Danfoss Impact
Issue no. 4

Energy Efficiency 2.0

Engineering the future energy system

It’s time to rethink energy efficiency

Foreword by Jürgen Fischer

President, Danfoss Climate Solutions

Our power grid – the infrastructure delivering our electricity – is something most of us give little more than a passing thought. This is a paradox really since electricity has become so essential in our modern life. Everything from factories, hospitals, ports, police, military, and transport – not to mention communication systems – depend on a working power grid. When blackouts hit, losing light is indeed the least of our problems. And while these outages have become more frequent and longer lasting, this is nothing compared to the challenges we are facing in a future energy system, where the demands for electrical power will increase significantly. Unless we immediately start to rethink energy efficiency and place it at the core of energy policy and climate mitigation strategies, power outages are but one of the significant challenges we are facing.

By 2050, renewables need to make up roughly 70% of the energy mix if we are to reach net zero and the goals of the Paris Agreement.[1] Despite this, there is a lack of attention to what this entails for the energy system. Will we have the capacity and infrastructure to efficiently use all that renewable energy once we have it? Which steps must we have taken today to ensure this decarbonized future energy system becomes a reality?

Let’s start with wind and solar, the darlings of the renewable energy discussion. The energy these sources produce comes mostly in the form of electricity. But if we don’t have the infrastructure in place to effectively use that electricity – across transport, buildings, industry – producing so much of it is a relatively pointless endeavor. To use the electricity generated by renewables, **we must undergo an engineering-led revolution to electrify all possible elements of our energy system.**

An electrified society could cut up to 40% of final energy consumption simply because electric technologies waste less energy than their fossil-fuel counterparts.[2] At the same time, energy efficiency measures can accelerate the electrification of sectors – for instance, making heavy-duty vehicles more efficient is fundamental for reducing the size of the batteries needed to electrify them. This is why we must begin thinking about electrification itself as a form of energy efficiency.

Timing is everything. In the future energy system, it is not sufficient to only use the right kind of energy – we need to use it at the right time as well. Our habits and behaviors currently dictate when energy is needed; when we are awake, we use a lot, and when we are asleep, we do not. Similarly, nature dictates when the sun shines and the wind blows. Because of this, our need for energy will not always line up with nature’s weather plans, forcing us to use fossil power plants as residual energy sources when renewable supply is low. This not only leads to more expensive electricity, but also a far heavier carbon footprint in peak hours. Fortunately, **energy efficiency in the form of demand-side flexibility solutions can better mediate the relationship between supply and demand, which is necessary to avoid carbon-intensive demand peaks.** Through existing demand side-flexibility technologies, we can save money, reduce CO_2 emissions, and stabilize the grid.

Even in the future, not everything will run directly on electricity. We will still need clean alternatives to deeply decarbonize sectors such as heavy industry, aviation, and long-distance shipping. Here, hydrogen is the most promising alternative. Hydrogen will be crucial in the future energy system, where there inevitably will be periods of excess renewable electricity. However, water electrolysis – the process of producing hydrogen from electricity – will create an enormous demand for electricity, putting significant strain on our already-outdated energy grid. But together, **energy efficiency and electrification can keep hydrogen demand at a realistic and attainable level while at the same time producing hydrogen in the most energy-efficient way possible.** Urgent political attention to energy-efficient hydrogen production is necessary if we want the future energy equation to add up.

Renewable energy production will not be near sufficient to meet the energy demand in an electrified energy system serving a population of 9.8 billion in 2050. To supplement demand, excess heat will be our best friend. In 2030, up to 53% of the global energy input will be wasted as excess heat.[3] But **by capturing and reusing it, excess heat can replace significant amounts of electricity, gas, or other fuels that are otherwise needed to produce heat.** It can help stabilize the future electricity grid and ease the green transition.

As the above themes indicate, energy efficiency is not an afterthought to renewables. In the future energy system, **energy efficiency must take center stage and work in harmony with the build out of renewables** to meet our climate goals, ensure energy security, boost the economy, and fundamentally transform the way energy is governed and consumed. This revised understanding of energy efficiency – what we are calling “energy efficiency 2.0” – is the fastest and most cost-efficient way to turn a 2050 net-zero scenario into a reality. The good news is that we already have the necessary technology. We don’t need magic, but immediate political action to scale the solutions.

> **”Using the word ’blackout’ to refer to a power outage is something of a misnomer. Losing light is the least of our problems when our electricity systems crash.”**
>
> Gretchen Bakke, The Grid[4]

“Any sufficiently advanced technology is indistinguishable from magic.”

Arthur C. Clarke,
Hazards of Prophecy [5]

Only got 2 minutes?

This is Energy Efficiency 2.0

1. Electrify wherever possible

By transitioning from a fossil energy system to a fully electrified one, we can cut up to 40% of final energy consumption.[6] Electrification is itself a form of energy efficiency, as most electric technologies have a lower rate of energy loss while performing the same function as a fossil-driven equivalent.

2. Implement flexibility solutions

Reinventing energy efficiency is not only about using less energy, but also using the energy at the right time. By maximizing the potential of demand-side flexibility, **the EU and UK can annually save 40 million tons of CO_2 emissions and reduce the electricity generation from natural gas by 106 TWh**, or about one-fifth of the EU’s natural gas consumption for electricity generation in 2022. Adding to this, the **annual societal cost savings amounts to €10.5 billion by 2030. Similarly, households can save on average 7% on their electricity bills.**

3. Use hydrogen wisely

Powering our future energy system with renewables will require a rapid scale-up of hydrogen. However, hydrogen conversion requires incredible amounts of energy; by 2050, **hydrogen production will require more than half the total electricity demand today.**[7,8,9,10] High-efficiency technologies for electrolysis will be essential to ensure energy security and stability as well as to lower energy demand for hydrogen.

4. Integrate sectors

By strategically integrating sectors and deploying excess heat, we can ultimately lower demand on energy production and maximize efficiency. **By 2030, up to 53% of the global energy input will be wasted as excess heat.**[11] **However, this heat can be captured and reused** to power machinery, as well as heat buildings and water through deeper sector integration.

Energy Efficiency 2.0

Engineering the Future Energy System

In a net-zero scenario, it is not only the sources of energy that must change; so too must the ways that energy is deployed, converted, stored, used, and reused.

This paper builds a new narrative around energy efficiency, showing how **electrification, demand-side flexibility, conversion, storage, and sector integration** must take center stage in a future energy system enabling an energy grid powered by renewables.

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Drawing on empirical evidence and data from various credible sources, Danfoss Impact Issue No. 4 shows how an alternate understanding of energy efficiency, referred to in the paper as “energy efficiency 2.0” (EE 2.0), will be critical to a fully electrified and decarbonized energy system.

Across the literature, the term ‘smart grid’ is widely used to describe the interconnected energy system of the future. In the smart grid, electrification, sector integration, flexibility, conversion, and storage will complement each other in a more efficient system that delivers the right energy at the right time. This is what we are referring to as ‘the future energy system’ in this issue.

The future production of hydrogen must rely on electricity to be decarbonizable. In this issue, hydrogen produced from renewable electricity is referred to as ‘low-emissions hydrogen’, in accordance with the IEA’s World Energy Outlook. This term is interchangeable with the term ‘green hydrogen’, which is widely used across the literature, but with no standard definition.

A special thank you to Prof. Nick Eyre (Professor of Energy and Climate Policy at University of Oxford & Senior Research Fellow in Energy at the Environmental Change Institute), Dr. Jan Rosenow (Director of European Programs at the Regulatory Assistance Project, Honorary Research Associate at University of Oxford’s Environmental Change Institute), Frederik Dahl Nielsen (PhD Fellow, Sustainable Energy Planning at Aalborg University), and Dr. Brian Vad Mathiesen (Professor, Sustainable Energy Planning at Aalborg University) for offering valuable input and comments on preliminary drafts of this paper.

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The great grid transformation

"We are witnessing the beginning of the end of the fossil fuel era and we have to prepare ourselves for the next era."

Fatih Birol, Executive Director, International Energy Agency[12]

In a future energy system with net zero emissions, the world energy supply must decrease by 15% from 2021 to 2050 alongside a rapid expansion of renewables (Figure 1).

In 2021, 79% of the energy globally was produced from fossil-fuel sources. By 2050, this must be cut to at least 18% – and preferably more – 8% of which must be abated through carbon capture and storage. While there is still some debate around the potential of carbon capture and storage, the scientific consensus is that we need to drastically cut back our reliance on fossil fuels. Meanwhile, renewables constituted 11% of the supply in 2021, a number which must increase to 70% by 2050, with solar and wind constituting a combined 39%. Perhaps unsurprisingly, we need more action than the current stated policies and even than the announced pledges to reach net zero in 2050. In other words, **nothing short of a full-scale revolution of our energy supply must be undertaken to reach an energy system compatible with net-zero goals.**

From a pure energy supply perspective, we will need substantial investments in solar, wind, and other renewables far beyond what is currently stated or even pledged. And of course, this must come alongside a simultaneous abatement of fossil energy.[13] Fortunately, **the cost of renewables has dropped sharply in recent years, with solar and onshore wind seeing the greatest progress.**[14] At the same time, the price of coal has stagnated while nuclear energy prices have increased notably, a jump largely associated with increased safety regulations. Put simply, it is economically favorable to invest in renewables instead of fossil energy sources. And it will only become more attractive as technologies such as wind power converters and solar inverters increase the efficiency with which these renewables sources can generate clean electricity. This means that we can supply the world with low-emissions energy that is also the cheapest and most efficient option. However, **a transition to renewable energy comes with a need to restructure our energy grid.**

Enabling a world powered by electricity

To decarbonize our future energy system, renewable energy must replace fossil fuels and the energy system must be electrified from end to end. Such a full-scale electrification will not

The transformation of the world energy supply

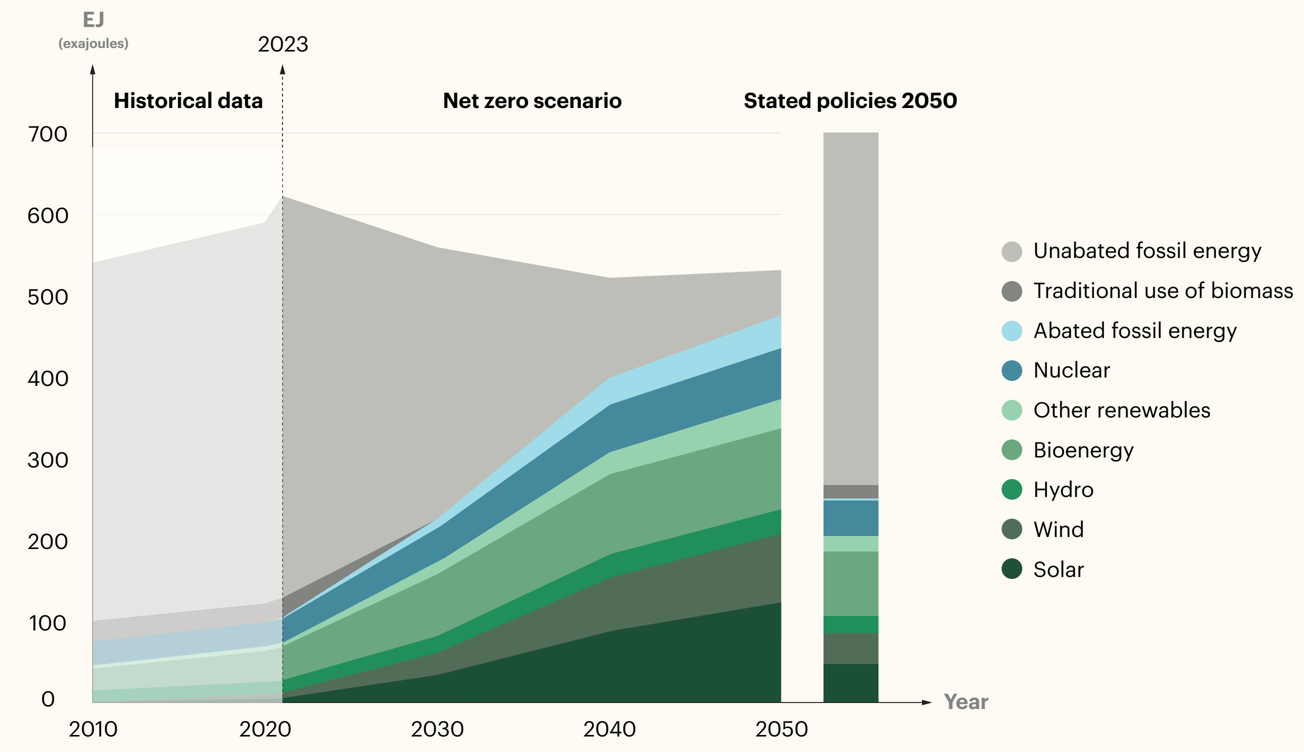


Figure 1: The necessary transformation of the world energy supply if we are to reach net zero, and where we will be in 2050 if we continue at the current trajectory with the stated policies. Source: IEA World Energy Outlook 2022 [16]

only lead to drastic decreases in greenhouse gas emissions but will also entail substantial decreases in the final energy demand and major economic savings.[15]

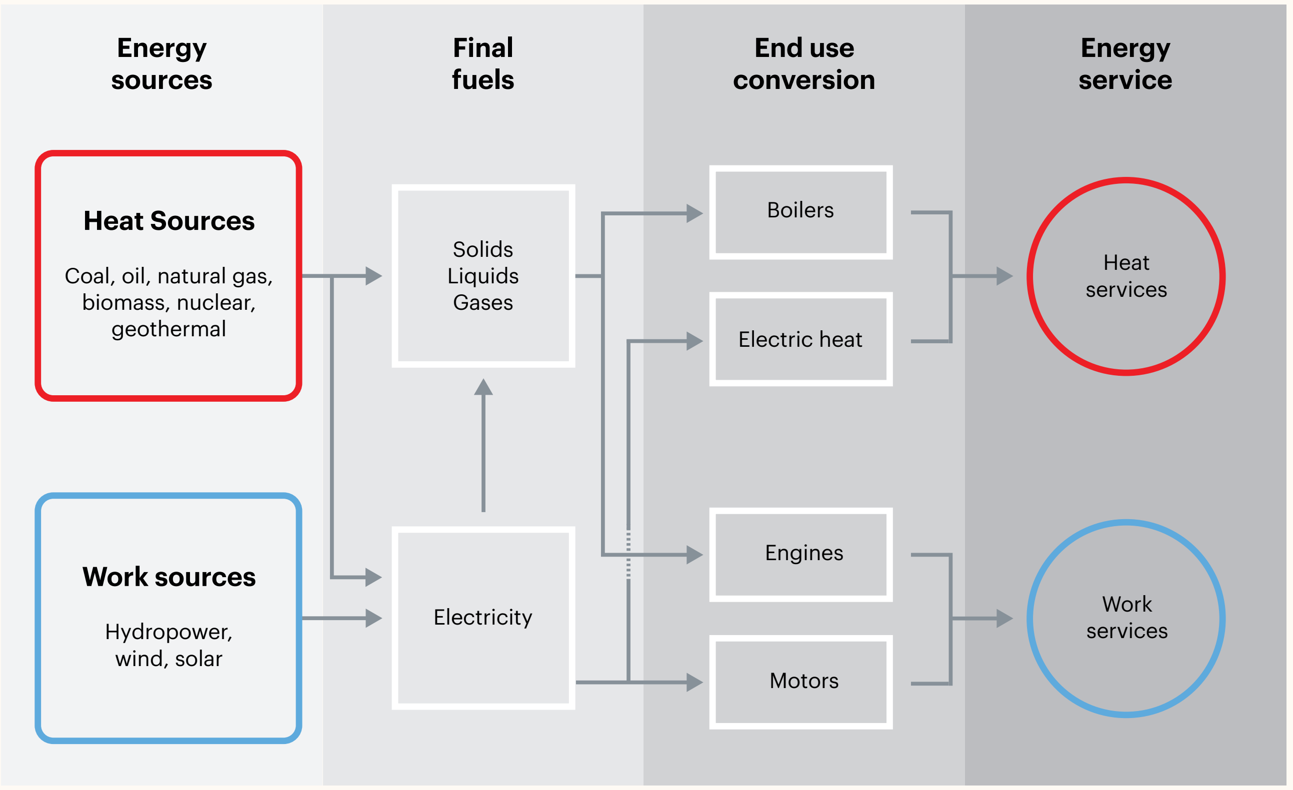
To understand the great transformation of the grid, University of Oxford Professor Nick Eyre has described how moving from heat-producing to work-producing energy sources is necessary to reach the goals of the Paris Agreement.

All functions of our economies and societies are powered either by heat or by work. Fossil fuels are the primary source of heat power; when burned, they turn into heat, which is used for anything from space heating to propelling a car down the road. Work, on the other hand, is about using movement, such as a rotating wind turbine, to power activities. As can be seen in Figure 1 above, this will become one of the primary sources of energy in the future, alongside other work sources such as solar and hydropower.

Currently, major parts of our societies are powered by heat sources that require the burning of fossil fuels. To decarbonize the energy system, we will have to fundamentally transform the majority of sources from heat producers to work producers.

The major challenge in the transition from heat to work is not producing electricity but enabling the end-use to be powered by electricity. **Around 80% of end-use energy is currently not electrified.**[17] The change we are facing is essentially a reversal of the changes from the Industrial Revolution; instead of exploiting energy from heat to power services that require work, we will provide energy from work to power nearly all services. In other words, work will be the source for both heat- and work-powered services. This means that the entire way we have thought about our energy system thus far will be turned upside down, away from converting heat into work, towards converting work into heat.

Heat and Work in the Current Energy System



Heat and Work in the Future Energy System

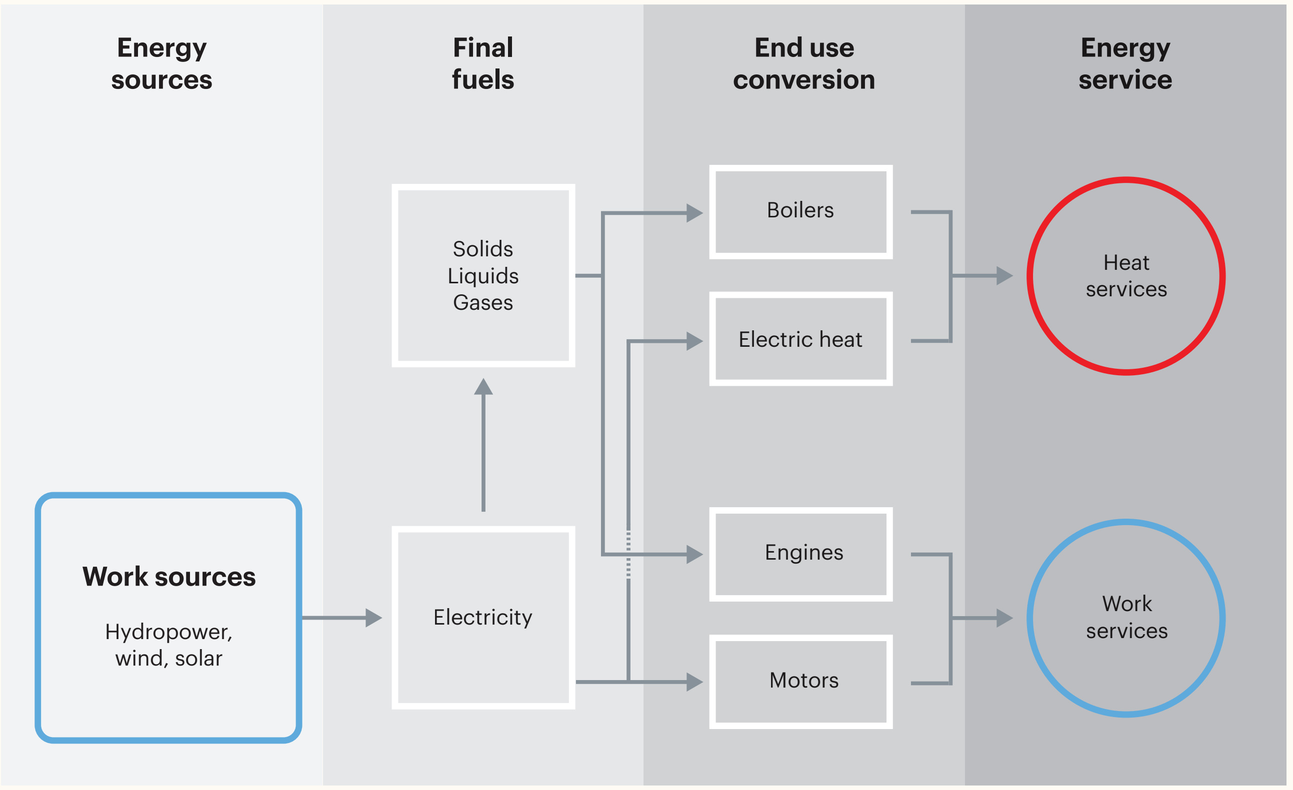


Figure 2: Figure adapted from Eyre, N. (2021). Heat energy sources are biomass, coal, oil, natural gas, nuclear, and geothermal. Work energy sources are hydropower, wind, and solar. In the renewable electricity system we will expect some energy from nuclear and geothermal, however this source is negligible on a global scale. Heat services are e.g. space heating, washing, cooking, drying, steam raising, and melting. Work services are e.g. stationary power, transportation, lighting, data processing, and electro chemistry. Source: Eyre, N. (2021). From using heat to using work: reconceptualising the zero carbon energy transition. Energy Efficiency. 14:77, 1-20.

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Steps to electrify the energy grid

In a net-zero scenario, it is not only the sources of energy that must change; so too must the ways that energy is used. Our power grid must undergo a transformation to deliver the energy services without sacrificing comfort, energy security, or economic growth. This transformation entails:

1

Electrify wherever possible. Most renewables produce electricity.
To accommodate the major build-out of renewables necessary to reach net zero, the scope and depth of electrification needs to go much further. This is the focus of the following section of the paper.

2

Move away from producing heat through fuels, but instead produce it through electricity – either directly through heat pumps or indirectly through district energy, as we explore on page 13. Electricity is more efficient than fuels for heat under 100°C, which is more than sufficient for space heating as well as many industrial processes.[18]

3

Electrify indirectly in hard-to-abate sectors. While not yet completely mapped, we will have to look at alternatives in sectors such as long-haul aviation, long-distance shipping, and some high-temperature industrial processes. One of the most promising alternatives is low-emissions hydrogen as we explore on page 15.

The future is electric

Transitioning to a fully electrified energy system could cut up to 40% of final energy consumption.[19]

The 20th century was the golden age of electrification. With major breakthroughs in efficiency, reliability, and application, electricity became and remains to this day the fundamental infrastructure of almost all modern technologies.[20] It is only thanks to electricity that the lion's share of all engineering breakthroughs since were even possible in the first place. Just imagine the internet, a refrigerator, or a light bulb without electricity.

So, if electrification defined the 20th century, what can we expect from the 21st? It turns out that **we have not even scratched the surface of the ability of electricity to transform our lives.** While electrification has already enabled the innovation of millions of technologies that have drastically improved human health and quality of life, we must once again call on it to fundamentally transform our societies and economies. In much the same way that fossil fuels such as coal and gas powered the Industrial Revolution, electrification will power our future energy system.

The pathways of electrification

When we think about electrification, we typically think about converting machinery that is currently directly driven by fossil fuels – such as passenger cars – into something that we can charge, ideally using renewable energy sources. This is what we refer to as direct electrification.

However, electrification is not just about plugging things into an outlet. For example, within the transport sector, it may seem simple to follow the same path as passenger cars: make everything battery-electric and charge them with energy derived from renewable sources. But for large parts of the transport sector, this is easier said than done.

Let's take heavy-duty vehicles as an example. First, compared to passenger cars, many heavy-duty vehicles need to work much harder and for much longer between charges, meaning that they need extremely large batteries to match the productivity of the diesel equivalent. Secondly, operational and logistical barriers often complicate battery swapping, such as in the field or at large construction sites. And thirdly, there is not unlimited renewable energy in the grid and the amount of additional renewable energy needed for electrifying the excavator fleet is not trivial: a rough estimate says that if all the world's excavators were electric, they would consume as much energy as is generated by all the world's offshore wind turbines today.[21] In cases such as this, functions within fossil-powered machines, such as hydraulic pumps, should be electrified to increase the efficiency of the engine. This form of hybrid electrification is a very useful short- to medium-term solution for heavy-duty machinery,

Case: Decarbonizing heavy-duty vehicles

Construction machines worldwide emit 400MT of CO_2 per year,[22] as much as the emissions from international aviation.[23] 50% of that comes from excavators.[24] Today's excavator systems are only 30% efficient, meaning that 70% of the energy the engine generates is wasted instead of helping the excavator bucket move any earth. To identify the energy losses in a heavy vehicle, it is not enough to look at the engine of the vehicle. In construction machines, a hydraulic system consists of a pump that pressurizes fluids (oil) to transmit the power from the engine to perform work such as lifting or digging. Whether the vehicle has an electric motor or combustion engine, the energy consumption of the vehicle can be reduced significantly by introducing energy efficiency measures. For instance, energy consumption can be reduced significantly when the vehicle is not operating through solutions such as variable displacement pumps, digital displacement, variable speed pumps, and decentralized drives.

Such energy efficiency measures enable excavators to deliver more work with a smaller engine and less fuel. They also reduce the capacity of the battery needed to electrify them by up to 24.8%.[25] **The technology is developing fast and some of these measures can deliver fuel savings of 15-30% in excavators over 15 tons while at the same time increasing the work capacity of the machines.**[26] Soon it will be possible to apply this technology on all sizes of excavators and even reach fuel savings of up to 50%.[27]

15-30%
fuel savings through energy efficiency

especially in industry, construction, and maritime transport. As we can see on page 12, these improvements in the efficiency of the vehicles also paves the way for a full electrification.

Finally, there are many parts of our energy system that will not be able to be turned into this form of direct or hybrid electric machinery – or at least not anytime soon. Here, we often think of sectors such as aviation, long-distance shipping, and cement and steel production. To directly electrify these sectors would require batteries that are too large for the vessel in which they would be used (e.g., aviation) or require tremendous amounts of heat production (e.g., cement and steel). While they are very difficult to directly electrify in an efficient way, these sectors are major GHG emitters and therefore their electrification would contribute greatly to reducing GHG emissions and reaching net-zero goals. This is where indirect electrification comes into play.

Indirect electrification primarily comes in the form of hydrogen electrolysis. Using electricity to produce hydrogen, electricity can indirectly be stored or used as fuel in hard-to-electrify processes. We will expand more on this in the section entitled *Conversion is key to net zero*, but also address it here, as it is a fundamental element of a full-scale electrification of our future energy system.

Case: Efficient electric heating

Around 60% of all heating demand globally is currently supplied by fossil fuels,[28] translating to roughly four gigatons of annual CO_2 emissions, or 10% of global emissions.[29] This is because many residential and commercial buildings are running on legacy heating technologies such as gas boilers. However, heat pumps can provide the same level of heat, but with lower energy usage and fewer carbon emissions. In fact, the output of energy in the form of heat from a heat pump is four times greater than the electrical energy used to run it for a typical household.[30] **Individual heat pumps are also 3-5 times more energy efficient than fuel-based or electric resistance systems, depending on the type of heat pump.**[31] This is because they use electricity to source pre-existing heat from air, water, or ground sources rather than using gas or electricity to generate new heat. In other words, they recycle heat, thereby cutting the amount of energy needed to heat the same amount of space. Additionally, the cost savings of heat pumps on energy bills can be substantial – up to 45% in Germany or even up to 60% in France when compared to gas boilers, depending on gas prices and the type of heat pump installed.[32] District energy is a good alternative to heat pumps in individual buildings, especially in urban areas, as it allows different sources such as renewable energy and excess heat to penetrate deeper into the energy grid. But heat pumps can also complement district energy. For example, heat pumps are used to upgrade the temperature in the district energy grid, if the temperature is lower than the required level.

Heat pumps are

3-5 times

more efficient than fuel-based or electric resistence systems

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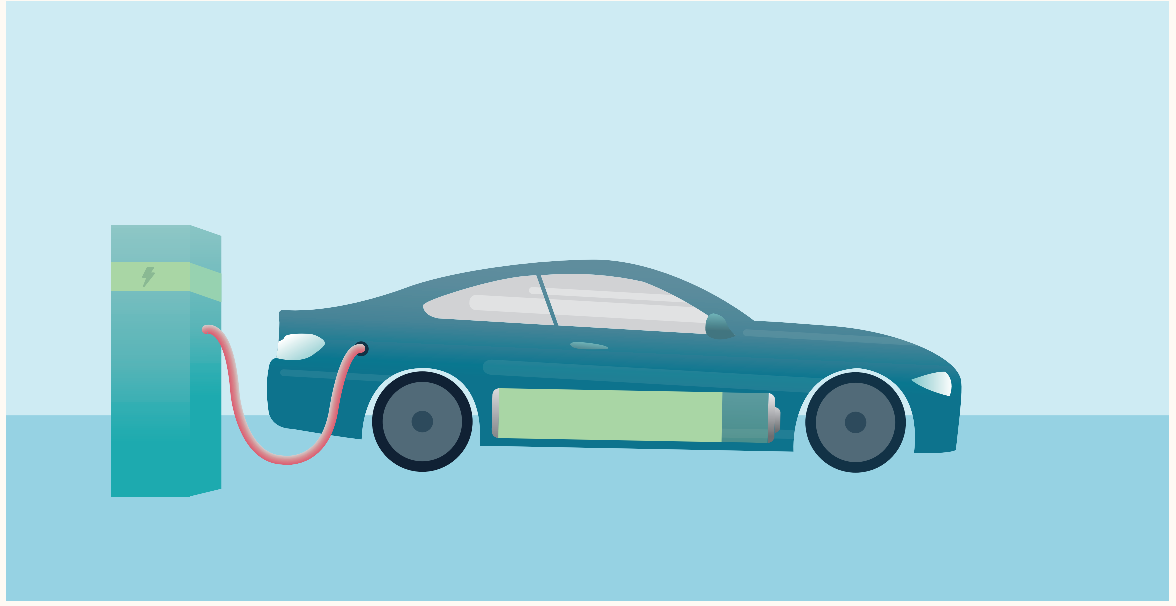
Case: Electric vehicles are driving down emissions



Road transport accounts for over 15% of global energy-related emissions.[33] However, it is widely accepted that electric vehicles (EV) are our greatest opportunity to bring these road transport emissions down in line with the Net Zero Emissions by 2050 Scenario. In fact, according to the IEA, goals related to the scaleup of electric vehicles are some of the very few that are actually on track to reach net zero.[34] But what is it about EVs that can help to drastically reduce carbon emissions?

There is the obvious point that they do not emit greenhouse gases directly into the atmosphere, and the electricity can be decarbonized. But another key force driving a decarbonization of the sector is that **EV electric drive systems are simply more efficient than their combustion counterparts, with an energy loss of only 15-20% compared to 64-75% for gasoline engines.**[35] And this energy loss can be decreased even further with the implementation of energy-efficient power modules, paving the way for a 5-10% reduction in battery size or a 4-10% increase in driving range.[36,37,38,39] In other words, there is simply less energy waste in driving an EV the same distance, meaning drivers can consume less to achieve the same result.

What about production? Though the production of electric vehicles can oftentimes be more carbon-intensive than combustion engine vehicles due to the emissions-intensive process of battery manufacturing, one MIT study estimates that these emissions would be quickly offset in six to 18 months, depending on the origin of the energy used to charge the car.[40] If these technological developments continue, EVs will become even better alternatives to ICE vehicles.

Case: Decarbonizing hard-to-abate sectors

Where we cannot yet electrify, 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 engines 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.

Through a process called electrolysis, electricity is used to split water into hydrogen and oxygen. While the oxygen can simply be released back into the atmosphere, the hydrogen can be captured, stored, or further 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.

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%.[41] When then converting that hydrogen back into some form of deployable energy (such as e-fuels), there is an additional energy loss, resulting in a total round-trip energy efficiency of 18-42%.[42] 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.

The fundamentals of decarbonization

The examples above all show how electrification and energy efficiency are deeply connected. By increasing energy efficiency, it becomes easier and cheaper to electrify. At the same time, electrification enables lower energy loss, ultimately making it a form of energy efficiency. What's more is that all these examples become even more efficient when they operate within an energy system powered entirely by renewable energies. But here's the kicker: **this is only possible in a system that reduces energy demand enough via energy efficiency measures and electrification to ensure that renewable supply can keep up with demand.**

This takes us back to the opening point of this section: that a transformation from a fossil energy system to a fully electrified energy system could cut up to 40% of final energy consumption.[43] For example, a heat pump is more efficient than a gas boiler under normal conditions even if the electricity used to power that heat pump is created from burned fossil fuels - though the efficiency does vary from fuel to fuel. By adopting electric technologies, even in our current energy system, we can reduce carbon emissions through decreased fossil energy demand. However, in a future where the electricity comes from renewable sources, the efficiency of the heat pump skyrockets, as there is no energy loss occurring further down the system when fuels are burned to create the electricity. The same goes for electric vehicle charging or for any other function where electricity is used as the primary energy source.

If by 2050 we are to run our world on renewable sources, we will need to reduce energy demand through energy efficiency measures alongside a full-scale electric overhaul of our infrastructure to accommodate it. Similarly, if we are installing millions of heat pumps and electric vehicle charging stations, we will need renewable electricity to power them and to ensure they are holistically decarbonized. The point of this is that **energy efficiency, renewables, and electric technologies must all be considered together if we are to fully decarbonize our energy system.** None can be successful without the others.

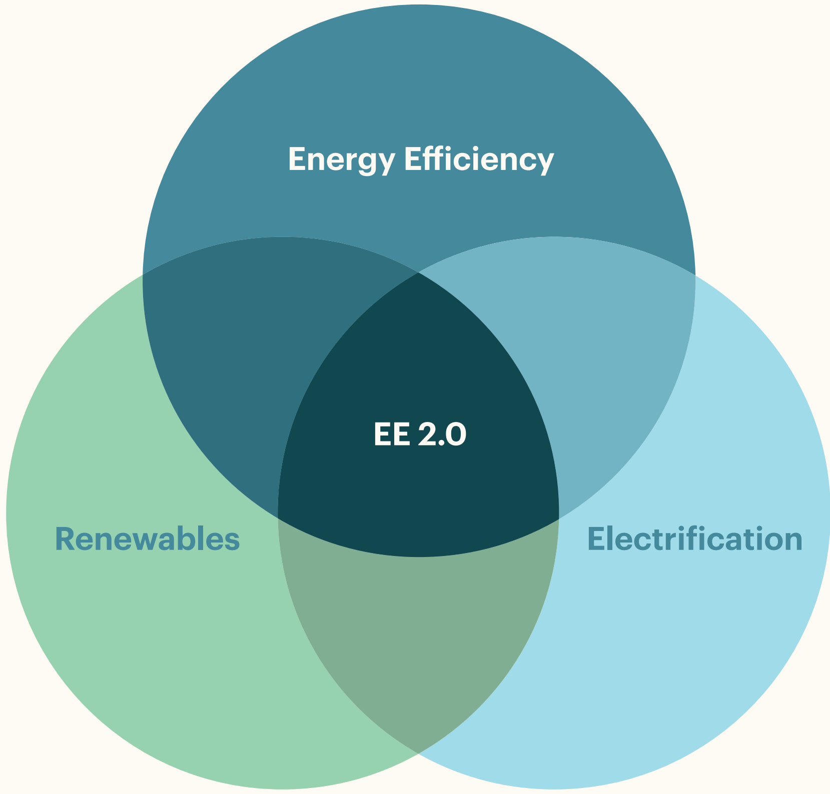


Figure 3: Energy efficiency, electrification, and renewables must be considered together if we are to reach net zero by 2050.

"More efficient electrified technologies will enable renewables to take a larger share of the energy market more quickly."

Dr. Jan Rosenow & Prof. Nick Eyre,
Reinventing energy efficiency for net zero[44]

Electrify wherever possible

1 Energy efficiency can accelerate electrification

Improved efficiency can accelerate electrification. For instance, in passenger cars, heavy-duty vehicles, and in marine transport, efficiency measures can reduce the size of batteries required. This then reduces the amount of charging power required, and the amount of renewable energy generation required, thus making it possible and cheaper to electrify them. Increasing efficiency can also bring down the demand for charging infrastructure and increase the productivity and range of the vehicle.

2 Electrification is energy efficiency

Electrification leads to emissions reductions both by replacing fossil fuel energy with renewable electricity generation, and by saving energy due to the higher efficiency of electric technologies. In fact, one study from Oxford University suggests that **a transformation from a fossil energy system to a fully electrified energy system could cut up to 40% of final energy consumption.**[45] This is because by generating electricity with renewables rather than from heat-producing sources such as coal or natural gas, we do not waste energy in the form of heat (see Figure 2).

Flexibility: timing is everything

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. The streetlights are on, and the train only comes every half hour. But as we wake up to start our day, water flows to buildings, gas to stoves, and electricity to homes. Kids head off to school and adults leave for work, leaving houses empty of energy consumers. However, while many houses sit empty during the day, the rest of the city comes to life. Stores open, offices begin to fill up, and the train arrives more frequently. After a brief lunch peak and an air-conditioned battle against the afternoon heat, 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. The sharp peak in energy consumption that the energy 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 (see Figure 7 on page 32).

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.** However, in a world where we can no longer fire up natural gas power plants to meet peaks in demand, we must find new ways to manage energy more flexibly. This section presents pathways for enabling a more flexible energy system, as well as new data on the possible energy and cost savings of implementing demand-side flexibility solutions at scale.

> **"Saving a unit of electricity during peak hours on a day with little renewable generation delivers significantly more carbon savings and environmental benefit than saving the same unit during hours of excess renewable generation."**
>
> Prof. Nick Eyre, Reinventing energy efficiency for net zero[46]

What is demand-side flexibility?

Demand-side flexibility is about using the renewable energy when it is plentiful and lowering demand during peak hours. It is about leveling out energy consumption, so we do not experience periods of simultaneous high demand and low supply. The primary methods of achieving this are demand-side flexibility measures such as load-shifting or peak-shaving. In one way or another, both of these methods are about reducing peak energy demand either by shifting energy use away from peak consumption periods or by avoiding peaks altogether by reducing energy usage for one function to serve another. Essentially, equipment can be switched off or turned down during peak demand periods, instead choosing to use it at another time. And while this process can actually lead to higher energy use in some instances, it is less problematic – and sometimes even cheaper and greener – because the energy is being used outside the peak demand period. This reduces strain on the energy grid and saves money, as energy is cheaper in off-peak periods. In fact, **in the US, optimizing efficiency, demand flexibility, and electrification in buildings can save up to $107 billion in annual power system cost savings alongside a 91% reduction in carbon emissions from buildings by 2050.**[47]

Demand-side flexibility solutions become even more effective when coupled with efficient energy storage mechanisms (see Storage section), as they can automate energy storage during low-demand periods to be deployed when demand is higher. In much the same way, this enables consumers to use cheap, renewable energy during times when energy is otherwise expensive and carbon intensive.

Case: Model predictive controls

Both load-shifting and peak-shaving processes can be automated with digital technologies that control how or when equipment or machinery use energy. This is achieved primarily through implementing digital tools known as model predictive controls. In buildings, for example, these **AI-driven technologies can save up to 20% in a building's energy costs by combining building, weather, and user data to predict heating and ventilation demand.** By utilizing such controls, buildings can pre-heat ahead of peak hours, or lower heating when the sun is about to shine on the building facades, thus saving energy. Observations on 100,000 flats equipped with this technology, based mainly in Finland, show that the maximum power usage was reduced by 10-30%.[48] Meanwhile, by shifting the consumption to the most economical period, the system ensures up to 20% savings in a building's energy costs without impairing the comfort of residents.[49] In 2021, a London Local Authority installed model predictive controls in eight residential buildings. In the first 11 months of operation, the technology paid back its initial cost and saved 600 MWh of heat – the equivalent of heating 50 homes in the UK for a year.

Case: Energy flexibility in the EU and UK

Let's imagine a future where our cars automatically start charging when the electricity is plentiful and deliver electricity back when it is scarce. Where heating and cooling are automated to run during optimal demand hours without sacrificing comfort. Or where refrigerators in supermarkets can be automatically overcooled when electricity is cheap. This is far from a sci-fi scenario. Many of these flexibility solutions already exist and are ready to be implemented today (see "Model predictive controls" case).

With demand-side flexibility, the potential to save energy, emissions, and money while increasing energy security is enormous. Many government entities, including the EU, recognize that demand-side flexibility is important to succeed in large-scale integration of renewables.[50] However, while recognition is high, political action to incentivize a full-scale implementation of demand-side flexibility is not.

A new analysis commissioned by Danfoss examines the potential of demand-side flexibility in the EU and UK wholesale energy market.[51] 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.

Demand-side flexibility is 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.[52] 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.[53] 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.

€10.5 billion
annual societal cost savings by 2030

During the very recent energy crisis, the UK earmarked €103 billion for the energy crisis, and the EU countries earmarked €681 billion.[54] The entire EU and UK can roll out demand-side flexibility technologies and make the grid more resilient. 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 EU and UK, **the average consumer can save 7% on the electricity bill by 2030 and 10% by 2050.**

To reach the goals of the Paris Agreement, the EU and UK must electrify the energy system. This will require a major expansion of electricity generation including vast battery capacities. However, **with a full-scale implementation of demand-side flexibility, this expansion of electricity generation can be reduced by 313 GW before 2050, or about 10% of the total capacity.**

This includes dramatic reductions in the need for grid-scale battery storage from 298 GW to less than 2 GW. To put this in perspective, the global battery capacity was 28 GW in 2022.[55] The world is already facing challenges supplying enough scarce raw minerals for batteries.[56] By reducing demand for batteries, we will put less strain on critical mineral supply chains and limit the environmental degradation that accompanies mineral mining.

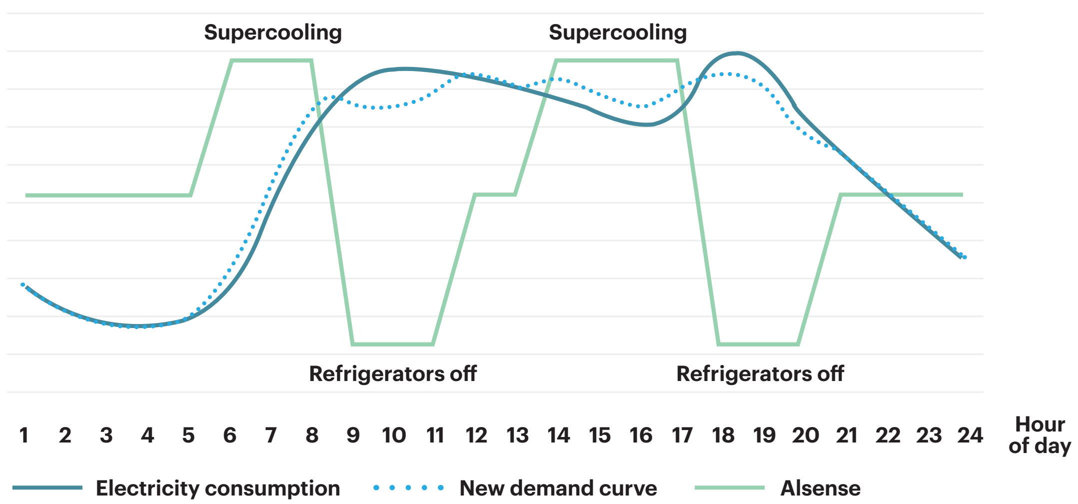
Failing to roll out demand-side flexibility at scale may have major societal and environmental consequences. **Today, we pay renewable energy producers hundreds of millions per year to shut down production in periods with too much wind or sun.**[57] **However, demand-side flexibility can reduce this curtailment by 25% already by 2030.**[58] Similarly, if we do not design a renewable system to cope with periods of low energy supply, we risk power outages, which can have massive economic costs.[59,60,61] Demand-side flexibility will be an important tool to avoid these costly outages.

40 million
tons of CO_2 saved annually by 2030

This should leave policymakers with one question: "can we afford to miss out on the opportunities of demand-side flexibility?"

Case: Supercooling supermarket freezers

Figure 4: How Alsense lowers demand peaks



Supermarkets account for 3% of the total electricity used in industrialized countries.[62] And within supermarkets, refrigeration systems represent by far the highest share of the total energy consumed. However, it is possible to lower supermarkets' energy demand during peak hours by optimizing or shifting loads during a demand-response event.

With digital technologies such as Alsense, load-shifting can for example be automated to cool supermarket freezers down to a much lower temperature than required – also called supercooling – outside the peak demand hours with the freezers effectively operating like a battery storing energy. By doing so, **the refrigerators can be switched off during the peak hours of energy demand, both lowering stress on the grid and saving money for the supermarket.**

And though the system uses more electricity than conventional refrigerator systems, by using energy when it is renewable and plentiful, supermarkets can help reduce the need to resort to carbon-intensive energy sources by lowering demand peaks. Learn more in Danfoss case study "Building better supermarkets for the world".[63]

3%

of total electricity demand in industrialized countries comes from supermarkets

Implement flexibility solutions

1 Flexible energy demand saves emissions

By implementing demand-side flexibility solutions, electricity demand can be better aligned with peak supply hours. In the EU and UK, **shifting energy use away from carbon-intensive demand peaks can save 40 million tons of CO_2 emissions annually by 2030**, or more than Denmark's domestic climate footprint in 2021. Similarly, **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.

2 Flexibility will create major economic benefits for societies and households

A new analysis shows an ambitious but realistic rollout of demand-side flexibility will lead to substantial economic benefits both for consumers and society at large. **The EU and UK can achieve annual societal cost savings of €10.5 billion by 2030. On top of this, the average consumer can save 7% on the electricity bill by 2030.**

3 Reduce need for grid-scale battery storage

With a full-scale implementation of demand-side flexibility, the EU's expansion of electricity generation can be reduced by 313 GW before 2050, or about 10% of the total capacity. This includes **dramatic reductions in the need for grid-scale battery storage from 298 GW to less than 2 GW.** To put this in perspective, the global battery capacity was 28 GW in 2022.

Conversion is key to net zero

Renewable energy sources can produce incredible amounts of low-emissions electricity. However, in periods where electricity supply exceeds the demand, renewable energy infrastructure – such as wind turbines and solar panels – are turned off. Too much electricity supply destabilizes the grid frequencies, risking power outages if some of the energy supply is not curtailed by system operators. Renewable energy producers are, at times, then paid to shut down production for a period. In Germany, the compensation packages to shut down production reached €710 million in 2019.[64]

However, as we explored on page 22, demand-side flexibility can reduce this curtailment by 25% already by 2030.[65] Two of the main methods for achieving this are conversion and storage. In this section, we will explore the challenges and opportunities within conversion before shifting focus to storage in the next section.

What is conversion?

Conversion is both very simple and astonishingly complex. Put simply, it means changing one form of energy to another. This could be wind to electricity, electricity to hydrogen, or any other number of combinations. 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.

In our future energy system, virtually all our energy will stem from the conversion of renewable sources like sun and wind into usable electricity. Furthermore, hydrogen conversion will be an important mechanism for energy storage. Let's take a deep dive into how we can deliver enough electricity to support hydrogen production and how the production can help stabilize the grid.

The future need for hydrogen will be massive

We are going to need vast amounts of low-emissions hydrogen in the future to reach the goals of the Paris Agreement. On the one hand, hydrogen is a useful tool for storing excess renewable electricity. However, it is also vital in industries for producing low-emissions steel, e-ammonia, e-methanol, and other e-fuels where it replaces fossil fuels. Furthermore, it has potential as a sustainable low-emissions fuel for hard-to-abate areas like long-distance international shipping, heavy trucks, and even aircraft. And while estimates vary across studies, the bottom line is that the share of hydrogen in the energy mix will only continue to grow.[66,67,68,69]

But how can these ambitious hydrogen goals be met? In the future, water electrolysis – the process of converting electricity into hydrogen by splitting water into hydrogen and oxygen – will be massively scaled up. If the electricity used to power this process is generated by renewable sources, we can indirectly electrify and decarbonize anything that can run on hydrogen or hydrogen-generated e-fuels. However, electrolysis requires an enormous supply of electricity – the IEA estimates we will need an additional 11 EJ of hydrogen by 2030 and 54 EJ by 2050.[70] To set this in perspective, **hydrogen production will require more than half of the total electricity demand today.**[71,72,73,74] This will inevitably create a need for rapid expansions of the supply of low-emissions electricity, and it could turn out to be one of the biggest challenges for the future to supply the grid with this power.

It will require substantial investments to produce the low-emissions hydrogen required in 2050.[75] But how much hydrogen will we actually need in the future? The EU plans to produce and import a total 666 TWh of hydrogen by 2030, all produced by low-emissions sources.[76] This is equivalent to the energy production from about 140 nuclear power plants.[77] 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.**[78] Regardless, 116 TWh of hydrogen by 2030 is still ambitious and will require a huge amount of electricity, which will pose major challenges to the stability and security of the energy grid.

Hydrogen production can stabilize the grid

The entire energy system, including the power outlets in your home, is tuned to a specific and stable voltage and frequency. A lot of engineering goes into maintaining this frequency on the grid. However, this ideal frequency can be destabilized when there is a mismatch between supply and demand of electricity, which can lead to problems in the energy supply. Thermal power plants have large rotating masses in the huge turbines, which effectively serve as stabilizers for the grid. In other words, when the demand increases, the power plant can deliver more power to the grid on the short term – allowing

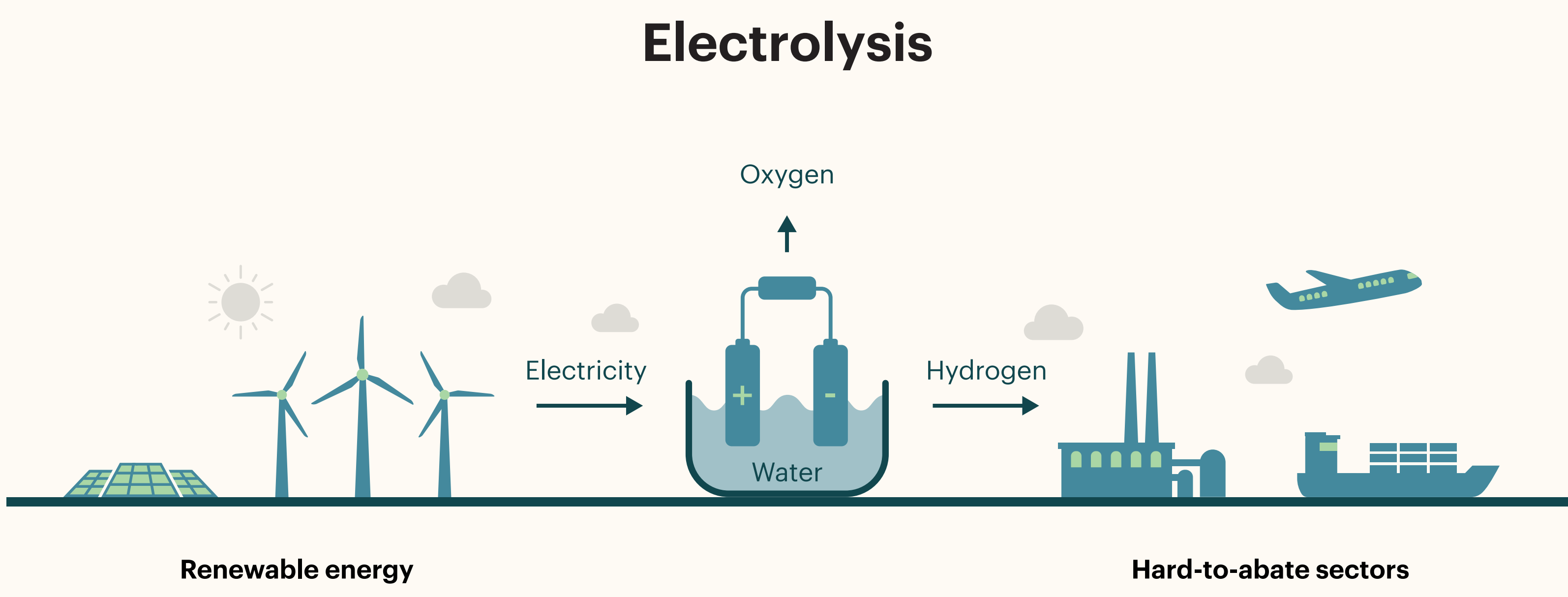


Figure 5: Converting renewable electricity to hydrogen through electrolysis

the grid company enough time to put more steam into the turbine – just like stepping harder on the accelerator pedal to maintain the same speed as your car approaches a hill.

In the future energy system, we will shift from central power plants to decentralized renewable sources. These new sources do not have rotating stabilizing masses in the form of huge turbines, so we must think of other ways to stabilize our grid. For shorter periods, batteries can be very good at bridging the destabilizing gap between supply and demand. For longer periods of imbalance – such as when the wind is blowing for days or weeks – there is too much electricity in the system. In these periods, **turning up the hydrogen production can help to adapt the electricity demand to the production and thus the hydrogen production itself can function as a stabilizing mechanism.**

Beyond the benefits hydrogen can bring to grid stability and energy security, it can also help to keep costs down. Following the basic law of supply and demand, electricity is cheap when the production is high, and it is expensive when production is low – or rather, when demand outstrips production. But hydrogen production can be turned up and down according to the electricity price. As such, once all the necessary infrastructure is in place, it will make economic sense to produce hydrogen in periods of high electricity production and low demand, ensuring cost-efficient use of excess renewable energy when it is available.

Using hydrogen in the right way

Hydrogen is an effective energy carrier and the end-uses are many. However, as with all forms of energy, we must use hydrogen as efficiently as possible if we are to undergo a full transformation to renewable energy sources.

An example of inefficient use of hydrogen would be space heating. 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.[79] 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 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 52,000 km^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,[80] and even less if heat pumps were combined with district energy.

As stated above, however, there are many good uses of hydrogen. **For hard-to-abate areas, we cannot rely on batteries**, as batteries for container ships or international aviation would simply be too big. However, **we can produce e-fuels from hydrogen which will lower the emissions from the transport sector.** In the future, we expect to see ships sailing on e-ammonia and e-methanol, and planes flying on e-kerosene – all produced with hydrogen instead of fossil sources. Other industries such as **steel production require extremely high temperatures, and here hydrogen can also play a critical role in decarbonization.**

Heating the UK with Heat Pumps or Green Hydrogen

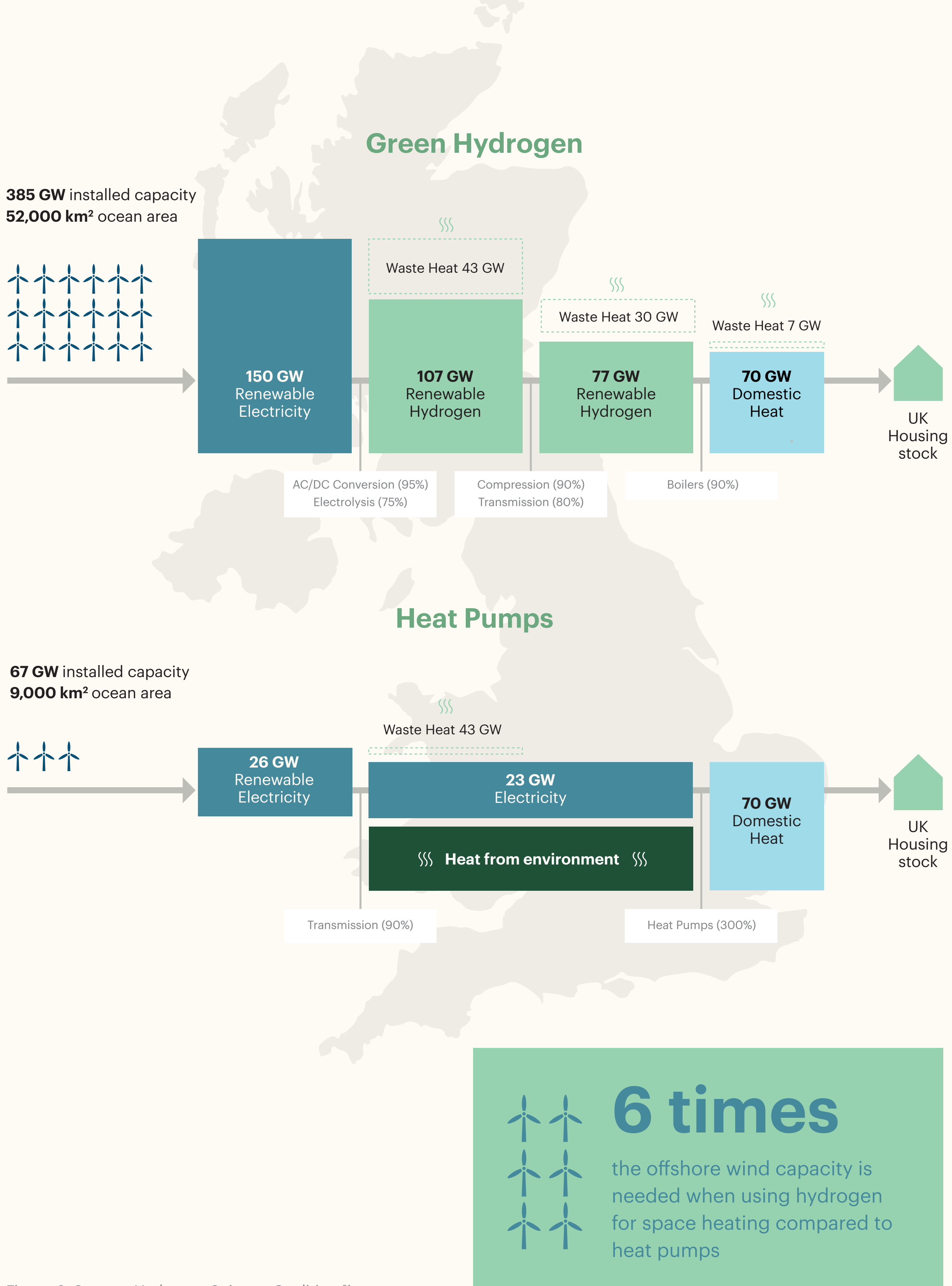
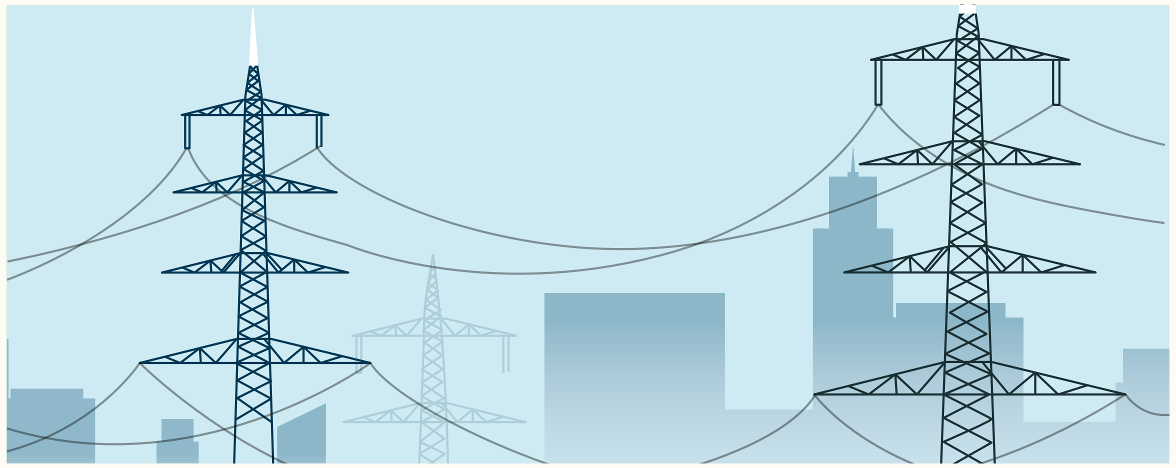


Figure 6. Source: Hydrogen Science Coalition.[81]

Case: Good converters can save electricity and money



Hydrogen production will have a massive pull on the electricity grid in the future, so we must make sure to produce hydrogen as efficiently as possible and not create unnecessary disturbances on the grid. 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 compensation equipment will be needed to restore power quality.

Such disturbances of the grid from low-quality converters are a growing concern when discussing hydrogen production. Also, such a converter 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 on 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%.[82] 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**, lowering electricity costs across the grid as a whole.[83] Similarly, 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.

> Good converters can save enough electricity to power London for
>
> **4 years**

Use hydrogen wisely

1 Converting electricity to hydrogen will be essential for a deep decarbonization

Excess renewable energy can be converted and stored as hydrogen. And while this conversion comes with an energy loss, hydrogen will be key to decarbonizing hard-to-abate sectors such as steel production, long-distance shipping, and long-haul aviation.

2 Efficient hydrogen production is essential

Hydrogen production will have a massive pull on the electricity grid in the future, so we must make sure to produce hydrogen as efficiently as possible and not create unnecessary disturbances on the grid. By using efficient converters, we can save electricity and money.

3 Hydrogen must be used for the right purposes

Using hydrogen for heating is extremely inefficient. Providing the UK with domestic heating from low-emissions hydrogen produced from offshore wind farms would need a capacity of 385 GW to produce enough hydrogen to heat the UK. With heat pumps, a capacity of only 67 GW of offshore wind farms would be needed, and even less if densely populated areas were supplied with district heating.

Storage for the future energy

Energy storage will be essential in the smart grid of the future. With a more decentralized grid, there is a greater need to store energy so we can supply electricity when nature does not provide favorable conditions. In fact, the global installed storage capacity is expected to expand by 56% from 2020 to 2026, mainly driven by a higher need for flexibility and storage around the world to integrate a growing share of renewables.[84]

Storing energy is not a simple or cheap task, so there is a need to weigh the right measures when deciding where to apply which technology. Choosing the right solution will depend on many factors such as geography, energy source, land use, the duration of storage, and for how long electricity needs to be pulled from the energy storage. Within energy storage, there are many technologies – some well-established, others cutting edge – which can be deployed. On the next page, we present a few of the key technologies and demonstrate their potential.

Short vs. long-term storage

On a daily basis, the sun produces excess electricity before the peak of demand (see Figure 7), and yet we can only rely completely on renewables if we store this excess electricity for the evening and overnight. Some of the ideal solutions for short-term storage include lithium-ion batteries and thermal storage, for example in district energy. **District energy systems are excellent solutions for storing thermal energy when there is plenty of green electricity in the grid.** It can supply heating or cooling on demand and can serve as energy storage for hours to months, which makes it a great enabler of demand-side flexibility (read more on demand-side flexibility on page 20).

Just as there are daily peaks in electricity consumption, there are also seasonal variations. At Earth's higher latitudes, it is necessary to heat the homes during winter, while mid- to low-latitude countries will have a higher demand for air-conditioning during summer. Similarly, for the higher latitudes, there will also be a gap between producing more renewable electricity in the summer while having the greatest need for electricity during winter. To fill out this gap, we must look at long-term storage options. Due to cost and capacity depletion over time - think of the ancient AAA's at the back of the kitchen drawer - batteries are an ineffective solution for this. Much better options for long-term storage are thermal storage, hydrogen, and pumped-storage hydropower, which can hold large amounts of energy with only a very small energy loss over time at a low cost per MWh.

Another important factor when deciding what storage solution to use is the cost. The storage prices are generally dropping across technologies, and the larger the storage, the cheaper per stored unit. Even though all technologies are expected to be cheaper in the future, thermal storage, hydrogen, and pumped-storage hydropower are currently the cheapest, and are expected to remain relatively cheap.[85] Lithium-ion batteries are expected to fall in price, but they are very dependent on critical minerals and therefore also the price of these is affected by mineral supply.[86]

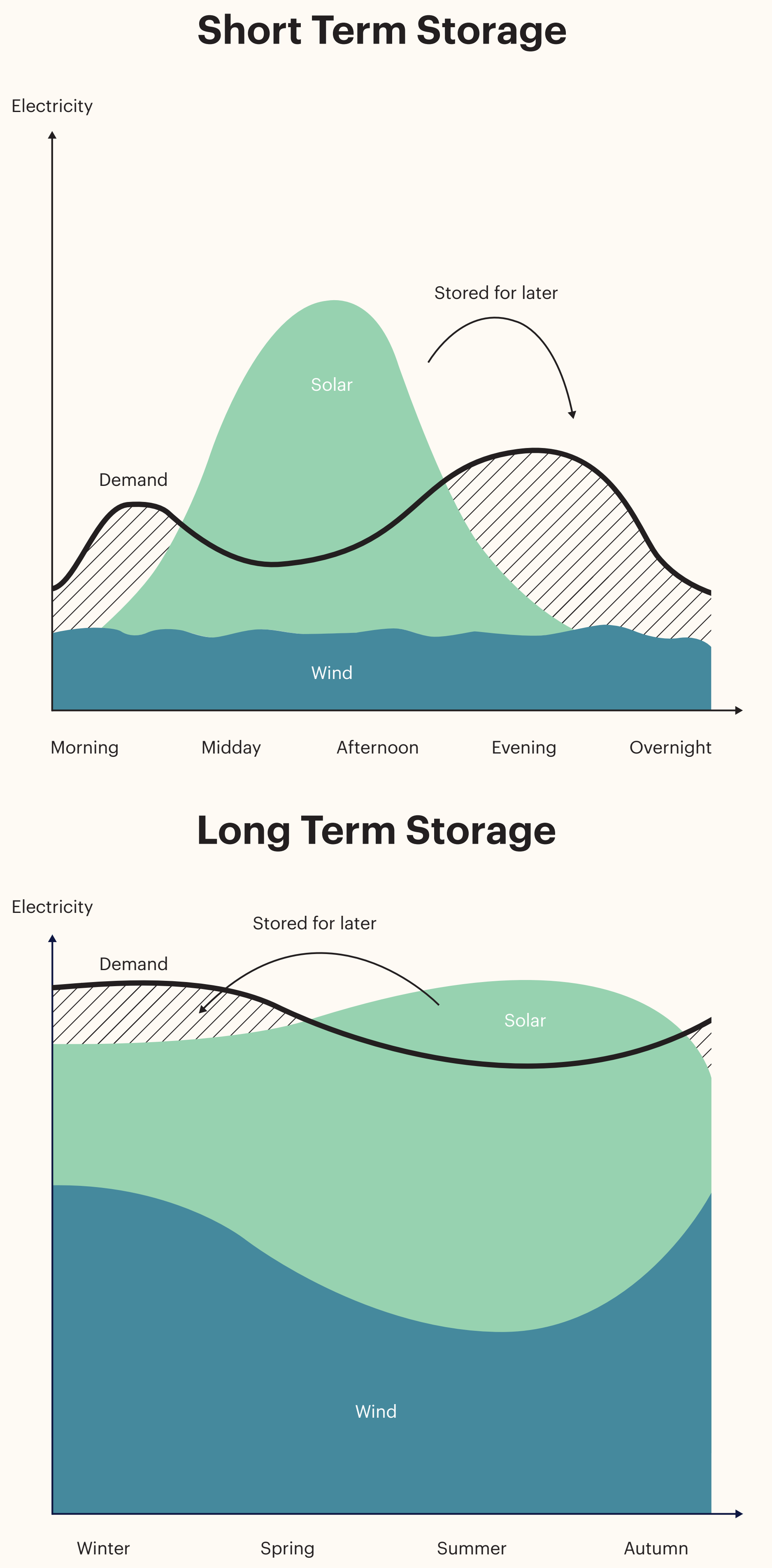


Figure 7: Short vs. long-term storage

Thermal storage through district energy

Thermal energy storage means heating or cooling a medium to use the energy when needed later. In its simplest form, this could mean using a water tank for heat storage, where the water is heated at times when there is a lot of energy, and the energy is then stored in the water for use when energy is less plentiful. Thermal energy storage can also be used to balance energy consumption between day and night.

Modern district energy systems have a flexible thermal infrastructure where available energy sources can be "plugged in". The energy, in the form of hot or chilled water, can then be distributed to buildings via a pipe network for immediate use or be stored in thermal storages for later use. With heat storage tanks, thermal energy can be stored for a few hours or days. With larger pits or other storage facilities, it can be stored for up to several months. In this way, district energy systems can provide flexibility to the energy system through two key functions: by providing storage and by enabling a switch between different energy sources such as large-scale heat pumps, waste heat, solar thermal storage, and geothermal.[87]

Hydrogen

Energy can be stored as hydrogen by converting low-emissions electricity into hydrogen through electrolysis. There are several viable ways to store hydrogen on a large scale, from salt caverns to compressed gas in tanks,[88] and hydrogen can be stored without energy loss over a long time. This makes it ideal for seasonal energy balancing.[89] Moreover, the current pipelines for natural gas can be converted to transport hydrogen.[90] 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 as other forms of storage such as batteries. The process of converting electricity-to-hydrogen-to-electricity can have an energy efficiency as low as only 18%,[91] as each conversion process comes with a certain degree of energy loss. There is also a large energy loss when using hydrogen in industries to reach high temperatures or to produce e-fuels for shipping and aviation. But for these hard-to-abate areas, we may have to accept an energy loss to be able to decarbonize, and the technological developments will make e-fuels an economically viable option.[92] For now, it is very expensive to store energy as hydrogen but the price is expected to decrease in the future with technological developments.[93,94] You can read more about hydrogen on pages 25-30.

Pumped-storage hydropower

Pumped-storage hydropower uses excess electricity to pump water to a higher elevated reservoir, and when the electricity is needed, the water is released back to a lower elevation through turbines that generate electricity.[95] Today, pumped-storage hydropower is the most widely deployed storage technology, accounting for 90% of total electricity storage in 2020.[96]

It is cheap to store energy as pumped-storage hydropower even for very big facilities,[97] and it can deliver power for anywhere from hours up to several weeks.[98] However, even though the technology is mature and cheap, it is widely believed that there are limited suitable locations to construct new facilities.[99] Pumped-storage hydropower is a low-emissions energy storage, but we must keep in mind that there can be negative environmental and biodiversity impacts of damming up large hydro-reservoirs.[100]

Lithium-ion batteries

Batteries are a viable short-term storage solution. Although still expensive, lithium-ion batteries have dropped in price in the past decade. These grid-scale batteries are resource demanding, and even if they become increasingly cheaper, will still depend on critical mineral prices. The current global battery storage capacity is much lower than pumped-storage hydropower, though is expected to increase dramatically from 28 GW in 2022 to 967 GW in 2030, catching up with the global pumped-storage hydropower capacity.[101]

However, each of these storage mechanisms have specific advantages. Batteries are particularly suitable to combine with solar panels, especially in areas with a predictable and stable sunshine pattern such as semi-arid and arid areas. This is because you can scale the battery storage to match the electricity needs outside the sunny hours. Batteries do, however, have two main drawbacks: 1) they have a limited number of cycles, and 2) there are environmental considerations, specifically the reliance of batteries upon intensive mining for critical minerals. But the technological developments are moving fast, and it is likely that we soon can have batteries that can maintain performance over 25-30 years.[102]

Reusing energy through sector integration

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.

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.

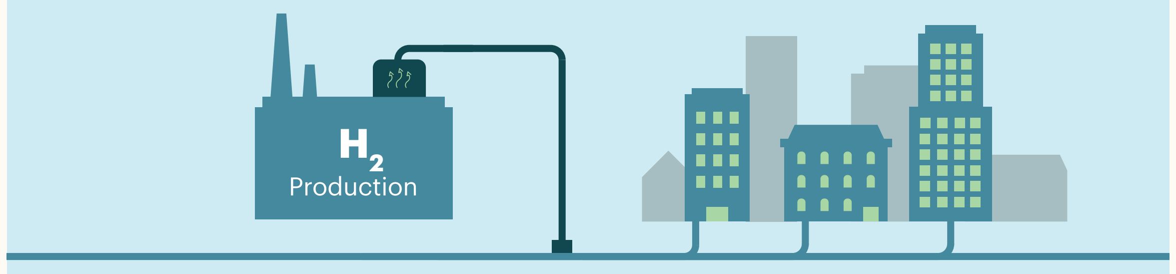
Potentials of excess heat

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, and hydrogen electrolysis facilities** found in cities across the globe. By 2030, up to 53% of the global energy input will be wasted as excess heat.[103] Furthermore, the climate can benefit greatly if we recover excess heat. In fact, we can reduce the global emissions by 10-19% if we recover the full theoretical potential of excess heat.[104]

Heating is one of the largest energy consumers in the 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.[105] At the same time, all urban areas in Europe have access to numerous excess heat resources. There is about 2,860 TWh per year of waste heat accessible in the EU, much of which could be reused.[106] 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.[107]

In some countries, the excess heat potential even matches the total heat demand.[108] In the Netherlands, for instance, excess heat amounts to 156 TWh per year,[109] while the water and space heating demand is only 152 TWh per year.[110] 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.[111] Just imagine what the total amount of excess heat across all sectors in the whole of China looks like!

Case: Excess heat from hydrogen production



The excess heat from hydrogen produced through electrolysis can be captured and used to heat homes and supply heat for industries. Low-emission hydrogen production will be massive by 2050 – the IEA estimates the global electricity demand for electrolysis to be 14,800 TWh.[112] Roughly **two-thirds of the electricity input is converted to hydrogen and the rest is wasted as heat. From this energy loss, about 17% can theoretically be recovered and put into district energy in 2030** – enabling cities to lighten the load on renewables for heat generation.[113]

Figure 8 presents the sources of global power demand in Bloomberg's Energy Outlook. It is evident that the power demand for hydrogen production will be huge. Because of this, we must make sure to use as much waste heat as possible from the electrolysis process. However, this heat potential can only be utilized if we plan our hydrogen production wisely, constructing electrolysis plants near planned or existing district energy systems. In fact, this can already be done today. Several projects are already underway and can soon distribute the excess heat from electrolysis plants through district energy systems to heat homes.[114,115] Several factors influence how much of the excess heat can actually be realized. For instance, using the full potential would require a large build-out of district energy, and hydrogen production must occur near a district energy system. Additionally, many regions have little or no demand for heat. However, the theoretical potentials for recovering excess heat from electrolysis is so enormous that we must simply consider it when planning future energy infrastructure.

On a global scale, we can theoretically recover 1,228 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 in perspective, 1,228 TWh of heat is equivalent to almost two-thirds of today's global heat generation from coal, the largest source of heat.**[116] In the EU alone, about 83 TWh can be recovered already by 2030, enough to cover Germany's current domestic heating more than 1.5 times.[117] In China, 296-427 TWh can be recovered in 2060, between 18% and 26% of China's current heat generation.[118] Of course these are theoretical potentials, but they demonstrate that if district energy and excess heat are considered in long-term energy system planning, it can be a key contributor to the 1.5°C target.

Electricity Demand from Hydrogen Production

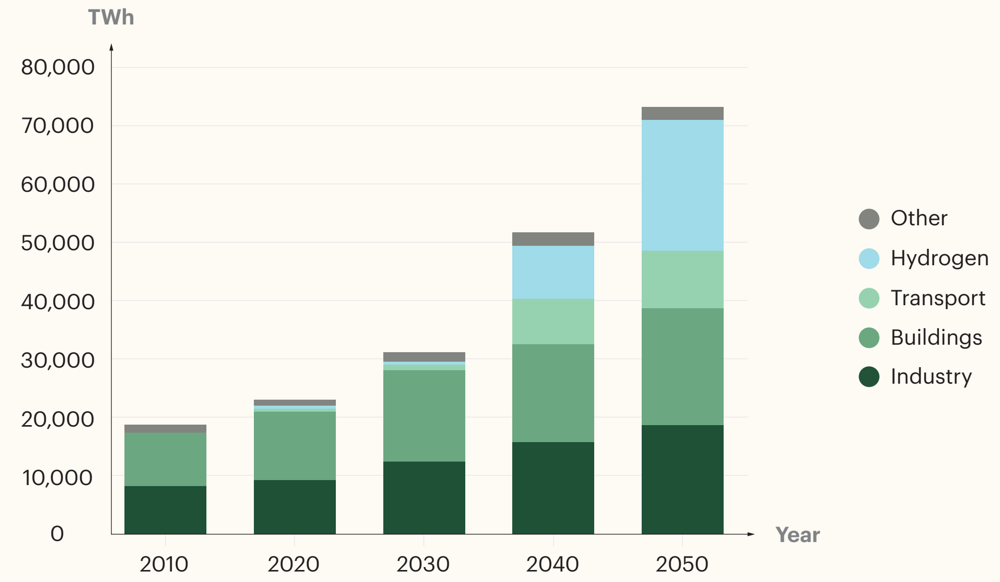


Figure 8: Sources of global power demand in BloombergNEF's Net Zero Scenario[119]

Link energy consumers and producers

Heat producers can reuse heat they produce within their own internal processes to increase efficiency. For example, excess heat can often be found in manufacturing processes or where heating, cooling, freezing, and burning processes occur. And the simplest way to use excess heat is to reintegrate the heat into the same processes. For instance, in supermarkets, excess heat produced by the freezers and refrigerators can be used to provide hot water or to heat the supermarket itself. The primary way to use waste heat internally is by installing a heat recovery unit. A heat recovery unit is worth considering in almost all cases where unused heat energy is produced as a "waste product".

In cities, sector integration can happen on a small scale through urban planning, or it can happen on a larger scale through district energy networks. Urban planning can leverage the potential of sector integration and excess heat by connecting energy producers with energy consumers through a smart grid. Large synergies can occur when a producer of excess heat – for instance, a data center – is located close to entities that can buy and use large amounts of the excess heat (for example, horticulture). Looking at possibilities for such synergies between energy producers and users in urban planning is called industrial cluster planning and it contributes to decarbonizing our energy system. Furthermore, the collaboration between nearby companies has been shown to provide economic benefits to both the buyer and the seller.

In many parts of the world, district energy systems supply homes and companies with heating as well as cooling. A district heating network taps into heat from a combination of sources, such as renewable sources (solar, geothermal, and biomass) and fossil sources, such as at power plants, and distributes it through pipelines to end users in the form of heated water. Today, the majority of global district heat production relies on fossil fuels. However, **one of the main strengths of district energy systems is their capacity to integrate different heat sources that can push fossil fuels out of the heating and cooling mix**. As district energy technology evolves, increasing numbers of excess heat sources can be integrated into the system. Today, the so-called 4th generation district energy system allows very low-temperature heat sources to be integrated into the district energy system and provide heating for new buildings that can operate on low-temperatures.

Danfoss Impact
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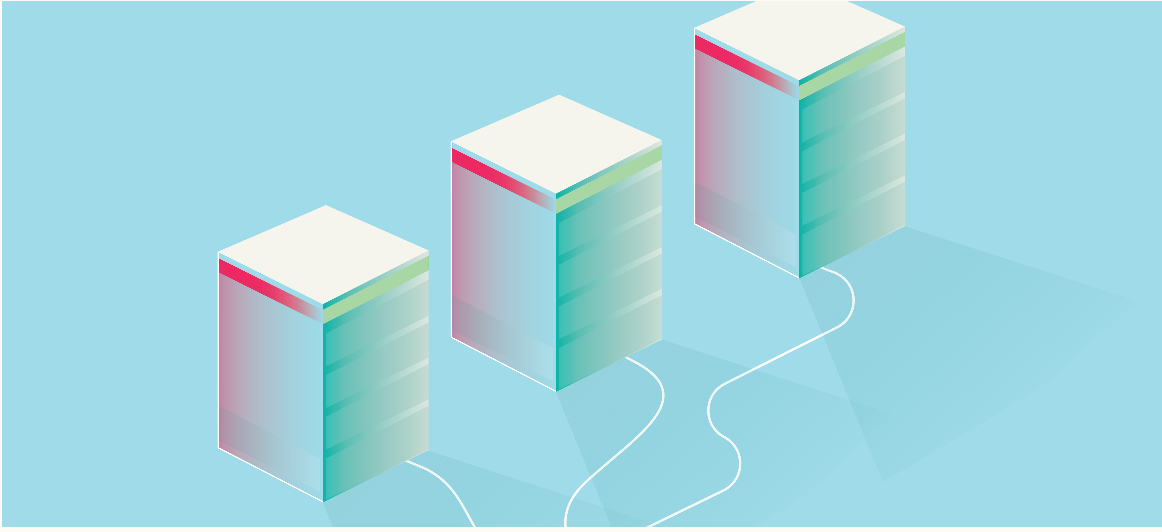
Case: The potential of excess heat from data centers



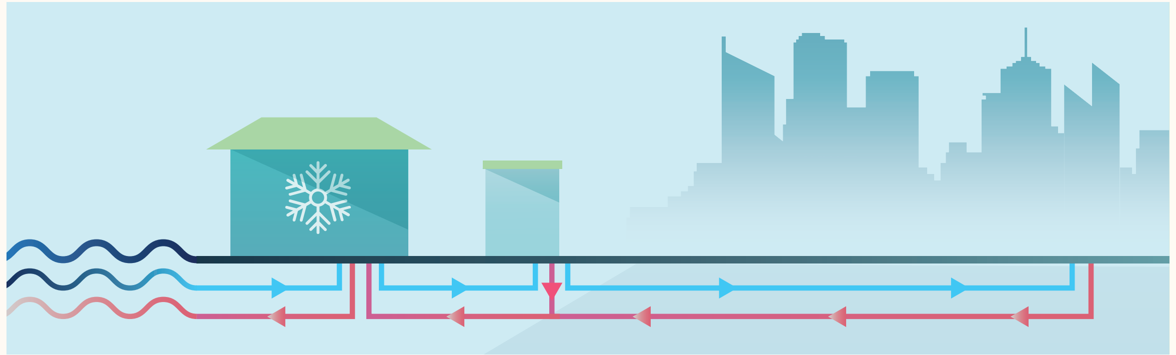
Data has become the lifeblood of today's global digital economy, forming the backbone of the flow of information and powering a range of activities from infrastructure and transport to retail and manufacturing. According to the IEA, in 2021 data centers consumed 220-320 TWh of electricity or around 0.9-1.3% of global final electricity demand[120] – this is as much as the electricity consumption of Australia or Spain.[121]

Data centers are also significant producers of excess heat. The servers within a data center generate heat equivalent to their electricity use, and the necessary cooling of these machines also produces a great deal of excess heat. Compared with other sources of excess heat, **the flow of excess heat from data centers is uninterruptible and therefore constitutes a very reliable source of clean energy.** There are multiple examples that the excess heat from data centers can be reused to heat nearby buildings through a microgrid or it can be exported to the district energy network and used for multiple purposes.

In the city of Frankfurt am Main, there are several projects in the pipeline working towards assisting the city in taking excess heat from data centers and using it towards its entire heat demand of private households and offices. Mathematically, it has been estimated that the waste heat from the data centers in Frankfurt could, by the year 2030, cover the city's entire heat demand stemming from private households and office buildings.[122]

In Dublin, Amazon Web Services has built Ireland's first, custom-built sustainable solution to provide low-carbon heat to a growing Dublin suburb. The recently completed data center will provide heat for initially 47,000m^2 of public sector buildings. It will also provide heat for 3,000m^2 of commercial space and 135 affordable rental apartments.[123]

Case: District cooling systems use half as much energy as air conditioners



In a district cooling system, chilled water is supplied from a central cooling utility to commercial and residential buildings through pipelines. The cold water for the district cooling is supplied by free, natural cold-water resources – sea, lakes, rivers, or underground reservoirs – or is produced from waste heat from power generation or industries, or via central electric chillers. The cold water in the district cooling system can be produced at night and distributed at peak hours during the day. This reduces the need for chiller capacity during peak demand hours and reduces operating costs, as electricity is cheaper and ambient temperatures are lower at night.

Around 10% of the world's electricity demand comes from space cooling and the IEA estimates that by 2050, around two-thirds of the world's households could have an air conditioner.[124] According to international studies, the demand for cooling of commercial and residential buildings will grow exponentially in the years to come, especially in high-income countries and emerging economies, such as India, China, and Indonesia.[125] However, district cooling systems use half as much energy as air conditioners and will also reduce the consumption of the environmentally damaging F-gasses.[126]

Existing district cooling systems in cities like Paris, Dubai, Helsinki, Copenhagen, and Port Louis have proved that district cooling can be more than twice as efficient as traditional, decentralized systems.[127] In Dubai, for instance, 70% of electricity is consumed by air conditioners, and in order to meet the cooling demand, the city has developed one of the world's largest district cooling networks. By 2030, 40% of the city's cooling demand will be met by district cooling.[128] And **in cases where water from lakes or the ocean can be utilized – also called "free cooling" – the energy demand can even be reduced up to 90% compared to conventional cooling operations.**[129] An example of such a system is found in Toronto, Canada, where water from the bottom of Lake Ontario is utilized for a large-scale district cooling supply.[130]

Integrate sectors

1 Much of the world's energy is wasted as excess heat

By 2030, up to 53% of the global energy input will be wasted as excess heat. However, the climate can benefit greatly if we increase efforts to recover this excess heat. In fact, **recovering the full theoretical potential of excess heat can reduce the global emissions by 10-19%.**

2 Link energy producers and consumers

By capturing excess heat and redistributing it through smart urban planning and district energy systems, **heavy energy consumers such as data centers, supermarkets, hydrogen production, and wastewater treatment facilities can become major energy suppliers.**

3 Increased hydrogen production creates major excess heat potential

By 2050, the IEA estimates the global electricity demand for electrolysis to be 14.800 TWh. Without action, roughly one-third of this electricity will be wasted as excess heat. However, **on a global scale we can theoretically recover 1,228 TWh of heat in 2050 to district heat** – this is equivalent to almost two-thirds of today's global heat generation from coal.

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Policy Recommendations

Now is the time for decisionmakers at all levels to set the right regulatory and economic framework to reach net zero by 2050. Energy efficiency 2.0 has the potential not only to reduce carbon emissions, but also to deliver substantial economic savings both at a societal and customer level. But for this to become a reality, the regulatory framework must be implemented now.

These policy recommendations are necessary steps to take to ensure the solutions for our future energy system are not only engineered but also implemented.

Include flexibility solutions in energy policy at all levels to mediate the relationship between supply and demand of renewable energy and to ensure energy security.

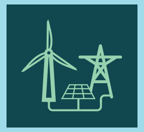
The new smart grid must include load-shifting and peak-shaving technologies. Introduce demand-side flexibility (DSF) guidelines in building and industry regulations guiding consumers to implement flexibility solutions faster. Give both consumers and producers access to consumption data, facilitating active participation and opportunities for system operators to further integrate demand-side flexibility solutions. Implement pricing mechanisms to incentivize energy use in off-peak hours.

- **In buildings and industries**, implement local, national, and international flexibility standards regulation, guiding electricity consumers to implement flexibility solutions faster. Provide consumers with economic incentives to actively increase flexibility by offering installation of smart meters via government subsidies or building regulations. Allow system operators access to building, industry, and household electricity consumption data.
- **In the energy market**, implement flexibility market standards to ensure easy integration of new devices and local renewable energy sources, leading to a competitive market for manufacturers, system operators, and utility companies. For example, the EU's S2 Standard enables communication and interoperability across devices while retrieving grid information to coordinate energy consumption and synchronize it with production, ensuring effective implementation of DSF solutions.

Save energy and electrify everything across transport, industries, and buildings.

Increasing efficiency across sectors alongside a full-scale electric overhaul of our infrastructure is the crucial first step to take. Reducing energy waste across sectors starts with mapping energy use to identify areas for improvement. Mandate energy planning, set ambitious and actionable short-, mid-, and long-term targets and plans, and implement a suitable regulatory framework to incentivize investments.

- **In buildings,** design and implement mandatory building energy codes to accelerate the transition towards zero-carbon-ready buildings. Set up long-term renovation strategies, including suitable regulation and incentives to stimulate renovation, to use renewable energy, and to boost renovation rates of existing buildings. Incentivize the replacement of technical building systems running on fossil fuels for space heating, domestic hot water, and cooling with those using renewable energy, such as heat pumps or district energy networks.
- **In industries,** set minimum energy performance standards for key equipment, such as motors and pumps, that can increase industrial efficiency levels. Ensure that taxes and fiscal policy push industries towards becoming more energy efficient, for example by utilizing carrot-and-stick policies that encourage action via carbon pricing. Initiate programs that ensure SMEs get an overview and create a plan for their decarbonization. Develop programs that integrate energy audits with instructions on effectively conveying green initiatives. Invoke mandatory short-payback efficiency measures identified through energy audits.
- **In transport,** increase efficiency and electrify through investments, regulation, and incentives. Create a market for full electrification technologies by setting high carbon-intensity standards for new machinery and vehicles. Structure vehicle taxation to incentivize the purchase efficient vehicles and plan for EV parking and charging stations. Include the building process in charging station life-cycle assessments. Provide incentives to retrofit existing long-lifespan diesel engines to enhance energy efficiency. Use local regulation and permitting options to create low- or zero-emission zones and construction sites. Electrify last-mile inner city freight and goods delivery traffic. Build charging infrastructure and ensure financial incentives prioritize smart charging to fully leverage digitalization and enable electric vehicles to be a contributor to fix flexibility and storage challenges.



Invest in upgrading the energy grid to accommodate an increase of renewable energy in the system.

Investments in the grid are necessary to accommodate the increased electricity demand and higher renewable energy supply. To get back on track to reach the Net Zero by 2050 Scenario, investments in the future energy system must double by 2030.[131] Such investments will reduce the societal costs and reduce both energy costs and consumer energy bills. Several initiatives could be followed through to counter the aging grid infrastructure and address the urgent expansion. Most power distribution grids are situated around centralized power plants and need to be upgraded to distribute power from the fleet of local solar panels and wind farms. Implement a "one-stop-shop" approach, where renewable energy investors only need to send the project application to one entity, who then coordinates all the authorization processes with the relevant authorities.

- **In grid planning,** priority should be given to the uptake of renewable energy sources coming from applications such as wind turbines, photo-voltaic, and other longer-term infrastructure projects that are expected to be launched in the coming decades. Public funding allocated to innovation and research should be focused on efficient system integration of renewable energy technology. This could entail development of new products and processes, testing and demonstrating new applications and models, and extensive collaboration with academia, industry, and civil society.
- **In transitioning to future energy grid,** provide legal framework conditions allowing for smart grid technologies such as smart meters, sensors, inverters, switches, and software to be implemented quickly and efficiently. Improve regional coordination and cooperation to ensure uptake of renewable energy in the grid. Increase sharing of information, resources, and services as well as harmonizing policies and regulations. Through setting prices, rules, and standards for energy and ancillary services, an improved market design would help incentivize and add mechanisms for efficient and fair allocation of costs and benefits of renewable energy integration.
- **In securing the energy supply,** invest in electricity conversion and storage facilities to realize the full potential and availability of renewable energy on the grid. Hydrogen electrolysis facilities will play an essential role in both storage and conversion; however, its usage must be optimized through thorough planning. Regulate such facilities and ensure high efficiency standards are met to curb energy usage and plan for integrating the excess heat from electrolysis facilities.

Invest in sector integration.

Market barriers prevent market players from leveraging the potential of excess heat. Remove these barriers by, for example, supporting an equal treatment of waste heat and renewable energy sources used in heat networks. Redesign energy markets to allow for the participation of sector integration technologies in specific markets and internalize all positive externalities of low-carbon technologies.

- **In national governments,** set goals to reach a certain threshold of sector integration. Establish a target for repurposing waste energy and use as a guideline for the energy market and to encourage a holistic approach to sector integration. Remove administrative barriers to incentivize users to connect to district heating networks and encourage district heating utilities to boost their efficiency.
- **In urban and rural planning,** implement mandatory energy planning to enable assessment of the waste energy potential and make the best use of locally available resources. Grid planning as a tool should be guided by an "energy efficiency first" principle, which would reduce the need of new grid investments – both on national and international levels. Push for greater use of excess energy by making it mandatory for entities to plan for utilizing excess heat. Heat planning must be detailed and include potential future sources of excess heat, such as electrolysis facilities. Energy planning can both reveal small-scale potential or potential of larger-scale opportunities, such as the rollout of district heating.
- **In the energy market,** lower the minimum bid-size to allow for smaller actors to offer their energy services to the energy grid, creating local flexibility markets to tackle local grid issues. Incentivize sector integration through tax legislation in favor of using excess heat and ensure that appropriate network tariff structures are considered.

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