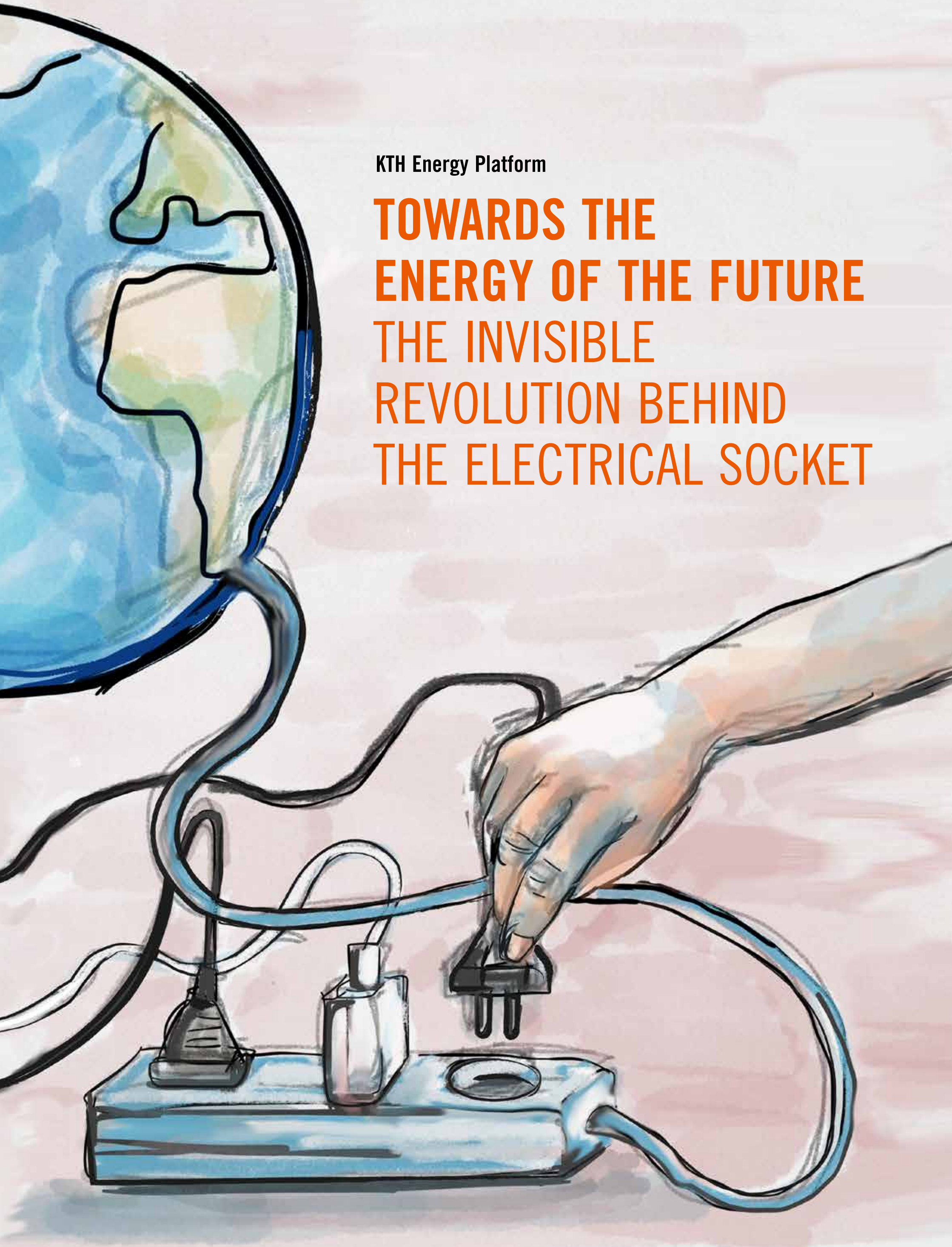
KTH Energy Platform

TOWARDS THE ENERGY OF THE FUTURE

THE INVISIBLE REVOLUTION BEHIND THE ELECTRICAL SOCKET



Towards the Energy of the Future
– the invisible revolution behind
the electrical socket

TOWARDS THE ENERGY OF THE FUTURE

THE INVISIBLE REVOLUTION BEHIND THE ELECTRICAL SOCKET

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The KTH Energy Platform

The KTH Energy Platform is an arena for collaboration between different research groups at KTH. The aim is to enable the transition to a sustainable society by creating and communicating knowledge on energy. An important function of the platform is to facilitate interaction between KTH experts and external partners within academia, public sector and private companies. More than 450 researchers are affiliated with the platform. Read more at www.kth.se/forskning/forskningsplattformar/energi/

VA (Public & Science)

VA (Public & Science) is a non-profit organisation that promotes dialogue and openness between the public and researchers. This includes inspiring and training researchers to communicate their work, developing new formats for discussing research, and carrying out studies on the science–society interface. Read more at www.v-a.se

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PREFACE

Energy is everywhere. It is inseparable from our everyday lives – what would we do without electricity, chemicals or heat? Despite being completely dependent on energy, and being surrounded by it everywhere we go, it is often invisible to us.

This anthology is written by researchers connected to the KTH Energy Platform, in collaboration with the non-profit organisation VA (Public & Science). The platform is an arena where we researchers learn from each other and create new ideas for understanding our world and the challenges we are facing. Energy is an incredibly complex area and not even the brightest scientists on the planet understand it all. Together, however, we are slowly advancing the knowledge, every day aiming to understand more for the benefit of the world. This togetherness is key, and our platform is an open place where it can happen.

To tackle climate change, our energy system needs to be transformed almost entirely in about two decades. It will be a historically unparalleled process, where there is no ready-to-go plan at hand. As researchers, our role is to enable the necessary changes by creating knowledge. We do not make the political decisions, but we are supplying the knowledge to make them successful.

It is often challenging to discuss and analyse complex problems in the societal debate. The media is looking for attractive headlines and short punchlines. In a polarised political climate, parties may be over-simplifying arguments to please voters while ignoring the complexity of the issues at hand. The tone of such debates often seems the opposite of the discussions we researchers enjoy with colleagues, and the pleasure we take in learning and sharing different discoveries and insights.

The challenges we are facing today call for a knowledge-driven transformation to create a sustainable society. All the challenges are complex – many, by nature, in conflict with each other. That is why we need to address them together, in an open arena where facts and knowledge shape our way of working. In our work, we must also be completely open about the inherent uncertainty in this transformation and where it will take us.

A democratic society rests upon well-informed and engaged citizens. With this book we want to share some of the complexities that we encounter in our research. Our hope is that readers will appreciate these fascinating research questions and also gain an understanding of the world and the upcoming challenges our society faces in terms of energy.

Perhaps you will find some facts and ideas to share with friends and family, or topics to power constructive discussions at coffee breaks, parties, or family dinners? If so, please join us in our aim to spread knowledge and inspire curiosity about energy, by communicating facts and taking an active part in the debate – wherever it may be taking place.

Lina Bertling Tjernberg, Director KTH Energy Platform
Christophe Duwig, Deputy Director KTH Energy Platform

TOWARDS THE ENERGY OF THE FUTURE

THE INVISIBLE REVOLUTION BEHIND THE ELECTRICAL SOCKET

WHAT IS ENERGY?

Matthäus Bäbler & Fredrik Brounéus

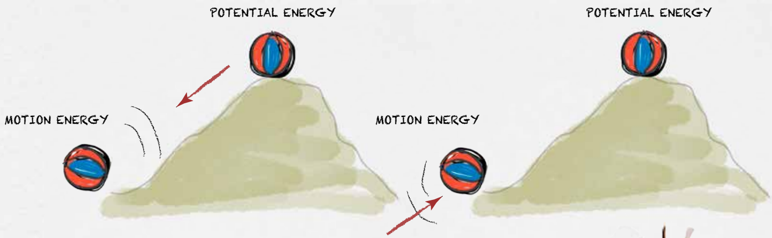
As stated in the beginning of this book, *energy is everywhere*. We are literally and physically surrounded by it, completely dependent on it, and it is now a fundamental part of our lives. It is heating our homes, powering our computers, mobile phones, home appliances, buses, trains, airplanes and cars. We were painstakingly reminded of this in the wake of the events of spring 2022, when Russia's invasion of Ukraine showed how interdependent and fragile our global energy relations are. Geopolitics aside, energy was already a major talking point on the public agenda. During the past decades we have come to an alarming realisation that the resources of our planet are finite, and that if we continue to exploit them the way that we have done historically, there will be dire consequences for future generations. We also know that we urgently need to cut down on the fossil fuels that are powering most of our everyday lives, or else carbon emissions will accelerate climate change to a point where it will set in motion events far beyond human control (read more in chapter about the oil dependency). At the same time, our global village of humans is steadily increasing in size and living standards, steadily increasing its consumption of energy. When talking about *living standards* we not only mean factors that add convenience or luxury to our lives, such as cars, TVs and holiday travel. Fundamental functions of a modern society such as healthcare, communication, education and the production and transport of necessary goods such as food, clothes and building materials, all require energy.

Let us now leave this somber line of thought for a while, take a step back and ask: What is energy? From the viewpoint of natural

ENERGY AS A PHYSICAL QUANTITY

POTENTIAL ENERGY - THE SYSTEM (THE BALL) CAN PERFORM WORK AS THE POTENTIAL ENERGY (POSITIONAL ENERGY) IS TURNED INTO **KINETIC ENERGY** (MOTION ENERGY) WHEN THE BALL ROLLS DOWN THE HILL.

TO RESTORE THE POTENTIAL ENERGY, MOTION ENERGY NEEDS TO BE SUPPLIED (THE BALL IS ROLLED BACK UP THE HILL).

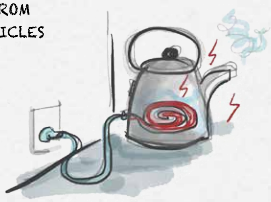


CHEMICAL ENERGY - ENERGY THAT IS STORED IN CHEMICAL BONDS (E.G. IN BIOMASS AND FOSSIL FUELS), AND CAN BE RELEASED E.G. AS **THERMAL ENERGY** - HEAT.

SEE CHAPTERS ON ENERGY FROM BIOMASS, HYDROGEN, FAECES, AND ENERGY FROM A HISTORICAL PERSPECTIVE.

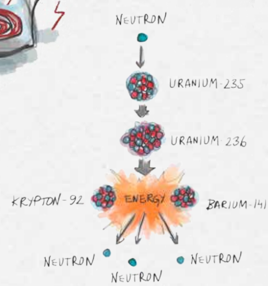
ELECTRICAL ENERGY - ENERGY FROM THE MOVEMENT OF CHARGED ATOMIC PARTICLES (E.G. WHEN ELECTRONS MOVE THROUGH AN ELECTRIC BOILER AND GENERATE HEAT).

SEE CHAPTERS ON ELECTRICITY, POWER GRIDS, AND MATERIALS FOR THE ELECTRIFICATION OF SOCIETY.



NUCLEAR ENERGY - ENERGY FROM THE NUCLEI (CORES) OF ATOMS (E.G. FISSION, WHEN URANIUM NUCLEI ARE SPLIT WITH THE HELP OF NEUTRONS).

SEE CHAPTER ON NUCLEAR ENERGY.



science, energy is a *physical quantity* defined as the *capacity of a system for performing work*. More energy in the system – higher capacity for doing work. This physical quantity can take a number of different forms, such as electricity, heat, motion or radiation (see Figure 1). From an economic and societal viewpoint, energy can be seen as a *commodity* that our human society can produce, transfer, trade and consume. Just like the physical quantity, this commodity can exist in different forms, such as electricity or heat, in every stage of the production, transfer, trade and consumption process (see Figure 2).

Let us stick for the moment with energy as a *physical quantity*.

An inherent characteristic of energy is that it cannot be destroyed – ever. Energy is thereby a *conserved quantity* meaning that there is a fixed amount of energy in the universe we are living in. Energy cannot be formed nor can it be destroyed – it only changes from one form into another. However, as humans we still experience losses of energy whenever we transform it from one form to another, e.g. from heat to electricity. But it is never lost in the physical sense; just in the sense that we are not able to capture and use the forms of energy that the losses may take (read more in the chapter on energy waste). These losses occur as fundamental principles of nature and form the basis of *thermodynamics* – the scientific term for how energy, work and temperature relate to each other. In practical terms we talk about the energy *efficiency* of an energy *conversion* process. For example, the energy efficiency of a gas power plant relates to the amount of energy *released* (in the form of heat when burning gas as fuel) to the amount of energy that is *produced* (in the form of electricity).

The mentioning of power plants brings us to energy as a *commodity* that is produced, traded and consumed. How does this

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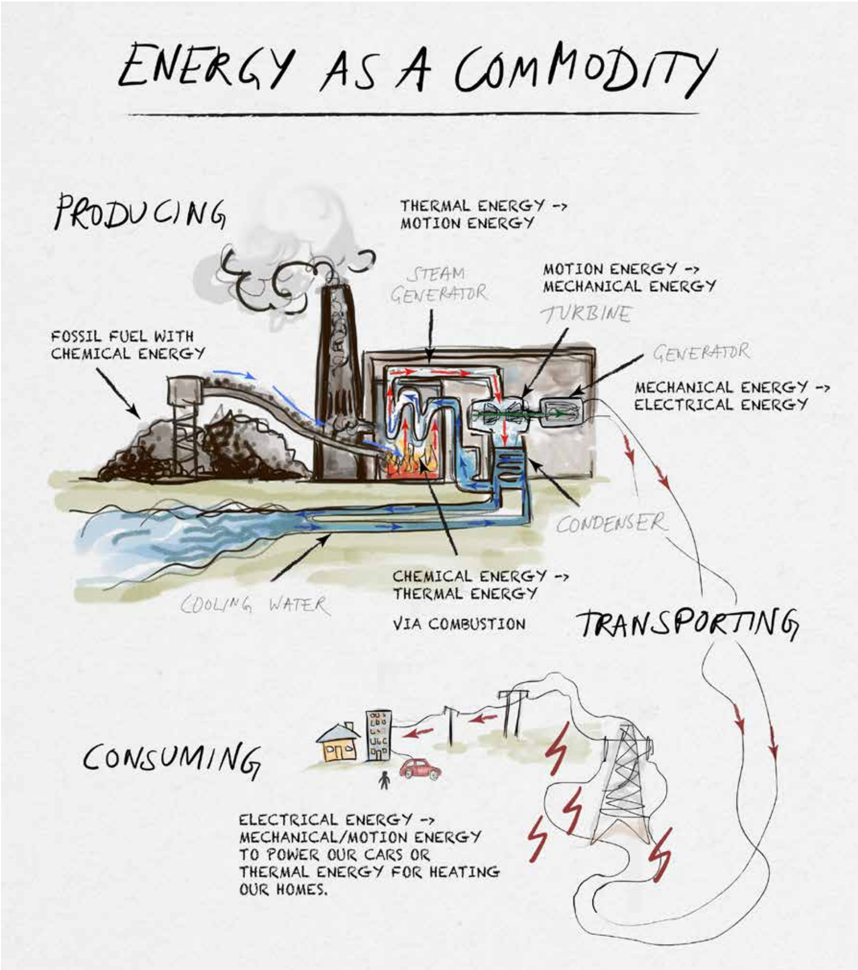
◀ *Figure 1:* Energy as a physical quantity.



▲ *Figure 2:* Energy as a commodity. In the case of fossil fuels, we transform their chemical energy, via combustion, to thermal energy; which, via steam, is turned into motion energy; which, via the turbines' mechanical energy, is turned into electrical energy. And then we transform the electrical energy again, as we are using it e.g. for heating in our homes, or to power our cars (mechanical energy; motion energy). In this case, the energy can be traded and transported either in the chemical form (e.g. as oil in barrels or pipelines; as gas in containers or pipelines; as batteries) or as electricity (via power lines).

notion relate to the concept of energy as a conserved quantity? To explore the relationship between the two concepts, we should bring our focus to planet Earth. Within Earth's boundaries, all the energy around us essentially traces back to the sun and geological activity inside the planet. Energy from the sun reaches our planet in the form of electromagnetic radiation, enabling trees and plants to grow via photosynthesis, and driving the weather. As a source for sustainable energy, not only does the sun provide the radiation for photovoltaic power plants, but it also generates wind and rain to drive wind parks and hydropower plants. However, the sun is also the origin of fossil fuels; over millions of years solar radiation powered the growth of trees and plants, converting and storing solar energy as chemical energy. As the plants died, decayed and were buried underground, they transformed – with the help of geothermal heat – into coal, oil or natural gas. When treating energy as a commodity that can be produced and consumed, we are looking at it within the boundaries of planet Earth, which has a steady input of energy in the form of solar radiation. This solar radiation provides us with clean, renewable sources of energy, as well as unsustainable ones, and unfortunately, up until now mankind has favoured the latter.

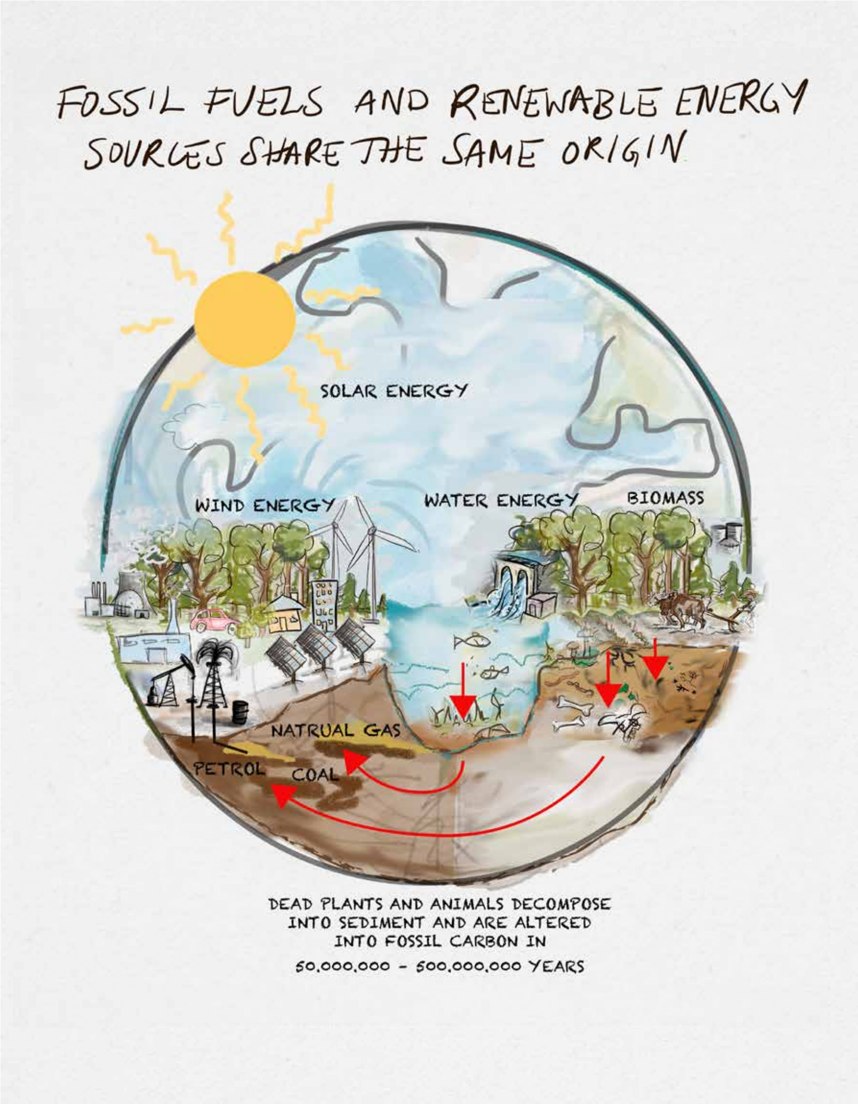
This leads us back to the slightly apocalyptic storyline from the beginning of this chapter. When we transform the chemical energy in fossil fuels to other forms of energy, we release greenhouse gases into the atmosphere. But why is this a problem? Oil, coal and natural gas are all natural products, derived from the sun. The problem is that the chemical energy in the fossil fuels, in the form of hydrocarbons, has been transformed from solar and geothermal energy accumulated on Earth over *millions of years*. And now, our industrial activities are releasing this carbon in a matter of a few hundred years, which results in a massive CO_2 overload in the atmosphere.

But couldn't we just recycle the CO_2 in the atmosphere to make more energy or manufacture some useful products? With all this

▲ *Figure 3:* If we were able to generate new energy sources from carbon dioxide, we would need to first add energy.

precious carbon in the air, we should be set for several human lifetimes. *And* we could keep using fossil fuels. Unfortunately, the CO_2 in the atmosphere was produced in chemical reactions that *released* large amounts of heat (e.g. in combustion engines burning petrol in vehicles or in power plants burning natural gas), which means that the carbon in CO_2 now holds a lot less energy (again, thermodynamics). Compared with some of the 'original' fossil fuel molecules (such as methane) CO_2 is on a very low energy level. This means that if we were to recycle CO_2 into 'new' energy or new products, we would need to add large amounts of energy to 'lift' the end product to a higher level (see Figure 3).

From an historical point of view, human harvesting of energy (i.e. converting chemical energy into heat and mechanical energy)



▲ *Figure 4:* Renewable energy sources are related to the same "parents" as fossil fuels. However, we use different processes to extract their energy, with different end results.

has always been a dirty and noisy process, often including chemicals (leaded gasoline, automotive catalysts) harmful to ourselves and our environment. Today, we are painfully aware that the process is also deeply unsustainable – for ourselves and our environment. Consequently, energy is a fundamental part of the UN Sustainable Development Goals (see chapter on energy and the Sustainable Development Goals). To attain the Goals we must find new ways to transform energy for our needs in sustainable ways. In this context, when we are talking about *renewable energy* we mean energy sources that are virtually endless on a human timescale (on a more cosmic timescale, even the sun will eventually go out) (see Figure 4).

Regardless of how we secure the energy needs of our current and future society, all solutions will come with trade-offs and synergies. The ongoing electrification of society will put us at new crossroads, with new sustainability conundrums to consider – for both human and planetary health (see chapter on materials for the electrification of society). Such considerations are an inherent part of every research and development process. However, what we need to do differently from now on is to have a holistic "think first" approach in the development of our future energy system. This means considering all the possible effects any new technology can have on ourselves and our planet. Fortunately, digitalisation has put us in a position to do this. We are now able to collect and analyse vast amounts of data over the whole energy chain, which will allow us to understand and control the different components of an entire energy system. This way, artificial intelligence will help us model and operate new scenarios which facilitate the transition to a truly sustainable energy future (see chapter on energy waste). But, again, this development too will bring new challenges that we need to take into account (see chapters on Internet of Things, homes in the smart grid, cyber security and electrical power grids).

Finally, we will end this chapter on a more philosophical note. In our quest for a sustainable energy future, perhaps we will also need to consider decoupling energy consumption from economic growth? How can we, as a society, improve without consuming more energy? Another way of looking at it could be decoupling economic growth from human progress. Perhaps we will reach a point where less will actually be more – also in terms of energy production and consumption?

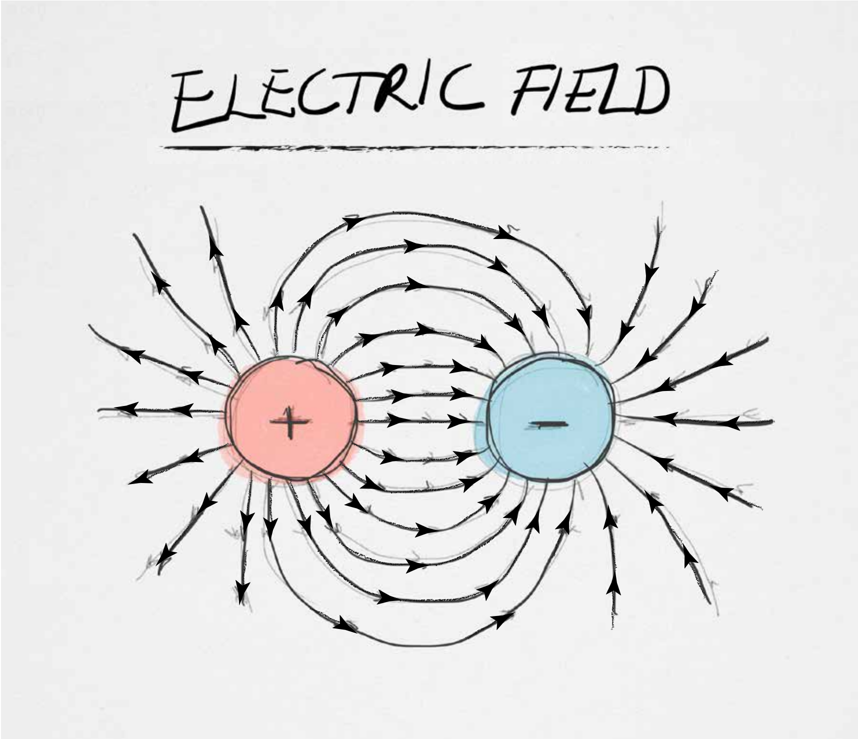
WHAT IS ELECTRICITY?

Lina Bertling Tjernberg

Electrical phenomena are forces of nature that have been studied since ancient times. An early discovery was static electricity that occurred when a fur coat was rubbed against amber. The word electricity comes from the Latin *electricus* and the Greek *electron*, both of which mean amber. However, the great scientific breakthroughs in electricity did not take place until the 18th and 19th centuries, and their practical applications were delayed until the end of the 19th century. Today, we are completely dependent on electricity for a variety of applications, such as lighting, transport, heating, communication and mathematical calculations.

So how is electricity made? An atom consists of a number of smaller particles with opposite charges that are held together thanks to their electrical attraction to each other. The nucleus of the atom contains *protons* that have a positive electric charge and *neutrons* that have no charge, and is *surrounded* by electrons with a negative charge. An atom with an equal number of protons and electrons is electrically neutral. Friction – such as when a fur coat is rubbed against amber – can cause electrons to move from one material to another. The material that acquires an *excess* of electrons (in this case the amber) becomes negatively charged and the material that loses electrons (the fur) becomes positively charged. An *electric field* arises between these positive and negative charges – the greater the difference in the charge, the higher the voltage in the field (see Figure 1). Voltage is measured in the unit volts [V].

An *electric current* occurs when electrons move from one point to another. The magnitude of the motion – the current – is meas-



▲ *Figure 1:* Electric field.

ured in the unit amperes [A]. Electrical devices are powered by this current of electrons. Figure 2 shows the relationship between current and voltage, as expressed in *Ohm's law*. The law states that the electric current (i) between two points is equal to the electric voltage (v) divided by the resistance (R) measured in [Ohm]. Resistance is an opposition to the flow of electric current and can be described as a loss in the current transmission.

The electric power system is an infrastructure that moves electrical energy, in the form of electricity, from the energy source to the user (read more in the chapter on electric power systems). To

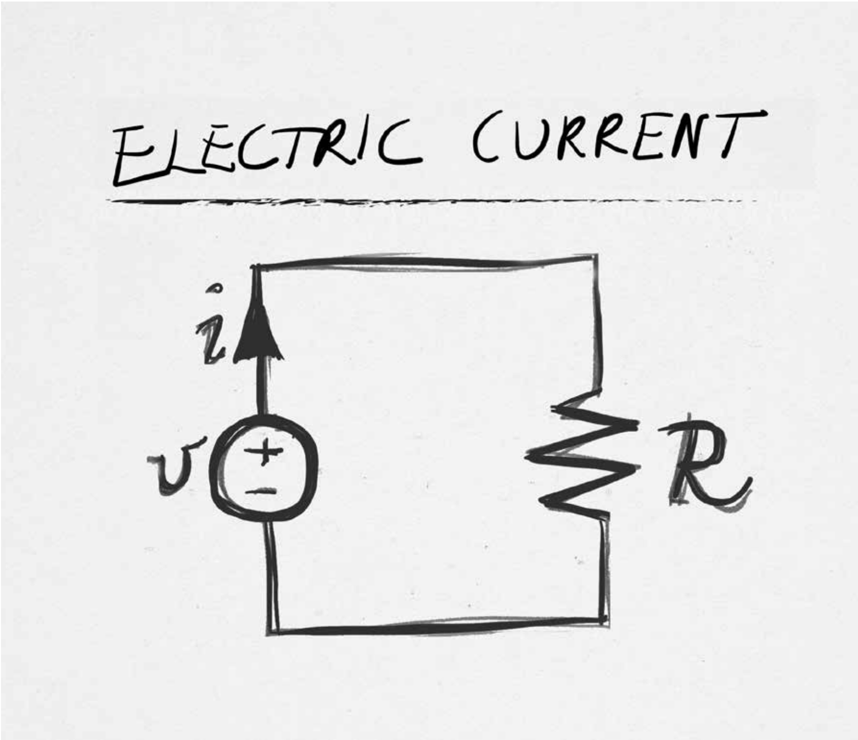


Figure 2: Electric current. The letter *i* signifies current [A], *v* is voltage [V], and *R* is resistance [Ohm] (where i = V / R, Ohm's law).

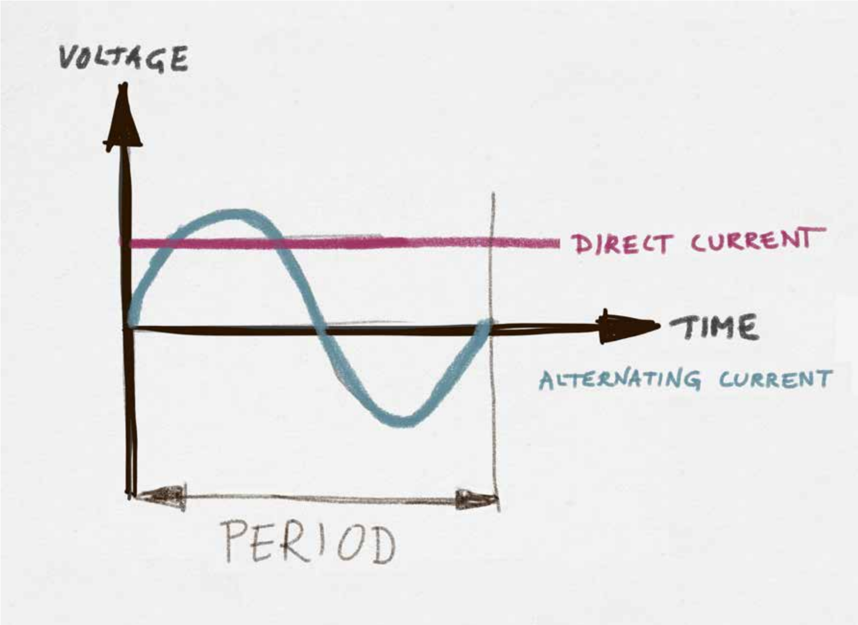
do this in a reliable, safe and efficient way, an electrical system has been developed using a mixture of direct voltage/direct current and alternating voltage/alternating current. Direct current/direct voltage means a constant voltage level, while alternating voltage/alternating current means that voltage and current change direction with a particular frequency (see Figure 3). The frequency is measured in Hertz [Hz], where 1 Hz corresponds to a period per second – that is, an entire oscillation in one second. In Europe, an electric power system with 50 Hz alternating voltage (50 periods per second) is used, but in North America, for example, 60 Hz is used. For the transmission of electricity over very long distances, for example between different countries, direct current voltage is used.

For over a hundred years, electricity has been a cornerstone of modern society. Today, most things in our cities and homes stop working without electricity. Throughout history, we have developed different ways of producing and storing electricity to meet our needs.

HOW IS ELECTRICITY PRODUCED?

Electricity is produced from various energy sources, which can be divided into renewable and non-renewable sources. The availability of *renewable energy sources* varies depending on the season and weather. Examples of renewable energy sources are hydropower, wind, solar and biomass. Biomass can consist of forest residues, vegetable oil or household waste (see chapters on energy from biomass and faeces, respectively). Non-renewable energy sources are formed slowly and consumed faster than they are formed. A special group of non-renewable energy sources are fossil fuels, such as coal, oil and natural gas. When energy is extracted from these, greenhouse gases are produced, such as carbon dioxide, which causes global warming. Another non-renewable energy source is uranium, which is used as a fuel in nuclear power plants (see chapter on nuclear energy). In transforming the energy system to create a sustainable society, the goal is to stop producing electricity from fossil-free fuels. The EU's new classification (2022) of energy types that are part of the transition to a sustainable society therefore includes both electricity produced from renewable energy sources and nuclear power. Natural gas is also included as a bridge to allow time for renewable energy solutions to be developed, for example in Germany.

Electricity production is also usually divided into *planable* and *non-planable*, based on how predictable the amount of electricity produced is. Electricity from renewable energy sources such as



▲ *Figure 3:* Direct voltage/direct current and alternating voltage/alternating current.

solar and wind, which can vary greatly in the short term, is usually called non-planable, while, for example, nuclear power is a planable source with a consistent and predictable production of electricity.

Electricity can therefore be produced from various energy sources. Once the electricity is produced, it is the same, regardless of how it has been produced – so it is impossible to distinguish electricity from different energy sources. This can be compared to a bathtub that is filled from several different taps. It is impossible to distinguish which tap the electricity/water came from once it is in the tub. It is therefore impossible to use electricity just from one particular tap (e.g. the fossil-free one) if the tub is still being filled with electricity from taps containing fossil fuels. It is also impossible to use more than the amount in the tub – or the system risks collapsing (read more in the chapter on electric power systems).

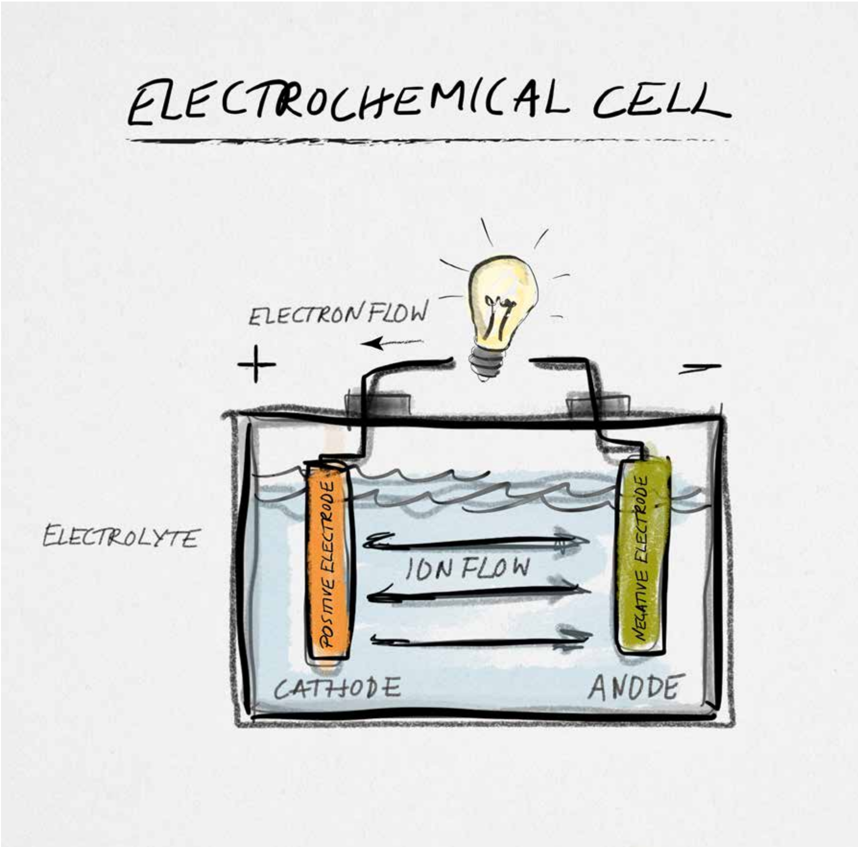
WHAT IS THE DIFFERENCE BETWEEN ELECTRICITY AND ELECTRICAL ENERGY AND WHAT IS THE ORDER OF MAGNITUDE?

Electricity involves a flow of electrons, and is present at the same time as it is produced. The capacity of a plant that produces electricity is usually measured in *installed power*, and is measured in the unit Watts [W]. This indicates how much electricity the plant can produce at a given time. For a wind turbine, the installed power can, for example, be around 3MW (1 megawatts = 1 million watts) compared to a nuclear power reactor of 1,000 MW. Nowadays, there are large offshore wind turbines under development that produce up to 15–20 MW and small nuclear power reactors that produce less than 300 MW.

When we talk about electrical energy, we mean the amount of electricity that is produced or used during a certain period of time. For example, the annual production of electrical energy from a wind turbine can amount to 6,000 MWh, where h stands for hours – i.e. 6,000 megawatts-hours. For comparison, annual electricity consumption in Sweden stands at approximately 140 TWh (1 terawatt-hour = 1 million MWh).

HOW CAN WE STORE ELECTRICITY?

One challenge with electricity is that it is consumed at the same time as it is produced. Therefore, you need different storage technologies. Traditionally, hydropower from dams or pumped storage power plants has been used to produce electricity (where the water's position and kinetic energy is converted into electricity). In a dam, water is stored so that the falling height and flow of water can be used to produce electricity. In a pumped storage power plant, water can be pumped up and then released when electricity is needed (the same principle can be used in disused mines; water is pumped up and produces electricity when it is dropped down the shaft).



▲ *Figure 4:* Electric current from chemical reactions.

Another technology is storing energy as high-pressure air. Excess electricity is then used to drive a motor that pumps air into a tank or cave. The stored air can then be mixed with natural gas and used to produce electricity.

Today, various types of batteries are the dominant technology for energy storage. A battery consists of one or more cells of stored energy that can be converted into electricity to power components that are connected to the battery. A common technology in batteries is based on chemical processes (see Figure 4 and Fact box on page 31). In recent years, batteries have had a major impact on the transport sector, where they are increasingly replacing fossil fuels. Lithium-ion batteries are the dominant technology used in electric vehicles (see chapter on materials for the electrification of society). Although the price of batteries has dropped significantly, it is still an expensive technology to use for large-scale energy storage and has not yet had a major impact.

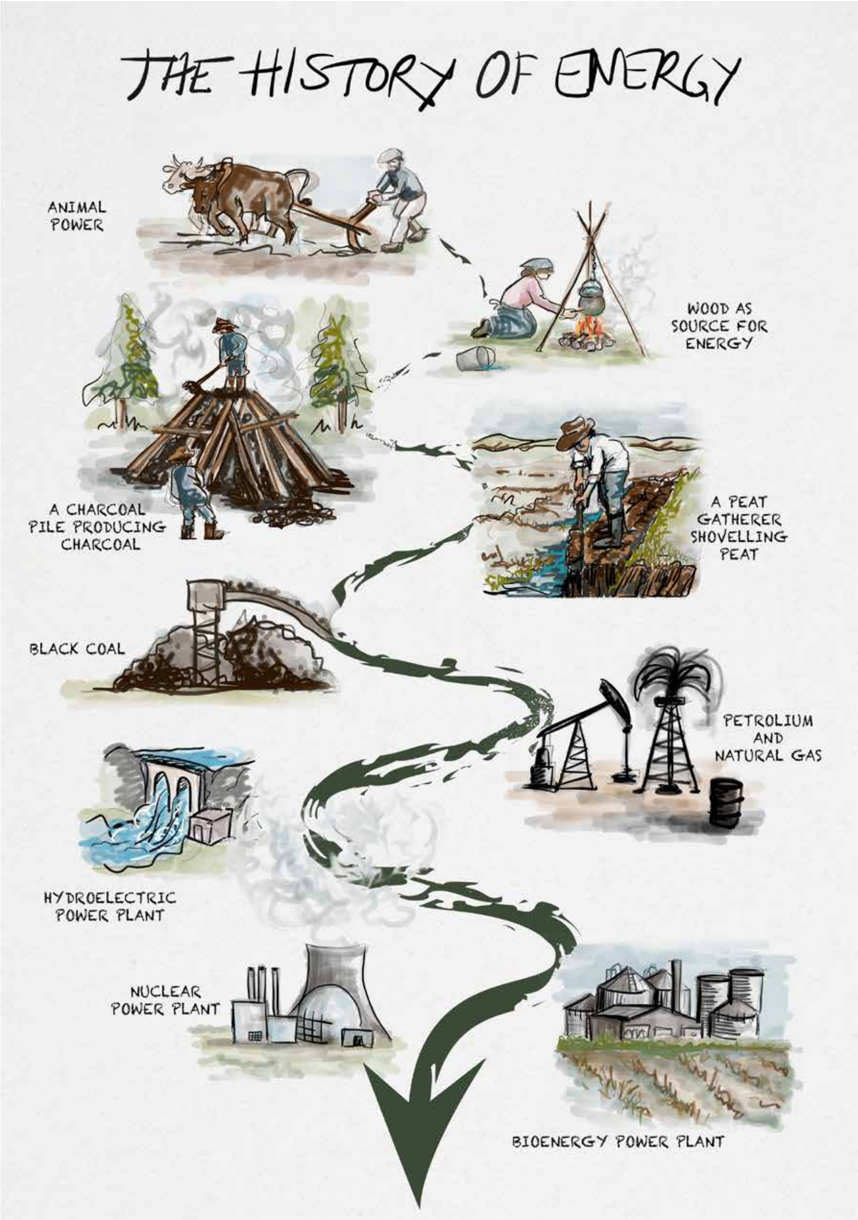
Fuel cells are another type of energy storage. They are supplied with a fuel in the form of a liquid or gas, after which a chemical reaction takes place and electricity is discharged. One technology that is currently being explored for fuel cells is hydrogen (see chapter on hydrogen). Hydrogen, for example, could be produced using electricity from wind power and then stored. When required, the stored gas could then be used as fuel in fuel cells to produce electricity. Combining these technologies would provide an opportunity to avoid "wasting" electricity that could not otherwise be used. It would also lead to wind power being used in a *planned* way, which is otherwise a weakness compared with, for example, hydropower or nuclear power.

We may also want to store electricity to have access to back-up energy when the normal electricity supply is interrupted. In certain places, such as hospitals, a power cut would otherwise have severe consequences. Traditionally, diesel generators have been used to supply back-up power. If batteries and fuel cells could be used instead as back-up power, this would be an important step in the transition to a fossil-free society.

BATTERIES BASED ON CHEMICAL PROCESSES

In this type of battery, chemical energy is converted into electricity. The current-generating part of the battery consists of three parts – anode (minus pole), cathode (plus pole) and electrolyte (a solution that can conduct electricity) – which together are called a cell. Today, the anode is often made of lithium, while the cathode is usually a metal oxide (a combination of metal and oxygen), e.g. manganese or lead. The electrolyte must be good at conducting ions but poor at conducting electrons and can, for example, consist of dilute sulfuric acid. It can also take the form of a gel or polymer (a plastic material) in liquid or solid form. When the battery is connected to the device it is to operate, e.g. a mobile phone, the metal in the anode begins to emit electrons. As the electrons cannot take a shortcut via the electrolyte to the cathode, a current of electrons moves from the anode, through the appliance, to the cathode. Inside the cell, ions are simultaneously transported between the positive and negative electrodes via the electrolyte. In rechargeable batteries, the electrons can be made to flow in the other direction, by connecting an external voltage source (a battery charger).

When designing batteries, you want them to be as light as possible, but have a high voltage and capacity (how much current the battery can emit over time). The constraints are determined by costs, the simplicity of manufacture, stability in the chemical process, and whether the materials can be recycled. The latter criterion is becoming increasingly important to meet the goal of a circular economy where materials are recycled instead of consumed.


THE HISTORY OF ENERGY
ANIMAL POWER
WOOD AS SOURCE FOR ENERGY
A CHARCOAL PILE PRODUCING CHARCOAL
A PEAT GATHERER SHOVELLING PEAT
BLACK COAL
PETROLIUM AND NATURAL GAS
HYDROELECTRIC POWER PLANT
NUCLEAR POWER PLANT
BIOENERGY POWER PLANT

ENERGY IN A HISTORICAL PERSPECTIVE

Per Högselius

Humans have always used energy in various forms. From a historical perspective, our global energy use has increased – and periodically decreased – over time. A number of energy transitions have happened, as new energy sources have been introduced, and older, traditional fuels have been partly phased out. There have been very large variations between different regions and countries, and even today we live in different 'energy worlds'. In Sweden, we just need to press a switch to get access to the energy we need, whereas a large part of the global population, particularly women, in many poor countries spend several hours a day collecting fuel to be able to cook for the family. Yet, we are all interconnected in a multifaceted global system where we are all dependent on each other.

Today, in the 2020s, the world's energy supply is dominated by fossil fuels. Coal, oil and natural gas account for around 83 percent of the world's energy. The average person consumes around one tonne of coal, four barrels of oil and 500 cubic meters of natural gas per year. The rest of our energy comes from nuclear power as well as renewable energy sources such as biofuels, hydropower, wind power and solar energy.

At the dawn of humanity, it looked very different. Our earliest ancestors relied entirely on renewable energy sources to produce light, power and heat. The power supply came from our own muscles. Whatever needed to be lifted, moved, built, was done by hand. Eventually we learned to tame wild animals and use their muscle strength too. Horses, donkeys, llamas and camels came to play an important role in transportation. Oxen were one of the most important sources of power in agricultural development. We produced light and heat by burning wood, vegetable oils, animal droppings and other organic materials.

In pre-industrial Europe, the 'energy mix' was dominated entirely by wood. Wood was used everywhere in society. Homes had wood fires to heat cold rooms, heat water and cook. Huge amounts were consumed by the large 'fire industries' such as bakeries, breweries, laundries, glassworks and salt works. During the Middle Ages, but especially from the 16th century onwards, the iron industry also grew rapidly. This fire industry was distinguished not only by the fact that it consumed far more energy than any other type of activity, but also by the fact that the smelting furnaces were fired using charcoal instead of wood. Charcoal is a refined form of wood fuel that was traditionally produced by burning wood in a low oxygen environment. Through this conversion (dry distillation), contaminants such as sulphur were removed, which could otherwise impair the quality of the iron.

The wood was usually sourced from nearby forests. The charcoal piles were also erected there. In the forests Europeans were forced early on to think in a 'sustainable' way. It was important not to cut down too much forest when trying to meet society's needs for wood and charcoal; consumption was adapted to how quickly the forest would grow back. In other words, there was a clear limit to how much energy use could increase without the pre-industrial energy system collapsing.

During the 18th century, energy needs grew rapidly. It was a result of economic growth, increased long-distance trade, a rapidly expanding iron industry and rapid population growth. Many countries were worried about the future of the forests. High energy prices made it attractive for many forest owners to cut down more forest than was actually sustainable. Denmark and England were among the countries that saw a large part of their forests disappear during this time. At the same time, urban populations complained about sharply rising fuel prices. Fuel issues were high on the agenda, including during the French Revolution of 1789, with its radical demands for political change. The current 'petrol protests' and demonstrations against high electricity prices echo these historical events.

But high wood prices also stimulated ingenuity. Ingenious wood-saving innovations were created, such as the tiled stove. At the same time, interest grew in alternative types of energy. Peat has long been an important source of energy in countries such as the Netherlands and Ireland and also in large parts of Eastern Europe. In China, hard coal had started to be used on a large scale as early as the 11th century, and in England, large quantities of coal had been burned since the 16th century. From a health perspective, coal burning was already perceived at the time as deeply problematic. London gained an early reputation as the city in Europe with by far the worst air. There was also a religiously rooted reluctance to dig up black coal from underground. But as energy needs increased and wood prices soared, it became tempting to exploit the 'subterranean forests', as the coal beds were often called. During the 19th century, a growing number of people undertook the radical move from wood to coal, both in the fire industries and in many households.

This transition happened at varying speeds in different parts of Europe. Sweden, with its abundant forests, was one of the countries that, for the longest time, stuck to a wood and charcoal-based energy system. Admittedly, hard coal was used early on in Sweden for the production of town gas (for lighting) and also for rail and steamboat transport from the 1850s. In the cities, you could also hear the noise of steam engines. But in homes, people continued to burn wood, and the growing Swedish iron industry continued to rely on forests and charcoal to smelt and reduce iron ore. At the beginning of the 20th century, a clear majority of all Swedish blast furnaces were still fired by charcoal. Only during the interwar period did coal become the dominant energy source in Sweden. In addition to the iron industry switching from charcoal to coke (dry distilled coal), households were also increasingly burning coal and coke. At the same time, municipalities and industrial companies were building coal-fired power plants to meet society's electricity demands.

Coal soon faced competition from oil. The term 'oil' has historically referred to various types of vegetable and animal oils, such as olive oil and whale oil. This changed during the decades around 1900, when petroleum – 'rock oil' – began to be extracted in large quantities. Over time, this fossil fuel competed with the older, renewable oils. Petroleum was initially used mainly for lighting purposes, and by far the most important refined oil product was therefore kerosene. At the beginning of the 20th century, rock oil also began to be used for transport, both on land and at sea. The discovery of new oil deposits and a sharp increase in extraction went effectively hand in hand with new inventions such as the internal combustion engine. Petrol and diesel then took over the role of kerosene as the most important refined oil products. The motorisation that followed had an enormous impact on society. In Sweden, the breakthrough took place in the decades after the Second World War.

For a long time, there was a large global surplus of oil. Prices were driven down and oil became so cheap that it also began to be used for heating. Fuel oil was a much cleaner fuel than coal, and when the oil became cheaper, many people switched from burning coal to burning oil. An even cleaner fuel was natural gas, which was often extracted together with oil. Combustion of natural gas gave rise to almost no pollutants at all (except carbon dioxide). Natural gas therefore became extremely popular and remains so today. The transition from coal and oil to natural gas has in many big cities contributed to eliminating problems with smog.

An important difference between the previous energy systems, where wood and charcoal took centre stage, and the fossil energy systems, is that not all countries have had access to coal, oil and gas within their own borders. Over the years, the vast majority of countries in the world have become heavily dependent on imported fossil energy. This trend has intensified over time as more and more countries use up the last of their domestic resources. In Europe, for example, the Netherlands has long been a major player in the natural gas field and one of the world's largest gas exporters. But in the 2000s, the country's domestic resources became largely depleted and the Dutch have instead become major importers of this coveted fuel.

Sweden is one of the countries that has been, and still is, completely dependent on imports of fossil fuels. Without these imports, we would not be able to drive our petrol and diesel cars, heavy goods traffic would come to a halt, we would not be able to fly, we would not have a steel or cement industry, and the Swedish armed forces would be completely paralysed. Our dependence on imported oil is particularly high – in 2019, 325,000 (imported) barrels of oil were consumed in Sweden every day, corresponding to around one barrel (159 litres) per person per month.

Sweden's dependence on imports gave rise to some concern as early as the turn of the twentieth century (1900). At that time, Swedish coal imports were starting to be unreliable. This was partly due to ongoing strikes in the British coal mining regions, from which Sweden got most of its coal at the time. Sweden's dependence on foreign countries then reached its peak during the two World Wars. Imports were restricted and a 'reverse' energy transition took place. Among other things, during the Second World War, Swedish road vehicles were equipped with gasifiers (gas generators), which used wood as a raw material. Wood also made a comeback in other areas. Pressure on the country's forests increased again, in a way reminiscent of the tense situation of the 18th century.

After the Second World War, Sweden reverted to, and further scaled up, its imports of fossil fuels. The world's energy consumption was now increasing faster than ever. In energy history research, the post-war period is therefore often called 'the great acceleration'.

But oil imports became unreliable again during the 1956 Suez Crisis, the 1967 Six Days War in the Middle East and particularly in connection with the dramatic price increases and oil embargoes that led to the 1973 and 1979 oil crises. From then on, the main future challenge was how to use energy in a more efficient way, and there was consensus on the need to phase out fossil fuels in the long term. It was hoped they could be replaced with more environmentally friendly and geopolitically more reliable, preferably domestic, energy sources.

The 20th century was also characterised by the rapid electrification of society. Initially, electricity was something of a luxury product and an odd, exotic element in the Swedish energy system. But over time, electricity came to be considered almost a human right and its uses expanded. Like oil, electricity was initially used for lighting. During the first decades of the 20th century, it then began to be used for cooking and as a source of power. During the latter part of the 20th century, electricity, like oil, was also used to heat houses and water. This development went hand in hand with huge investments in new electricity production, focused around hydropower and coal power plants. These two types of power plant worked together to ensure an abundant and reliable electricity supply.

Central to this was the construction of a system for distributing electricity across the country. A national interconnected electricity grid existed in Sweden from 1937. Thanks to this grid, industries in the Stockholm area and southern Sweden were able to benefit from power produced in power plants tens or even hundreds of miles away.

During most of the 20th century, Swedish electricity consumption grew exponentially, with consumption doubling approximately every twelve years. In other words, Vattenfall and the other players needed to double their power plants and the transmission capacity of the electricity grid within every twelve-year period. Therefore, they were constantly looking for new opportunities to increase production in the system. In the 1950s, nuclear power became interesting as a possible complement to existing hydropower and coal power plants. Some even believed that nuclear power, which was expected to be extremely cheap, could completely take over as the electricity supply of the future. An ambitious nuclear power programme was developed consisting of a plan for 24 large nuclear power reactors. But technical safety problems, increased complexity in the construction of nuclear power and increased investment costs combined with growing public opposition to nuclear power brought the nuclear visionaries back down to earth. Of the planned 24 power plants, twelve were eventually realised. In 1980, Sweden held a referendum on the future of nuclear power, and a parliamentary decision ruled that nuclear power would be phased out within a couple of decades. Five years later, when the last large reactors were connected to the grid, Sweden had, however, become one of the most nuclear-dependent countries in the world. Today, nuclear power remains a very important source of energy in our country, despite the fact that half of our reactors have been shut down.

Meanwhile, something of a revolution in the field of heating took place. Oil heating was gradually phased out and replaced to some extent by direct acting electricity, but mostly by electric heat pumps and biofuels. Bioenergy, together with waste incineration formed the basis of the district heating supply. In this way, Sweden managed to halve its oil consumption in just one decade.

Sweden's total energy consumption peaked in the early 1970s. Electricity consumption continued to rise for some time, but leveled off from about 1987 and has since then remained at a plateau. For a while, you almost had the impression that the energy system, and in particular the electricity system, was 'complete'. But in recent years, this picture has been thrown into disarray. Today, several scenarios point to a huge growing demand for electricity in the coming decades as a result of Swedish efforts to phase out all fossil fuels and replace a large part of them with electricity. There are many contradictory visions of our energy in the future, and we can expect many conflicts and fierce power struggles along the way. But one thing is certain: Sweden's energy history is entering a new, exciting chapter.

A SUSTAINABLE SOCIETY CANNOT AFFORD TO WASTE ENERGY

Christophe Duwig

The previous chapter took us back in time to show the positive impact of cheap energy on our living standards. Today, we usually do not think about it – we just plug in our appliances and electricity is always there, ready and waiting. This experience of abundant, maybe even unlimited, energy, may lead us to believe that energy waste is not such a big issue. It's cheap – we can afford it. When mapping our use of energy on a global scale, researchers have estimated that about 70 percent of the used energy is not providing any service. This unused energy usually ends up as heat – often called waste heat – that is released into the atmosphere.

This invisible, enormous energy waste is happening constantly, all around us. Walk past a diesel/biofuel bus on a cold day and feel the heat discharge from the cooling systems of the engine. Put your hand on your charging, warm smartphone. Or make yourself a cup of tea: A recent study in the UK showed that people, on average, boil about twice as much water as they use for making the tea. The remaining hot water in the kettle is left to cool – not providing any service. This waste heat alone corresponds to about 0.9 percent of the entire UK electricity production in a year, enough to power about 60,000 households.

The invisibility of waste heat is a challenge when we want to do something about it. For identifying thermal leaks in buildings, professionals have long used infrared (IR) cameras. These make it easy to spot heat escaping through the facade, or via badly insulated

▲ *Figure 1:* Boiling too much water to make tea results in a huge waste of energy. In the UK, this waste heat would be enough to power around 60,000 households.

windows. Nowadays, such cameras are available to rent for anyone who wants to see for themselves when, where and how heat is lost, to improve the energy efficiency of their homes.

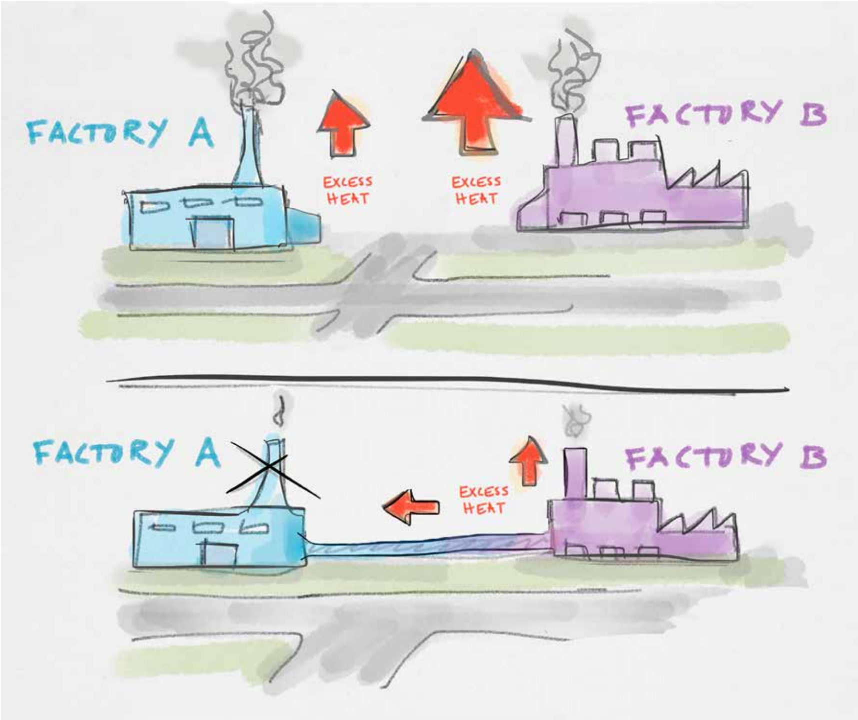
Another challenge is that heat is not coming from a single large source, but rather a large range of small sources. It is present in everything that we do: industry, transport, buildings, business, internet servers, and so on. To address this one big problem, we need to come up with a myriad of small solutions. Sometimes the solutions are about preventing the heat from escaping (e.g. by insulating houses), at other times they may be aimed at preventing the waste of heat from occurring in the first place (e.g. energy-efficient lightbulbs). Currently, much research is focusing on how heat can be harvested, or recycled, and put to use. Despite its name, waste heat is, after all, perfectly usable and valuable energy. Perhaps a better name would be lost heat.

Engineers and scientists categorise lost heat according to temperature. Typically, more than 60 percent of this heat is at temperatures below 100 °C. Unfortunately, current technologies that harvest and use heat typically need temperatures above 300 °C in order to work. Lost heat at those higher temperatures is mostly related to the transport sector, such as the exhaust of combustion engines. For instance, the cabin of a non-electrical car is heated by the heat generated by the engine. At lower temperatures, technical solutions become less efficient, less economically attractive (at least as long as wasting energy is cheaper) and less researched.

As we replace our vehicles' fossil fuels with electricity, we also remove the hot exhaust. This significantly reduces the amount of lost heat at higher temperatures. However, heat will still be generated (and lost) at lower temperatures, through electricity generation, transport, and conversion (e.g. as heating of a battery while charging or at discharging during operation).

The industrial process of making steel with hydrogen is another illustrative example of how complex the question of lost heat is. This is an exciting technique with the potential to make steel production greenhouse gas emissions-free. But today, when producing the hydrogen by electrolysis (see chapter about hydrogen), about 40 percent of the electricity ends up as low temperature lost heat. Hopefully, research will be able to mitigate this issue, but it is a reminder that we need to choose our future technologies to be truly sustainable and not reproduce the errors of the past.

Harvesting rather than wasting heat can accelerate the transformation of our energy system. It is a timely challenge, but unfortunately it is not reflected in the political debate. As a researcher in the field, I would like to point out a couple of key points that



▲ *Figure 2:* It is more economical and results in less emissions if factories coordinate their heat production and consumption.

need to be on the political agenda if we are to create a sustainable energy system.

Firstly, we need to accelerate the pace of innovation and knowledge creation. This means that we must abandon traditional industrial development based upon trial-and-error. Instead, we should rapidly and simultaneously develop and test several different ideas. To accelerate early development loops beyond what is possible in the physical world, we can use the virtual world created by (super-) computers. The virtual world lets us explore and test our ideas, and select promising options for further investigation, much faster than what would ever be possible in the physical world. For instance, scientists and engineers are currently researching heat transfer in complex novel materials, examining smaller and smaller details to understand the finest mechanisms of the process. We can do that thanks to recent advances in supercomputing and predictive simulations – in the virtual world, the invisible heat fluxes become visible.

Secondly, and perhaps more importantly, we need to make the challenge itself visible and understandable for all. With more knowledge, we can make better demands of our representatives and decision makers, and be aware of what we ourselves can do in our everyday lives. The way forward will be a mix of technical solutions and us changing our behaviour, where our way of using – and valuing – energy will play a significant role. The challenge, as well as the solution, is global and needs to involve all actors. It is by being informed and critical citizens that we can push for new regulations and incentives to get industry and society in general to understand that wasting energy is not going to lead us where we want.

To finish this chapter, I would like to encourage all readers to explore where heat escapes and is lost in your own homes. This can be a first step towards changing how we value energy, and – in the long run – making our energy system sustainable. And maybe think about how much water you put in the kettle, next time you are making a cup of tea.

CHANGE OF HABITS FOR INDUSTRIES

In most of the World, different industries have developed at different times, often focusing on single sites and businesses. This development in *silos* has often not been questioned until recently. We can find quite a few examples like Factory A building its own furnace to produce steam, while Factory B, a few hundred meters down the road, has an excess of waste heat (see Figure 2). Since there has not been any incentive (except fuel/energy prices) for integrating their energy flows, A and B will both produce waste-heat instead of collaborating. Clearly a way forward would be to update performance indicators (measurements used by companies to evaluate how well they are performing their work) to include integration between nearby sites.

Motivating mankind to stop wasting energy – even though we can afford it – is an important societal challenge. Otherwise, today's wasting of cheap energy will cost us dearly in the future.

DID YOU KNOW THAT?

Power is measured in the unit of Watt (after Scottish inventor James Watt, 1736–1819). To express energy consumption, we use kWh (kilowatt-hour), which is the amount of energy used by a certain device during an hour. As an example, 1 kWh is enough energy to lift a medium size electric car (1.800 kg) to the top of the turning torso tower in Malmö. In 2021, 1 kWh of electricity cost on average 1 SEK.

SHAPING ENERGY PROJECTS AND POLICIES WITH THE UN SUSTAINABLE DEVELOPMENT GOALS

Francesco Fuso Nerini

With only ten years remaining until 2030, progress towards the UN Sustainable Development Goals is slow, and in some cases, moving backwards. If we are to achieve any of the goals on a global scale, we will need a much more ambitious transformation. One of the barriers to achieving the goals is a lack of understanding about the connections between different aspects of sustainable development. To overcome this barrier, a new scientific field has been created to assess interlinkages among the SDGs and propose methods to achieve the goals holistically. Such assessments include, for instance, how one sector or topic (or a single SDG) affects the achievement of all SDGs, and how to devise strategies for avoiding trade-offs and capitalising on synergies.

Significant work has been put into assessing how the SDGs could be used for shaping energy projects and policies. The impacts of energy projects on the SDGs are multifaceted. For instance, renewable energy projects can affect the achievement of all SDGs – from energy, and mitigation of climate change (Goals 7 and 13, respectively) to poverty, and economic growth (Goals 1 and 8, respectively). Almost three billion people in the world are cooking with energy from gathered wood so modern energy for cooking has clear implications on gender equality (Goal 5) and health outcomes (Goal 3). More broadly, access to energy can affect all the SDGs, ranging from societal and human wellbeing to environment and natural resources.

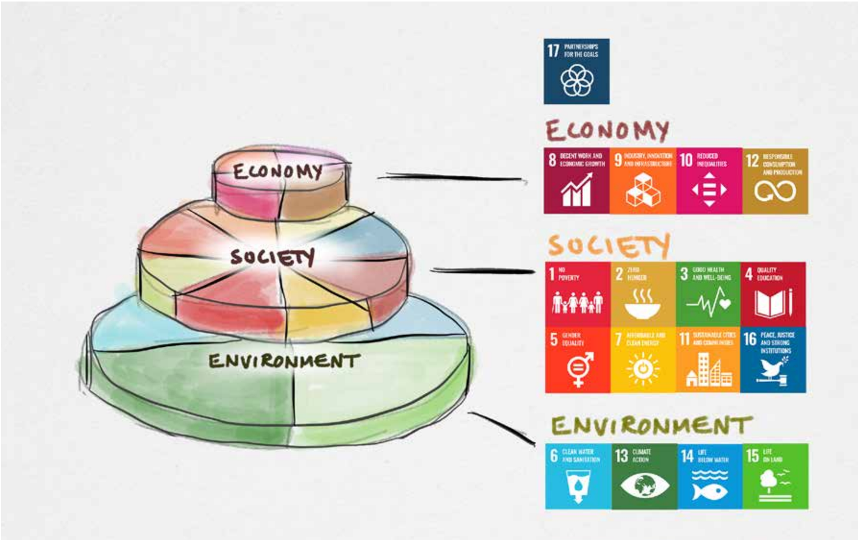


Figure 1: The UN Sustainable Development Goals. In the 1987 Brundtland Commission Report, sustainable development was defined as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs".

In all, there are seventeen Sustainable Development Goals, and each goal is broken down into several targets. For instance, one of the targets for Goal 7 – Affordable and Clean Energy – is to "increase substantially the share of renewable energy in the global energy mix" by 2030. Five years ago, in 2017, my colleagues and I made a first attempt to understand the global connections between energy and the SDGs. In our research, we assessed how each of the 169 targets in the 2030 Agenda was connected to energy systems, by answering two questions for each target: (A) Does the target call for action in relation to energy systems? and (B) Is there published scientific evidence of synergies or trade-offs between the target, and decisions about energy systems in pursuit of Goal 7 (Affordable and Clean Energy)?

Regarding the first question, we found that approximately two thirds (113/169) of all targets require actions on energy systems. Those actions are diverse and include efforts to address climate change, reduce deaths from pollution, and end certain human rights abuses. This result shows how substantial the changes in global energy systems need to be to achieve the SDGs. We also identified synergies or trade-offs between almost nine out of ten (143/169) targets, spanning all the SDGs. On the positive side, we found more than twice as many synergies than trade-offs between Goal 7 (Affordable and Clean Energy) and other targets. Nearly all trade-offs relate to the tension between the need for *rapid action* on key issues for human wellbeing (e.g., poverty eradication, access to clean water, food, and modern energy), and the *careful planning* needed to achieve efficient energy systems with a high integration of renewable energy.

Several researchers, including from my team, have recently attempted to use this knowledge on global SDG interlinkages for directing energy policies and projects. One example is the Sustainable Development Goals Impact Assessment Framework for Energy Projects (SDGs-IAE), which makes it possible to assess SDG target synergies and trade-offs in advance for a given energy project. The researchers tested the framework in two diverse case studies – the Grand Ethiopian Renaissance Dam (GERD) on the Blue Nile River in Ethiopia, and the Hinkley Point C Nuclear Power Station (HPC) in Somerset, England. The researchers then expanded the framework to also include actions that stakeholders can take to maximise project synergies with the SDGs while minimising trade-offs.

When analysing the GERD project using their framework, the researchers found 77 possible synergies and 43 trade-offs, shown in Figure 1. Most synergies are related to the expansion of electricity access for both urban and rural populations in Ethiopia and the surrounding region. This should boost progress toward many targets, including poverty, hunger, education, and equality.

▲ *Figure 2:* Results of application of the SDGs-IAE Framework to the GERD project. For each SDG, the targets are represented on the right. Synergies are coloured green, while trade-offs are in red. For targets coloured in white the researchers could not find published evidence of synergies or trade-offs, which does not necessarily mean an absence of impact in real life.

Hydropower is also a renewable, carbon-neutral form of energy, which enables many synergies, such as those related to minimising deaths related to air pollution, reduction of waste generation and integration of climate change measures into national planning. Together, these synergies demonstrate the many potential positive social and economic impacts of GERD in Ethiopia.

Important trade-offs with the GERD project arise mainly from conflicts related to the transboundary Blue Nile River and the unpredictable effect that the project will have on water availability in downstream countries. Other factors to consider include social conflicts related to the local communities' lack of influence in the decision-making process and their displacement. Displacement and resettlement of communities is considered one of the most pressing social justice problems associated with large hydropower projects. With regards to the SDGs, it brings trade-offs with targets on preservation of cultural heritage, and safe and responsible migration, among others. Ecosystem disruption is also a notable impact. All these trade-offs are serious concerns about the project's overall sustainability and should be further analysed and addressed to avoid further conflict and damage as the GERD construction and reservoir filling continue.

This application of the framework to the Grand Ethiopian Renaissance Dam in Ethiopia is an example of how the SDGs can be used to guide energy-related decisions.

Outside of academia, several national and international organisations are starting to use the SDGs to support decision-making processes. One example is the United Nations Office for Project Services (UNOPS), which has published an online tool to help assess the sustainability of infrastructure projects.

In sum, recent research shows how the SDGs can be used for analysing energy-related choices. Considering the abundance of interactions between energy and the SDGs, it is crucial to develop tools that can help people access knowledge of how specific energy projects may affect the local and global achievement of the SDGs. Improved knowledge and communication of the impacts of energy projects and policies will not only promote desirable outcomes but could strengthen democratic practice as well. When citizens have more knowledge about the synergies and trade-offs of the choices they make, it will be easier – and more motivating – to make a change.

OIL (AND GAS) ADDICTION

Christophe Duwig

From a historical perspective, we can see how technological development in society leads to new lifestyles and increasing demands for energy. To meet these demands, we need primary energy sources. Primary energy sources can be used to produce energy, and include fossil fuels, nuclear power, and renewable energy sources such as wind and solar power. Among the primary energy sources, oil and gas are particularly important. In 2019, 84 percent of the primary energy used in the world originated from fossil fuels, with oil and gas being a large fraction. Also in the European Union, these two sources make up two-thirds of the primary energy used, albeit with a slight decrease since 2008. And oil products are not only used directly as fuel – indirect usages such as for making plastics and paint also contribute to its importance. One interesting experiment is to simply look around you and spot human-made items not derived from oil (i.e. oil was not used to make this object). This means excluding all the plastics, paints, metals.

Why metals, you may wonder? Well, since oil is the primary energy source for mining and transportation today, no oil would mean no metals. The European Union, and Sweden in particular, are dependent on the import of a large range of metals and goods which, in turn, are dependent on oil. Often, this close connection only becomes visible to us when increased oil prices lead to increases in price for a wide range of other products – from manufactured goods to food.

Given the dominant role of oil in our society, we could look at it in terms of an addiction. An addiction is difficult to quit, although (almost) all of us want it to end. Giving up the addiction requires hard work and sustained efforts over a long period of time. During the Covid-19 pandemic, the European Union designed an unprecedentedly large support package with an ambition to maintain the economy, avoid job losses and power a shift toward renewable energy. Yet a sizable fraction of this package and subsequent investments was found to support fossil fuels. This may sound strange, but how could it have been any different? Supporting the economy without supporting some fossil fuels would simply not be possible in today's world.

In 2020, about 0.5 trillion Euro (equivalent to the gross domestic product (GDP) of Sweden) was paid to directly subsidise fossil fuels around the world. These subsidies are used to artificially lower the price for consumers or buyers. Naturally, it extends our addiction and delays the shift toward fossil free energy, indirectly supporting the waste of (cheap) energy. A recent example is when the oil and gas prices increased because of the war in Ukraine. Many European governments (including Sweden) acted by limiting the price increase for consumers, hence increasing the oil subsidies. While this response contradicts general policies and commitment to fulfill the Paris agreement, it highlights our addiction to cheap oil.

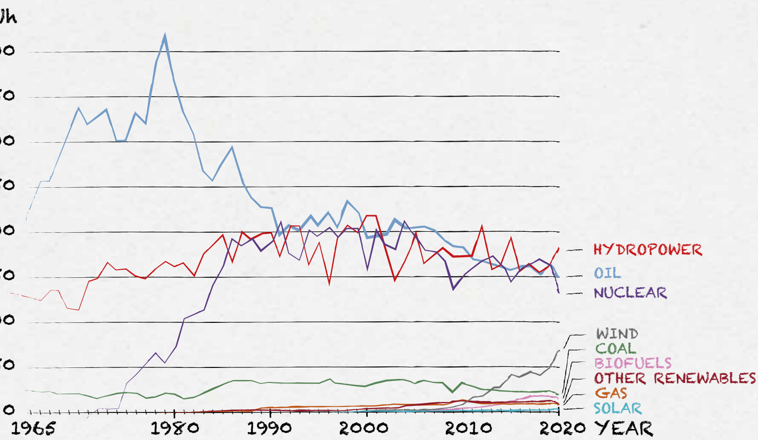
The World Energy Council has introduced three indicators to follow the energy situation in the world. Together the indicators make a "trilemma" – a dilemma but with three options, where it is easy to fulfill one but not all three at the same time. The first indicator in this trilemma is *energy security* – that energy is available continuously and dependably. Typically, European, and other rich countries score very high on this indicator. The second indicator is the *environmental sustainability* of the energy. Here, countries with large hydropower, wind or nuclear power facilities score high, which includes Sweden, Switzerland, France, among others. The third indicator is *energy equity* – measuring the affordability of energy for people. The top scoring countries for this indicator provide massive subsidies, making energy (often oil) almost free to use, and include, for example, Qatar and Kuwait.

As an example of this trilemma, let us now assume that in the aftermath of the Ukrainian war, countries decide to heavily tax oil usage (negative subsidies). This will be of immediate benefit to the climate and the environment, but also lead to increased energy prices and hence a deterioration of the energy equity. Other effects might include shortages of metals and food. Prices of renewable energy equipment will also increase accordingly. Many people will not be able to cope with these effects and will fall into poverty. Overall, the effects will hamper (and probably stop) the transition to clean energy. This example reveals the complexity of our energy system and how significant changes need careful planning with a clear long-term strategy. Otherwise, they may end up counter-productive to their initial aims.

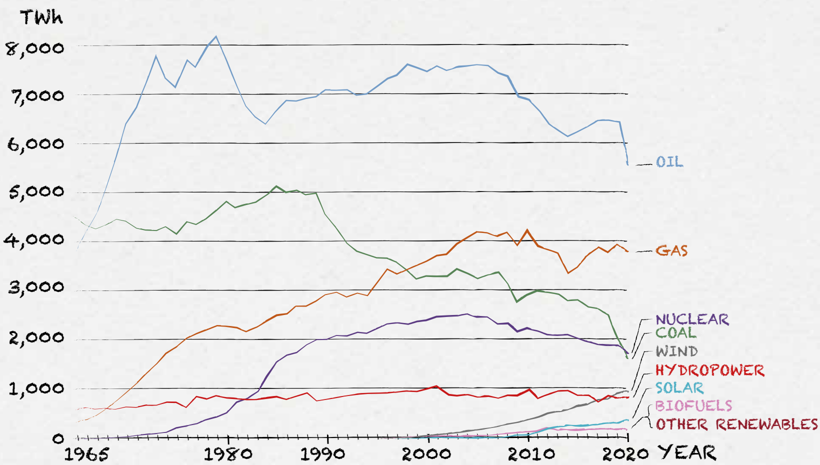
Despite seeming always available to us close to our homes, oil and gas are also limited in terms of availability and reserves. Oil is available and cheap simply because there is oil available to power the transportation of oil … until there is no more oil. The concept of "Peak Oil" was introduced in the 1970s and refers to a point in time where the world has reached its maximum capacity for oil production. Over the years, different projections have been made as to when this might occur. Making such predictions is particularly complex, since so many factors are interconnected, such as existing (known) oil reserves and their size, location and ease of access, geopolitics, decreasing demand, available technologies, competing technologies, investments (it might take up to a decade to open a new field or renovate outdated installations), and many others. Consequently, estimates of the Peak Oil day have varied a lot. Today, there seems to be an agreement to date a peak supply around 2010 for conventional oil, and sometime between 2020–2030 for all other kinds of oil. After these dates, the extraction of oil will decrease.

Traditionally, Peak Oil was understood to include both Peak Demand and Peak Supply. Peak Demand means that customers will

PRIMARY ENERGY CONSUMPTION BY SOURCE, SWEDEN



PRIMARY ENERGY CONSUMPTION BY SOURCE, EUROPEAN UNION



not be able to buy more oil, either because they cannot afford it or because they make alternative choices. The subsidies mentioned earlier help to keep the demand relatively high, while improving the energy equity.

Peak Supply relates to the limits of oil reserves and capacities of extraction. New oil reserves that have been discovered have not been big enough to cover annual production needs. Extraction requires investments and these have been historically low as well. Altogether, it suggests a decrease of production in the coming decade.

One recent scientific study pointed to an additional factor that has so far been overlooked – the decreasing energy-return-on-investment for oil liquids. In other words, the necessary energy costs for extracting energy from oil are dramatically increasing. Another word for it could be "oil cannibalism". Today, the energy cost is 15.5 percent, which means that if we extract 1 kWh worth of oil, we use 0.155 kWh to power the process, leaving 0.845 kWh for trading. This is considerably more expensive than in the 1950s and it keeps increasing. The reason is that the easily harvested oil fields are being emptied, making it necessary to extract oil from more energy-expensive fields. According to a projection made in the study, the energy cannibalism would reach 50 percent by 2050. This will negatively impact all three indicators in the trilemma: The *energy security*, since oil will not be always available; the *environmental sustainability* of energy, since oil production will result in increased emissions if carbon is not captured; and the *energy equity*, since inequalities will rise. Also, the policy tools used at present for softening the impact of oil prices on our society will be inefficient

◀ *Figure 1:* In 2019, the primary energy supply distribution for the world was: Nuclear 4.3%, Renewable 11.4% (biofuels excluded), Fossil fuels 83.3%. For Europe, it was nuclear 9.9%, renewable (biofuels excluded) 16.5% and fossil fuels 73.6%. Source: Our World in Data based on BP Statistical Review of World Energy.

since they focus on the demand while the cannibalism issue affects the *supply flow*.

Paradoxically, our present quest for renewable energies is highly dependent on oil to extract raw materials, transform them and produce equipment. Hence, Peak Oil is likely to be a "Peak All" and this timing needs to be understood and accounted for in policies and zero-carbon strategies. Today, our society depends on oil to work and to become truly sustainable. The coming decade will be about solving the climate challenge *and* ending our addiction to oil. To avoid being trapped by these conflicting goals, we need to debate priorities *and* plan a suitable timing for all our actions.

Looking back to the 1980s, Sweden managed to cut its use of oil by half in one single decade. Determined to decrease oil imports after the 1973 oil crisis, the government decided on a long-term plan leading to the construction of nuclear power plants, electrified heating of buildings, and using biomass and waste for district heating. The effects started to show about five years later and resulted in a spectacular decrease in the use of fossil fuels. But the transition to zero carbon is far from complete. In the European Union, on average, oil consumption is still at similar levels to the late 1970s while gas consumption has steadily increased. To make the transformation possible, we must tackle our addiction to oil with both determination and knowledge.

BIOMASS – A VERSATILE NATURAL RESOURCE

Henrik Kusar

Biomass accounts for about ten percent of all energy used in the world and constitutes the largest share of renewable fuels (biofuels). This is especially true for cooking and heating in many developing countries. Today, the use of biofuels for transport and electricity production is increasing in many countries as a way to reduce carbon dioxide emissions from fossil fuels.

But what is biomass? From a biological perspective, biomass is all forms of life that exist on earth. Biomass is trees, shrubs, grasses and all other kinds of plants, and all wildlife, including humans, bacteria and fungi. Biomass is also found in the oceans, such as algae, plankton, fish, whales, shellfish and all other organisms, but the absolute largest proportion is found on land. Although the oceans account for two-thirds of the Earth's surface, they contain only one percent of the total biomass.

However, not all organisms in nature can form biomass from scratch, it is mainly plants that can do this through photosynthesis. Thus plants form the basis for all other biomass on earth.

Plant photosynthesis is the key to new biomass being formed by water and carbon dioxide. This would otherwise require large amounts of energy, but in photosynthesis this energy is obtained for "free" from the sun's radiation. In photosynthesis, the plants use solar energy to form sugar and oxygen. The sugar, which consists of carbon and hydrogen molecules, can then be converted into all the large molecules that a plant needs.

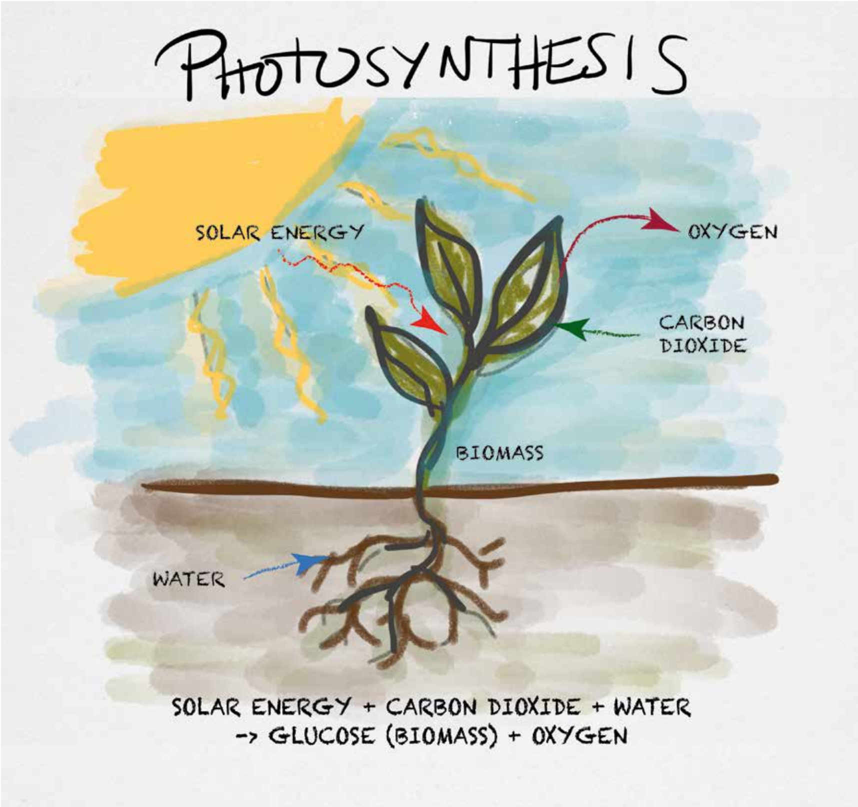
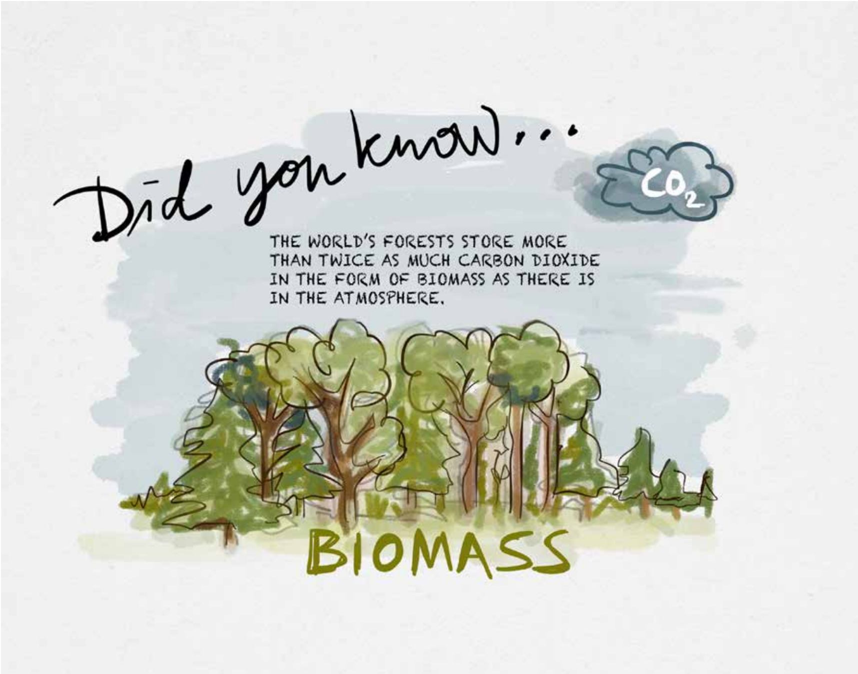


Figure 1: Plants form the basis of all other biomass on earth.

When we talk about biomass in relation to energy or other human uses, we mean that it both comes from living organisms and is *renewable*. Fossil fuels such as coal and oil also originate from biomass, but were formed millions of years ago and are therefore not considered renewable. Biomass is therefore a kind of stored solar energy and a renewable energy source that is part of nature's cycle. This means that the energy we extract from biomass does



not emit more carbon dioxide than the plants absorb during their lifetime.

On Earth, over 100 billion tonnes of new biomass are formed per year. That would be enough for more than 10 tonnes of biomass per person, which of course is impossible because we have to share it with animals and nature. A prerequisite for being able to form so much biomass every year is that the forests need to be left standing, otherwise the amount of biomass that can be formed decreases.

The largest amounts of biomass are found in the forest. Half of the world's forest area is found in the five largest countries: Russia and Canada have a lot of conifers, there is rainforest in Brazil, and in the USA and China you find more mixed deciduous forest. Forests are found in both warm and cold countries but grow much faster in warm countries, if it rains sufficiently. Of course, forests are not only important for forming new biomass. They are also crucial for biodiversity, provide us with oxygen and clean air, capture drinking water, and enable the abundance of ecosystems on which we depend.

Humans have always used biomass to produce both material and energy. Using biomass as a material is still very common – think of everything in our homes that is made of wood. Nowadays, however, plastics and composite materials have taken over; these are easier to shape, weigh less and can be given lots of special properties. Today, these plastics and composite materials are almost always made from fossil sources, but many of these materials could also be produced from biomass.

The most common use of biomass in the world is to extract energy. For example, we burn biomass to heat our houses and for cooking. Burning biomass in simple stoves has always been done, but today there are significantly more energy efficient and better ways to burn biomass without polluting the environment with a lot of dangerous smoke. Modern fireplaces and stoves remove virtually all dangerous emissions, except carbon dioxide. Unfortunately, there is not enough biomass to replace all fossil fuels used today. That is why we must use it wisely. In the EU and the rest of the world, there is a desire to globally increase the share of renewable energy. As mentioned already, the largest share of renewable energy already currently comes from biomass.

From a global perspective, valuable biomass is unfortunately wasted when it is burnt to produce heat, especially when this is done in large inefficient plants. If heat production is combined with the production of electricity (e.g. with fuel cells, gas or steam turbines) in thermal power plants, both heat and electricity can be generated in a sustainable way.

Producing biofuels from biomass has become increasingly popular in recent years. One of the advantages is that you can use the biomass in liquid form and thus directly replace petrol and

▲ *Figure 2:* Biomass can be used to produce new materials to replace plastics and composite materials from fossil sources. Today, researchers produce everything from electronic parts, solar cells, packaging and building materials from biomass.

diesel in most vehicles. In order to convert solid biomass, such as wood chips, to petrol or diesel, several changes need to be made to large industrial processes. For this conversion to have a positive impact on the climate, the processes need to provide more energy than they consume, and the biomass must also be produced in a sustainable way.

Nowadays, almost all bioethanol and biodiesel come from cultivated maize, wheat, soy and rapeseed. These food crops contain a lot of sugar and oils, and are therefore relatively easy to convert to bioethanol and biodiesel. But this presents a different challenge than the climate – the so-called *food versus fuel problem*. Unfortunately, there is a risk that arable land will be overused to produce large amounts of biofuels. This would mean less food being grown to feed the world's population, which in turn would make food more expensive and hit the poorest in the world the hardest.

Therefore, for energy purposes it is better to use biomass from agricultural and forestry waste, household waste and special energy crops. Energy crops can be grown on unused arable land and land that is not suitable for agriculture. In Sweden alone, it is estimated that close to half a million hectares could be used for the production of, for example, salix, reed canary grass and other fast-growing energy crops that thrive in our colder climate. In warmer countries, it is possible to grow fast-growing species such as eucalyptus, elephant grass and jatropha, depending on the climate and water supply.

Utilising agricultural and forestry waste to make biofuels also has enormous potential that is currently under utilised. There are many new technologies for converting this heavier waste from both forestry and agriculture to produce everything from aviation fuel, diesel and petrol to hydrogen, but to date these processes are not profitable. In order for them to become profitable, it is above all necessary to streamline the waste collection process. These biofuels are often called second or third generation biofuels, as they are more sustainable and do not compete with food production. One such example is biogas made from food waste and digestate from sewage sludge. This production process is relatively simple and, in fact, often commercially profitable (see chapter on energy from faeces).

In photosynthesis, plants absorb carbon dioxide from the air to form biomass. When we make things from biomass, for example, houses and furniture from wood, it means storing carbon. If the carbon can be stored for over a hundred years, it is called *negative emissions*. The product *biochar* from biomass has in recent years received a lot of attention because it has the potential to contribute to negative CO_2 emissions. Biochar can be used as a material in many different applications but is mainly seen as a great soil improver that can hold both important nutrients and large amounts of moisture in the fields. If we used biochar in agriculture, we would not only be able to store the carbon for thousands of years but also need to use less fertilizer in the fields, have fewer problems with eutrophication in lakes *and* at the same time get better harvests.

But the key question remains: How can we get enough biomass to produce all the food, all animal feed and all the bioenergy needed to support the future population? As previously mentioned, there are many areas of use for biomass, where different types of biomass are suitable for different products. In the future, one possibility would therefore be to build biorefineries where you could produce many different products from the biomass and utilise its full potential for high-quality products, including materials, electricity and biofuels, as well as utilise all the excess heat in the processes. For this to become a reality, however, large investments are needed.

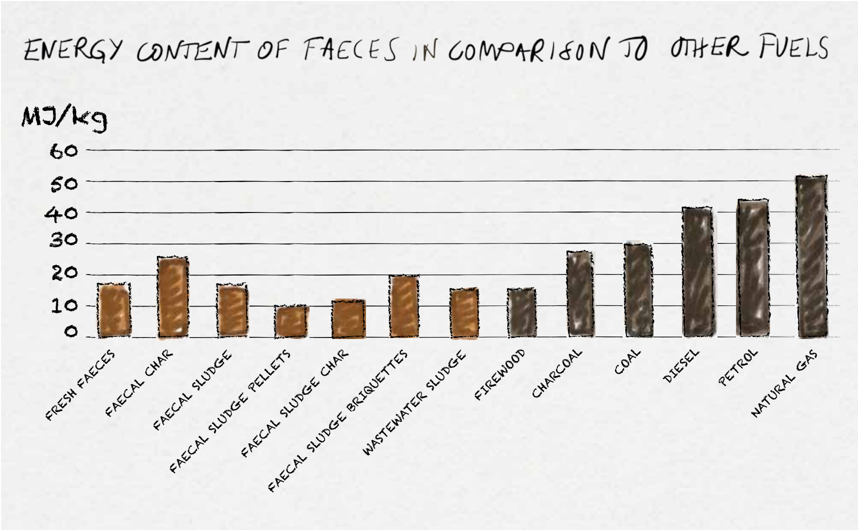
If we use biomass in a sustainable way, it will go a long way – both for humans and for all other life forms on our planet.

ENERGY FROM FAECES: HARNESSING ENERGY FROM ONE OF THE MOST ABUNDANT MATERIALS ON THE PLANET

Daniel Ddiba

As of 2022, there are 7.9 billion people on the planet. On average, each person generates about 1.5 litres of faeces per day, implying that the human generation of excreta would fill at least 4,700 Olympic-size swimming pools – per day! On one hand, faeces can be viewed as a public health hazard that should be hauled as far away as possible from where we live. But on the other hand, it can be seen as a valuable resource to be harvested and used in society. Apart from precious metals such as gold and silver, faeces contains nutrients and significant quantities of energy. The energy content is not as high as in some fossil fuels but compares well with solid fuels like charcoal and firewood (see Figure 1).

Humans have long known about the vast amounts of energy in faeces. This knowledge developed in parallel with our understanding of the energy content in other forms of biomass such as animal manure, food waste and other types of organic waste. The Belgian scientist Jan Baptista Van Helmont observed in the 17th century that flammable gases are emitted from decaying matter. This discovery was a precursor to later work by Humphrey Davy, Arthur Buswell and other scientists in understanding how the anaerobic (oxygen-free) digestion process happens. But long before that, biogas was used to heat Assyrian bath houses in the 10th



▲ *Figure 1:* The energy content in various forms of faeces in comparison with some common solid and fluid fuels. One MJ (megajoule) equals 0.278 kWh (kilowatt-hours).

century BC, and both archaeological and biblical records indicate that dried animal and human faeces were used as fuel in ancient Persia, Egypt, and Babylon.

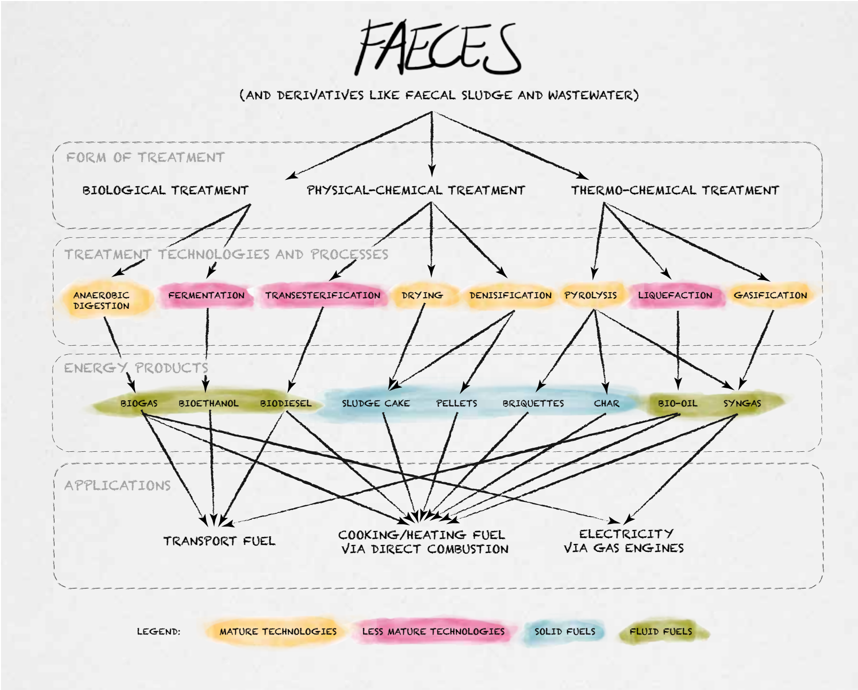
In China, anaerobic digestion of sewage was reported as far back as the 13th century, while the first anaerobic digester in India was set up in 1859. In England, septic tanks with digesters were constructed from 1895, with the resulting gas being used for street lighting. In Sweden, anaerobic digestion at wastewater treatment plants started to be developed in the 1940s. By the 1970s, interest in energy recovery from faeces had spread across the world, partly due to the energy crisis in that decade and our ensuing search for alternative sources of energy. Today, energy is being recovered from faeces in a variety of forms and for various applications depending on the local context.

FORMS OF ENERGY THAT CAN BE RECOVERED FROM FAECES AND APPLICABLE TECHNOLOGIES

Naturally, faeces need to to undergo some form of treatment before it can be converted into usable energy. Such treatment techniques can be biological, physical-chemical, or thermo-chemical (Figure 2). The anaerobic digestion mentioned in the previous section is an example of a biological treatment technique. Physical-chemical techniques include drying and compressing, while thermo-chemical techniques make use of high temperatures in their treatment processes. The treatment results in mainly two forms of fuel: solid fuels and fluid fuels.

Solid fuels primarily take the form of briquettes, pellets and sludge cake, which can be made from faecal sludge, sewage sludge or come directly from faeces through various physical-chemical techniques. Alternatively, thermo-chemical techniques can be used to create char – a solid fuel with a high energy density which looks more like coal or charcoal. Briquettes, pellets and char can be burned directly or fed into gasifiers to generate synthesis gas (syngas) – and, subsequently, electricity. These solid forms are widely used in low- and middle-income countries for household applications such as cooking and heating. Industrial applications in boilers and furnaces are more common in high-income industrialised countries. Sewage sludge, as an example, has been used for decades as a fuel in cement industries. Sewage sludge cake is also used in some incineration plants to generate district heating, and each year over 27 percent of all sewage sludge generated in the European Union is sent to incineration plants.

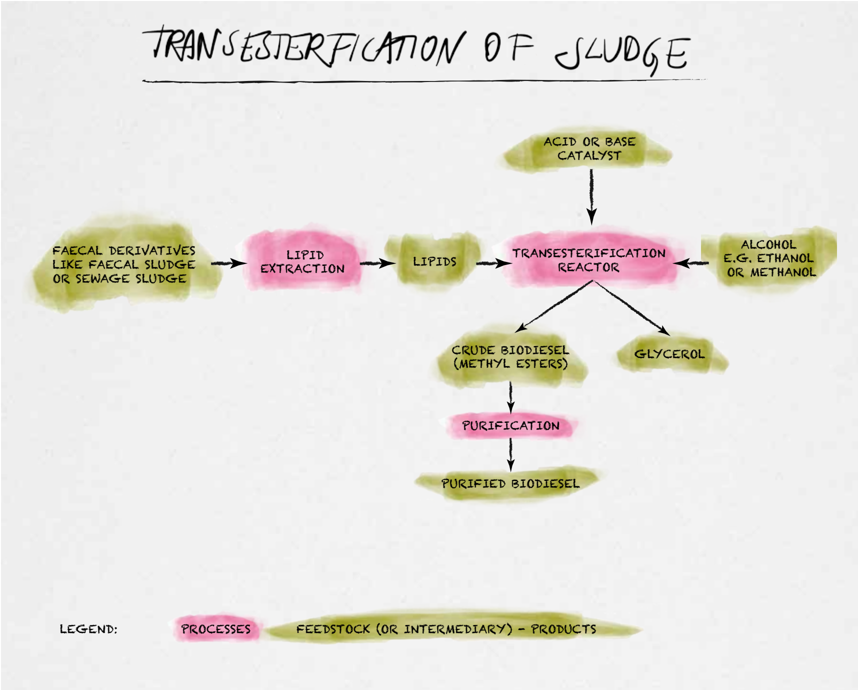
The most well-known type of *fluid fuel* that can be made from faeces is biogas. Biogas can be produced from anaerobic digestion of faecal sludge and sewage sludge in various contexts. Small household-scale bio-digesters are common in rural areas in low- and middle-income countries, with hundreds of millions of such systems located in Asia and sub-Saharan Africa. Large scale biogas production systems are found at centralised wastewater treatment



▲ *Figure 2:* Technologies, products and applications for energy recovery from faeces.

plants in many cities in Europe and North America, and increasingly in rapidly growing cities within Asia, Latin America, and Africa. Biogas can be used directly in stoves for cooking, in lamps for lighting and in furnaces for heating. It can also be used in gas engines to create heat and electricity or refined further to make vehicle fuel or to be fed into a natural gas grid.

Besides biogas, there are other types of fluid fuels that can be created from faeces. Bioethanol can be made from the fermentation (biological treatment) of sludge or fresh excreta, while biodiesel can be made from the transesterification (physical-chemical treatment) of



▲ *Figure 3:* Overview of the process and intermediary products from transesterification to produce biodiesel.

sludge (see Figure 3). The liquefaction (thermo-chemical treatment) of sludge can also be used to generate bio-oil. The products from these processes are mainly used as transportation fuel. Dried faecal sludge and sewage sludge can also be pyrolyzed (a thermo-chemical treatment) to create syngas and bio-oil, with the bio-oil being processed further into a transportation fuel, and the syngas being fed into gas engines to create heat and electricity. Fermentation, transesterification and liquefaction are relatively new technologies in energy recovery from faeces and there are not yet many full-scale commercial operations with these technologies. However, they have been used extensively on a commercial scale with other types of raw material e.g. energy crops for fermentation, vegetable oil for transesterification, and forest residues for liquefaction.

Besides the above-mentioned technologies for energy recovery, another indirect approach is to recover heat from wastewater treatment processes. These processes generate a lot of heat and by using heat exchangers or similar technologies, it can be harvested and used for district heating or other applications. Examples where this is being done are mostly in cities in colder climates like Stockholm and Oslo.

HOW RECOVERING ENERGY FROM FAECES CONTRIBUTES TO SUSTAINABLE DEVELOPMENT

About two billion people globally, especially in low- and middle-income countries, depend on wood-based fuels like firewood and charcoal for cooking. This is a significant driver of deforestation and subsequent environmental impacts. Replacing these wood-based fuels with faeces-derived fuels could widen access to energy while alleviating deforestation. Especially in urban areas, large populations could supply an equally large potential of raw material for such fuels for cooking and to power industries. For a city like Kampala in Uganda, with a resident population of about 1.6 million, solid fuel from faeces and other organic wastes could replace about a quarter of the city's wood fuel consumption. On a global level, if all the world's faeces could be turned into biogas, it could cover the electricity demands of at least 138 million households, which is equivalent to the combined populations of Brazil, Indonesia, and Ethiopia.

By using faeces-derived solid fuels as a replacement for wood-based fuels, we could alleviate deforestation and maintain forests which absorb carbon dioxide emissions. It would also be a basis for replacing fossil fuels like diesel, and hence reducing carbon emissions. In many cities around the world, wastewater treatment plants are generating energy by producing biogas from wastewater sludge. In Sweden, there are at least 134 wastewater treatment plants with biogas production facilities, and they are responsible for a third of Swedish biogas production. Most of the biogas is upgraded and used as fuel in vehicles. The greenhouse gas emissions from an average car running on upgraded biogas are about 27 g CO_2-eq/km (carbon-dioxide equivalents per kilometre), compared to petrol (167 g CO_2-eq/km) and diesel (137 g CO_2-eq/km).

CHALLENGES WHEN IMPLEMENTING ENERGY FROM FAECES, AND POTENTIAL SOLUTIONS

Despite the multiple benefits that can be gained from recovering energy from faeces, there are some challenges associated with implementing the idea. To begin with, energy is only one of many recoverable resources embedded within faeces. Other such resources include nutrients, water, and bio-based materials such as bioplastics, enzymes, minerals, and metals. Some forms of energy recovery could lead to other resources being lost, hence creating trade-offs. An example is when faecal sludge is used to make briquettes for household cooking, since nutrients cannot easily be recovered from the ashes in such contexts. Other forms of energy recovery can be combined with the recovery of other resources. One example is when biogas is generated from wastewater sludge and the "leftover" digestate is treated and applied as manure to agricultural land. But we also need to consider the logistics around linking sanitation systems to energy and agricultural systems. When *nutrients* are recovered from faeces in cities, the products (e.g. sewage sludge) must often be hauled long distances to reach the agricultural areas. On the other hand, any recovered *energy* can be used in the same city where it is generated. Therefore, when planning to recover energy from a city's sanitation system, we need to consider the synergies and trade-offs created by the type of energy recovery that is choosen. Since most nutrients are found in the urine, and most of the energy is concentrated in the faeces, one avenue for innovation in this area is using urine separation sanitation technologies. This way, each stream can be channelled into a separate form of resource recovery.

There are also technological and operational challenges with recovering energy from faeces. In many cities where large scale anaerobic digestion facilities have been established at wastewater treatment plants, methane leakages can occur and contribute significantly to greenhouse gas emissions. In some low and middle-income countries where large household biogas digester programmes have been implemented, inadequate technical capacity has led to challenges in sustaining the programmes. As a result, some infrastructure has been abandoned, while some is still in operation but with negative socio-economic and environmental impacts due to poor operational practices.

There can also be challenges to human health associated with both the *production* and *use* of energy from faeces. This is especially relevant for technologies that involve close human contact with faeces, such as the manual production of briquettes from faecal sludge. Other technologies with much less contact include large scale biogas production at wastewater treatment plants. Workers involved in the process of wastewater or faecal sludge treatment along with energy recovery, risk exposure to pathogens as well as the chemicals used in the process. Therefore, personal protective equipment is very important, as well as vaccinations e.g, against Hepatitis A and B. The use of some energy products also entails risks to human health. For example, the indoor use of briquettes for household cooking leads to emissions of particles and carbon monoxide which contribute to indoor air pollution. However, it should be noted that the indoor use of charcoal and firewood also contributes to indoor air pollution, and in some cases much more than faeces-derived solid fuels. Faeces-derived solid fuels that have been produced in an appropriate way typically do not entail any exposure to pathogens for the user. Using faeces-derived solid fuels for industrial applications could be one way to mitigate health risks, since it is easier to control emissions in industries, than in household use.

CONCLUSIONS

The global population is projected to rise to over 10 billion by the end of this century. It will continue to be a significant challenge to provide enough energy to power livelihoods while limiting climate change. Energy recovery from faeces could be a significant part of the societal energy mix, especially in urban areas where there is a large supply of raw material and demand for energy. There are already well-established technologies that can be scaled up to harvest the energy embedded in faeces. Ongoing technological developments will open even more possibilities and potentially address some of the challenges currently associated with the energy recovery. Hopefully, there will come a time when this ample source of sustainable energy is no longer just flushed down the drain but is harnessed to power the livelihoods of billions of people.

BACK TO THE FUTURE WITH HYDROGEN

Ann Cornell

"Water will one day be employed as fuel, that hydrogen and oxygen which constitute it, used singly or together, will furnish an inexhaustible source of heat and light, of an intensity of which coal is not capable." This citation comes from *The Mysterious Island* by Jules Verne – an adventure novel published in 1874. The book describes how a group of people escape a war, to eventually become stranded on a desert island. The group reached the island by means of a hydrogen-filled balloon, which was one of the first commercial uses for hydrogen gas. History has proved Jules Verne to be quite good at predicting the future. Today, replacing fossil fuels with hydrogen and oxygen is regarded as a crucial key for a sustainable energy system.

Hydrogen (H) is the lightest of all chemical elements. It is also the most abundant element in the universe, found in the sun and in most of the stars. In its gaseous form, hydrogen is present as molecules made up of two atoms (H_2). The gas is non-toxic, colourless and has neither smell nor taste. When hydrogen burns, water is generated; hence its name from the Greek words for *water* (hydro) and *produced* (gen). It has a high energy density (amount of energy per mass unit, e.g., gram), nearly three times that of gasoline, which

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◀ *Figure 1:* Balloon flights were one of the first commercial uses of hydrogen.

makes it an attractive fuel. A problem though, is its low energy density per *volume* unit (e.g., litre), making storage of hydrogen an important challenge. Whenever hydrogen is mentioned in the following text, it refers to the gas.

Hydrogen has been identified as an important vector in our energy system. It is also key in making the process industry less dependent on carbon-based fuels, for example in enabling a future fossil-free production of steel. Lately, both the EU and individual countries around the world, including Sweden, have launched hydrogen strategies with the goal of reaching carbon neutrality, a state where the country's emissions and absorption of carbon are in balance.

PRODUCTION METHODS

Globally, around 70 million tons of H_2 is used per year in pure form, with an additional 45 million tons in gas mixtures. In the olden days of balloons and airships, the hydrogen was produced from treating scrap metal with acid, but today there are much more efficient methods. Presently, most of the hydrogen is made from natural gas at refineries, unfortunately in processes where carbon dioxide (CO_2) is also produced.

In steam methane reforming from natural gas, the chemical reactions are:

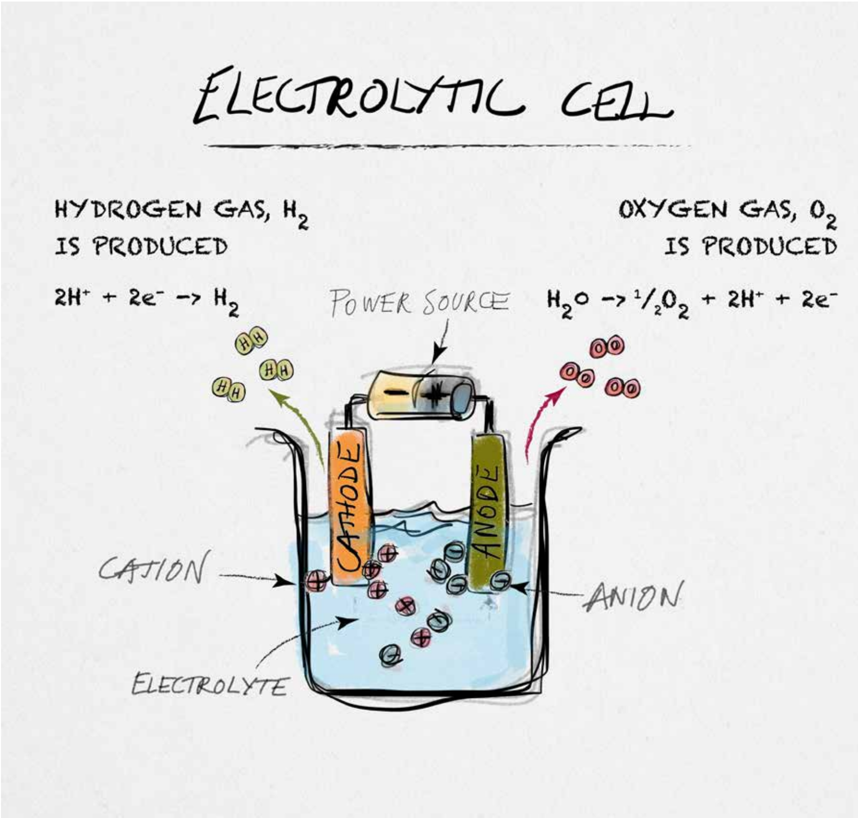
CH_4 (METHANE) + H_2O (WATER) (+ HEAT) -> CO (CARBON MONOXIDE) + $3H_2$ (HYDROGEN)

CO + H_2O -> CO_2 (CARBON DIOXIDE) + H_2 (+ SMALL AMOUNT OF HEAT)

If oxygen is added, the reactions are:

CH_4 + $\frac{1}{2}$ O_2 (OXYGEN) -> CO + $2H_2$ (+ HEAT)

CO + H_2O -> CO_2 + H_2 (+ SMALL AMOUNT OF HEAT)



▲ *Figure 2:* Schematic view of an electrolysis cell.

Another production method, for large as well as small-scale use, is electrolysis (see Figure 2). Here a source of electricity is applied to create a current between two electrodes in an electrolyte (e.g. water with dissolved salts). As a result, hydrogen is produced at the cathode (negative electrode) and oxygen at the anode (positive electrode). (Further along in this chapter, you will note that the electrode charges in electrolysis are reversed contrary to those in a *fuel cell*, where the anode is negative and the cathode positive.) As opposed to when natural gas is used as the source material, electrolysis offers a way to produce fossil-free hydrogen – *if* the electricity used in the production process comes from renewable sources. Today, less than five percent of the world's hydrogen is made by electrolysis, and then mainly as a product from chlor-alkali plants (where salt and electricity are used to produce chlorine gas and caustic soda).

The hydrogen strategies mentioned above anticipate large increases in electrolytic production of hydrogen. For example, the EU predicts a 40-fold increase in the production capacity in Europe from 2021 to 2030. Water electrolysis would be the dominating process. Here, there are currently three main commercial technologies: alkaline water electrolysis (AWE), proton-exchange membrane water electrolysis (PEMWE) and solid oxide water electrolysis (SOWE). The first two operate at low temperatures below 100°C, whereas SOWE needs a temperature of 700–900°C. In all three processes the total reaction is

$$2H_2O \rightarrow 2H_2 + O_2$$

where hydrogen is produced at the cathode and oxygen at the anode. The three processes have different characteristics, see Table 1. AWE is the most mature method, well proven on a large scale. PEMWE has advantages in more compact design, a higher energy efficiency and can be run in a wider current range. This feature is important when using electricity from renewable sources with intermittent supply, such as solar, wind or hydro power. While SOWE requires the lowest electrical current, it requires heat to produce the necessary steam for the process.

There are also other technologies for hydrogen production, such as biomass gasification and different types of reforming processes.

TECHNOLOGY	AWE (Alkaline water electrolysis)	PEMWE (Proton exchange membrane) water electrolysis	SOWE (Solid oxide water electrolysis)
PROCESS	AQUEOUS ELECTROLYSIS WITH A DIAPHRAGM SEPARATOR.	POLYMER MEMBRANE AS ELECTROLYTE. "REVERSED PEM FUEL CELL"	CERAMIC OXIDE AS ELECTROLYTE. "REVERSED SOLID OXIDE FUEL CELL"
TEMPERATURE	~ 80°C	25 – 100°C	700 – 900°C
INDUSTRIAL USE	WELL DEVELOPED LARGE SCALE	COMPACT DESIGN FLEXIBLE CURRENT RANGE	RECENTLY COMMERCIAL

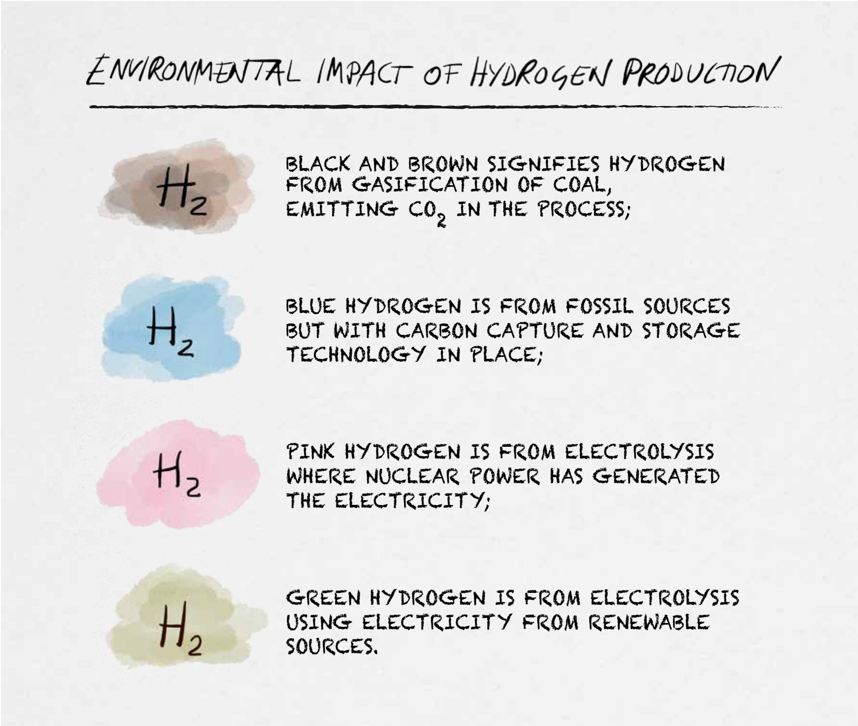
▲ *Table 1:* Characteristics of electrolysis technologies AWE, PEMWE and SOWE.

The carbon dioxide produced as a by-product can be captured and stored in a Carbon Capture and Storage (CCS) process.

To classify the environmental impact of hydrogen produced in the different processes, a colour scheme has been adopted:

FUEL CELLS

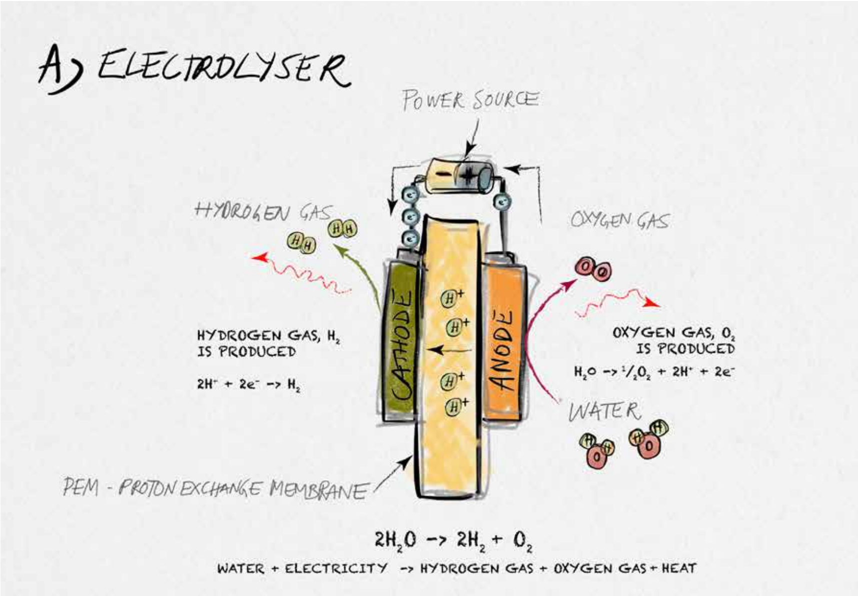
In a fuel cell, the energy in hydrogen and oxygen can be partly converted to electricity, which can power, for example, a car. The hydrogen is added as fuel and stored in the car, while oxygen is taken directly from the air. And out of the exhaust pipe comes just water, no carbon dioxide at all. Since a fuel cell is about twice as energy efficient as a normal combustion engine, the fuel cell-driven car can reach double the distance on the same amount of added energy.

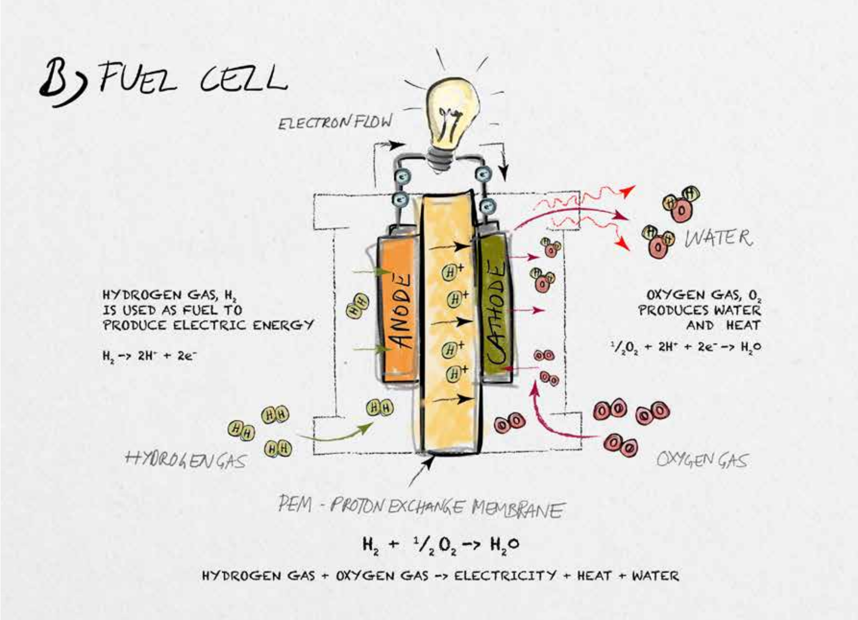


▲ *Figure 3:* Colour scheme for classifying the environmental impact of hydrogen produced in different ways.

▶ *Figure 4:* An electrochemical cell working as an electrolyser (2a) and a fuel cell (2b), respectively.

The fuel cell works like a reversed electrolysis cell. Some types of fuel cells can even work in both modes, depending on the direction of the current. Figure 4 shows an electrochemical cell equipped with a proton exchange membrane (PEM). In Figure 4a it is working as an *electrolyser*, consuming electricity and producing hydrogen and oxygen whereas in Figure 4b it is operating as a *fuel cell*, consuming H_2 and O_2 while producing electricity and water.


A) ELECTROLYSER
POWER SOURCE
HYDROGEN GAS
OXYGEN GAS
CATHODE
ANODE
HYDROGEN GAS, H_2 IS PRODUCED
$2H^+ + 2e^- \rightarrow H_2$
OXYGEN GAS, O_2 IS PRODUCED
$H_2O \rightarrow 1/2\,O_2 + 2H^+ + 2e^-$
WATER
PEM - PROTON EXCHANGE MEMBRANE
$2H_2O \rightarrow 2H_2 + O_2$
WATER + ELECTRICITY -> HYDROGEN GAS + OXYGEN GAS + HEAT


B) FUEL CELL
ELECTRON FLOW
WATER
ANODE
CATHODE
HYDROGEN GAS, H_2 IS USED AS FUEL TO PRODUCE ELECTRIC ENERGY
$H_2 \rightarrow 2H^+ + 2e^-$
OXYGEN GAS, O_2 PRODUCES WATER AND HEAT
$1/2\,O_2 + 2H^+ + 2e^- \rightarrow H_2O$
HYDROGEN GAS
OXYGEN GAS
PEM - PROTON EXCHANGE MEMBRANE
$H_2 + 1/2\,O_2 \rightarrow H_2O$
HYDROGEN GAS + OXYGEN GAS -> ELECTRICITY + HEAT + WATER

As with electrolysers there are several different types of fuel cells, operating at low temperature as the PEM fuel cell in Figure 4b or at high temperature as a reversed SOWE.

Fuel cell cars can travel around 100 km on 1 kg of hydrogen. Filling up the tank only takes a few minutes and is enough for a 500–800 km journey. At present there are only a few fueling stations in Sweden, but as the interest in fuel cell cars has increased, more are being built. Most likely, the country will have over 50 stations by 2025.

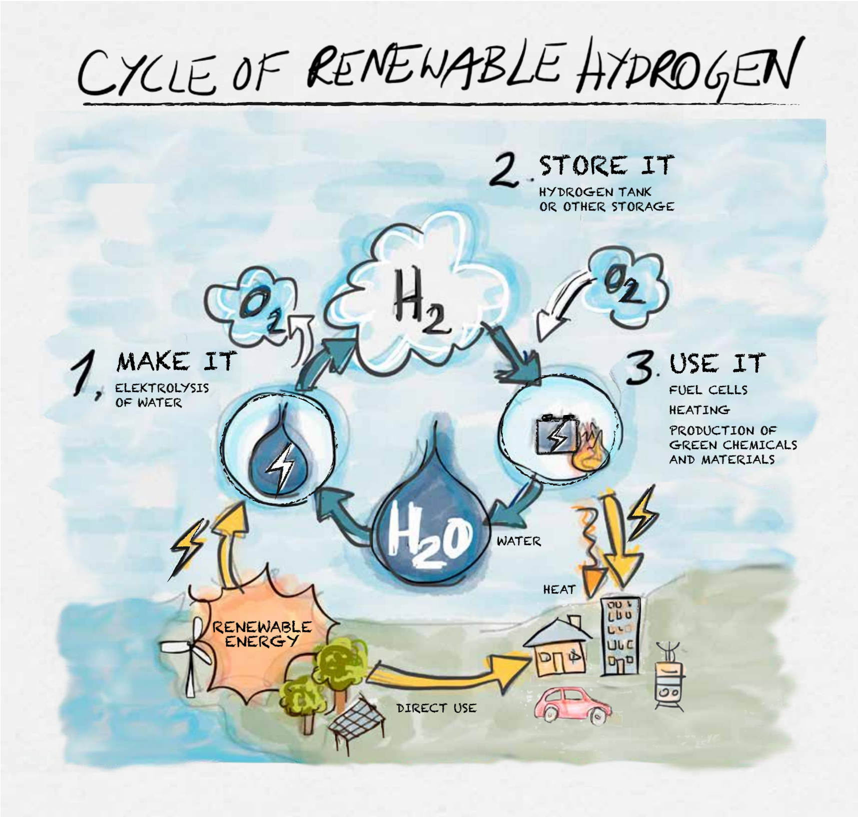
STORAGE OF HYDROGEN

As mentioned above, there is an international goal to increase the production of green hydrogen, to be used as an energy carrier, for transportation and in the process industry. Since the electricity for green hydrogen needs to come from renewable sources with intermittent operation – e.g. no wind power when there is no wind – the production rate needs to be adjusted to the availability and price of electricity. This, in turn, makes hydrogen storage important to reduce our vulnerability to an irregular supply of electricity.

Hydrogen may be stored in pure form as a gas or a liquid, adsorbed into/onto a material, or chemically bound in, for example, methanol. For large scale applications, there are several facilities using salt cavities underground for storing hydrogen at a pressure of a few hundred bar. There are also above ground types of storage in the form of pressure vessels or pipelines. When used for powering transportation, the hydrogen is stored on the vehicle itself. For such smaller scale applications, hydrogen is stored typically at 350 or 700 bar in containers made of materials that do not allow leakage of the small H_2 molecules.

COMBINING PRODUCTION, USE AND STORAGE OF HYDROGEN IN A HYDROGEN SOCIETY

In a future fossil-free hydrogen society, hydrogen gas will be produced by electrolysis using electricity from renewable sources such



▲ *Figure 5:* A future hydrogen society.

as wind and solar power. The gas will be stored as an energy carrier for later use, for example, to produce chemicals, fuel vehicles or generate electricity in fuel cells. Heat is a byproduct during both electrolysis and fuel cell operation, and this heat may be used in applications such as district heating. There will be networks for the distribution of electricity, gas, and heat, respectively, which are controlled by artificial intelligence systems.

SAFETY

What about safety, then? The Hindenburg disaster of 1937, where the large Zeppelin airship filled with hydrogen went up in flames in Lakehurst, USA, is probably the most well-known accident involving hydrogen. The event caused the deaths of 36 people and put an end to passenger transportation using hydrogen-filled balloons. Hydrogen indeed has a high energy density per unit mass and burns fast. And the energy required to start a hydrogen fire is much lower than that required for the combustion of gasoline. Hydrogen, however, cannot burn in a tank containing only hydrogen – an oxidising agent such as oxygen is needed for a fire. And as hydrogen is about 14 times lighter than air, in case of a leak it rises and diffuses quickly to lower and safer concentrations. Hydrogen has now been used on an industrial scale for more than 100 years and over time we have accumulated a lot of knowledge on how to handle it, making it as safe as, or safer than other fuels in modern society.

THE FUTURE

So, what is needed to turn the hydrogen society vision into reality? The hydrogen strategies mentioned above suggest certain roadmaps and point out important challenges. For example, in the *Hydrogen strategy for fossil free competitiveness* launched in 2021 by the governmental initiative *Fossil Free Sweden*, several actions are listed. These include a plan for the electricity grid, a new infrastructure for hydrogen production with goals for e.g. electrolyser capacity, new legislation and market conditions to promote green hydrogen. Further governmental actions include financial support to promote green hydrogen as well as research and development and increased competence in the area.

In Europe, grey, blue, and green hydrogen today cost around 1.5, 2 and 2.5–5.5 Euro/kg, respectively. To make green hydrogen more competitive, we need more research and development of electrolyser design, and more efficient production of the electrolysers. Promisingly, in the last 10 years the cost of electrolysers has gone down by around 60 percent and is expected to further decrease by another 50 percent by 2030. Ways of lowering the cost include improving existing processes regarding, for example, electrode materials and membranes, developing more efficient electrolysis processes, and taking advantage of large-scale electrolyser production.

Almost 150 years have passed since *The Mysterious Island* was first published, and Jules Vernes' prediction of water one day being employed as fuel. What fiction is being written today that will become part of the reality of tomorrow?

MATERIALS – A TANGIBLE CHALLENGE FOR THE ELECTRIFICATION OF SOCIETY

Kerstin Forsberg & Christopher Hulme

The electrification of society means changing from current (non-electrical) technologies such as fossil fuel transportation to alternatives that are powered by electricity. This process is necessary for environmental reasons and is often portrayed as a solution to grand challenges such as climate change. It also creates several problems that are often ignored, but which could lead to severe consequences if they are not solved. This chapter considers one such problem: the supply of materials that are needed for electrical technologies. Some of these materials are very difficult to produce, or only exist in small amounts. Such materials are called critical, as the supply is not secure, and they play a very important role in society. Both the European Union and the United States of America publish their own lists of materials deemed critical. Our society's demand for these materials will keep increasing and so we must find a way to meet this demand. Most experts agree that more mining will be required to achieve this. Mining itself requires lots of energy and is currently associated with a large release of greenhouse gases. The amounts of these materials that will be available for extraction from the mines are also limited. To avoid severe long-term consequences, we must be careful when committing to actions that require such materials, to make sure that they are sustainable in a holistic sense.

WHY DO WE WANT TO ELECTRIFY SOCIETY?

Electrification of society is ongoing and accelerating. Politicians, researchers, and companies all recognise how important it is to replace other sources of fuel with electricity, which can then be generated in clean and renewable ways. This will enable us to reduce greenhouse gas emissions, conserve natural resources and become a more sustainable society to provide a brighter future for our children and grandchildren. There is no doubt that electrification should proceed. However, we must take care to ensure the supply of materials is secure and does not make electrification unsustainable.

WHAT IS NEEDED TO ACHIEVE A MORE ELECTRIFIED SOCIETY?

The most obvious answer is: *enough electricity*. However, this electricity must also be clean, renewable and the supply must be consistent and reliable. This is a huge challenge, as is discussed in many of the other chapters in this anthology. The other thing we need is the *materials* to build the electronic devices we want to use. This, too, presents a sizeable challenge.

CREATING A MATERIALS CRISIS

Some readers may remember the oil crises in the 1970s, where uncertainty over the supply of oil led to prices soaring by 400 percent in a very short time. Both of the two major crises started when some suppliers stopped selling their oil, which led to drastic changes in the world economy. Without careful planning and research, the current drive to electrify society could easily lead to a similar "materials crisis", where certain materials become so difficult to acquire that their prices rise very quickly, making electrification too expensive. Such a crisis might arise if a country stops supplying a certain material, or if the demand for a material rises faster than it can be produced. Such scenarios can be avoided, if the problem is recognised in time, and the right action is taken.

RARE EARTH METALS

One important way to generate fossil-free electricity is using wind turbines. For example, in 2021, the United Kingdom generated 19 percent of its total electricity demand using wind, and the highest contribution at any point in time during the year was 59 percent. In early 2022, the Swedish government announced plans to greatly expand wind generation capacity in Sweden. Wind turbines contain powerful magnets that use *rare earth metals*, in particular neodymium, dysprosium and samarium. Furthermore, the rare earth metal scandium is used in solid oxide fuel cells. As the name suggests, rare earth metals are limited in supply. Many are expensive and require large amounts of energy to be extracted from ores. In addition, rare earth metals are often found together in ores and, as they have similar chemical properties, they are difficult to separate from each other. This creates a balance problem since they are mined together but there is a difference in demand for the different metals. To ensure precious resources are not wasted, the excess metals less in demand therefore need to be stockpiled.

LITHIUM AND COBALT

The switch to electric cars has led to a rapid development in battery technologies. These batteries are similar to those in mobile phones and laptops, and use electrical energy to break apart lithium compounds to lithium ions and other chemicals. As long as the positive and negative ends of the battery are not connected, the chemicals just 'sit' in the battery. But when you use the device, the ends are connected, causing lithium ions to combine with the other chemicals to remake the lithium compounds and release electrical energy. This places an obvious demand on lithium. For electric cars, where the battery must store as much energy as possible, the lithium compounds very often contain cobalt.

Lithium is problematic since a lot of carbon dioxide is generated when the metal is extracted from its ores. This use of energy can be reduced significantly by recycling lithium metal. Unfortunately, it is often difficult to do so, since lithium is used in small components that are difficult to collect and separate from other metals. Also, in many cases, lithium is used in compounds that may not be easy to recover or convert to other forms for use in new applications. While this has not been a problem in the past, it may become one as the use of lithium-based batteries rapidly expands as the electrification and digitalisation of society intensifies. We must keep this in mind to ensure it does not stop electrification and digitalisation from happening.

About half of all cobalt is produced in the Democratic Republic of the Congo (Congo-Kinshasa). This country is considered to be quite unstable (the fifth least stable country in the world, according to the Fragile States Index 2021). The amount of energy required to extract cobalt from ore is huge. Carbon dioxide is also generated in large quantities as a result of cobalt production. All of these problems can be reduced by recycling cobalt.

SILICON

Another potent source of electricity is solar power (specifically, photovoltaic power). It has been estimated that if solar cells covering a total area equal to that of Germany were placed in the Sahara Desert, they would provide enough electricity to meet the needs of the entire planet. Many solar cells that generate electricity are based on silicon. While there is plenty of silicon around (it is found in normal sand on most beaches), the production of silicon solar cells still requires a lot of energy. There are two types of silicon solar cells: single crystal cells, that use very large crystals of silicon, and multi-crystal cells that use "normal silicon". The first type is produced using a technique that requires large amounts of energy, often in the form of electricity. The second type requires less energy to manufacture; but also generates less power than the first type when used in a solar cell. It is difficult to know how much electricity a solar panel generates, partly as there are many different types of panels available, but also as it depends strongly on where you are in the world. In Europe, both types typically require about four times more energy to make than what they generate in a year. This means that a solar cell must operate for four years before it starts making a net contribution to energy generation. This is called the *energy payback time*.

In Sweden, solar cells generate around 400 MW of power, and 300 GWh of electricity per year. Some of this electricity is used immediately, some is physically stored by melting a material that is then allowed to freeze later to give out energy when needed, or by pumping water uphill, which can be released to generate power when needed (this technology works like a wind turbine and might require rare earth magnets). In addition, some is stored in batteries (which might require lithium and cobalt).

VANADIUM

Vanadium is listed as a critical raw material for the European Union. The main producers globally are China, South Africa, and Russia, with no extraction from ores undertaken in Europe. Vanadium is important for energy storage due to its use in vanadium redox flow batteries and in a new generation of lithium-ion batteries. Furthermore, vanadium alloys are used in nuclear reactors.

HOW CAN WE SUPPLY THE MATERIALS WE NEED?

MINING

One obvious way is to dig up more of the materials. There is widespread acceptance that we will need to do this to allow us to electrify and digitalise society. However, it is not necessarily possible to dig up more material over a long period of time. We use the concept of a "reserve" to get an idea of how much material there is to dig up. This "reserve" represents the mass of material that can be processed profitably at current prices. Thus, reserve figures may go up if more material is found underground or if the price of the material rises; and might go down if the price falls or if the material is used up quickly. Usually, a material is supplied for a longer time than is predicted by the current reserve, as the price of a material normally goes up when the reserve runs low, so more material can be extracted profitably.

As mentioned earlier, mining uses a lot of energy. We use the idea of "embodied energy" to understand the total energy needed to convert a material from its native state in the ground into a useful material. For virgin material (material that is not from recycled waste), these steps include mining, transportation, and processing. The carbon dioxide footprint of these steps is also measured. For recycled materials, we can calculate the corresponding statistics if we consider the following steps: waste collection, transportation, and all processes required to make a useful material from the waste.

RECYCLING

Recycling often uses less energy and emits less carbon dioxide than mining and related processes. In addition, it allows us to extend the reserve by generating new material from waste rather than from resources in the ground. This is especially important for materials that are controlled or produced largely by one country, such as cobalt, and some rare earths, which are mostly produced by the Democratic Republic of the Congo and the People's Republic of China, respectively.

HOW DO WE ENABLE RECYCLING?

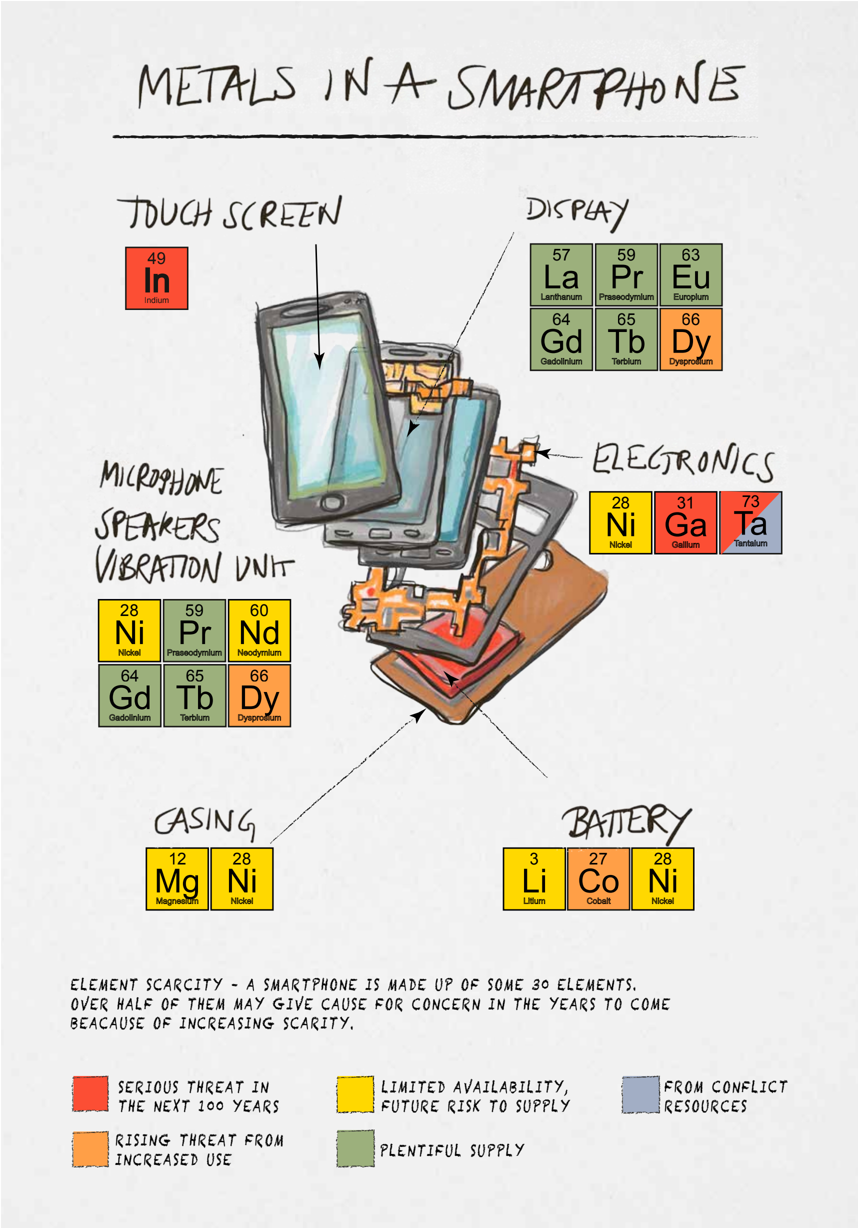
To enable and improve recycling, many different stakeholders as well as the public must be involved. The devices to be recycled must be collected, sorted, and disassembled in the best possible way. It may be possible to refurbish and use some devices again in a 'second life'. For example, electric vehicle lithium-ion batteries can be refurbished for energy storage applications in a second life. In this case, it is important to have information about the battery's origin, health and previous use, which relies on a well-developed blockchain technology for tracing battery components. To give batteries a sec-

SUPPLY, ENERGY FOOTPRINT AND CARBON DIOXIDE FOOTPRINTS OF SOME CRITICAL MATERIALS

	COBALT	LITHIUM	NdFeB MAGNET	SILICON
PRICE (EUR/KG)	65	65	21	10
2020 PRODUCTION (MT/YEAR)	0.15	0.03	0.02	11
2020 RESERVES (MT)	7.2	13	140	106
YEARS OF SUPPLY	50	> 400	7000	MANY!
EMBODIED ENERGY (virgin) (MJ/KG)	2000	600	55	120
CARBON DIOXIDE FOOTPRINT (virgin) (KG/KG)	43	46	6	5
EMBODIED ENERGY (recycled) (MJ/KG)	24	70	19	2.4
CARBON DIOXIDE FOOTPRINT (recycled) (KG/KG)	2	5.5	1.5	0.8
PERCENTAGE OF RECYCLED MATERIAL IN CURRENT SUPPLY	30%	< 1%	50%	0.6%

▲ *Table 1:* The table shows the supply, price, energy and carbon footprints of some critical materials. MT = megaton = billion kilograms. MJ = megajoule. The carbon footprint is stated in kilograms of carbon dioxide per kilogram of material.

ond life there is a need to develop standardisation and regulations. Furthermore, the safety aspects in transporting and storing a large volume of batteries are important and need to be studied more.



METALS IN A SMARTPHONE
TOUCH SCREEN
49 In Indium
DISPLAY
57 La Lanthanum
59 Pr Praseodymium
63 Eu Europium
64 Gd Gadolinium
65 Tb Terbium
66 Dy Dysprosium
ELECTRONICS
28 Ni Nickel
31 Ga Gallium
73 Ta Tantalum
MICROPHONE
SPEAKERS
VIBRATION UNIT
28 Ni Nickel
59 Pr Praseodymium
60 Nd Neodymium
64 Gd Gadolinium
65 Tb Terbium
66 Dy Dysprosium
CASING
12 Mg Magnesium
28 Ni Nickel
BATTERY
3 Li Litium
27 Co Cobalt
28 Ni Nickel
ELEMENT SCARCITY - A SMARTPHONE IS MADE UP OF SOME 30 ELEMENTS. OVER HALF OF THEM MAY GIVE CAUSE FOR CONCERN IN THE YEARS TO COME BEACAUSE OF INCREASING SCARITY.
SERIOUS THREAT IN THE NEXT 100 YEARS
LIMITED AVAILABILITY, FUTURE RISK TO SUPPLY
FROM CONFLICT RESOURCES
RISING THREAT FROM INCREASED USE
PLENTIFUL SUPPLY

When the devices have reached their end of life they should be recycled. Recycling can be challenging, especially when devices contain a mixture of different materials. Since end-of-life devices can contain high amounts of valuable and critical raw materials, there is also great potential for resource recovery. Sometimes the concentration of valuable metals in end-of-life devices greatly exceeds that which can be found in ores. From a recycling perspective, the current direction towards decreasing the content of critical raw materials in devices can become a challenge. If less value can be extracted from the recycling process, it can lead to a lower incentive for recycling.

There is still potential to improve the design for recycling of several devices, for example by choosing materials that are easier to recycle or by facilitating disassembly of the device. When recycling batteries, they are usually discharged, manually dismantled, and then shredded and processed mechanically to produce a so-called black mass. This process includes thermal treatment and physical separation using magnetism, air, or sieving. The black mass is a new product on the resource recovery market and has varying composition depending on the chemistry of the batteries and the treatment. Resource recovery processes from black mass and other end-of-life devices can either be based on pyrometallurgy (thermal treatment) or hydrometallurgy (aqueous solutions) or a combination. As new devices are developed, for example introducing new chemistry in its materials, there is equally a need to develop new recycling processes combining different recycling techniques. Furthermore, there is a need to develop the fundamental understanding of each technique to be able to optimise yield and product quality and to create economically and environmentally sustainable processes.

◂ *Figure 1:* A smartphone contains a number of elements that will be in short supply in the future. Source: https://www.birmingham.ac.uk/documents/college-eps/energy/policy/policy-comission-securing-technology-critical-metals-for-britain.pdf and https://www.euchems.eu/euchems-periodic-table/

SUSTAINABLE ELECTRICITY GRIDS – A PREREQUISITE FOR THE ENERGY SYSTEM OF THE FUTURE

Lina Bertling Tjernberg

Electricity is considered to be one of humanity's greatest inventions. Electrification revolutionised society from creating light in homes to enabling industrial development. Today we are facing a dilemma: We are using more and more energy, whilst at the same time we need to reduce our emissions of carbon dioxide. An important part of the solution to this dilemma is to use more energy from renewable sources such as solar and wind. But we also need a sustainable electricity grid.

THE ELECTRIC POWER GRID – TRANSPORTING AND BALANCING ELECTRICAL ENERGY

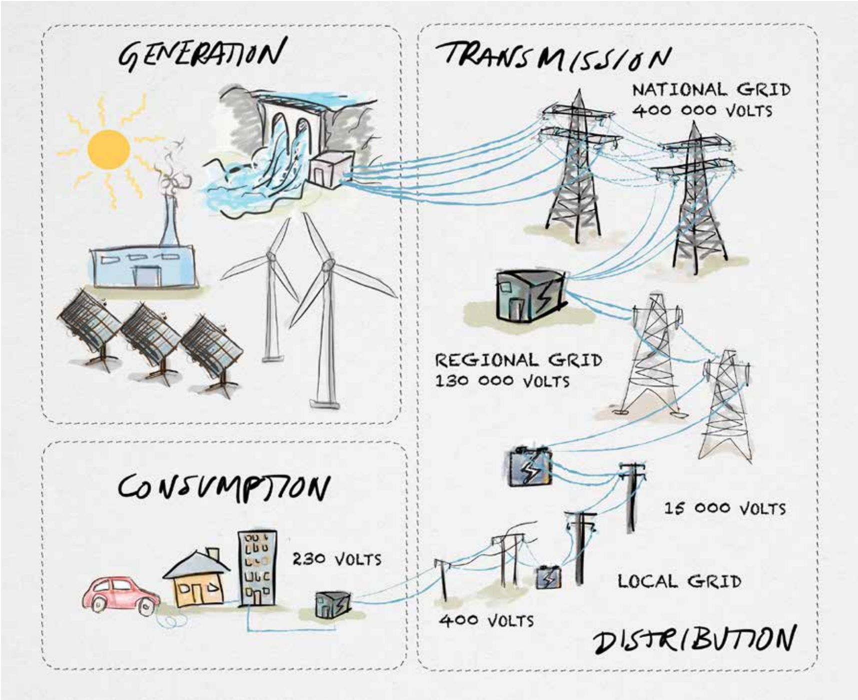
The electricity grid is the infrastructure that makes it possible to transport electrical energy, electricity, from producer to consumer (Figure 1). The electricity grid consists of components such as overhead lines, cables, transformers, as well as switching devices (between different voltage levels and components) and converters (for example between direct current and alternating current). Today's electricity grid is made up of individual electric power plants that supply large geographical areas with electrical energy via power lines.

The electricity grid can be divided into three parts: the *national grid* (also called transmission grid) and the *regional* and *local* electricity grids (see Figure 1). The voltage in the power lines is extremely high in the national grid (up to 400,000 volts). It is then gradually decreased via transformers in the national grid and the regional and local grids to be at a much lower level when it reaches the consumer (230 volts in our electrical outlets). The high voltage makes it possible to transport electricity over long distances without losing energy along the way; while the lower voltage makes the electricity safer for the consumer to use.

One of the main challenges in the electricity grid is to keep a constant balance between the production and consumption of electricity in the electrical system. This balance includes maintaining a stable voltage level and frequency (the number of oscillations in the alternating current per unit time – see also chapter on electricity). Many of the components in the electric power system are therefore designed to adjust frequency and voltage levels. Another important function is for components to be able to disconnect and insulate parts of the power grid, for example after an electrical fault or to carry out maintenance.

How resistant the electricity grid is to interference is determined by the available *rotational energy* in the electrical system. The rotational energy, also called the *rotational mass*, consists of the stored kinetic energy in the system. Let us take a hydropower plant as an example: Here the kinetic energy of the water is converted into mechanical energy in turbines, which in turn drive generators that generate electrical energy. The rotating parts of the turbines and generators have a mechanical inertia against changes in the speed of rotation that limits how fast they can be accelerated or decelerated (think of a carousel on a playground, and how the number of children on the carousel affects how quickly it can be decelerated or started up). This inertia helps maintain the balance of the electrical system by acting as a short-term buffer. The larger the rotational mass (the more children in the carousel), the more energy is stored and can be used to stabilise the frequency.

Globally, Sweden has played a leading role in the research, development and innovation of electricity grids. Allmänna Svenska Elektriska AB (ASEA), which was founded in 1883, developed new



▲ *Figure 1:* Schematic image of the electricity grid.

technology that made it possible to transmit electricity over very long distances (even in the sea) with a high voltage and direct current. The world's first commercial high voltage direct current cable (HVDC) was commissioned in 1954 and was a submarine cable between the Swedish mainland and the island of Gotland. ASEA manufactured this HVDC cable for the state-owned power company Vattenfall in a project led by the world-renowned inventor and engineer Uno Lamm. He is often mentioned as the father of high voltage direct current. During his lifetime, he developed as many as 150 patents in the field, and in 1980, the international organisation the *Institute of Electrical and Electronics Engineers* (IEEE) instituted an award in his honour. The prize is awarded annually to a person who has made great contributions to high-voltage technology. In 2017, the first HVDC cable was recognised as an IEEE milestone – an award similar to UNESCO's World Heritage Site, though in technology.

SMART GRIDS

The global energy system is undergoing a gigantic transformation. The ambition is to use less fossil fuels and more renewable energy sources, and to use energy more efficiently. Major investments have been made around the world to expand and modernise electricity grids to achieve these goals. One of the most important ways to achieve these goals is through *smart grids*.

There are many examples of the benefits of smart grids. Households' demand for electricity can be optimised with the help of smart meters, pricing of electricity in real time and smart appliances (also see chapter on homes in the smart grid). Voltage and power can be controlled whilst electricity is being delivered, with smart meters automatically reporting outages. Companies can remotely monitor high-voltage components and power stations to plan and carry out preventive maintenance of, for example, transformers or power lines.

The various technologies included in smart grids can be divided into ten categories:

1. *Home energy control*: a device that responds to electricity price information to optimise heat consumption and the use of electric appliances such as washing machines.
2. *Information and communication technology (ICT):* devices that monitor and provide consumer feedback on actual electricity consumption depending on the market price.
3. *Demand control:* combined smart meters and screens that visualise energy consumption.
4. *Smart meters:* record the consumption of electrical energy at intervals of one hour or less and communicate this information to monitoring and billing tools.

5. *In-home display:* a screen that shows electricity and energy consumption in the home.
6. *Energy storage:* makes it possible to balance production and consumption, and even out large variations.
7. *Virtual Power Plant (VPP):* coordinates small-scale electricity production, such as wind turbines and small-scale hydropower, and enables new producers to support the peak load power system.
8. *Coordination of distributed energy resources:* can, for example, coordinate local production of electricity from solar cells, connected district heating or heat pumps, battery systems and electric vehicles and smaller hydropower plants or wind turbines for smaller communities.
9. *A central control system:* manages the various functions of the smart grid.
10. *Charging optimisation for electric vehicles:* makes it easy to integrate electric vehicles in the power system, at a lower cost, and with better power.

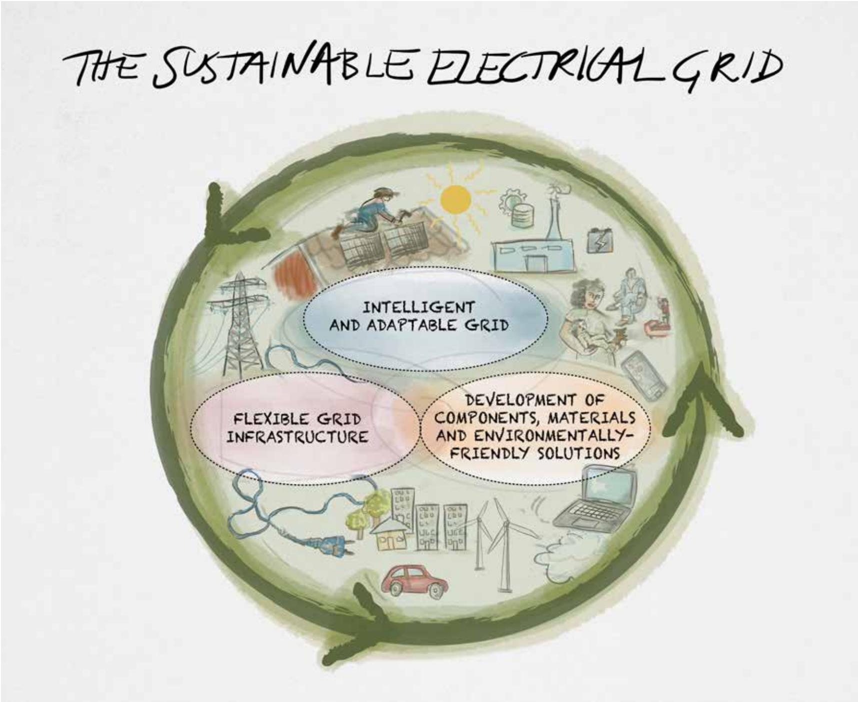
Smart meters represent a revolution for electricity consumers. In traditional electricity networks, the consumer is only one node in the transmission system. With smart meters, the consumer can now get continuous information about their own consumption, how much electricity is *consumed* by individual appliances in the household, or how much electricity the household *produces* using, for example, solar cells, so-called *micro-production*.

Another central part of the transformation of the electricity grid is to integrate electricity from *intermittent power production* such as solar and wind. The power created from these sources is not constant over time but depends on weather conditions – wind and sunshine. This presents several challenges for the electricity grid, which must be able to create a balance between the production and consumption of electricity, and maintain that balance without the help of more consistent power sources, such as hydropower. The future electricity grid will be an increasingly complex technical system with a mixture of alternating current and direct current, local and remotely produced electricity. Other new aspects are electric vehicles, which can consume electricity (when charging their batteries), as well as act as a source of electricity (when batteries are connected to the grid and *contribute* electricity).

In the transition to the smart electricity grid, two key areas are *standardisation* and *interoperability*. Standardisation includes which rules and guidelines apply, as well as which properties the electricity grid has. This is necessary for both security purposes and to reduce costs. *Interoperability* is the ability of different systems and organisations to work together. In the smart electricity grid, electricity systems are connected to information systems (telecommunications and data networks). This interconnection makes it possible to automate and communicate via current and future electricity networks. An important driving force for investments in smart electricity networks is that large parts of today's electricity grids are aging and need to be modernised. Other important driving forces are improved customer experience, increased efficiency in the operation of the electricity grid, and increased efficiency in how the energy is used.

GREENGRIDS – INTELLIGENT, FLEXIBLE AND CIRCULAR ELECTRICITY GRIDS WITH A VISION OF A SUSTAINABLE SOCIETY

An intelligent and adaptable electricity grid is key to a sustainable, cost-effective and resilient electricity supply. In the future, the electricity grid will be under increasing pressure, and demands on reliability, monitoring and components will be higher. New electricity grids can benefit from materials and components that are designed with the circular economy in mind. Millions of electricity customers can contribute to the electricity grid with local small-scale electricity production from solar panels and with connected electric vehicles for charging or storage. Digital technology will be



▲ *Figure 2:* GreenGrid's vision for a sustainable society with three interconnected thematic areas.

used in devices and systems to improve the monitoring and control of components in the electricity grid.

In the vision of the sustainable electricity grid (GreenGrids), the ingredients of electrification for a sustainable society are divided into three parts (see Figure 2).

1. *The intelligent and adaptable grid*, which creates new values for electric power plants and electricity customers. This electricity grid will support a reliable and smooth transition to a sustainable energy system and add

significant value to the economy, society and the environment. How to make full use of digital technology in an intelligent network is a challenge that requires huge investment and collaboration between authorities, academia and industry. This requires interdisciplinary research in control, communication, data analysis and AI, and in-depth knowledge of power systems and power electronics, with the involvement of all stakeholders.

2. *The flexible grid infrastructur*e, which integrates renewable energy sources and energy storage systems to even out variations in electricity generation. A flexible electricity grid must be able to connect large amounts of electricity from the intermittent production of electricity from solar and wind (see also chapters on electricity) without compromising the stability of the electricity grid. Developing technology and systems to create more flexible electricity grids in the future is a challenge. The challenge is not only to develop an economical and sustainable system, but also to do so quickly. An immediate reduction in the use of fossil fuels is needed for the climate. Reducing the use of fossil fuels also reduces our dependency on the import of fossil fuels. There is a huge need for technological development to create flexible networks and efficient storage and control. Technology and markets for system services also need to be further developed in order to ensure an efficient and reliable continuous power supply. Also see the chapters on electricity for a description of different technologies used for energy storage.

3. *Development of components, materials and environmentally-friendly solutions*. This includes new technologies for transformers, cables and connection technologies,

improved materials and knowledge about how they age in order to be able to plan for their maintenance and replacement. Components and their materials form the backbone of the electricity grid. In flexible, dynamic and optimised electricity grids of the future, components need to be able to withstand increased pressure and guarantee reliable and efficient grid operation. In the development of these solutions, research needs to be based on a circular economy. The circular economy involves a cycle from component design, operation and maintenance over their lifetime, possible life extension, and finally the recycling of materials. The goal is to reduce the impact on nature and reduce emissions of greenhouse gases as well as carbon dioxide. The circular economy can also mean that components, as well as materials, can be used for several different functions. For example, battery systems that are first used in electric cars and then are given a second life for energy storage. Already technology solutions exist whereby used batteries are converted into mobile electric car chargers that can be placed wherever they are needed.

The user perspective is key to the successful transition to a sustainable electricity grid and a sustainable energy system. In particular, the question of user acceptance needs to be taken into account. Here, the attitude "not in my backyard" presents a challenge – for example "preferably wind power, but not here" or "preferably solar panels, but not on my neighbour's roof". For wind power, for example, a great deal of work has been done to bring various relevant stakeholders together, e.g. from the military, reindeer husbandry and municipalities, as well as industry and investors. The focus is on openness and dialogue, as well as education and creating a knowledge base.

To meet the needs of the future, we need to greatly expand the production of electricity as well as a corresponding capacity to be able to transport it. Municipalities have focused on contributing to the transition by reducing lead times for environmental permits and providing financial support for development. However, more instruments need to be developed in order to motivate all of the different parties to contribute to the transition.

CHALLENGES FOR SWEDEN

Smart electricity networks provide opportunities for new innovation and cost efficiency. In addition, they contribute to a sustainable energy system, higher GDP and more jobs. But what are the challenges? What experiences can Sweden benefit from? Collaboration and alliances are critical. Integrating multiple suppliers and products (interoperability) is effective, but then you have to ensure that they meet standards and are built in a way that allows users to make adjustments and updates. Extensive testing is also necessary before the technology is put into use, which is expensive and time consuming, but it is even more expensive and time consuming to have to redo once the technology is in use.

Sweden has come a long way when it comes to using electricity from renewable energy sources and we have been a pioneer in introducing smart electricity meters. The next step is a transition in the transport sector from fossil energy sources to an electric vehicle fleet, which is currently taking place on a large scale. This in turn places demands on smart electricity grid infrastructure to be able to charge the vehicles' batteries or connect them to the grid. What is needed is standardised infrastructure, support for the industry so that it can invest in technology, plus some kind of stimulus to get the market going. The next step is to ensure that there is sufficient capacity in the electricity transmission system to be able to connect new charging points. To solve this quickly, a great deal of cooperation is needed between different actors. For example, in Stockholm there is an electrification pact with an ambition of having only fossil-free transport within the city by 2030. The pact is led by the City of Stockholm and was initiated together with Scania, Ellevio and Volkswagen. All actors are welcome to participate and work to accelerate the expansion of the city's charging infrastructure to achieve this goal.

Modernising the electricity grid places new demands on education and there is a shortage of experienced and trained staff. Here we must set requirements in terms of educating future engineers in order to develop these competences.

If we succeed in overcoming these challenges, a sustainable electricity grid will enable fossil-free electricity production in the future. In the same way that the internet shaped the development of the entertainment industry through the efficient distribution of media, the electricity grid will facilitate the increase of renewable energy and transform industries and communities giving them secure and flexible access to electricity.

THE WAR AND ENERGY – TOWARDS AN INDEPENDENT EUROPEAN ENERGY SYSTEM

At the time of writing, there is a war in Europe. Russia invaded Ukraine on 24 February 2022. This has major consequences for people, the economy, the supply of energy and food, and much more. Many countries have responded with harsh sanctions against Russia and various forms of support for Ukraine, including healthcare, weapons and energy. Sweden and several other countries are contributing with military support, which is a paradigm shift. This is a situation Europe has not been in since World War II and represents a new era for the world.

On 16 March, the electricity system for Ukraine-Moldova was connected to the European electricity system. The electricity system in continental Europe is the world's largest interconnected electricity system, and includes a number of connected electricity systems, such as the Nordic one, which includes Sweden. Electricity is transported by direct current long distances between different countries. The direct current is then converted to alternating current and connected to the local electrical system. The fact that electrical systems are interconnected means that they work together to maintain stability and balance in the system. This interconnection means that Europe can now support Ukraine with a stable energy supply.

The sanctions against Russia have a major impact on the world's energy supply. Russia holds 40 percent of the world's fossil fuel assets. Before the war, Europe's imports of oil and natural gas from Russia had been increasing for a long time, with the expansion of infrastructure mainly for the transmission of natural gas. Whilst reducing the use of fossil fuels, the focus has been on phasing out oil and coal in the first instance, which has led to an increased use of natural gas. Germany is a telling example here: They were early in shutting down coal power and invested heavily in offshore wind and solar power.

However, this was not enough to cover the country's energy needs and they therefore also invested heavily in natural gas from Russia. With the war, the need for alternative energy sources and increased electricity production from energy sources with low climate emissions has become even more urgent.

The war has clearly shown that it is not just to meet climate goals that a change in the energy system is required. It is also a geopolitical security issue in which Europe and Sweden are now urgently switching to an independent energy supply.

NUCLEAR POWER OF THE FUTURE

Pär Olsson

The neutron – the uncharged particle in the atomic nucleus – was discovered by the British physicist James Chadwick in 1932. After that, it was not long before scientists began to discuss the possibility of releasing energy by splitting atomic nuclei. The first nuclear reactor, the Chicago Pile-1, started operating as early as 1942, but then it was unfortunately the atomic bombs that were dropped in the mid-1940s that really demonstrated the power of nuclear fission. It took until the mid-1950s before this form of energy began to be used for the benefit of mankind, when the first nuclear reactors were connected to the electricity grid to supply society with electricity. Since then, nuclear power has been a controversial source of energy. Important advantages, such as being able to produce large amounts of planable fossil-free electrical energy have been set against disadvantages, such as the risk of accidents, like those in Chernobyl in 1986 or Fukushima in 2011, and how to store dangerous waste products in a way that doesn't expose present or future generations to health risks.

My research is about how we can develop new, sustainable ways to use nuclear power. In this chapter, I want to address some of the most common questions I usually get about current and future nuclear power reactors.

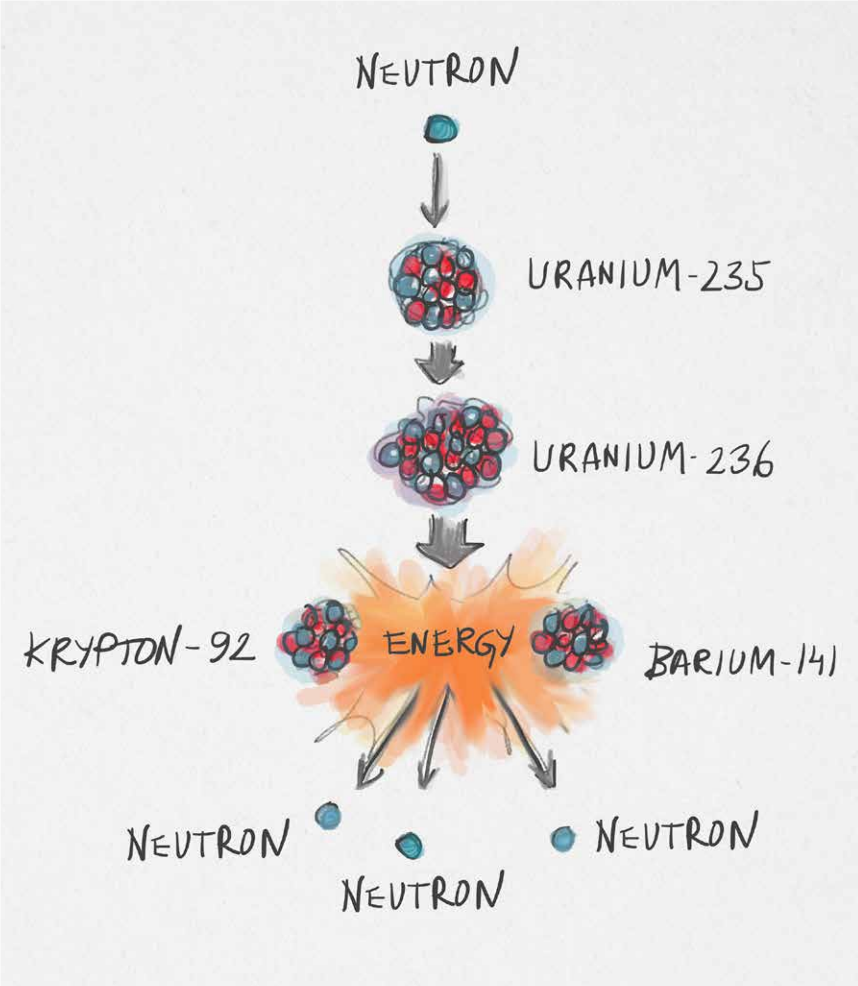
LET'S START WITH: HOW DOES A NUCLEAR REACTOR WORK?

In a nuclear reactor, the radioactive element uranium is used as fuel to release energy. This happens when the uranium nuclei are split with the help of neutrons. The fission creates lighter atoms – *fission products* – as well as new neutrons and releases large amounts of energy (see Figure 1). The reactor is designed so that the number of neutrons is constantly kept in balance, which results in a stable and controlled chain reaction. Several different types of safety mechanisms work together to keep the reactor stable. The passive mechanisms, driven by the laws of physics (e.g. pressure or gravity), not by human intervention, are the most important. The neutrons that do not split uranium atoms can instead be captured in them and those atoms are then transformed into heavier elements. These remain radioactive for a very long time and mean that the spent fuel must be safely disposed of for hundreds of thousands of years before it becomes harmless to humans and nature. However, thanks to the extremely high energy density of uranium, several million times higher than in, for example, coal or oil, the volumes that must be disposed of are relatively small.

IN DISCUSSIONS ABOUT THE ENERGY SYSTEM OF THE FUTURE, THERE IS A LOT OF TALK ABOUT SMR AND "FOURTH GENERATION NUCLEAR POWER" – WHAT ARE THESE?

Small modular reactors, or SMRs, are a collective name for smaller nuclear reactors. They are constructed of standardised parts (modules) that can be manufactured quickly and with high precision in a factory and then transported and installed at the location where the reactor is to operate. These types of reactors have a significantly shorter construction time, are more flexible and at the same time safer to use, thanks to standardisation. Reactors that can deliver between 10 and 300 MW of electric power are usually classified as SMR (in comparison to a conventional reactor such as Forsmark 3, which produces over 1,100 MW).

There are already several smaller reactors in operation around the world that can be classified as SMR. The newest ones are reactors mounted on barges located in Siberia that can be transported to where they are needed. In the United Kingdom and Canada,



▲ *Figure 1:* In a nuclear reactor, uranium nuclei are split using neutrons.

there are long-term plans to develop and build SMRs for a number of purposes. There are about thirty companies around the world, which have reactor concepts at an advanced stage of development.

"Fourth generation nuclear power" is also a collective name for a number of different reactor systems under development. These systems have in common that they should:

- use fuel significantly more efficiently than current nuclear power systems;
- not leave long-lived waste behind;
- be designed so that they cannot cause accidents with serious consequences;
- be economically competitive with today's nuclear power and other types of energy; and
- prevent radioactive substances being used for the manufacture of weapons.

To meet all these requirements, new types of nuclear reactors alone are not enough – other facilities are also required, especially factories for fuel recycling. In these, the spent fuel can be separated into fission products (which become waste) and heavier elements (which can become new fuel). The fourth generation therefore implies a paradigm shift from using the fuel once, to using it multiple times, until basically all available energy is spent.

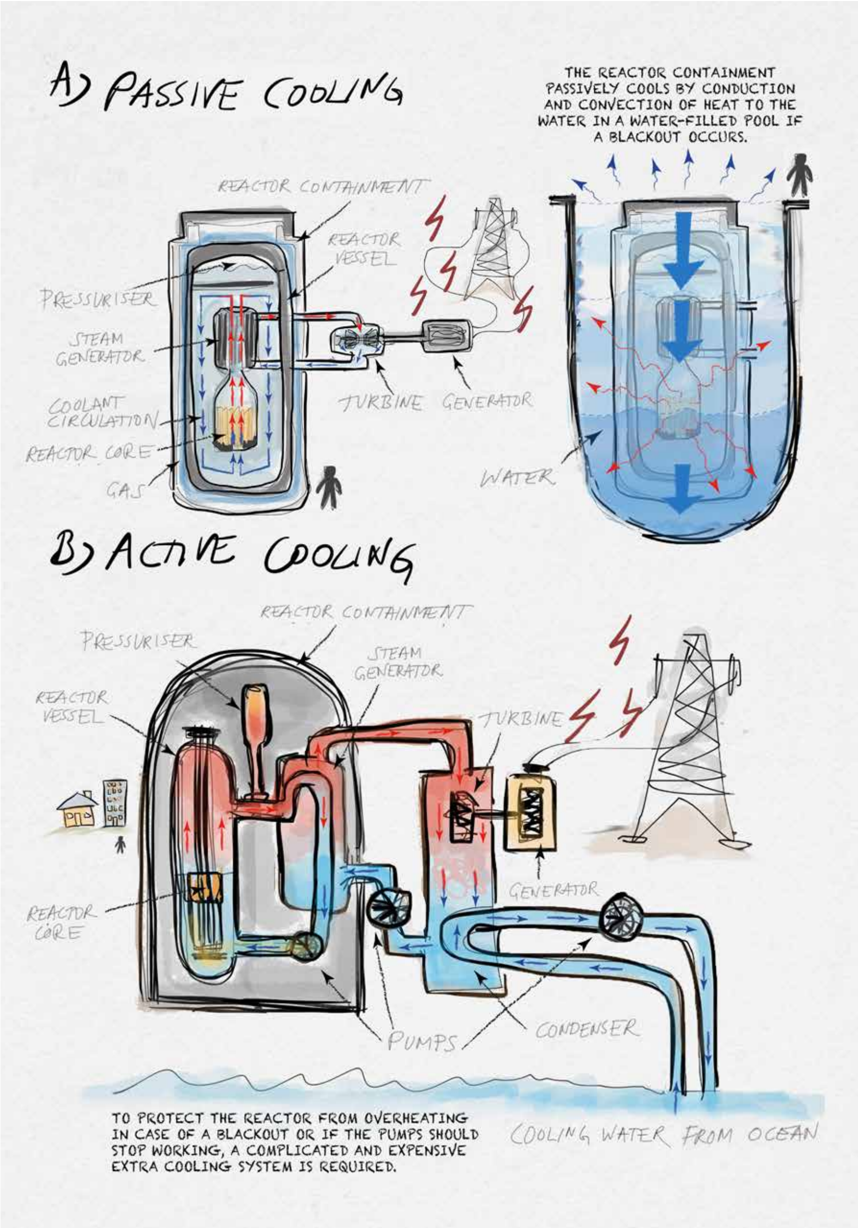
The fourth generation of nuclear power has a longer time horizon, especially as it is not yet economically profitable to recycle the fuel. Various fourth generation reactors both exist and are being built in several countries, but no country has yet decided to build the entire system needed to achieve a circular flow of fuel. If a country decides to invest in such an infrastructure project, it would be feasible within 10–20 years.

In public discussion, it is not uncommon for SMR to be confused with the fourth generation, as a lot of SMR concepts can be used in fourth generation reactor systems. However, there are also many third generation SMR concepts, which will be first to hit the market. At the same time, there are also plenty of different fourth generation reactor concepts that are neither small nor modular.

WHAT ARE THE ADVANTAGES OF SMR COMPARED TO CURRENT NUCLEAR POWER PLANTS?

SMR can be built faster, cheaper and with standardised high levels of safety. They are also more flexible and can be used to produce not only electricity, but also other energy carriers such as hydrogen or electric fuels (combinations of hydrogen and other substances). Many large industries have energy needs, either in the form of heat or electricity, of the size that an SMR can meet. This may open up new future applications and investments in nuclear technology, whereby SMR can supply industries with fossil-free and planable energy in various forms. The fact that they are relatively small and provide a consistent production of energy means that they can supply a stable and secure electricity supply for Sweden in times of global uncertainty. Several smaller power plants in different locations are less vulnerable than if all the reactors are located together in large power plants. From a global perspective, SMR can be used to replace fossil power plants where they are sited ensuring optimal use of existing facilities, such as switchgear, power lines, fire brigades and laboratories.

Another advantage of small reactors is that more parts of the reactor fit inside the internal protective barriers (see Figure 2). This means a simplified design and higher safety levels. Because they contain smaller amounts of radioactive substances than a large reactor, the protective shielding is easier to manage, and any emissions in the event of a serious accident will be smaller. Another advantage is that it is easier to achieve completely passive cooling for SMR than for large reactors. Passive cooling is a very important technology that few ordinary nuclear reactors have today, but for which, in principle, all new reactors are adapted (see Figure 2). On large reactors, complicated and expensive extra systems are required, whereas on a smaller reactor, its large outer surface and smaller volume are better suited for efficient passive cooling.



A) PASSIVE COOLING
THE REACTOR CONTAINMENT PASSIVELY COOLS BY CONDUCTION AND CONVECTION OF HEAT TO THE WATER IN A WATER-FILLED POOL IF A BLACKOUT OCCURS.
REACTOR CONTAINMENT
REACTOR VESSEL
PRESSURISER
STEAM GENERATOR
COOLANT CIRCULATION
REACTOR CORE
GAS
TURBINE
GENERATOR
WATER
B) ACTIVE COOLING
REACTOR CONTAINMENT
PRESSURISER
STEAM GENERATOR
REACTOR VESSEL
TURBINE
GENERATOR
REACTOR CORE
PUMPS
CONDENSER
TO PROTECT THE REACTOR FROM OVERHEATING IN CASE OF A BLACKOUT OR IF THE PUMPS SHOULD STOP WORKING, A COMPLICATED AND EXPENSIVE EXTRA COOLING SYSTEM IS REQUIRED.
COOLING WATER FROM OCEAN

WHAT ARE THE BIGGEST RESEARCH AND DEVELOPMENT CHALLENGES AROUND SMR?

With SMR, the focus shifts from economies of scale (large-scale operations) to a standardisation economy (ready-made "kits") and different countries' regulations are not yet adapted for this. In order for SMR to have a major international impact, a harmonised regulatory framework is needed, so that a reactor that is approved in, for example, the USA can be approved relatively quickly in another country as well. Different national authorities should be able to work together through the IAEA (International Atomic Energy Agency) to create this kind of framework. The SMRs that are based on water cooling, and are similar to today's reactors, could then enter the market and be established within a relatively short time.

Advanced concepts, such as the reactors that are the heart of fourth-generation nuclear power, still require some research. This is mainly about which materials can be used in a sustainable and safe way, but also about how the reactors can be designed to produce different energy carriers (e.g. hydrogen) in a flexible way. It is also vital that their built-in safety mechanisms are tested in prototype and demonstration facilities. In Sweden, there is a relatively collective focus on research and development of SMRs that are cooled with lead. Hot lead is very challenging to handle using current technology, and we are therefore developing and testing various solutions using advanced steels and composite materials.

◂ *Figure 2:* Top: Small reactor (SMR) with passive cooling and more parts inside the internal protective barrier. Bottom: Traditional reactor with active cooling via pumps. The human figure and houses show the difference in size between an SMR and a traditional reactor.

WHAT ROLE WILL SMR PLAY IN MEETING THE WORLD'S GROWING ELECTRICITY DEMAND?

Nuclear energy is an essential part of any scenario for a sustainable society that involves mitigating climate change. Whether it will be SMR or conventional nuclear power (large reactors) that will form the core of this framework is both a political and economic issue. Today, it is mainly in non-Western countries where we are seeing new projects involving large-scale nuclear power, while SMR looks set to gain ground regardless of region and political system. Thanks to its standardised production, SMR has the potential to be significantly cheaper than conventional nuclear power.

As an energy source for humanity, nuclear power is still very young – it has not yet been a hundred years since the idea of splitting atomic nuclei for energy was first raised. Today, research is advancing rapidly and huge leaps are being made in, for example, materials technology for future nuclear power. It is impossible to say what the technology will look like in twenty years. As researchers in nuclear energy technology, we have an exciting time ahead of us.

HOMES IN THE SMART GRID

Cecilia Katzeff

– Coffee?
– Yes, please. And a slice of toast too. It's in the freezer. You probably need to thaw it before toasting it.
– OK, will do. I just need to have a quick shower first.

This is what a morning conversation can look like in an ordinary Swedish household. Not very exciting. But if we read between the lines to identify the use of electricity, it becomes more interesting. The coffee needs electricity to brew and the coffee beans may need to be ground in an electric coffee grinder. The slice of bread is in the freezer, which is powered by electricity, and it might be thawed in a microwave before it ends up in the toaster, which is also powered by electricity. Then, of course, there is the shower, where the hot water probably comes from an electric water heater.

Everyday life in our homes consists of a number of these types of activities. Sometimes it is clear that they involve the use of electricity and energy, while in other cases it is not as obvious. We are consuming energy and electricity only by living in a building. We notice this as soon as there is a power cut. We always consume energy to be able to carry out activities; the consumption is therefore not an end in itself.

The nature of our most energy-intensive activities can change over time. In Sweden, for example, the amount of water we use for personal hygiene is increasing. While previous generations washed once a week, the norm today is to shower every day or even several times a day. Norms change over time, affecting our activities and, in turn, our energy consumption.

HUMANS' RELATIONSHIP TO ENERGY AND HOW IT HAS CHANGED

Let us think about what the introductory morning conversation might have sounded like before we had electricity. Before the coffee could be brewed, we had to cut down trees, split the wood, carry it into the house, and light a fire to heat up the stove. You could feel in your body how much energy was needed to cook a meal. At this time, people had a more direct relationship to energy. As a result of the electricity system, humans' relationship to energy changed radically. As soon as we were able to use electricity for heating, lighting, cooking and transport, we were no longer dependent on using our own physical effort. Today, in our part of the world, both the electricity, and the energy required to produce it, have become invisible. However, in other societies the relationship to energy is still quite direct.

A few years ago, my family and I hosted some visitors from Zimbabwe. I told them that my work involves trying to make electricity consumption visible, because electricity is so invisible. They were interested but didn't agree at all. At home in Zimbabwe, the power often gets cut off – and for a long time – and each time they become painfully aware that they have been using it. The non-existence of electricity makes it tangible and becomes the proof that it exists. By scheduling the supply of electricity to about six hours per day, the state-owned Zimbabwean electricity company is trying to make it easier for people to plan their electricity consumption. Unfortunately, the company is often unable to keep to the

‣ *Figure 1:* In a society without electricity, people have a more direct relationship to energy.

scheduled times. The unpredictable availability of electricity means that my friends have to plan their everyday lives in a completely different way than we do. They need to take the opportunity to wash, iron, cook and charge computers when they have electricity, fully aware that it will shortly become unavailable again.

As illustrated by the example above, our everyday lives are greatly affected by the political and technological environment that surrounds us. The electricity system is usually called a socio-technical system – a system that includes both people and technology. From having been constructed in much the same way for over 100 years (see the chapter on energy in a historical perspective), the system is now changing. Two challenges that have spurred this change are, firstly, that we need to reduce the use of fossil fuels and increase renewable energy sources for electricity production; and secondly the increased use of electricity in society. By combining research and innovation in digital technology and the electricity system, a new kind of electricity system has been created. This 'smart' electricity grid means a new socio-technical system with new expectations on us as citizens. Through new services and technology, our electricity consumption can become more visible. A positive consequence may be that it recreates a more direct relationship to energy. But smart grids can also have disadvantages, which we need to be aware of.

THE ELECTRICITY SYSTEM OF THE FUTURE – SMART GRIDS

Smart electricity grids can both collect and act on information to manage the demand and supply of electricity. They will bring a radical change to our society's electricity consumption when fully introduced. By being connected to renewable energy sources, such as solar and wind power, they form a good foundation for a sustainable transformation of the energy system.

Renewable energy sources mean that the electricity supply becomes weather-dependent and sometimes inconsistent. At the same time, the electrification of society is growing, which puts increased demands on the electricity grid. The load on the electricity grid is higher at certain times of the day than others. In order for the electricity system to be able to withstand the load and deliver the electricity needed to the whole community, flexible electricity consumption is needed. Here, private households have a key role to play, as, in the future, the balance in the electricity grid depends on households' electricity consumption becoming more adapted to the capacity of the grid.

SMART GRIDS

- use *digital* technology to collect and act on what is happening in the electricity grid.
- can integrate *renewable energy*, such as solar and wind power, into the system.
- are flexible and can *balance the load* in the power grids so that electricity consumption is adapted to the amount of electricity being delivered.
- make electricity consumption visible to households via technology that *visualises, automates and controls* their electricity consumption.
- *increases the vulnerability* of the electricity system.

WHAT ARE THE EXPECTATIONS/REQUIREMENTS THAT WILL BE PLACED ON HOUSEHOLDS/PEOPLE IN THE SMART ELECTRICITY GRID?

On page 125 (top) is a picture of a person in a smart home. The home has sensors that detect what is happening in the room, such as presence, motion and automatic temperature functions. There are also displays where people can check their energy consumption and get information, for example, about future electricity prices so that they can adapt their activities in the home accordingly. But what kind of image is conveyed about the person in this smart home? Personally, I am struck by how clean and tidy it always is in these future scenarios and how good the people who live there are expected to be at managing these new smart technologies. The Australian sociologist Yolande Strengers believes that the new energy systems simplify the image of a person into a rational and masculine individual. This individual is interested in their own energy consumption, understands it in detail, and wants to track it and control it in a rational way based on information about costs, kilowatt-hours and environmental impact. Strengers calls this type of person a 'resource man'.

But how might new technologies be designed for more normal and less perfect homes like the one on page 125 (bottom), which in addition to adults also includes children and pets? How can technology take into account a less efficient way of living, characterised by slowness instead of speed? Yolande Strengers is critical of the vision she calls "smart utopia". It distorts the social context of which technology is a part. We need to deal with the pile of dirty laundry, cook dinner for a hungry family, and juggle work and leisure in our home environment. We need to understand that social and behavioural changes cannot take place simply by providing households with data and technology.

ACTIVE OR PASSIVE HOUSEHOLDS

In discussions about households' energy consumption and smart electricity grids, there is often talk of active users. What does this mean? And why is it important? Producing your own electricity sounds active, but the activity may stop once you have installed the electricity supply. Adapting your activities to when the electricity

▸ *Figure 2:* The image of the smart home often does not correspond to the chaotic reality. How can technology be designed to work for even the most unorganised households?

supply is best also sounds active. But living in a home controlled by automated processes sounds pretty passive.

My colleagues, design researchers Karin Ehrnberger and Loove Broms, interviewed people in different households about their energy consumption. As part of the study, they visited their homes to identify spaces associated with energy consumption. It turned out that some energy spaces, such as electricity and water metres, were well hidden from most people in the household. They were often found in the corners of basements or garages, spaces that have traditionally been used more by men than by women. When energy metres are located in these spaces, they are therefore not equally accessible to women and children. As the meters were not so aesthetically pleasing in their design either, it was good for them to be out of sight. My colleagues asked how electricity meters could be designed to fit nicely in rooms occupied by more members of the household and how the information could be presented to make it more accessible to more people.

The Energy Aware Clock on page 127 is one of the results of this. It was designed to visualise information about electricity consumption in a new way. The clock metaphor signals to the household to place energy consumption centre-stage, in a central and shared place such as in the kitchen. Just like a kitchen clock that is accessible and easy for all members of the household to use.

CHALLENGES THAT RESEARCH IS ADDRESSING – THE NEXT STEPS

A general challenge associated with smart electrical systems is finding a good balance between automatic and user-controlled systems. Automatic systems reduce the need for households to be active, but can also lead to difficulties in complex situations that arise in everyday life. One dilemma could be about handing over control of the home's heat pump or other electrical equipment to an electricity company. To increase capacity in the electricity grid during certain times, the company would 'borrow' from the household's flexibility

▲ *Figure 3:* The Energy Aware Clock is designed to make information about a household's electricity consumption more accessible. Design: Loove Broms and Karin Ehrnberger and the household's electricity consumption would be automatically reduced at times when the capacity of the electricity grid needs to be increased. This type of control is already being used within industry, but so far only on a small scale for private households. It is of course good that households can contribute electricity that is not needed in the home to boost the wider electricity grid as well as use electricity from renewable energy sources. But it is also important to understand how households are affected by this type of strategy. Here, research can play an important role in answering questions about everything from how households should be compensated for lending their flexibility to what happens in terms of privacy and vulnerability when someone outside of your home takes control over your building. What risks arise when households no longer have control over, nor can understand, their home's technical system? How does it affect people's trust in the energy system, and in energy companies and businesses developing other energy services? We also need to better understand how citizens can have a say in the development of energy systems, so that both environmental and social aspects are taken into account.

THE INTERNET OF THINGS

Carlo Fischione

The Internet of Things (IoT) is a technology that makes it possible to connect the Internet to physical objects, information and communication systems, or even the human body.

For example, let's have a look at our future homes, where *sensors* in the electricity system can monitor our energy consumption or how we use appliances such as refrigerators, freezers, and stoves. The sensors can *transmit* the information over the Internet to a monitoring centre, where our energy consumption patterns are *analysed*. We can also imagine that somewhere on the Internet there will be an artificial intelligence algorithm that – based on the analyses of the data from our and other people's homes, electricity production sites, and the price of energy – will give us *feedback* on how to use energy in a more sustainable manner. For instance, the algorithm may tell us that at a certain time of day, the electrical energy is being produced by sustainable sources, whereas at other times it is being produced by coal. Based on this information, we could decide to use more, or less, energy at different times of the day. We can also imagine that in the future, the artificial intelligence algorithms could be placed in the sensors themselves. This way, the sensors become capable of running advanced algorithms that currently demand huge computational capabilities. The sensors would be communicating with each other over the Internet, and also with the units that produce energy. Together, they could make all the decisions to use energy in a completely automatic manner. Moreover, in this future, we could have local energy production at our homes, using

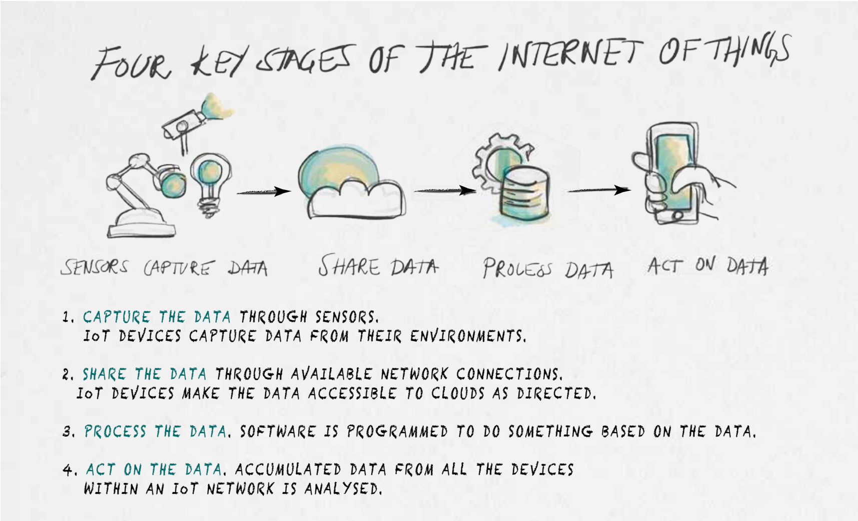
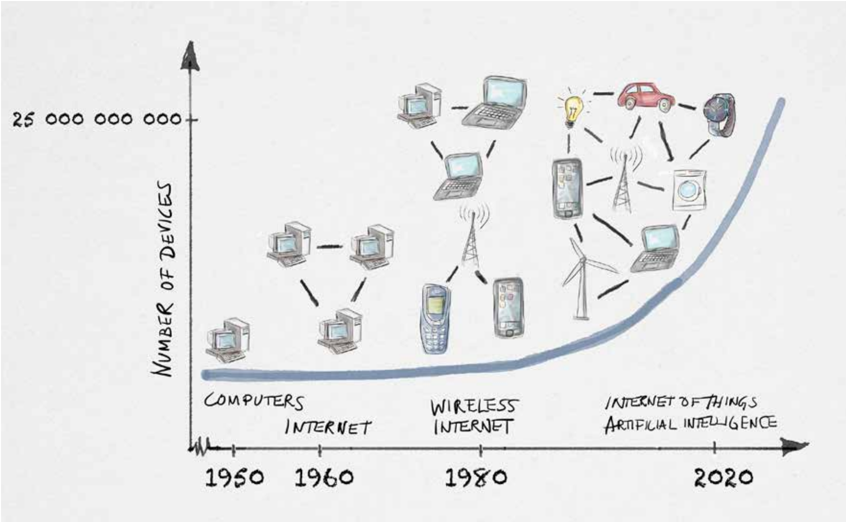


Figure 1: The four key stages of the Internet of things.
Source: https://www.sap.com/uk/insights/what-is-iot-internet-of-things.html.

windmills or solar panels. We could then decide whether to use the produced energy ourselves or to sell it to others.

For all this to be possible, we need the Internet of Things as a coordinating communication and decision-making infrastructure.

The IoT is a complex technology that consists of sensing devices that can collect data and communicate over the Internet with other devices, as well as with monitoring and control centres. It is a composition of data collection units, communication technologies, artificial intelligence technologies, and actuation technologies to carry out the decided actions. In energy systems, the goal of the IoT is to make the overall systems more sustainable. These include both small-scale systems (e.g. our home) and large-scale systems (e.g. entire cities, and regions), with thousands of sensors covering large geographic areas. Other examples of such large-scale systems are drinking water production and distribution, smart city monitoring

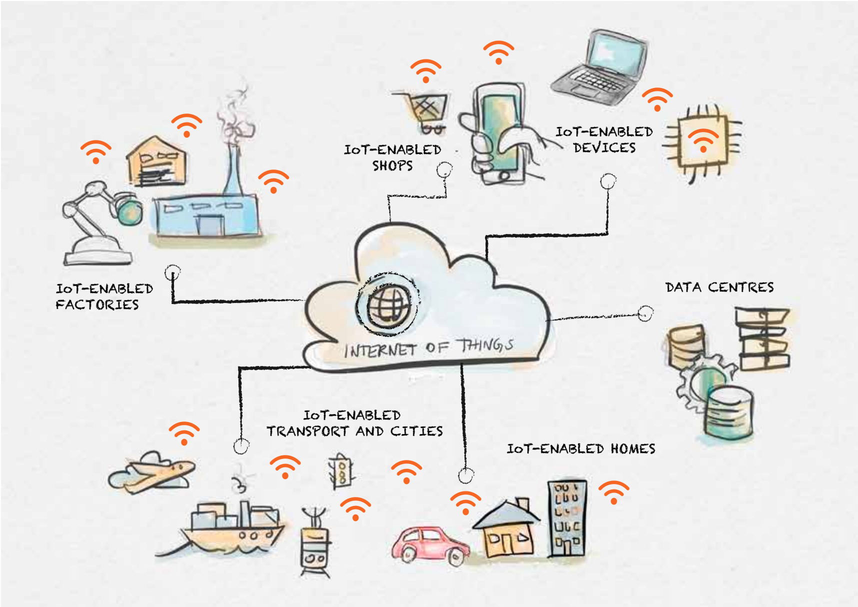


▲ *Figure 2:* The number of connected data collection devices is growing rapidly.

(e.g. traffic, pollution), and agriculture monitoring. Apart from our individual houses and apartments, small-scale system examples also include human body monitoring (e.g. of blood pressure).

Academic researchers first proposed the idea of the Internet of Things in the mid-1990s. It took more than 20 years before the fundamental aspects had been investigated and the idea was ready to make an impact in the real world. Today, IoT is having a major commercial impact in the order of several billion Euros per year. An important component that is making IoT more and more successful and widespread is 5th generation wireless cellular systems (5G). Through 5G it is much easier to connect data collection devices to the Internet. Researchers believe that in 2025, 5G will support tens of thousands IoT devices *per square kilometer*, totalling 50 billion devices around the world.

This development will make us more and more reliant on IoT technology. Many positive applications will be enabled for people



▲ *Figure 3:* Internet of Things technology is used for many purposes in several sectors.

and society in general, but there are also potentially some negative consequences. In principle, devices monitoring a smart city or an apartment can track our behaviour or choices, and this information could be used to influence our behaviour. Such considerations fall within privacy protection. But there are also security aspects to be aware of. What if the IoT devices were hacked by an attacker who injects false data into the system? What if the technology was modified so that, for example, some IoT devices were worsening the use of energy, instead of improving it? These are essential questions for us to consider if we want to make IoT technology both reliable and trustworthy. To date, technical research has already come up with several protective solutions, but more research is needed. For the time being, however, the positive effects introduced by IoT in our lives are overwhelming compared to the potential threats.

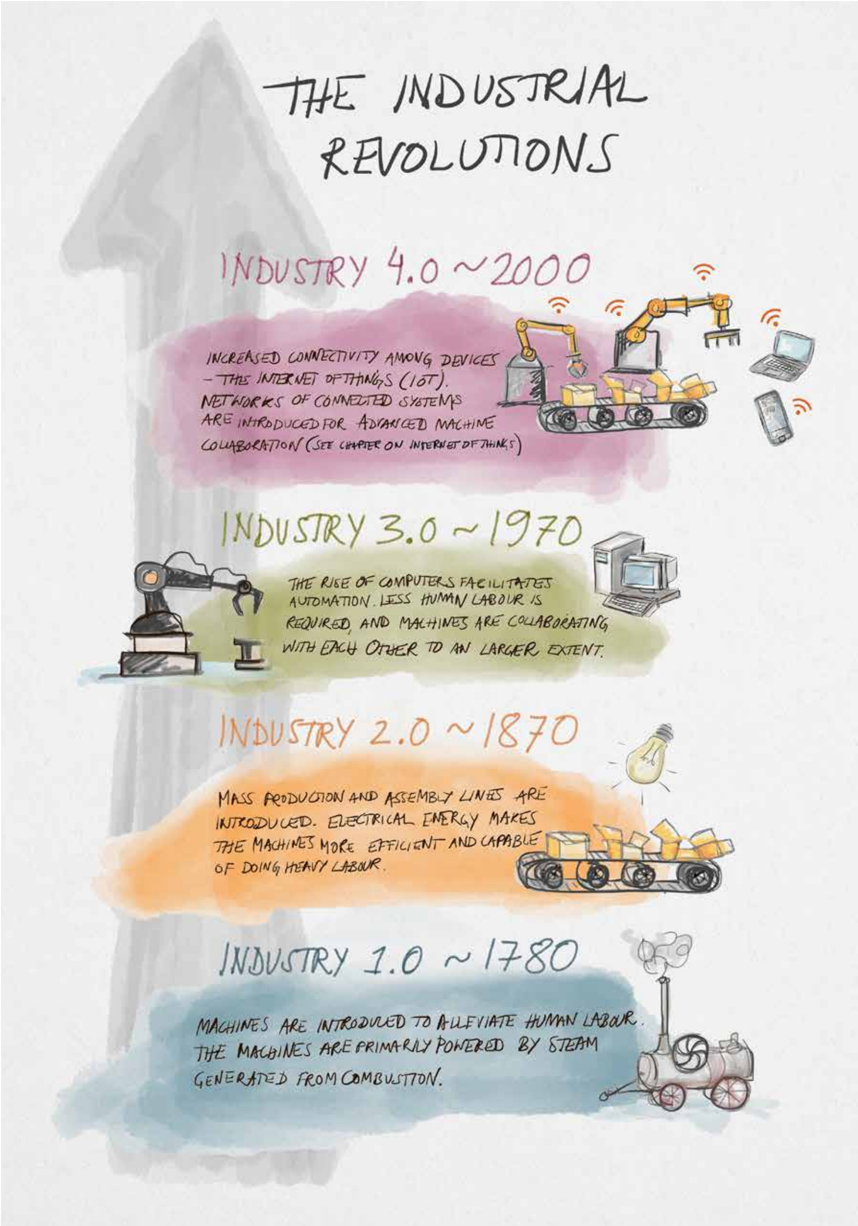
CYBER SECURITY IN THE ENERGY SYSTEM

Fredrik Heiding

Modern infrastructures are undergoing rapid digitalisation, often referred to as the fourth industrial revolution or *Industry 4.0*. In this technical revolution, connectivity is increasing drastically and devices that were previously analogue and isolated are becoming digital and connected to the internet. The energy sector is not an exception to this trend – on the contrary, it is an important part of the revolution. New trends within the energy sector are changing how electricity is produced, distributed, and consumed. Traditional power grids are transformed into *smart grids*, digitalised, and highly connected versions of the traditional power grids (see chapter on power grids). Individual households are also connected as smart metres are installed in more and more homes. By using small-scale wind or solar power to produce energy, consumers are becoming "prosumers", contributing to the smart grid with home-produced power (see chapter on homes in the smart grid).

These changes bring many advantages, but they come with a risk: The communication channels added for the connectivity can be used by malicious actors wanting to get unlawful access to the system. As systems are getting digitalised and connected, they are becoming more exposed to cyber-attacks. Such cyberwarfare is becoming a central part of the modern world, where organisations within the energy sector are some of the most promising targets for attackers.

When my colleagues and I interviewed 15 cyber security officials from various energy organisations in Europe, we found that almost


THE INDUSTRIAL REVOLUTIONS
INDUSTRY 4.0 ~ 2000
INCREASED CONNECTIVITY AMONG DEVICES – THE INTERNET OF THINGS (IOT). NETWORKS OF CONNECTED SYSTEMS ARE INTRODUCED FOR ADVANCED MACHINE COLLABORATION (SEE CHAPTER ON INTERNET OF THINGS)
INDUSTRY 3.0 ~ 1970
THE RISE OF COMPUTERS FACILITATES AUTOMATION. LESS HUMAN LABOUR IS REQUIRED, AND MACHINES ARE COLLABORATING WITH EACH OTHER TO AN LARGER EXTENT.
INDUSTRY 2.0 ~ 1870
MASS PRODUCTION AND ASSEMBLY LINES ARE INTRODUCED. ELECTRICAL ENERGY MAKES THE MACHINES MORE EFFICIENT AND CAPABLE OF DOING HEAVY LABOUR.
INDUSTRY 1.0 ~ 1780
MACHINES ARE INTRODUCED TO ALLEVIATE HUMAN LABOUR. THE MACHINES ARE PRIMARILY POWERED BY STEAM GENERATED FROM COMBUSTION.

all of them believed cyber-attacks on the energy sector would increase in the years to come. Since the energy sector is such a lucrative target, governments around the world are secretly spending massive resources on training cyber-attackers. For the energy sector, it is essential to continuously enhance cyber-defences to stay on par with the increasingly competent attackers. A commonly recurring problem is that power plants deal with many OT (Operational Technology) devices. OT devices use a combination of hardware and software to monitor or control various parts of an industrial complex. One such example are sensors that monitor the smart grid to track production metrics or other statistics. Safety and availability (to ensure that the operation continues to do what it is intended to do without interruption) are often heavily premiered for OT devices. Because they are generally good at maintaining safe operability, many of them can have a considerably longer lifespan than modern systems and software. This poses a cyber security problem as the devices may rely on old technology with poor security standards. Some OT units have a life span of more than 20 years; to ensure cyber security for such a long time is almost incomprehensible. Another pressing concern for the energy sector (as for many other sectors) is attracting personnel with adequate cyber security competence. Many organisations in the energy sector are planning to scale up their cyber security divisions but finding new co-workers with the right skill sets is a challenge.

Finding examples of cyber-attacks on the energy sector, on the other hand, is easy; some of which have had profound consequences. The attacks can be launched for different purposes and come from a variety of actors with different agendas. Some attacks are made to obtain financial gains. Ransomware attacks are a good example, where the attacker encrypts the target company's devices

◀ *Figure 1:* The industrial revolutions.

so that they cannot be accessed unless a ransom fee is paid. The Norwegian energy producer Hydro was targeted by such an attack in 2019, causing loss of production and other damages worth more than 70M USD. It has not been established who was responsible for the attack.

Other attacks are made to disrupt operations or destabilise critical societal functions. An example of this is the Stuxnet malware that targeted systems of an Iranian nuclear refinery, causing severe disruption to the production and operations of the facility. The malware was discovered in 2010 and although it is hypothesised that America and Israel were behind the attack, no country or group has accepted responsibility.

Tracking the origin of cyber attackers is hard as skilled hackers have many ways of hiding or falsifying their tracks. This can be done in many ways, for example by using a style of code and attacking that is traditionally associated with another hacking group. This causes major problems for crime investigation as it can give the impression that an innocent group was responsible for the hack.

Another disruptive cyber-attack was the infamous BlackEnergy malware. The attack was carried out in April 2022 rendering over 30 substations of a Ukrainian power plant unavailable, and leaving 200,000 Ukrainian citizens without electricity for up to 6 hours. The malware was used in conjunction with phishing emails (falsified emails that often contain links to malicious content). Fortunately, the attacked power plant was not fully digitalised and had several manual fallback systems to continue operations. This was crucial for the plant's ability to swiftly regain control of operations. If the powerplant had been fully digitalised (as many modern power plants are) the power outage could have lasted far longer. In contrast to the Stuxnet malware, the BlackEnergy attack is officially acknowledged to have been launched by Sandworm, a Russian hacker group believed to be financed by the Russian government. Disruptive attacks like Stuxnet and BlackEnergy are often associated with government-sponsored hacking groups.

While there is no single solution to all cyber security problems affecting the energy sector, several actions can be taken. Attackers often take advantage of different vulnerabilities in the system they are attacking. Such vulnerabilities can be likened to cracks in a wall, secret passages, or weaknesses that provide a way into the system. Proactive vulnerability testing (penetration testing) of systems and users is therefore important for securing future systems. Penetration testing means assuming the role of an attacking hacker, and traditionally involves several stages.

1. *Reconnaissance*: gathering information about the target, for example reading reports, open-source code, documentation, and online information.
2. *Scanning:* probing the system to find potential attack paths that can be further exploited.
3. *Exploitation:* using various hacking technologies to get a foothold into the system via the paths discovered during the scanning phase.
4. *Privilege escalation:* when hackers have secured access to a machine through an unknowing user, they may elevate the privileges of the user, for example, moving from a guest user account to an administrative user account. This allows the attacker deeper access to the system.
5. *Post-exploitation:* after successfully getting into the target system, hackers may leave malware in the infiltrated system that can communicate back to their own systems, providing information, or allowing them to initiate a new attack at a later point in time. Hackers also want to cover the tracks of their attack.

Testing Operational Technology (OT) environments is somewhat different from traditional penetration testing, as the OT environments can include complex physical machinery that is hard to simulate in a test environment. Performing tests in the real production environments is generally not recommended as it could risk harming the actual production line. This could be solved by installing test machinery that simulates the real OT environment, but as the machinery is often expensive and complex, this might not be feasible.

This type of active vulnerability testing helps us to better understand the inherent weaknesses of the systems, which allows us to become better at defending ourselves. Today (and for an unforeseeable future) there are numerous unknown vulnerabilities in all kinds of products and systems – including those used in power production facilities. Active vulnerability testing of these devices is one important part of enhancing the cyber security of the energy sector, ensuring that technological advancements are built on a solid foundation.

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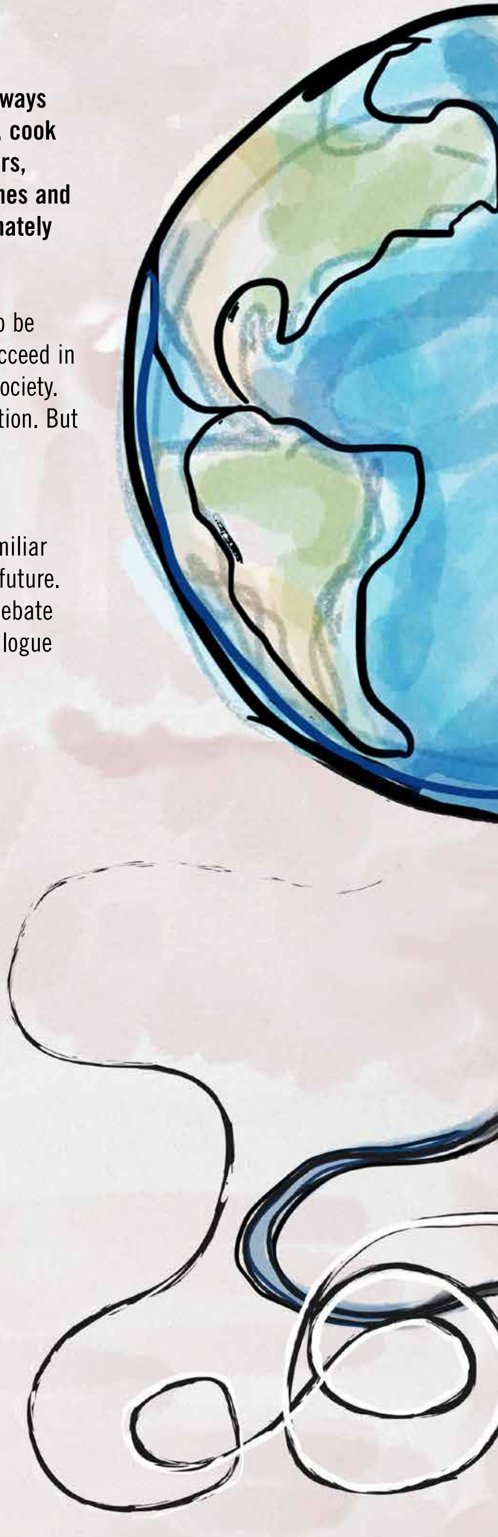
Energy is everywhere. We just assume that it will always be there whenever we need to warm up our houses, cook dinner, use our computers, mobile phones, escalators, X-ray machines, tower cranes, buses, trains, airplanes and cars. It is a given, yet often invisible – and unfortunately unsustainable part of our lives.

Today we know that the global energy system needs to be transformed to its core. This is crucial if we are to succeed in tackling climate change and creating a sustainable society. And we all have important parts to play in this transition. But how do we change something that we cannot see?

In this anthology, some of Sweden's leading energy researchers share their views on familiar and less familiar challenges and solutions regarding the energy of the future. The aim is to stimulate discussion and constructive debate so that we can address the challenges in an open dialogue where facts and knowledge shape our future.

The book is written by researchers affiliated with the **KTH Royal Institute of Technology Energy Platform**, in collaboration with the non-profit organisation **VA (Public & Science)**.



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