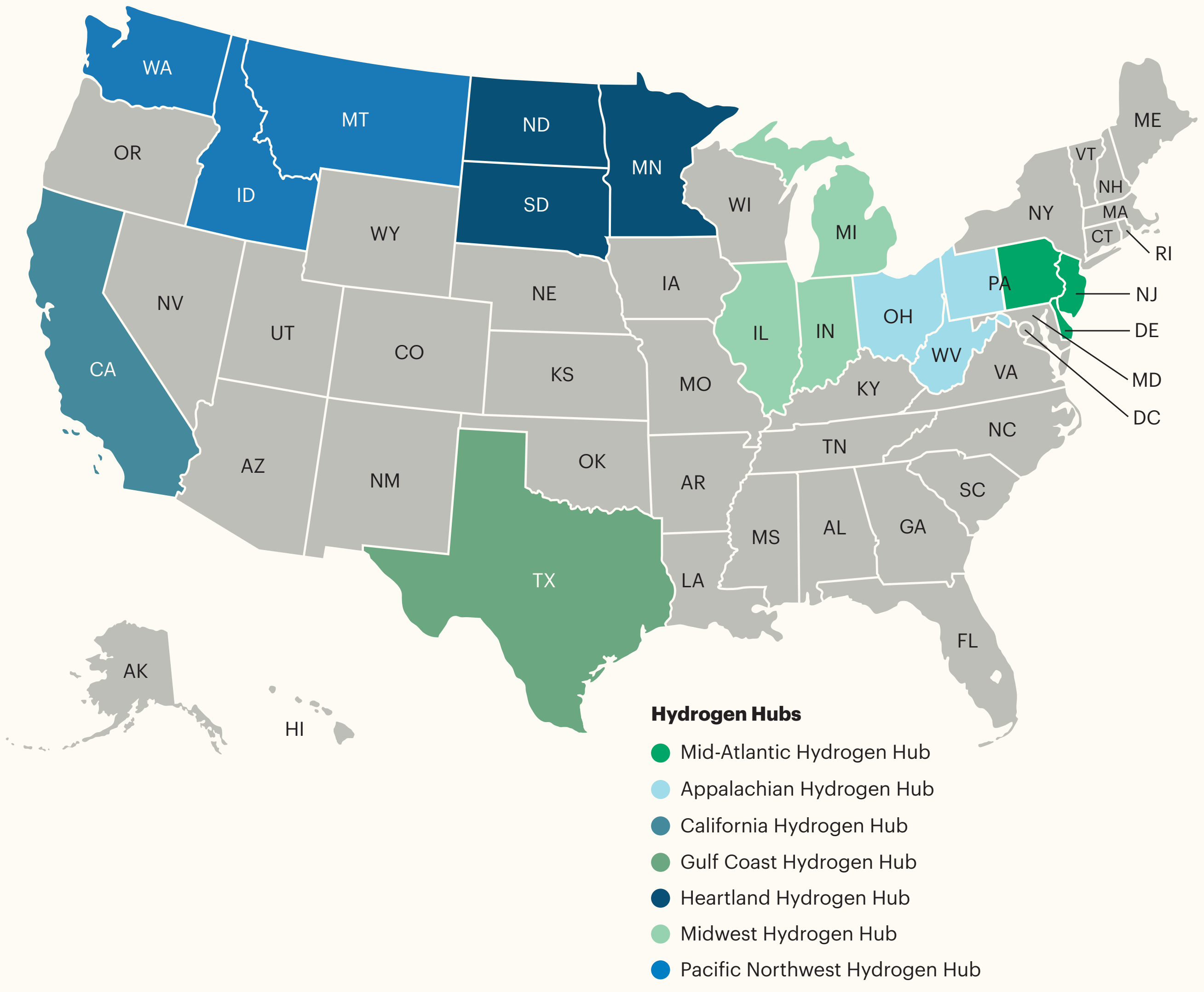


Figure 5: Seven new "clean" hydrogen hubs across the United States will drastically increase the country's domestic production of hydrogen. If planned strategically, the vast amounts of excess heat generated from these hubs can serve as a low-emission heating source for district heating networks and industrial hubs.

# Use hydrogen wisely

Hydrogen is an effective energy carrier and the end uses are many. However, just because it is effective does not mean that it is efficient. Indeed, green hydrogen production is costly and requires large amounts of renewable electricity when produced at scale. In the electrolysis process, energy is lost. And in cases where we need to convert hydrogen back to electricity or further into other forms of low-emission fuels, more energy is lost. Hydrogen will play a key role in decarbonizing our energy system, but it must be considered a costly and therefore limited resource.

It will require substantial investments to produce the low-emissions hydrogen required in 2050.[68] But how much hydrogen will we actually need in the future? The EU plans to produce and import a total of 666 TWh of hydrogen by 2030, all produced by low-emissions sources.[69] This is equivalent to the energy production from about 140 nuclear power plants.[70] One analysis suggests that **the EU can reduce the need for hydrogen to about 116 TWh – less than a fifth – by focusing on energy efficiency and electrification while massively scaling solar and wind energy, district heating, and highly efficient heat pumps.**[71] Regardless, 116 TWh of hydrogen by 2030 is still ambitious and will require a very large amount of electricity, which will pose challenges to the stability and security of the energy grid. The necessary investments will also be tremendous, underlining that **a cost-efficient transition must consider where the greatest potential benefits of hydrogen can be yielded.** As mentioned on page 7, less than 1% of today's hydrogen production is based on water electrolysis and makes green hydrogen. Decarbonizing current production facilities is essential, and grey hydrogen production facilities should start repurposing and adapting to green hydrogen production, making use of existing hydrogen infrastructure.

Producing green hydrogen is energy intensive, and we will need vast amounts of electricity for this. This means that we must use hydrogen as a last resort in sectors that are otherwise hard to decarbonize, such as long-distance shipping, international aviation, and steel and cement production. Many countries are considering powering their electricity production or heat supply with hydrogen. While this is a good application when used for meeting peak demand, it is highly inefficient to use hydrogen as a regular source of electricity or heat. For primary use, there are many better alternatives, such as renewables and heat pumps. Hydrogen will be a scarce resource, so the use of it must be considered carefully.

> **A cost-efficient transition must consider where the greatest potential benefits of hydrogen can be yielded.**

# Using hydrogen the right way

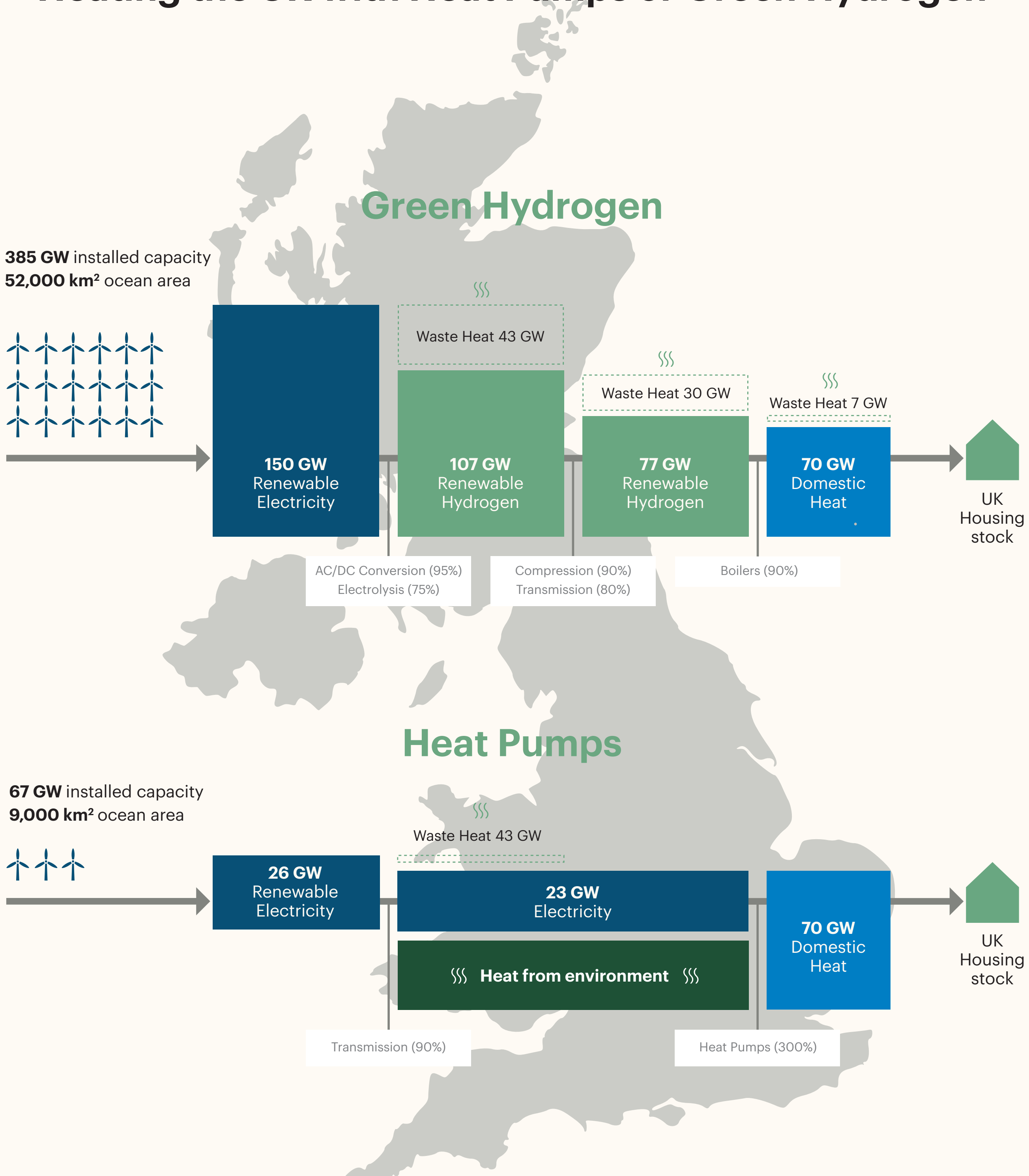
There are efficient and inefficient ways to use hydrogen. An example of inefficient use of hydrogen is space heating.[72] If we were to provide the UK with domestic heating from low-emissions hydrogen produced from offshore wind farms, we would need a capacity of 385 GW to produce enough hydrogen to heat the UK. However, the global offshore wind capacity is only expected to grow by 380 GW in the next ten years.[73] But if we instead heated the UK with heat pumps and district energy, we would need a much smaller capacity. With heat pumps, we would only need a capacity of 67 GW of offshore wind farms, and even less power if we supplied the more densely populated areas with district heating – this way it would also be easier to use excess heat from surrounding buildings and processes to heat local homes. The offshore wind farms for the hydrogen solution would take up 52,000km$^2$. However, it would take up only 9,000 km$^2$ for offshore wind farms to supply heat pumps. Essentially, it would take one-sixth of the power to get the British through the winter with heat pumps instead of hydrogen,[74] and even less if heat pumps were combined with district energy.

Fortunately, with a ban on boilers in all homes built from 2025,[75] the debate on whether to use hydrogen for home heating has come to an end in the UK. However, there are many other countries, especially in Europe,[76,77] where the discussion is still very much alive. The science unequivocally shows that heat pumps and district energy are more effective solutions and should be considered the primary sources for home heating in a decarbonized future.[78]

In the following cases, we take a deep dive into use cases where hydrogen is the wise choice, such as the production of virtually carbon-free fuels, as well as how it can be a great lever to decarbonize food production.

> **"Even if electrolysis capacity grows as fast as wind and solar power have done, green hydrogen supply will remain scarce in the short term and uncertain in the long term."[79]**

## Heating the UK with Heat Pumps or Green Hydrogen



**6 times**

the offshore wind capacity is needed when using hydrogen for space heating compared to heat pumps

Figure 6. Source: Hydrogen Science Coalition.[80]

# **Case:** E-fueling the future

Where we cannot yet electrify efficiently, we can at least decarbonize. For example, steel and cement production require extremely high temperatures – so high, in fact, that electric furnaces cannot yet produce them efficiently. And while we are seeing positive technological developments for electrifying high-temperature processes, these are not currently operating at scale, leaving us with few options other than fossil fuels. Similarly, in industries such as aviation and long-distance shipping, electric motors actually can produce enough power. However, they also require batteries, which are far too heavy and require too much space to be practical. In both cases, hydrogen is our best hope for decarbonization.

Hydrogen can be converted into alternative fuels, such as e-ammonia, e-kerosene, and e-methanol. These can then be used to fuel industries or processes requiring either high temperatures or long-distance mobility. Additionally, though still in development, hydrogen can be utilized in fuel cells, where it is mixed with oxygen and releases energy in the process. With a fuel cell, ships, planes, and long-distance trucks can be fueled without fossil sources.

At each step in the conversion process, there is energy loss. For example, when converting electricity to hydrogen, there is an energy loss of roughly 30%.[81] When then converting that hydrogen back into some other form of deployable energy (such as e-fuels), there is an additional energy loss. Because of this energy loss, these e-fuels are not necessarily more energy efficient than fossil fuels. However, assuming that the electricity used to create the initial hydrogen comes from renewable sources, as the vast majority will in our 2050 energy system, this is a viable pathway to decarbonize these energy-intensive sectors, where until recently decarbonization was seen as nothing but a pipe dream.

# **Case:** Decarbonizing agriculture with low-emissions ammonia

Agriculture emits 12% of global emissions[82] – a number which is only projected to increase over the coming decade.[83] It is one of the most challenging sectors to decarbonize, given the GHG-intensive nature of crop and livestock production. This carbon intensity is in part due to fertilizer production. Ammonia is an essential nutrient in fertilizer, and 70% of today's ammonia is used in fertilizer production. Without it we cannot grow crops. However, the production of ammonia accounts for about 1.3% of global $CO_2$ emissions and 2% of the final global energy consumption.[84]

By 2040, the ammonia demand for fertilizer will have almost doubled and the total demand will have more than doubled.[85] And regardless of this increasing demand, the emissions from ammonia production must be reduced by 95%.[86] **Decarbonizing ammonia production with hydrogen can prove one of the greatest levers in decarbonizing our food production** and this is one of the areas that can be decarbonized without disrupting the existing production processes in agriculture.[87]

Today, ammonia is produced by splitting natural gas into hydrogen and $CO_2$, and then combining the hydrogen with nitrogen from the atmosphere under high pressure and temperature – also known as the Haber-Bosch process.[88] This is a very GHG-intensive process since the $CO_2$ is released into the atmosphere. Actually, 1.6 to 2.6 tons of $CO_2$ are emitted for every ton of ammonia produced.[89,90,91] In the future, the hydrogen and electricity for ammonia production can be supplied from renewable sources, drastically lowering the climate footprint from ammonia.[92] According to the IEA, about one-third of the GHG reductions in ammonia production must stem from electrolytic hydrogen to reach the Paris goals.[93]

There are currently nearly 250 projects worldwide in the pipeline that plan to produce electrolysis-based ammonia,[94] and international organizations and policy makers are increasingly realizing that green ammonia is a part of the future.[95]

# Policy Recommendations

Now is the time for decisionmakers to set the right regulatory and economic framework for an efficient large-scale rollout of hydrogen. Public support is needed at the local, regional, and national level to address regulatory barriers and improve implementation plans. Similarly, we must stimulate more international cooperation and cross-industry collaboration and synergies. These are also likely to be a driving force behind innovation, demand, and growth of green hydrogen.

Hydrogen has its complications, and those need to be addressed to unlock the full potential of a hydrogen economy. Today, hydrogen is largely being produced with natural gas, and less than 1% of today's global production is green hydrogen, produced via water electrolysis based on renewable electricity (see page 7). To reach the goals of the Paris Agreement, significant upscaling needs to happen sooner rather than later. A good place to start would be to repurpose grey hydrogen production facilities and have them produce green hydrogen, making good use of the already established hydrogen infrastructure. Moreover, the demand for hydrogen is still overwhelmingly focused on traditional purposes, such as ammonia production or refining, while use in hard-to-abate sectors like steel-making or heavy transport is still very limited.[96] As such, hydrogen is still an immature technology in the green transition. The following overall principles and policy measures can accelerate a transition to a cost-efficient deployment of green hydrogen.

### Overall policy principles

- **Energy efficiency and electrification first.** While green hydrogen can open doors for the transition to a green economy, focus should remain on direct electrification of as many elements of our energy systems as possible. Next, a rapid scale up of green hydrogen as opposed to high-emission hydrogen is needed.
- **Use hydrogen for hard-to-abate sectors.** Green hydrogen provides a means to decarbonize and indirectly electrify sectors in which full decarbonization is not yet possible. This includes decarbonizing heavy industry, ammonia to decarbonize agriculture, and using green hydrogen for e-fuels.
- **Build out of hydrogen must go hand in hand with the build out of renewables.** Electrolysis will have a significant pull on the electricity grid, and hydrogen production must not overload an increasing demand. Renewable energy sources driving hydrogen production must be auxiliary.
- **Leverage excess heat from green hydrogen production.** Electrolytic hydrogen production generates a substantial proportion of heat loss. If hydrogen production is planned strategically, much of the excess heat can be repurposed in district heating or microgrids.
- **Examine potential sector integration opportunities.** Green hydrogen production has a large electricity pull, high water consumption, and vast amounts of excess heat accessible. Before building facilities, thorough sector integration due diligence must be conducted. For instance, areas with water scarcity issues might benefit from optimized desalination facilities, which are critical in providing the pure water needed for electrolysis as well as drinking water.

### Incentivize green hydrogen production

- **Subsidize research and development to increase feasibility of green hydrogen production.** High production costs limit the economic feasibility of electrolysis facilities. Investment costs are estimated to be reduced by 80% if electrolyzers become cheaper (see page 7). Lowering tariffs and creating tax incentives, such as the tax credit on green hydrogen in the Inflation Reduction Act, are pivotal (IRA Clean Hydrogen Production Credit). Financing instruments like the EU Hydrogen Bank can also play an important role in facilitating investments into the green hydrogen value chain. On the demand side, research and development into novel applications such as green hydrogen for steel-making or heavy transport should also be supported.
- **Strengthen the willingness of investors and customers to pay.** Clear goals supported by national hydrogen strategies create predictability and stability for investors. Ensuring future demand for green hydrogen – especially in hard-to-abate sectors – is key to de-risk projects today and incentivize upstream investments. Accommodating lack of long-term viability is therefore essential in creating a green hydrogen market.
- **Lower tariffs on hydrogen as a commodity.** Address barriers limiting trade and investment in the entire green hydrogen supply chain. Tariffs on electrolyzers and hydrogen derivatives create barriers for promoting green hydrogen. To increase green hydrogen demand and incentivize investments, green hydrogen and its derivatives should benefit from tax and tariff exemptions. Phasing out subsidies on fossil fuels would further close the economic gap between grey, blue, and green hydrogen.
- **Incentivize hydrogen transition through build out of infrastructure.** In many use cases, infrastructure will inform applicability. Lack of ambition and planning of hydrogen infrastructure limit investors and market actors' ability to predict green hydrogen applicability. In some cases, it is both possible and feasible to retrofit existing natural gas pipelines to enable them to transport hydrogen.
- **Regulate government procurement strategies to stimulate a green hydrogen market.** Introduce requirements for hard-to-abate sectors' deliveries on government contracts like green steel in new buildings and long-haul shipping imports running on e-fuels.
- **Incentivize investments in developing countries with high renewable energy potential.** Many developing economies have access to vast amounts of renewable energy and will thus be able to produce a lot of green hydrogen when they receive the investments needed to scale up production. Apart from sparking developing countries' economy by exporting, it can support other economies' hydrogen import requirements.

### Produce efficiently

- **Implement high standards for efficient hydrogen production.** To lower the amount of renewable energy used on green hydrogen production, standards should dictate the efficiency of production. For example, regulation incentivizing the use of high-efficiency grid converters and eliminating inefficient pressurization methods and technologies could be considered.
- **Ensure hydrogen production does not add to an increasing water scarcity issue.** All forms of hydrogen production are water intensive. For example, conventional, carbon-intensive methods of hydrogen production, as well as production utilizing carbon capture and storage, require large amounts of water for steam generation and cooling. But despite requiring water for electrolysis, green hydrogen is actually the least water-intensive production method. Careful planning of production and use of efficient desalination technologies are pivotal.
- **Use hydrogen as a tool to increase flexibility.** Efficient hydrogen production is not just about how we produce it, but also when we produce it. Producing green hydrogen in periods of high renewable electricity supply and low demand means we can store it for peak demand periods, accelerating a phase out of fossil-fuel power plants. Flexible hydrogen production can also balance and stabilize the grid, meaning renewable electricity generation does not have to be curtailed.

# **Appendix:** Excess heat from electrolysis

In this case, we investigate the theoretical potentials of usable excess heat from electrolytic hydrogen production in the future. The included electrolysis technologies are alkaline electrolyzers (AEC), proton exchange membrane electrolyser (PEM), and solid oxide electrolyzers (SOEC). For technical descriptions of these technologies, see Technology Data for Renewable Fuels from the Danish Energy Agency.

### Weighted inputs and outputs of AEC, PEM, and SOEC

The future electrolytic hydrogen production will be distributed between AEC, PEM, SOEC, and other technologies. The expected distribution between these technologies in 2030 is presented in Table A.1 together with an extrapolation of AEC, PEM, and SOEC to cover other technologies. For the extrapolation, the distribution between AEC, PEM and SOEC is extended to cover "Other", in lack of better data. This distribution is dependent on technological advancements and cost developments for each technology and SOEC has seen some advances lately,[97] a more efficient technology with far less waste heat.

**Table A.1:** Expected distribution (%) between AEC, PEM, SOEC, and other technologies in 2030, and when AEC, PEM, and SOEC is extrapolated over Other technologies.

| **Technology** | **AEC** | **PEM** | **SOEC** | **Other** |
|---|---|---|---|---|
| 2030[a] | 54% | 23% | 9% | 14% |
| AEC, PEM, and SOEC extrapolation[b] | 63% | 27% | 10% | - |

**[a] IEA (2023). Global Hydrogen Review 2023. Figure 3.7: Electrolyzer manufacturing capacity by region and technology according to announced projects and in the Net Zero Emissions by 2050 Scenario, 2021- 2030 p. 72.**

**[b] AEC, PEM, and SOEC are extrapolated by extending their distribution to Other technologies. This is due to lack of data of efficiencies, inputs and outputs of Other technologies.**

Table A.2 presents estimates of the energy inputs (e.g., electricity) and outputs (e.g., hydrogen and heat) in 2030, 2040, and 2050 for AEC, PEM, and SOEC.[98] These are presented together with the weighted averages of the three electrolyzer technologies. The weighted averages are determined by the extrapolated expected distribution of AEC, PEM, and SOEC in table A.1. For the weighted average that reflects AEC, PEM, and SOEC, the electricity input is about 98% for 2030, 2040, and 2050. This is because heat is also an input for SOEC. To determine the recoverable heat loss for district heating per electricity input ($HL_{rec}$), the following equation is used. $HL_{rec}$ for the weighted average is presented in Table A.2.

$$HL_{rec}\ [\%\ electricity\ input] = \frac{\begin{array}{c}\text{Recoverable heat for district heating}\\ [\%\ \text{points of heat loss}]\end{array}}{Power_{in}\ [\%\ total\ input]} \cdot 100 \qquad (1)$$

**Table A.2:** Inputs and outputs of AEC, PEM, SOEC, and derived weighted average from the three.

| | **Abbreviation for formulas** | **Hydrogen production via alkaline electrolysis (AEC) for 100 MW plant[a]** | | | **Hydrogen production via PEMEC electrolysis for 100 MW plant[a]** | | | **Hydrogen production via solid oxide electrolysis (SOEC) for 100 MW plant[a]** | | | **Weighted average hydrogen production from AEC, PEM, and SOEC for 100 MW plant[b]** | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | **2030** | **2040** | **2050** | **2030** | **2040** | **2050** | **2030** | **2040** | **2050** | **2030** | **2040** | **2050** |
| **Input** | | | | | | | | | | | | | |
| *Electricity (% total input [MWh / MWh])* | $Power_{in}$ | 100 | 100 | 100 | 100 | 100 | 100 | 80.5 | 81.4 | 81.4 | 98.0 | 98.1 | 98.1 |
| *Heat (% total input [MWh / MWh])* | | 0 | 0 | 0 | 0 | 0 | 0 | 19.5 | 18.6 | 18.6 | 2.0 | 1.9 | 1.9 |
| **Output** | | | | | | | | | | | | | |
| *Hydrogen Output (% total input [MWh / MWh])* | $H_{2out}$ | 62.2 | 65.3 | 69.9 | 58.5 | 61.6 | 66.4 | 69.6 | 70.5 | 72.5 | 61.9 | 64.8 | 69.2 |
| *ΔE from HHV to LHV (% total input electricity [MWh / MWh])[c]* | | 12.6 | 13.2 | 14.1 | 12.0 | 12.7 | 13.7 | 16.0 | 16.3 | 16.8 | 12.8 | 13.4 | 14.3 |
| *Heat loss (% total input [MWh / MWh])* | | 25.3 | 21.5 | 15.9 | 29.5 | 25.7 | 19.9 | 14.4 | 13.2 | 10.7 | 25.3 | 21.8 | 16.5 |
| - hereof unrecoverable heat loss [%-points of heat loss] | | 3.0 | 3.0 | 3.0 | 3.0 | 3.0 | 3.0 | 14.4 | 13.2 | 10.7 | 4.2 | 4.0 | 3.8 |
| - hereof recoverable for district heating [%-points of heat loss] | | 22.3 | 18.5 | 12.9 | 26.5 | 22.7 | 16.9 | 0 | 0 | 0 | 21.2 | 17.8 | 12.7 |
| *Recoverable heat loss for district heating (% of electricity input [MWh/MWh])[d]* | $HL_{rec}$ | | | | | | | | | | 21.6 | 18.1 | 13.0 |

**[a] Source: The Danish Energy Agency (2024). Technology Data for Renewable Fuels**

**[b] Source: Danfoss calculations. Input and output of AEC, PEM, and SOEC are weighted after the extrapolated expected distribution of electrolysis technologies in 2030 (Table A.1). Due to lack of data, the 2030 distribution is applied to both 2040 and 2050.**

**[c] The Danish Energy Agency: The HHV electrolyser efficiency can be calculated as the sum of the rows: "ΔE from HHV to LHV" and "Hydrogen".**

**[d] Danfoss calculations, see equation 1.**

### Global excess heat potential from electrolytic hydrogen in 2050

The IEA estimate that the total electricity demand for electrolysis in 2050 will be 14,800 TWh.[99] Through equation 1 we find that $HL_{rec}$ for 2050 is 13%, which means that 13% of every electricity input can theoretically be recovered as excess heat for district heating in 2050. Applying this to the expected electricity demand for electrolysis in 2050, 14,800 TWh, we can derive that 1,917 TWh theoretically can be recovered for district heating.

In 2021, the global heat generation from coal was 8,022,699 TJ, or 2,229 TWh.[100] 1,917 TWh constitutes 86% of the global heat production from coal.

### Excess heat from electrolysis in the EU in 2030

The EU plans to produce 333 TWh of renewable hydrogen by 2030.[101] According to the EU, renewable hydrogen is hydrogen produced through electrolysis.[102] The power demand (Powerdem [TWh]) for electrolysis can be found as:

$$Power_{dem}\ [TWh] = \frac{Electrolytic\ hydrogen\ production\ [TWh]}{H_{2out}\ [\%\ total\ input]} \cdot Power_{in}\ [\%\ total\ input] \qquad (2)$$

Using equation 2, $Power_{dem}$ in 2030 equals 527 TWh in the EU. The recoverable heat per power input, $HL_{rec}$, is 22% in 2030, which means that 114 TWh excess heat can theoretically be recovered from the EU electrolytic hydrogen production in 2030.

In Germany, 51.5 TWh of heat was distributed to private households and residential buildings in 2017.[103] This means that the theoretical potential of recoverable excess heat from electrolysis in the EU in 2030 is enough to cover Germany's heat demand for households and residential buildings 2.2 times.

### Excess heat potentials from electrolysis in China in 2060

The hydrogen production in China in 2060 will be between 90 and 130 million tons and 80% of this is expected to be electrolytic.[104] Considering the energy content of hydrogen to be 33.3 kWh/kg $H_2$, we can derive that the energy content in the Chinese electrolytic hydrogen will be 2,400 to 3,467 TWh in 2060. In lack of better data, we assume that the weighted average hydrogen production for year 2050 (Table A.2) is representative for China in 2060. Using equation 2, we can derive that $Power_{dem}$ in 2060 is 2,401 TWh to 4,912 TWh.

$HL_{rec}$ for 2050 is 13%, which means that 13% of every electricity input can theoretically be recovered as excess heat for district heating in 2050. Applying this to $Power_{dem}$, the excess heat from electrolytic hydrogen production in China is 440-636 TWh.

Table A.3 presents China's 2021 heat generation by source and the theoretical excess heat potential from electrolysis relative to heat generation. The potential excess heat can cover 27-39% of China's heat generation from coal.

**Table A.3:** Heat generation by source in China 2021 and compared to potentially recoverable excess heat from electrolytic hydrogen production.

| **Heat generation by source in China 2021[105]** | **Coal** | **Oil** | **Natural gas** | **Biofuels** | **Waste** | **Total** | **Units** |
|---|---|---|---|---|---|---|---|
| | 5,922,803 | 229,998 | 778,876 | 10,735 | 38,240 | 6,980,652 | TJ |
| | 1,645 | 64 | 216 | 3 | 11 | 1,939 | TWh |
| **Potentially recoverable excess heat relative to heat generation by source in China 2021[a]** | | | | | | | |
| *From* | 27 | 689 | 204 | 14,771 | 4,147 | 23 | % |
| *To* | 39 | 996 | 294 | 21,336 | 5,990 | 33 | % |

**[a] Assuming that the recoverable excess heat potential from electrolytic hydrogen production in China in 2060 is from 440 to 636 TWh.**

### Excess heat potential from electrolysis in the US by 2030

The White House has presented a strategy to produce three million tons of clean hydrogen per year by 2030. Two-thirds of their announced investments will be directed towards electrolytic hydrogen.[106] The IEA estimate that 70% of the global hydrogen can come from electrolysis in 2030.[107] On basis of this, we assume that two-thirds of the produced hydrogen, or 2.1 million tons, in 2030 will be electrolytic.

Considering the energy content of hydrogen to be 33.3 kWh/kg $H_2$, we can derive that the energy content in the US electrolytic hydrogen will be 70 TWh. We use equation 2 to find the electricity demand for electrolytic production to be 111 TWh. Using equation 1, we find that $HL_{rec}$ is 22%, so the potentially recoverable excess heat is 24 TWh.

The US used 106 TWh to generate heat from coal, oil, and gas in 2022 (Table A.4). The potential recoverable excess heat from electrolysis is 24 TWh, as much as 22% of the heat generated from fossil fuels in the US.

**Table A.4:** Heat generation by source in the US 2022 and compared to potentially recoverable excess heat from electrolytic hydrogen production.

| **Heat generation by source in the US 2022[108]** | | | | | | | |
|---|---|---|---|---|---|---|---|
| **Coal** | **Oil** | **Natural gas** | **Biofuels** | **Waste** | **Total** | **Coal, oil and gas** | **Units** |
| 14,319 | 27,686 | 339,754 | 37,205 | 16,199 | 135,163 | 381,759 | TJ |
| 4.0 | 7.7 | 94.4 | 10.3 | 4.5 | 120.9 | 106.0 | TWh |
| **Potentially recoverable excess heat relative to heat generation by source in the US 2021[a]** | | | | | | | |
| 589 | 305 | 25 | 227 | 521 | 19 | 22 | % |

**[a] Assuming that the recoverable excess heat potential from electrolytic hydrogen production in the US is 24 TWh.**

### Excess heat potential from electrolysis in Chile by 2030

Latin America's electrolytic hydrogen production can reach 6 million tons annually by 2030, and 45% of this, or 2.7 million tons, could be in Chile.[109] Considering the energy content of hydrogen to be 33.3 kWh/kg $H_2$, we can derive that the energy content in the Chilean electrolytic hydrogen will be 90 TWh in 2030. Using equation 2, we can derive that $Power_{dem}$ in 2030 is 142 TWh. The recoverable heat per power input, $HL_{rec}$, is 22% in 2030, which means that 31 TWh excess heat theoretically can be recovered from the Chilean electrolytic hydrogen production in 2030.

Chile has already included district energy in its future planning,[110] and one roadmap suggests that in 2050, 40% of Chile's heat demand can be covered through district heating and that excess heat should be integrated in this.[111]

### General note on theoretical versus realizable potentials

The theoretical potentials of excess heat are different from the realizable potentials. With this case, we are aiming to demonstrate the potentials if all conditions are optimal for utilizing excess heat. Three examples of these conditions are: 1) that there must be a heating demand in the first place, an assumption which of course varies both temporally and geographically; 2) if there is an existing district heating infrastructure, it is simple to utilize the excess heat, but in many instances a build-out of district heating is necessary; and 3) the economic side must of course also be considered. Vicinity to the electricity supply and the district heating grid do not always go together, for example for offshore electrolysis plants.

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# What is Danfoss Impact?

Danfoss Impact is written to share our view on the potential of energy efficiency and electrification to transform our energy system. In the dialogue about the green transition, energy efficiency is often overlooked. One main reason for this is that experts and industrial leaders have inadequately explained its role in accelerating electrification to enable a future powered by renewables.

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