A sustainable energy supply for everyone

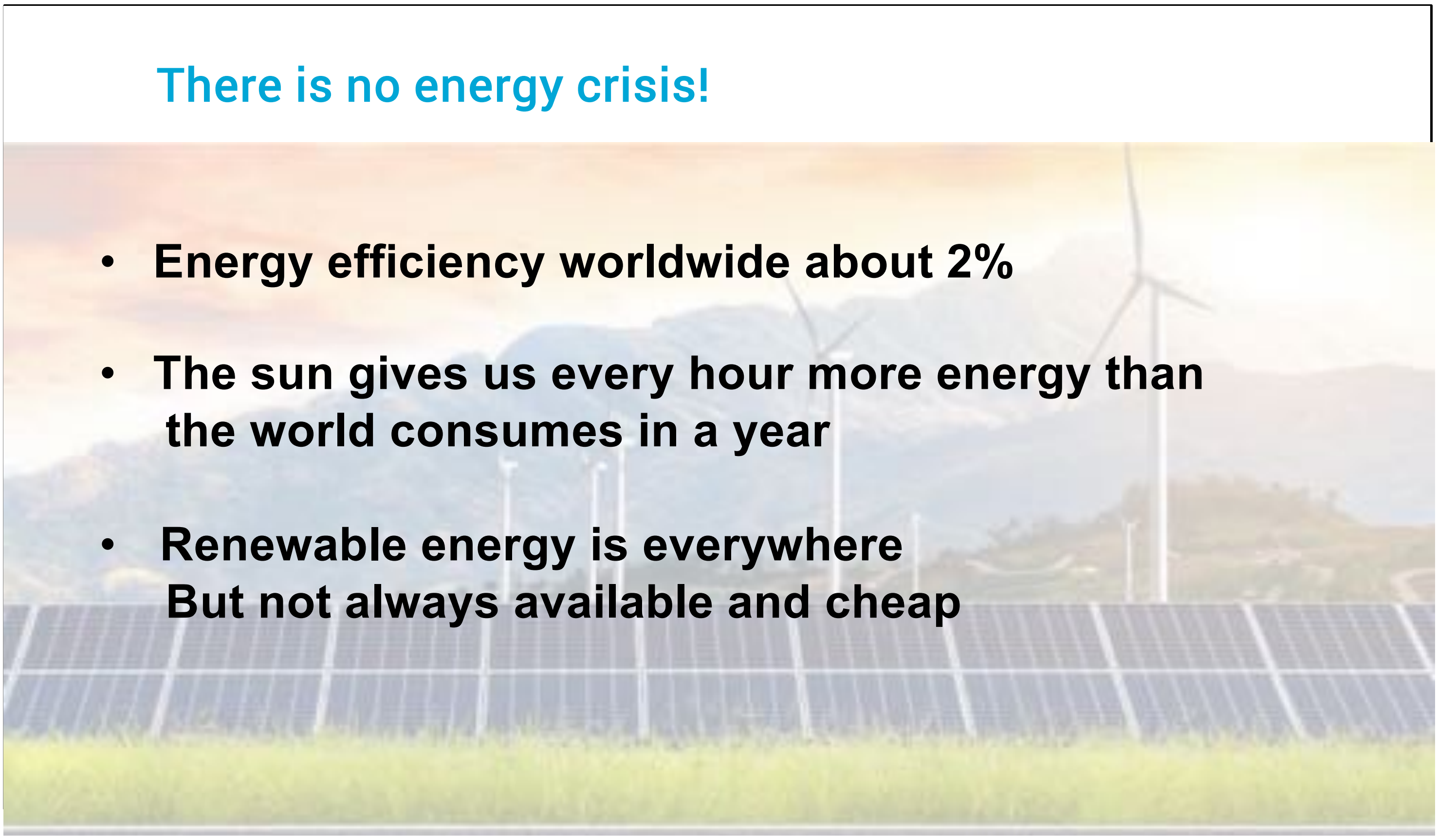
Ad van Wijk, 27-10-2023

TU Delft

Dear People, I am honoured to see you here in Delft at my farewell speech. For me it feels strange to give this farewell speech, because my chair is about Future Energy Systems. How can you ever say farewell to the Future? Therefore, I hope, even after this farewell speech, to contribute to the future and my mission ‘A sustainable energy supply for everyone’

My mission is the title of my speech today, but it was also the title of my inaugural speech that I held almost 12 years ago. What has changed in this 12 years? How can we realize A sustainable energy supply for everyone? And did we make some progress ?

In this farewell speech I will take you on a journey from the past to the future in future energy systems research.

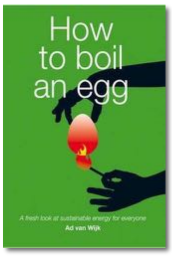


I started my inaugural speech 12 years ago, with this three observations;

- energy efficiency worldwide is about 2%,
- the sun gives us every hour more energy than the world consumes in a year,
- renewable energy is everywhere but not always available and cheap.

In this 12 years a lot has changed. We have made tremendous technology progress, which is very hopeful. Let me give you for every of these 3 observations an example of the changes.

How to boil an egg?



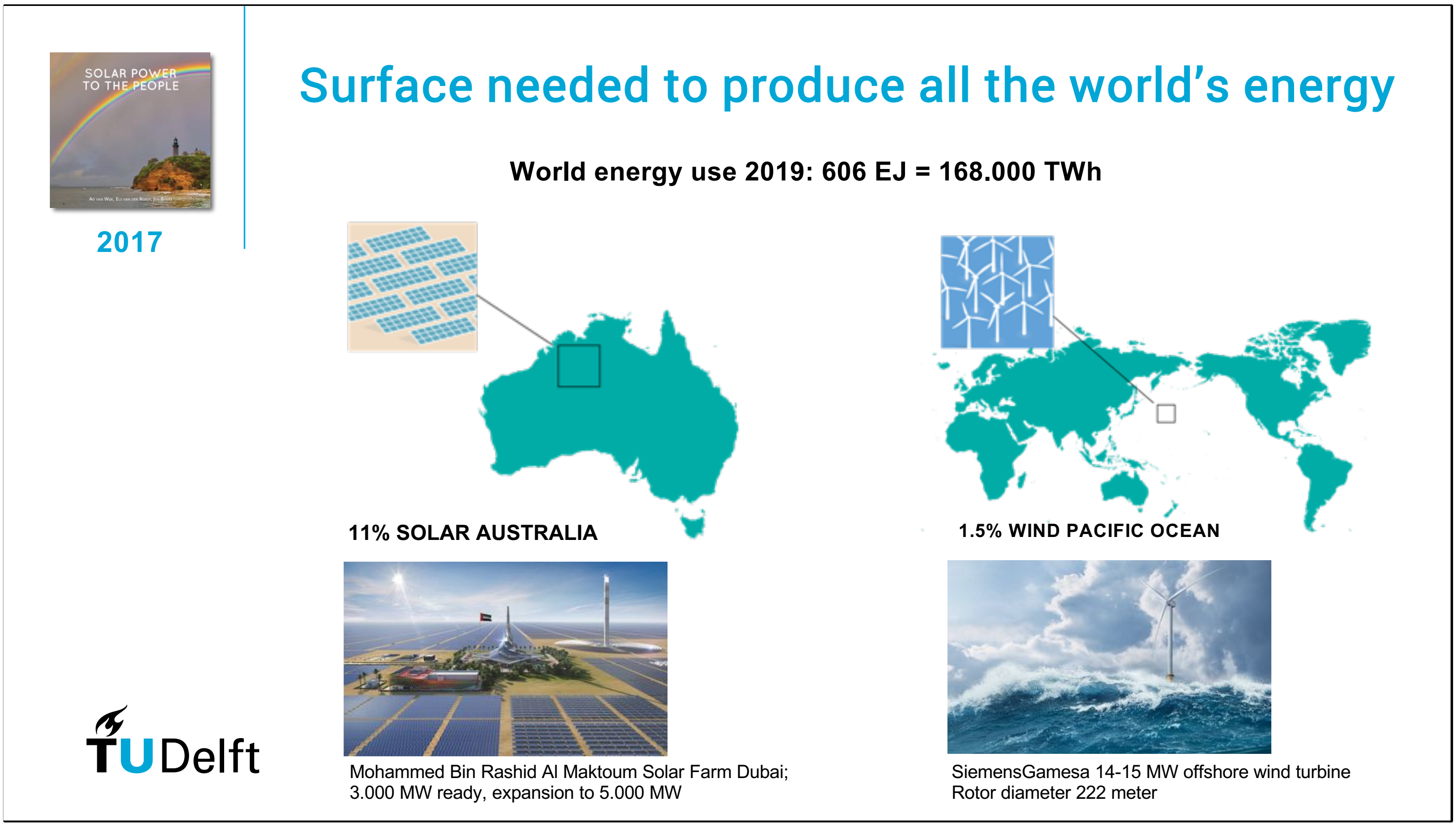
2011

First of all, the observation that energy efficiency is only 2%. Why is that so low? In my book how to boil an egg, I gave examples to show that the energy efficiency is very low, due to energy system losses.

Let me give you the example of boiling an egg. What do you do? You put water in a pan, put the pan on a stove, boil the water, put the eggs in the water and you get a soft-boiled egg in 5 minutes or a hard-boiled egg in 10 minutes time. And afterwards you throw away the hot water in your sink. But especially boiling the water has cost you most of the energy. It is therefore not the efficiency of the stove that determines the system energy efficiency, but it is especially the amount of water that you boil. In other words, there is next to technology efficiency losses also a lot of energy system losses.

12 years ago, I told you this story and tried to develop some solutions to get rid of the water. But to boil an egg in a microwave turned out to give a lot of mesh. However, new technology has entered the market, the air fryer. And in an air fryer you can boil an egg without using any water.

Energy technology efficiency improvement has been impressive over the past 12 years. But in many cases the energy system losses are still there or do even increase.



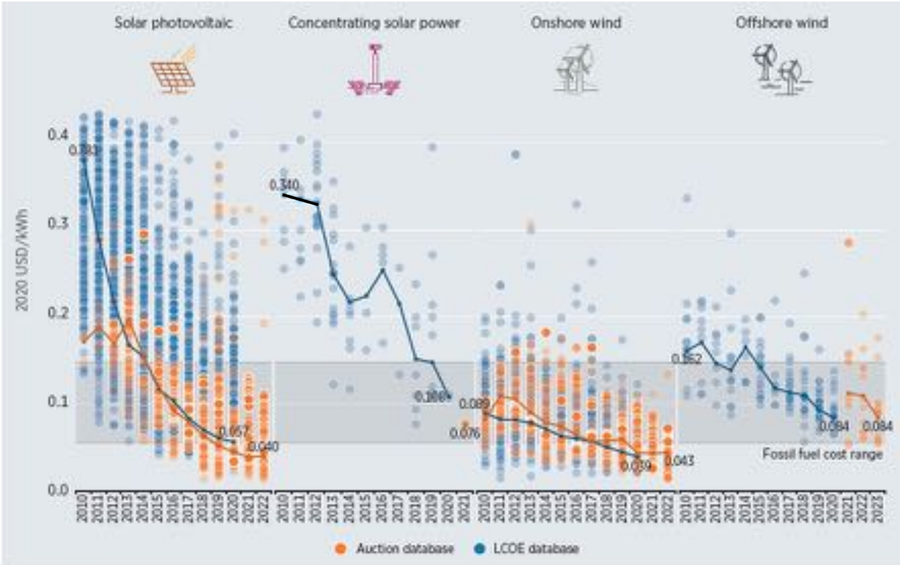
The second observation is that the sun gives us every hour more energy than the world consumes in a year. As you probably know, the energy from the sun is the driving force for almost all renewable energy such as wind energy, hydropower, biomass and wave energy. Over the past 12 years, renewable energy technology, especially solar and wind, has developed tremendously.

In 2019 the world's energy use was 168,000 TeraWattHour (TWh) or 168,000 billion kiloWatthour (kWh). This is all the energy use for industry, transport, heating and cooling and electricity.

If we install modern solar and wind technology and we calculate how much space we need to produce al the world's energy, it is not much. Using 11% of Australia's surface for solar energy production, is enough to produce all this energy. Or when we install large floating wind turbines, with a distance of 1.5-2 km from each other, we need about 1.5% of the Pacific Ocean surface.

So, there is more than enough renewable energy for everyone.

Over the years steep decrease in solar and wind electricity production cost



Source: IRENA Renewable Cost and Auction and PPA Databases

IRENA, "Renewable power generation costs in 2020," https://www.irena.org/publications/2021/Jun/Renewable-Power-Costs-in-2020

And there is more good news. Over the past 12 years the solar and wind electricity production cost have come down dramatically. In this graph from IRENA, we see the Cost of Electricity on the Y-axis and the years on the X-axis, for four technologies, Solar Photovoltaic (PV), Concentrating Solar Power, Onshore wind and Offshore Wind. Every of these dots represent a large solar or wind farm.

There has been a dramatic decrease in production cost over the years, showed by the black lines in this graph. Today we can produce at good locations with solar panels, electricity for 1-3 Eurocent per kWh and with wind for 2-4 Eurocent per kWh. This is even lower than electricity production cost from fossil fuels.

So, renewable electricity is not expensive anymore, no, at good locations, it is even cheaper than fossil fuel electricity!

Future Energy Systems, the Past

Easter morning 1900: 5th Ave, New York City. Spot the automobile.

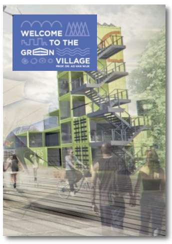
Easter morning 1913: 5th Ave, New York City. Spot the horse.

Overall, in 12 years time we have made progress in energy technology efficiency improvement, although the energy system losses are still a hurdle to take. Solar and wind have become cheap sources of clean electricity. And there is more than enough space on earth to produce all the renewable energy we need.

That is good news, but we have not realized a sustainable energy supply for everyone yet. Maybe you think, we never can change fast enough. However, history shows us that a fast technology and system change is possible, as this famous picture shows. In 13 years time the transport sector changed from horses to cars or in other words form bio-horse-power to oil-horse-power.

But, what have we contributed to a sustainable energy supply for everyone? Let us have a look into the achievements of our future energy systems research over the past 12 years.

The Green Village TU Delft; Field Lab for Sustainable Innovation



2013

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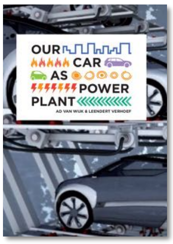
When I started at the TU Delft in 2011, I was introduced by Chris Hellinga into the TU Delft energy research community. He told me that there were about 700 scientists at the TU Delft doing energy research. He gave me a list of about 150 scientists that I certainly had to speak. That was an impossible task to speak with 150 scientist. So, I restricted myself to 20 people and learned a lot.

I learned that the energy research at TU Delft is fantastic, sometimes amazing and world class. But I learned also that it was disciplinary technological research. And I learned also, that the visibility of this research to the outside world was limited.

Could I develop a plan to integrate this great TU Delft energy research into application and system research and at the same time make it visible for the outside world. So, we developed a plan to realize 'The Green Village' at the TU Delft campus.

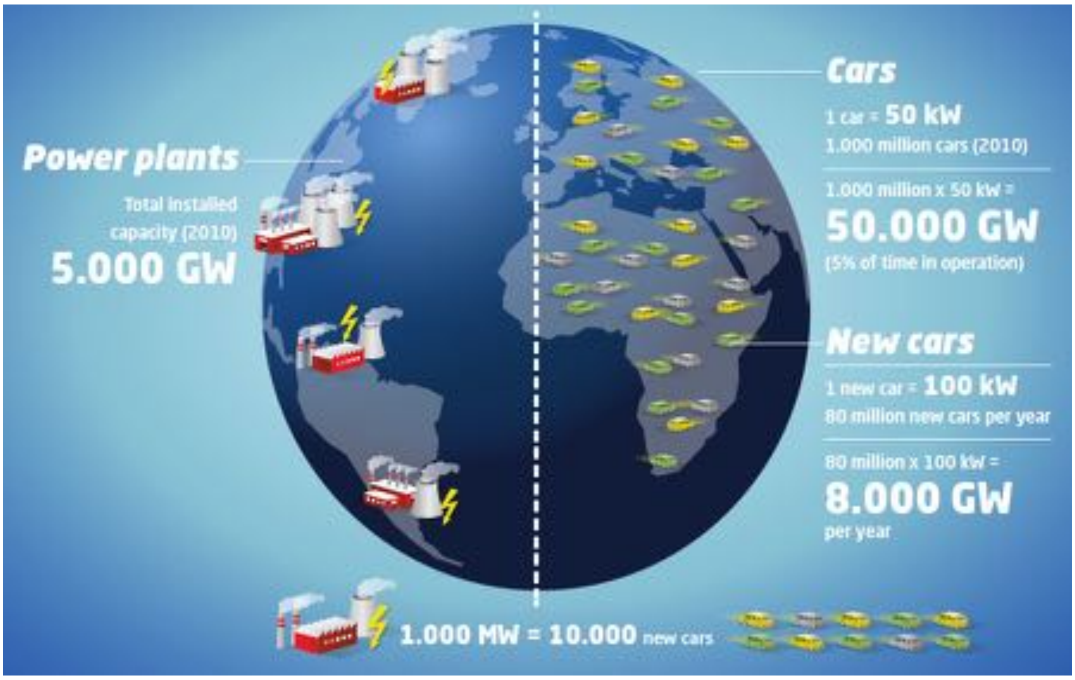
It was not an easy job, but finally it took off. It is now a vibrant area where a lot of interesting system research is conducted. Many events, workshops, training and courses are organized at the Green Village. And it attracts many visitors from all over the world.

I hope you have had the opportunity to visit the Green Village during lunch time.



2014

Our car as Power Plant



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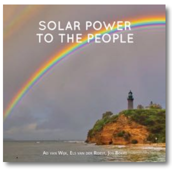
At the same time we started system research into fuel cell electric vehicles, fuelled by hydrogen. The idea is that these fuel cells could also provide power at moments that there is not enough renewable electricity available. After all, fuel cells are efficient power plants without any emissions to the environment.

We realized at the Green Village a fuel cell car that delivered electricity to one of the houses. For this we developed an electricity outlet at a fuel cell car. The first electricity outlet on a fuel cell car in the world ever.

When we now look to car statistics, as you can see on this slide, we learn that fuel cell electric vehicles can take over all the power plants in the world. Every year in the world about 80 million new cars are sold. This represents a capacity of about 8,000 GW. The installed capacity today in fossil power plants is 4,500 GW. So in one year we buy on the road, almost two times the total electricity production capacity installed in all fossil fuelled power plants world wide.

Of course not every car will be a fuel cell electric car. There will come a lot of battery electric cars on the road too, which can offer short term flexibility in the electricity system. But the fuel cell electric cars can offer large scale and long term power supply at any moment we want.



2017

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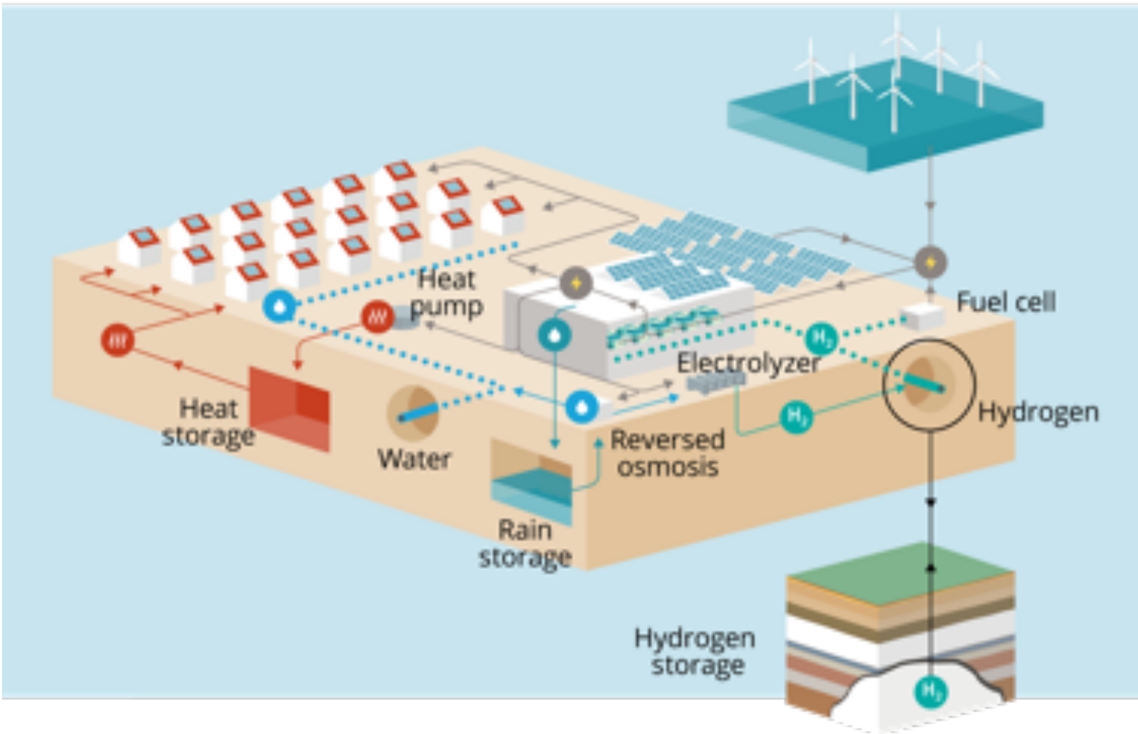
Power to X



I was appointed in 2016 as guest professor Energy and Water at KWR water research. There we started a research program Power to X. The motive was a solar farm build next to the office of KWR that faces grid congestion. We designed an energy system whereby part of the solar power was converted into heat and another part in hydrogen.

The heat that we produced in summer-time is stored in underground aquifers, for use in winter-time as space heating. The produced hydrogen was meant to be used for mobility and to provide back-up power. The hydrogen is stored centrally in underground salt caverns.

We also want to use the underground for rainwater storage, that we collect at the solar panels. This rainwater can be used for irrigation water, drinking water and demineralized water production. The underground is in many places in the world, the cheapest way to store large quantities of water and energy.

We modelled such an integrated energy system and did a lot of techno-economic system research to design, assess and analyse a zero-emission renewable energy system for a neighbourhood.

Power to Hydrogen and Heat Nieuwegein

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But, we want to realize such a Power to X system too and did this near the KWR office in Nieuwegein. We use renewable electricity from the solar farms next to the office and from the grid in a 2.5 MW electrolyser to produce hydrogen. The hydrogen will be transported by a pipeline to a public hydrogen refuelling station at the premises of JosScholman, a ground works and contracting company. This company has a lot of heavy machinery, such as tractors, cranes and trucks that they want to fuel with hydrogen.

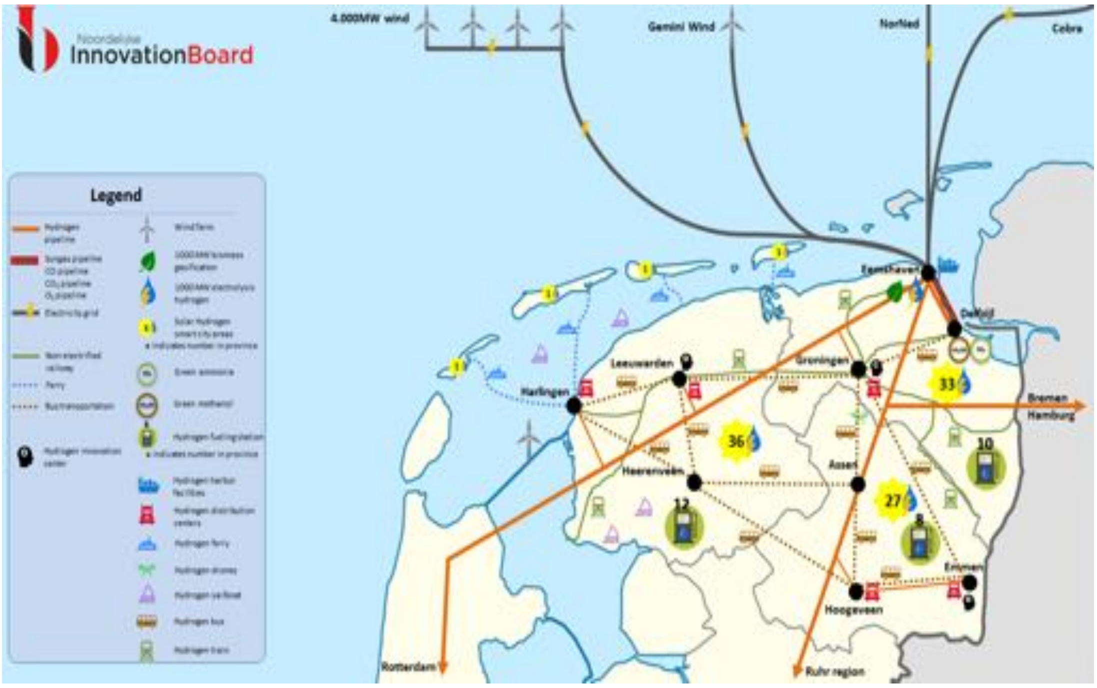
Today fuel cell electric machinery is still an expensive option. Therefore, they developed a dual fuel diesel engine, as a retrofit to existing diesel engines. Via the air inlet of the diesel engine, hydrogen can be mixed in the diesel, replacing 60% to 80% of the diesel.
Some of their hydrogen driven machinery is shown in front of the Aula.

The electrolyser produces not only hydrogen but also waste heat with a temperature of about 60 degrees Celsius that we will deliver at a corporate clothing laundry nearby.

This power to hydrogen and heat project shows that we can integrate more solar energy efficiently in the energy system, by delivering not only electricity, but also hydrogen and heat. In this way, it offers a solution for electricity grid congestion.

2017

The Northern Netherlands, First Hydrogen Valley



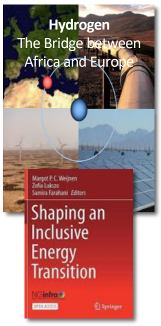
In 2016 I was also asked by the three Northern Dutch provinces to come up with a plan how this region could develop into a sustainable energy region and at the same time boost their economy.

In the province Groningen, a large natural gas reservoir is exploited for decades. Earthquakes, induced by pumping gas from the reservoirs, has caused damage to houses and buildings. It was clear that the gas production in Groningen needed to stop. But it has always been an economic pilar for the region. So, what to do?

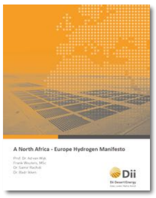
Together with industry, knowledge centra and politics, we have developed a plan to replace natural gas by green hydrogen. The interesting thing is that we could re-use a lot of the natural gas assets, hardware, software and people. We designed a regional hydrogen plan that includes the development of hydrogen production, infrastructure, storage and demand. It was the first, so-called, ‘Hydrogen Valley’. The EU has adopted this concept, and implemented a large Hydrogen Valley Programme.

Today, it has triggered an investment program in Groningen till 2030 of more than 9 billion Euro and to create about 25.000 jobs.

Hydrogen the bridge between Africa and Europe
First lay-out European Hydrogen backbone



2019



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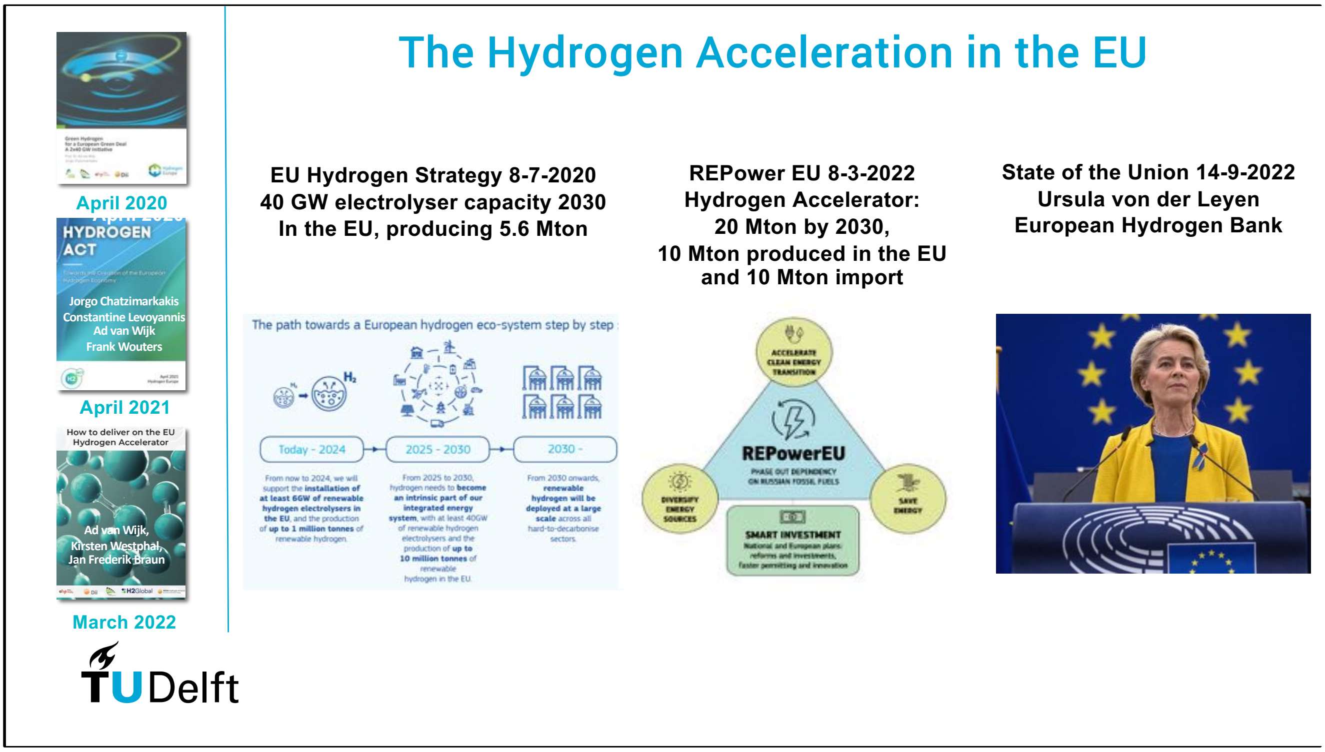
In December 2016 we spoke with the EU commissioner for Energy Maroš Šefčovič about our plans for a Green Hydrogen Economy in the Northern Netherlands. It turned out that hydrogen was not on the EU energy policy agenda. In fact, they were not aware of that role of hydrogen in the energy transition.

This conversation opened some eyes, but made also clear that we had to come up with an analysis why hydrogen is crucial to realize a sustainable energy system. Therefore, we have written a paper 'Hydrogen, the bridge between Africa and Europe. We showed that the EU itself was not able to produce all renewable energy they need. The EU simply does not have enough space and good renewable energy resources.
To put this in perspective, the Sahara desert is 2 times as large as all EU countries together and in the Sahara desert the population density is 1 person per km^2, while in the EU it is over 117 persons per km^2.

In North Africa and the Middle East there is space and good solar and wind resources. But the question is how do we get that cheap renewable energy at the right time at the right place to the energy demand in the EU. The answer is, by converting to hydrogen.

And the interesting thing is that we can re-use the existing natural gas infrastructure and salt caverns for hydrogen transport and storage. In this paper, we depicted a first lay out for a European hydrogen backbone with connections to Africa and the Middle East, based on re-using existing natural gas infrastructure.



The paper, ‘Hydrogen, the bridge between North-Africa and Europe’, has laid the foundation for the development of an EU hydrogen policy. But the paper did not contain clear goals, targets and measures. Therefore, we have written a couple of reports, in collaboration with Hydrogen Europe, DII Desert Energy and the African Hydrogen Partnership. These reports delivered building blocks for an EU hydrogen strategy and implementation framework.

We published in April 2020 the report ‘Green Hydrogen for a European Green Deal, A 2x40 GW Initiative’. We formulated for 2030 as goal, 40 GW electrolyser capacity in the EU and 40 GW outside the EU. In June 2020, the EU hydrogen strategy was published with similar goals.

As a reaction on the war in Ukraine, to become independent of Russian gas, the EU increased the hydrogen targets in 2022 to 10 million ton produced in the EU and 10 million ton import.
These hydrogen targets for 2030 are very ambitious. Especially when we realize that it is not only the green hydrogen production capacity that has to be realized, but also hydrogen infrastructure, storage facilities and hydrogen demand.

This is in my view only possible when governments take the lead. Therefore, we proposed in our report ‘How to deliver on the EU Hydrogen Accelerator’, that the EU and member countries need to establish an organisation that buys and sells hydrogen via tenders. In other words, a hydrogen bank, which Ursula von der Leyen has announced in her State of the Union in September 2022.

Future Energy Systems, the Future

VOETTEKST WIJZIGEN

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2. Typ de gewenste voettekst in, in het aangegeven tekstkader. Klik vervolgens op **'Overal toepassen'** om de gegevens op elke slide toe te passen.

Koptekst en voettekst

… but what will the future bring?

… students, PhD's, colleagues at the TU Delft and KWR water … teresting energy system research. We have tried to synthesize the results and insights of this energy system research in the book 'Green Energy for All, how Hydrogen and Electricity carry our Future'.

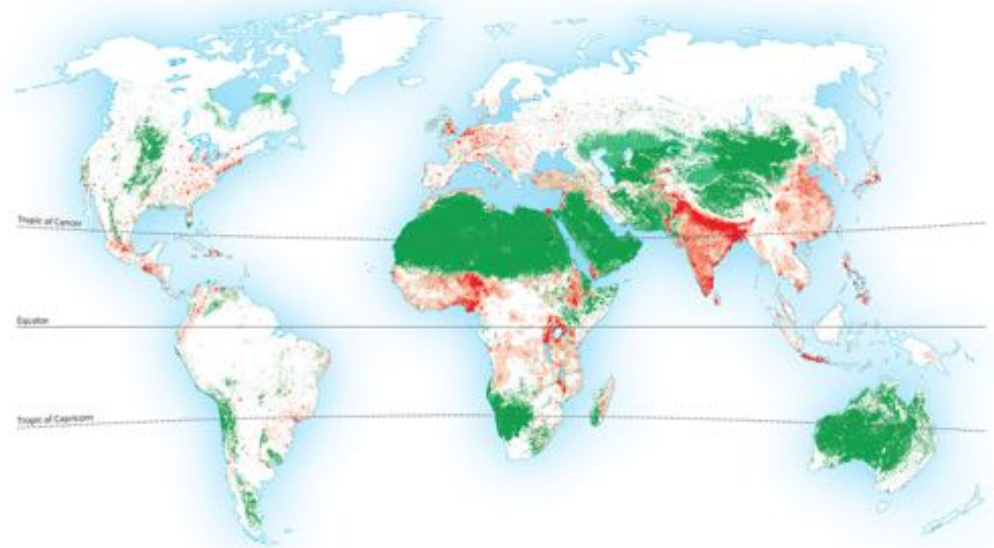
It gives you insights in the goals, the techno-economic energy system developments, challenges and possible solutions in realizing a sustainable energy system. The book outlines also how a sustainable energy system can be realized together with a sustainable materials, food and water system.

I hope that this book gives inspiration to the future generation that needs to realize a sustainable energy supply for everyone in time. Because it is unfortunately true that the future generation will have to fix what my generation has messed up.

Let me present some of these insights.

2023

Heat map Solar Energy 2100



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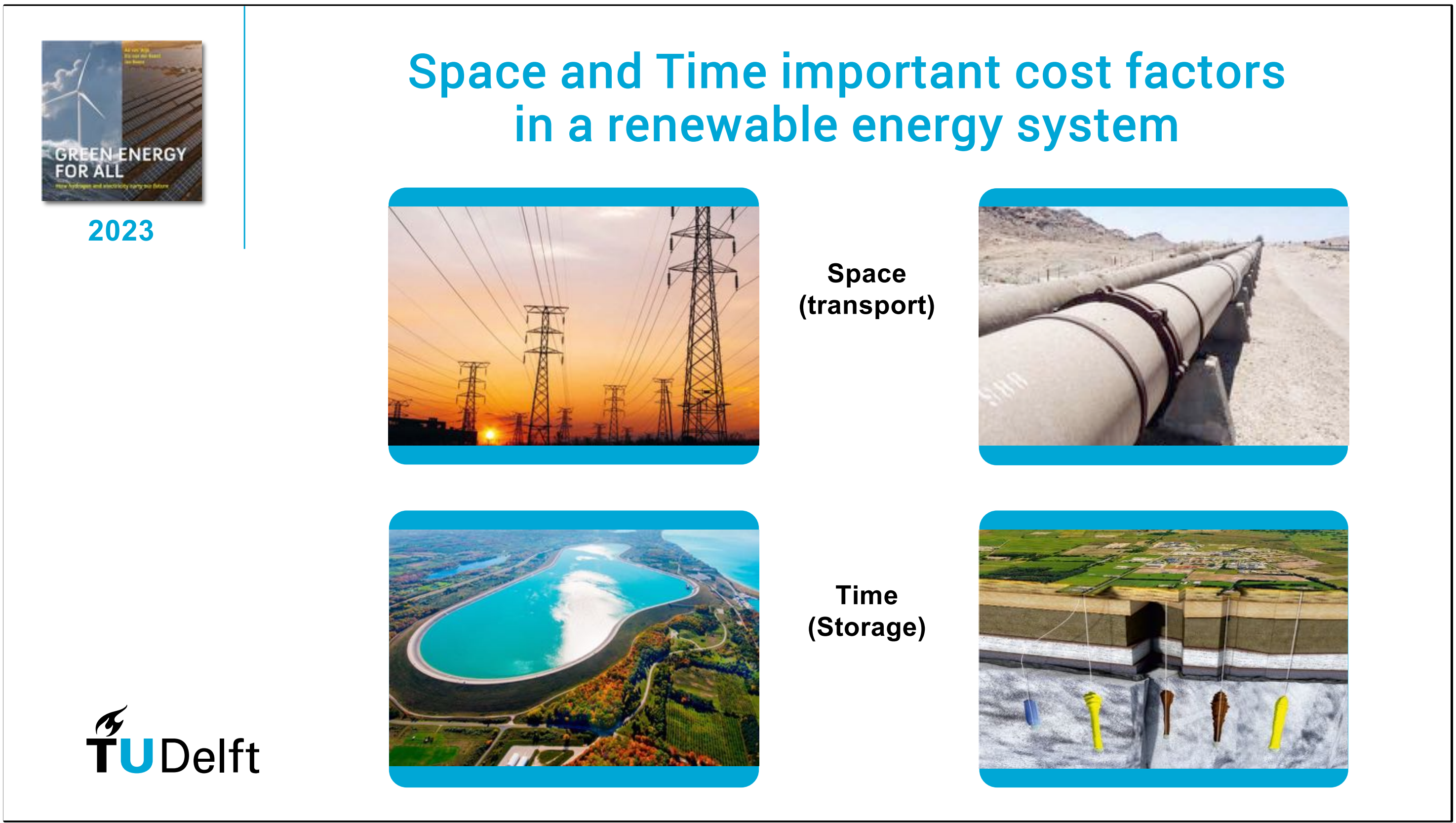
Surplus (green) or shortage (red) solar energy - energy use per km^2

Low cost solar and wind energy production areas we find in the deserts and at the oceans, but these areas are far from areas with high energy demand. But do we need to import renewable energy from far away, or can we produce enough renewable energy nearby the energy demand? To investigate this, we have constructed a so-called energy heat map.

The solar energy heat map at this slide, shows for every square kilometre if there is a solar energy surplus or a shortage. The surplus or shortage is calculated by subtracting the energy use from the solar energy potential.
But the solar energy potential is not simply the solar energy resource potential. The solar energy potential is reduced by several factors and circumstances. For example, in very densely populated cities, there will be less space to install solar panels and no space to install wind turbines. And in tropical forest areas, typically at the equator, you will not cut down the trees to install solar farms.

We made a solar energy heat map for the year 2100. This heat map shows that there is not only a solar energy shortage in industrialized areas such as Europe, Japan and China. But there is also shortage in areas with high population growth and increased standard of living, such as India. And there is also shortage in African countries around the equator.

Of course, in shortage areas we will produce renewable energy too. But what we learn from the heat map, is that we need to transport huge amounts of renewable energy from the surplus areas to the shortage areas to cover total energy demand.



VOETTEKST WIJZIGEN

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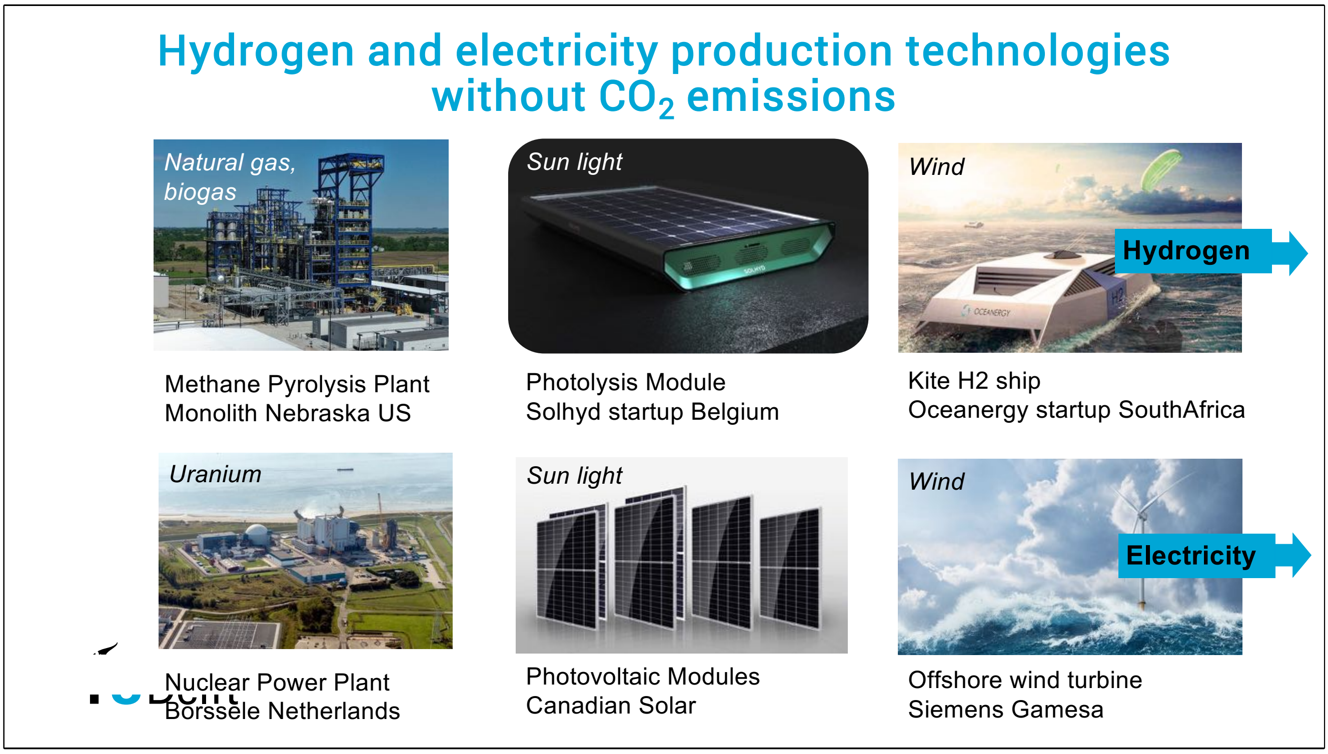
Koptekst en voettekst

...ow, how do we deliver renewable energy at the lowest system cost ...reas to the shortage areas?. To be able to use renewable energy ...t renewable energy into an energy carrier.

But what energy carriers can we use in a sustainable energy system? Of course, it need to be carbon-free energy carriers. This means, when you use that energy carrier, no greenhouse gas emissions to the atmosphere are released. The most important carbon-free energy carriers are hydrogen, electricity and heat.



Let us first have a look into the different technologies to produce the carbon free energy carriers, hydrogen and electricity. In fact, you do not produce hydrogen or electricity, but you convert an energy source in a useful energy carrier.

Hydrogen and electricity can be produced or converted from almost any energy resource. You can produce hydrogen and electricity from fossil fuels, renewable resources and from nuclear energy. At this slide you see different energy conversion technologies to produce hydrogen or electricity, without any CO_2 emissions.

For example, A solar photovoltaic cell converts sun light into electricity. A photolysis or electrochemical cell uses sunlight directly to split a water molecule into hydrogen and oxygen. In other words, it converts sunlight directly into hydrogen.

From natural gas or bio-gas we can also produce hydrogen without any CO_2 emissions, via methane pyrolysis. In this process we heat up the methane molecule to temperatures above 1,000 degrees Celsius, whereby it splits into hydrogen and solid carbon. Solid carbon is a useful product, it can be used for example as soil enhancer.

Hydrogen and electricity are zero carbon energy carriers, not energy sources

Electricity →  → Hydrogen

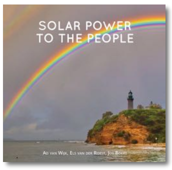
Alkaline electrolyser Thyssen Krupp Germany

Hydrogen →  → Electricity

PEM fuel cell, Toyota Japan

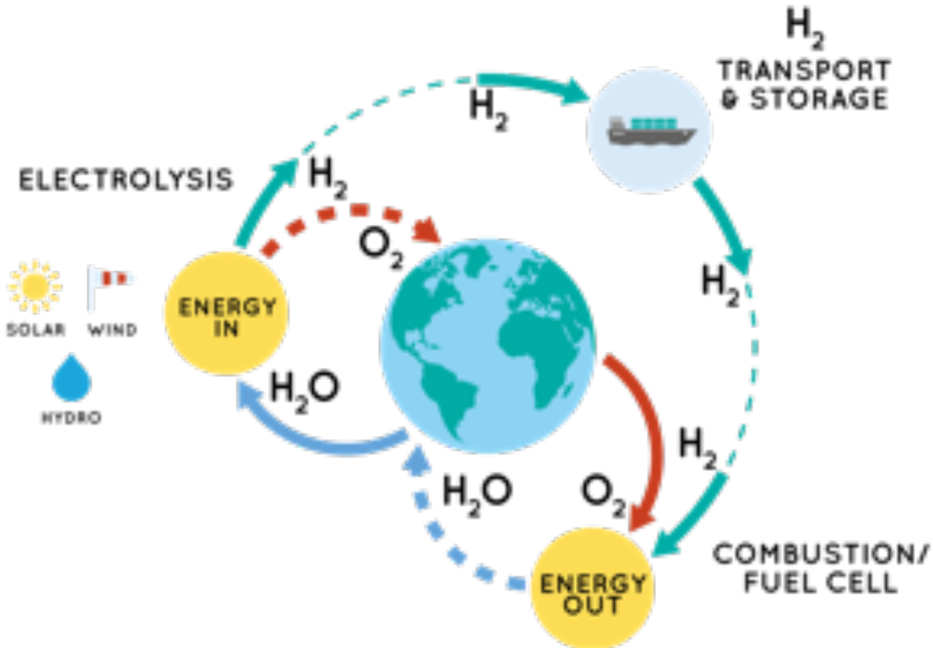
We can convert an energy source into an energy carrier. An energy carrier is therefore not an energy source. But we can convert also energy carriers into each other.

A fuel cell converts hydrogen into electricity. The reversed technology is called an electrolyser that splits a water molecule into hydrogen and oxygen. We often refer to this electrolyser technology for hydrogen production especially green hydrogen production. But as I showed you in the previous slide you can produce hydrogen in many more ways.



2017

The Hydrogen Cycle
Hydrogen, a circular energy carrier



Producing hydrogen via water electrolysis, needs of course water. Therefore, many people ask questions like; how much water does hydrogen production consume, is that water available and is it not competing with drinking or irrigation water supply.

However, the production **and** use of hydrogen does not consume any water. The water that we use to produce hydrogen via water electrolysis comes back when we use the hydrogen to produce electricity and/or heat. To produce 1 kg hydrogen, we need 9 litres very clean water. But when we use 1 kg hydrogen to produce electricity and/or heat, you get 9 litres of very clean water back.

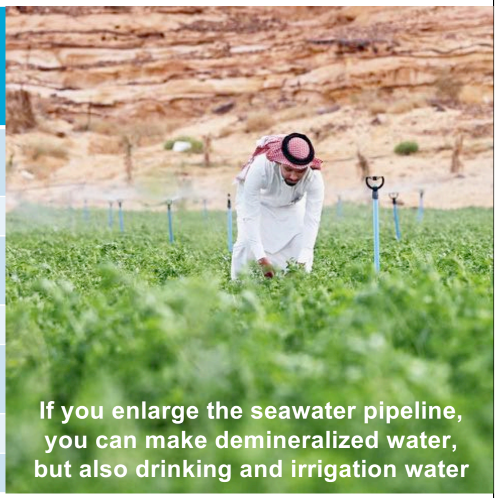
So, when using the hydrogen, we produce very clean water. As an example, when we drive 100 km in a fuel cell car, we use 1 kg hydrogen and produce 9 litres very clean water. Enough drinking water for 3 days for 1 person

Hydrogen produced from water is therefore a circular energy carrier, that do not use water. In fact, with hydrogen, you do not only transport energy, but also clean water over the world.

2023

Seawater as resource for water in the desert

Demineralized water for hydrogen production	Costs Demineralized water
1,000 km transport cost seawater and brine	2.0 Euro/m³
Production costs demineralized water from seawater	2.0 Euro/m³
TOTAL (Euro/m³)	**4.0 Euro/m³**
TOTAL (Euro/kg H_2)	**0.04 Euro/kg H_2**



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There is no net water consumption when hydrogen is produced and used, however, the question still remains; how do we get water in the dessert to produce hydrogen via water electrolysis? The answer is, from the oceans. But then the next question arises; is that not expensive?

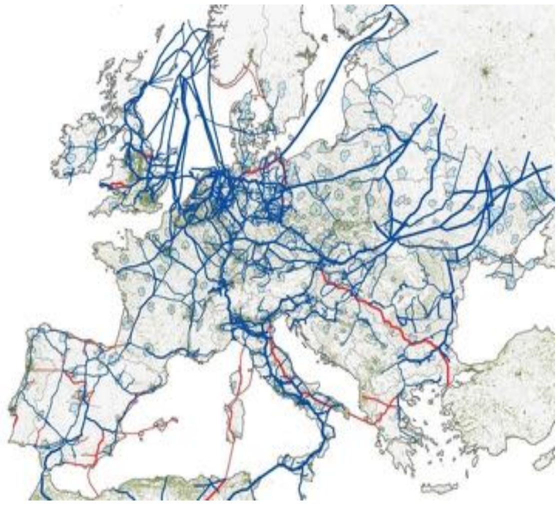
We did an analysis about the water supply cost for a multi-GW hydrogen production site in the desert at 1,000 km distance from the shore. In total the demineralized water cost for 1 m³ is 4 Euro. However, with 1 m³ demineralized water, we can produce 100 kg hydrogen. So, water cost for 1 kg hydrogen is 4 Eurocent per kg, which is only a few percent of the total hydrogen production cost.

If we transport seawater into the desert to produce demineralized water for hydrogen production, we need only a small pipeline. A bigger pipeline can be easily installed at marginal cost for the extra material. And then we are able to produce also drinking and irrigation water. This makes it possible to live in the desert, grow crops, and many more.

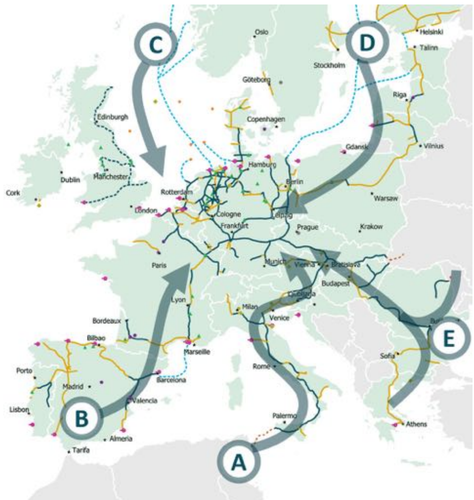
And the brine, the saltier water that remains, does not need to be transported back to the ocean. The brine volumes are so large that brine mining becomes interesting. In seawater you find a variety of valuable elements, such as lithium and rubidium for batteries, salts and chemicals. Brine becomes a source of all kinds of materials.

To conclude, bringing seawater into the desert for hydrogen production can trigger the development of new cities together with food and materials production.

Gas Infrastructure in Europe can be re-used for hydrogen



Gas Pipelines Europe
Transporting gas from gas fields at North Sea, Norway, Russia, Algeria, Libya to Europe



European Hydrogen Backbone 2030
Overall length pipelines: 32.616 km
Repurposed gas pipelines: 16.864 km

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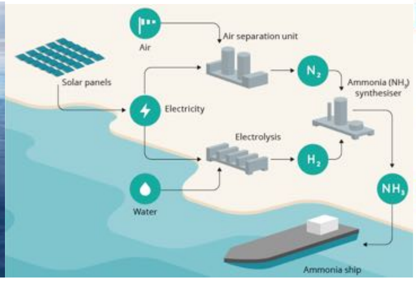
The next question is, how can we economically transport the low-cost green energy from the surplus areas to the shortage areas? I have already said it before, that is via hydrogen. Hydrogen is a gas and can be transported in the same way as natural gas. Hydrogen can be transported by pipelines, in fact hydrogen can even be transported by re-using existing natural gas pipelines.

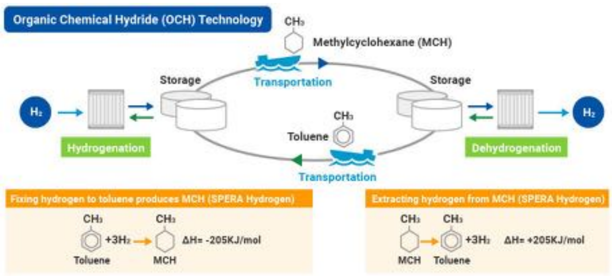
On this slide at the left we see the European natural gas transport pipeline system. There are pipelines connecting the gas production at the North Sea to Europe. Also, pipelines are crossing the Mediterranean Sea, connecting the gas production in Algeria and Libya to Europe. And of course, there are or were pipelines connecting Russian gas production to Europe.

The European gas transport companies have designed a European Hydrogen Backbone. In 2030 the total length will be about 32.000 km whereby 50% consists of re-used natural gas pipelines. The European Hydrogen Backbone in 2030 is already able to import from low-cost production areas to the demand areas. Hydrogen can be imported from Spain, the Sahara desert, the North Sea, Norway, and other countries.

At this very moment, at the Maasvlakte, the King of the Netherlands, Dutch minister Jetten and the German minister Habeck are officially opening the Dutch Hydrogen Backbone.

Hydrogen Transport by Ship; Conversion to a liquid is necessary





Liquid Hydrogen Ammonia LOHC Liquid Organic Hydrogen Carrier

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Hydrogen can also be transported by ship. But hydrogen as a gas has a low energy density per volume. To be able to transport hydrogen economically by ship, we need to convert this hydrogen gas to a liquid.

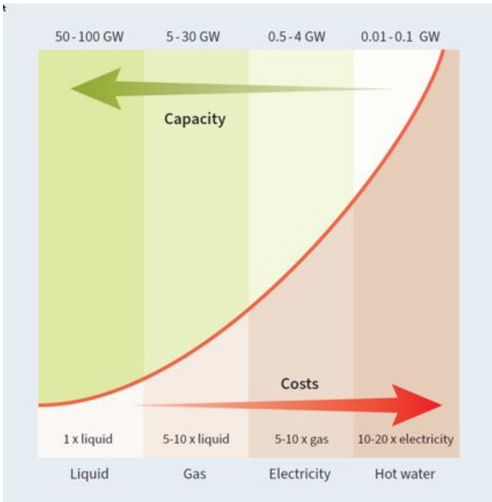
We can make a liquid hydrogen carrier in several ways.

- We cool down hydrogen to -253 degrees Celsius, then hydrogen is a liquid.
- Or we take nitrogen from the air and bind nitrogen to hydrogen, which gives ammonia Ammonia is the main component of fertilizers and is a liquid at -33 degrees Celsius.
- Or we bind hydrogen to a liquid organic hydrogen carrier, which is a liquid at normal outdoor temperatures.

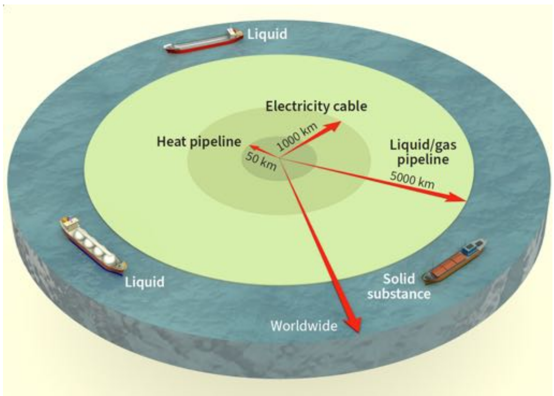
So, we first need to convert hydrogen gas to a liquid, then ship it and finally convert the liquid to hydrogen gas again. Despite these two conversions, it is overall cheaper than shipping the hydrogen as a gas.

2023

Energy transport system costs, capacities and configuration



Energy pipeline transport costs and capacities



Worldwide energy transport system

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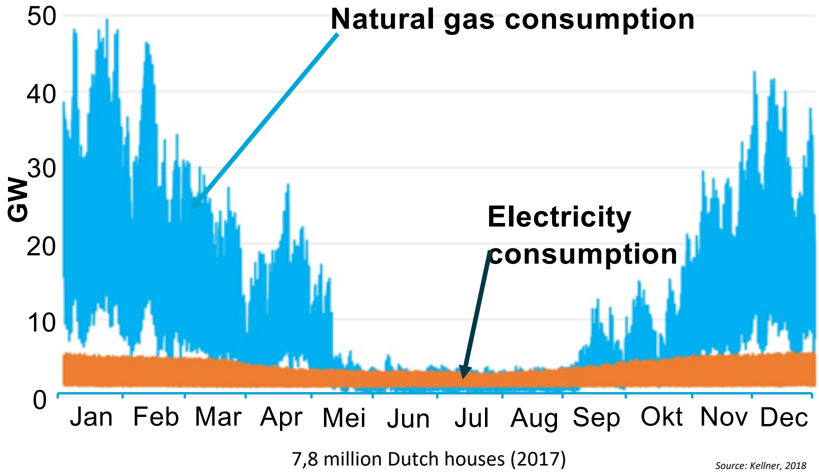
Indeed, transport cost differ among the different types of energy carriers. Transport costs have everything to do with the energy density per volume and weight. The lower the energy density the higher the transport cost.

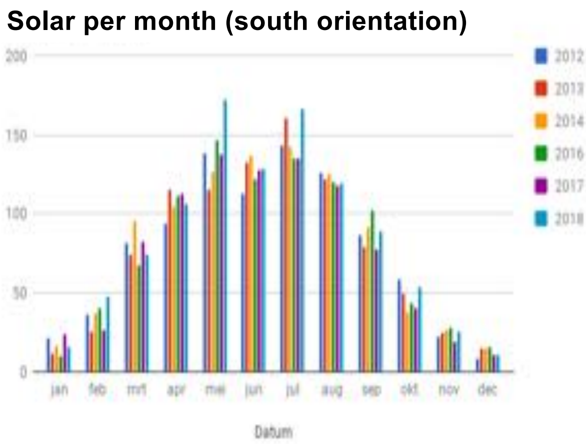
In the figure on the left, we see the transport cost by pipeline or cable for liquids, gas, electricity and hot water. The lowest transport cost is for liquids such as oil, 5 to 10 times more expensive is gas transport. Electricity transport is again 5 to 10 times more expensive than gas transport. And the most expensive is transporting hot water by pipeline.

On the other hand, the transport capacity is the highest when by transporting a liquid and the lowest for hot water transport. For example, the capacity of a big electricity cable is 2 GW, while a big hydrogen pipeline can transport 20 GW.

Therefore, an economic energy transport system will have the same characteristics in a fossil and a renewable energy system. Worldwide transport by ship will be liquids or solids. Up to around 5,000 km liquids or gas transport by pipelines will be the cheapest. Electricity can be transported economically over distances up to 1,000 km. And hot water transport is only feasible for local transport.

Energy transport system costs, capacities and configuration





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Another important question is how can we store renewable energy economically?

Today, in our fossil energy system, we only need to deal with fluctuations in the energy demand. On the left we see the natural gas and electricity consumption of all Dutch households. We see a large seasonal fluctuation in the gas consumption, because we need much more gas in winter-time for heating then in summer-time. But the production of gas is constant in time. So, in summer-time we produce too much gas that we store for use in winter-time.

However, in a future renewable energy system, we also have to deal with fluctuations in renewable energy production. On the right we see the monthly production by solar PV in the Netherlands. In winter months these solar panels produce about 8 times less electricity then in summer months. So, if we want to supply solar electricity for heating with electric heat-pumps we need to store seasonally huge amounts of solar energy.

Therefore, in a future renewable energy system, we need huge amounts of energy storage to deal with renewable energy production fluctuations **and** demand fluctuations especially on seasonal time scales.

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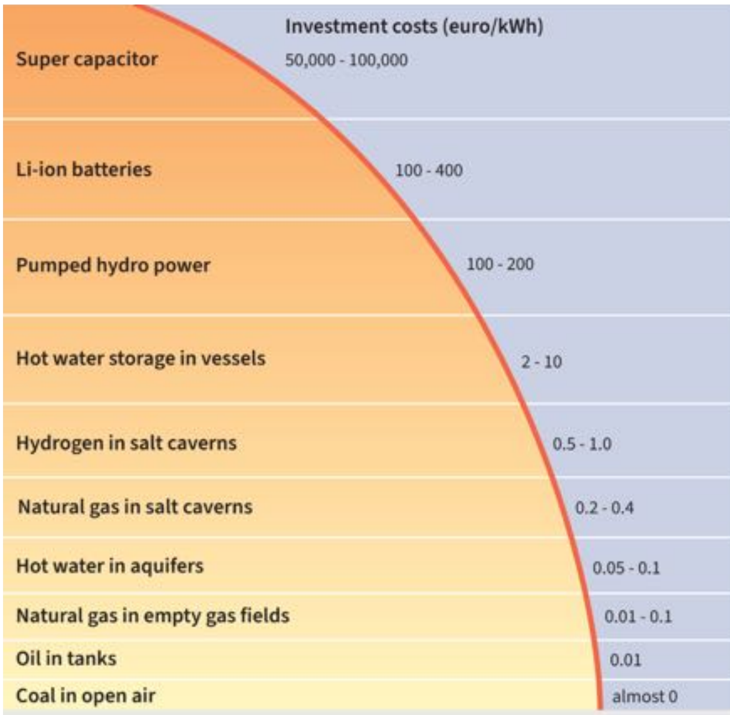
Energy storage Investment Costs



Finally, the question is, what are the energy storage cost for the different technologies. For a fair comparison, we compare the investment cost to store 1 kWh energy.

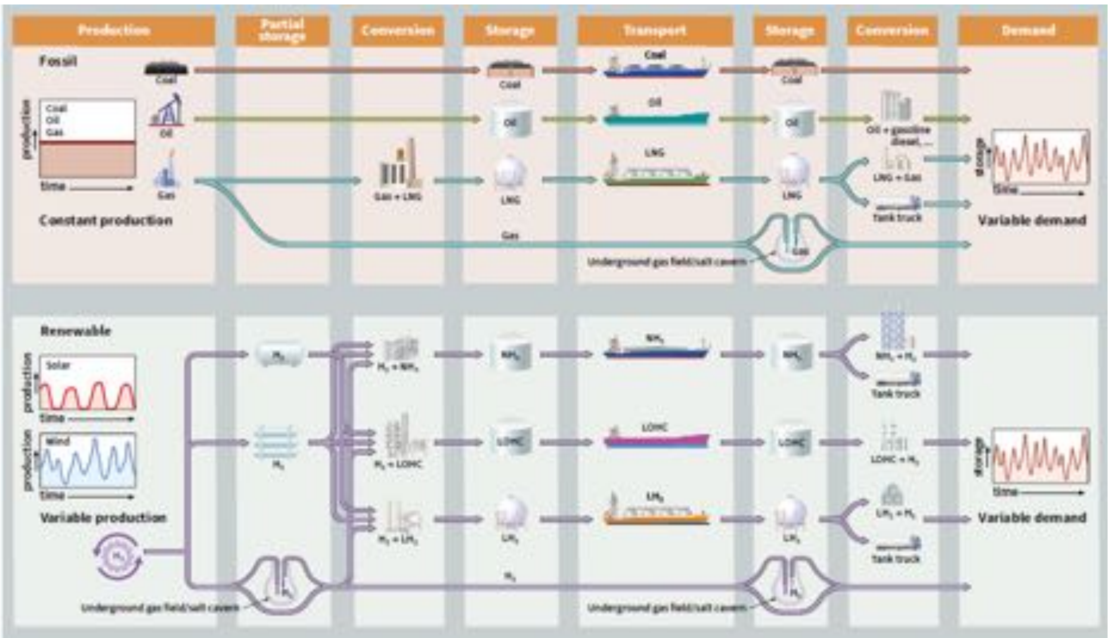
From this figure we learn that we can store very cheaply coal in the open air or oil in tanks. Hot water storage in underground aquifers, is also very cheap. A little more expensive is storage of natural gas or hydrogen in underground salt caverns.

The cheapest way to store electricity, is by pumping up water, so called pumped hydro power. Batteries can store electricity in smaller quantities for hours to weeks. The most expensive electricity storage is in super capacitors.

As we learn from this figure, hydrogen can be stored cheaper than electricity, at least a factor of 100 cheaper.

2023

Fossil and sustainable energy transport and storage system



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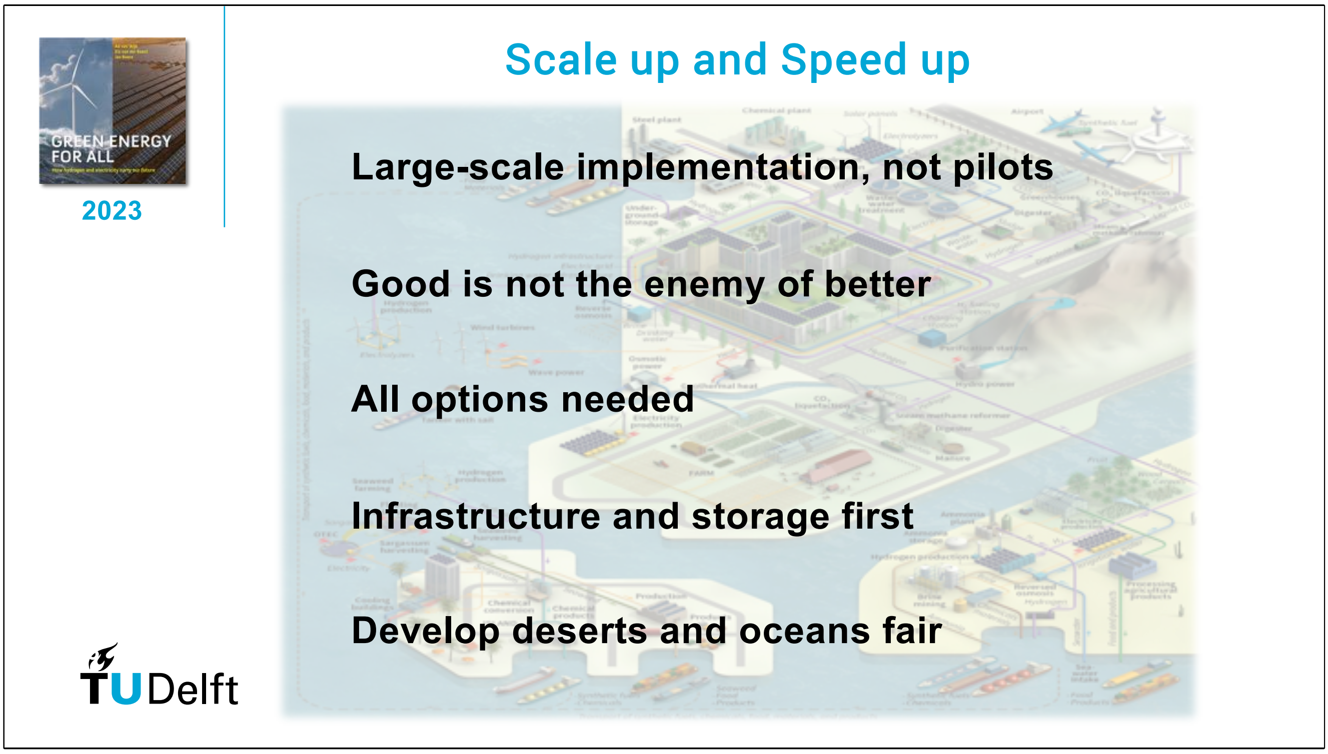
So, in a sustainable energy system, we have to deal with fluctuations in both energy supply and demand. Therefore, energy storage is necessary at the renewable energy production **and** nearby the energy demand. Furthermore, the zero carbon energy carriers, electricity and hydrogen, are not as easy and cheap to store and transport as coal or oil.

The impact is that transport and storage cost will be higher in a renewable energy system than in a fossil energy system. Our rough estimate is that transport and storage costs in a fossil energy system are about 10% of the total cost. And in a renewable energy system, we think that transport and storage costs are even about 50% of total cost.

Today, in our energy scenario's, transport and storage cost are not adequately taken into account. But if we want a transition to a fully renewable energy system, transport and storage costs needs to be properly modelled and calculated. Otherwise, we will make major mistakes and wrong choices that will lead to higher costs and delays in the energy transition.



I hope my new book gives you inspiration. I am optimistic that we are able to realize a sustainable energy supply for everyone. But are we able to realize it fast enough and in my lifetime? My colleague Kornelis Blok has argued in his farewell speech that we have to speed up. That is very true, let me add to this, that we also need to scale up. Let me give five recommendations to scale up and speed up the energy transition.

We need large scale implementation of renewable electricity and hydrogen production, energy infrastructure, storage facilities and de-carbonization the energy demand. We do not need pilots anymore, that is a waste of time and only shows that it is too expensive. Today technology is available and by large scale implementation, cost reduction will go fast. **As a result, we achieve cost competitiveness sooner and emit fewer greenhouse gases!**

There are sometimes fierce debates about which technology or system is the best to reduce greenhouse gases. As an example, people say, battery electric trucks are better than hydrogen fuel cell electric trucks and much better than hydrogen combustion engine trucks. But please that is not the way to go. We need to reduce greenhouse gas emissions as fast as we can. So, we need goals with timelines for greenhouse gas emission reduction, not technology exclusions. And then overall system cost and applicability are important factors that will determine how fast and what technologies we can implement in real life. **Let customers decide!**

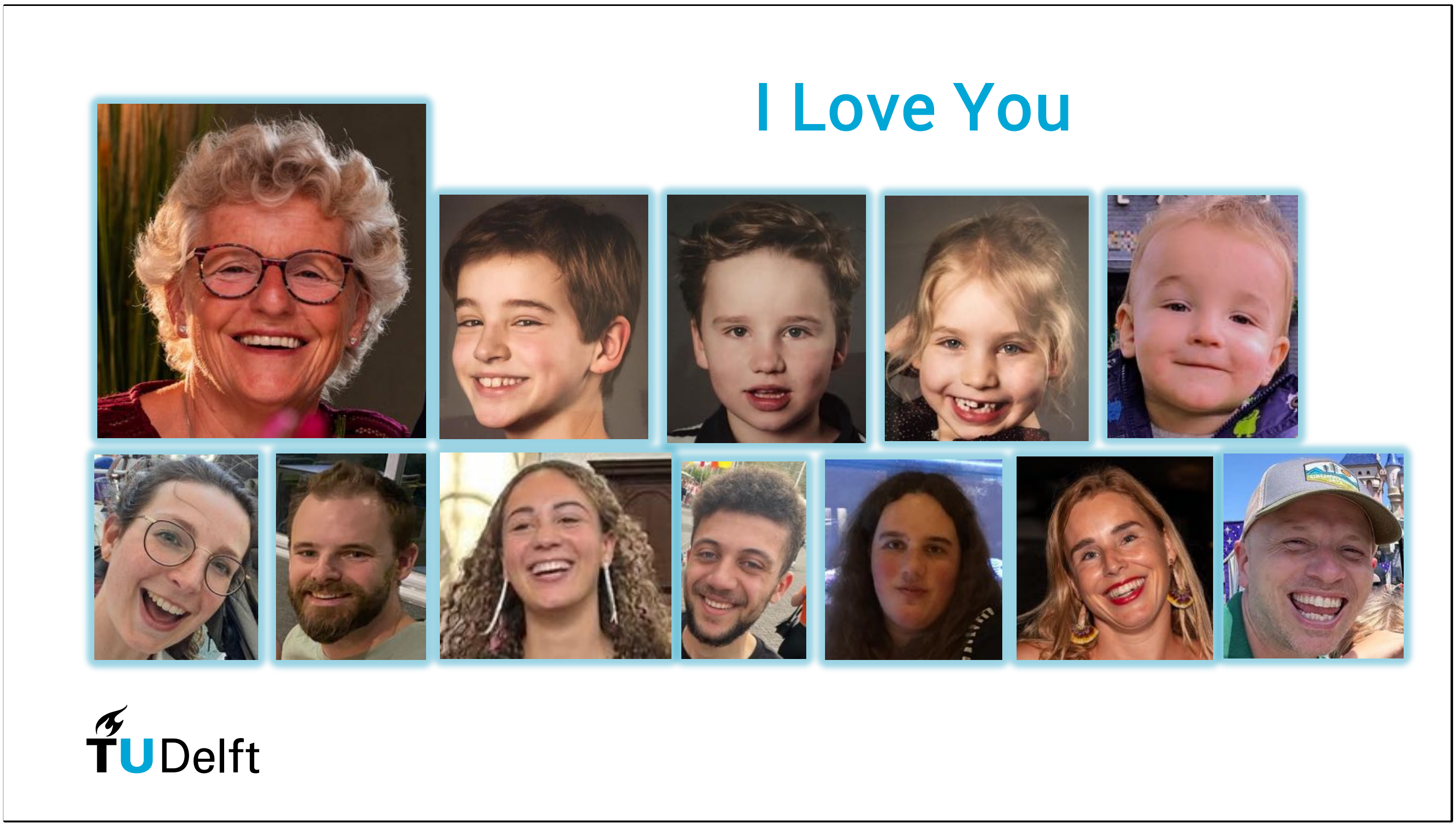
Thank you

TU Delft

Of course, we want to realize an energy system fully based on renewable energy. We need to do that as fast as we can, but this will take time. However, what we really need to do, is reducing greenhouse gas emissions as fast as we can. Therefore, it makes sense to reduce these emissions via every possible option. For example, natural gas conversion to hydrogen at the gas field and storing CO_2 directly in that gas field, makes sense. Or even better, use methane pyrolysis and we do not produce CO_2 but only solid carbon. And if you do this, you can fully convert the natural gas infrastructure into a hydrogen infrastructure. **This is really avoiding a natural gas lock-in!**

The focus today is a lot on increasing renewable energy production capacity and changing energy end use technologies using zero-carbon energy carriers. Energy infrastructure and storage are more or less forgotten elements in the energy transition. Now we experience the consequences of this ‘forgotten’, among others there is a lot of electricity grid congestion. To solve this, we need to expand the electricity grid, but at the same time we must realize a hydrogen grid too. The next challenge will be storage. Today balancing production and demand is still done by storing and using fossil fuels. Batteries will be part of the storage solutions, but especially large-scale hydrogen storage is needed. Therefore, **Energy policies need to incorporate transport and storage roadmaps now!**

Large scale and cheap renewable energy production from deserts and oceans, can supply all the world’s renewable energy we need. They can become major renewable energy exporting regions. But let us not develop it as we did in the past, not in a colonial way. If we develop it in a clever way, we can not only produce renewable energy but also clean drinking water, food and materials. Developing such an integrated sustainable energy, water, food and materials system for own use **and** export, will create jobs, welfare and better living conditions in less developed regions like deserts and islands. **That is a fair development!**



VOETTEKST WIJZIGEN

1 Ga naar de tab **'Invoegen'** en klik op **'Kop- en voettekst'**.

2 Typ de gewenste voettekst in, in het aangegeven tekstkader. Klik vervolgens op **'Overal toepassen'** om de gegevens op elke slide toe te passen.

Koptekst en voettekst

end of my farewell speech.

u all, for being here and listen patiently to my speech.

I want to thank also all my relations, colleagues, friends and family that could not be here. You never walk alone. My journey was not possible without you.

But it was certainly not possible without the support and love of my family. Especially not with the more than 50 year support of my friend, partner, and love of my life Sonja.

But the question remains, do we realize such a sustainable energy system for everyone in my life-time