

# A Comprehensive Engineering Approach to Shaping the Future Energy System



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**Abstract** The urgency to significantly reduce the impacts of climate change is felt around the globe. By signing the Paris agreement in 2016, 195 governments have agreed on a long-term goal of keeping the increase in global average temperature below 2 °C above preindustrial levels and on aiming to limit the increase to 1.5 °C. To reach these goals, major technological, organizational, and social changes in different sectors and their services are needed. To understand and steer the transition from the current energy system towards a carbon-free energy system, we propose a comprehensive engineering framework that integrates different aspects, such as technical, economic, cyber-physical, social, institutional and political, that are needed in the design of such a complex system. We explain the importance of combining different disciplines to provide comprehensive models and tools in order to support and achieve a sustainable, affordable, reliable and inclusive energy transition.

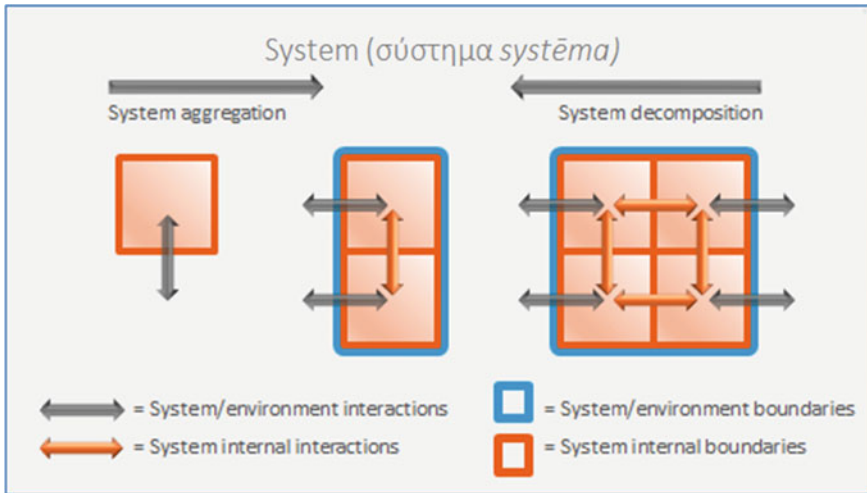
## Introduction

In the coming years of energy transition the world will undergo one of the most complex technological transformations in history, which will not leave society and everyday life untouched. The challenges regarding replacing the existing fossil-based energy system by a sustainable one are not only of a technological and economic nature, but also institutional, entrepreneurial and ethical. The challenge is not only to meet our current energy needs, but also the needs of a projected 10 billion people in 2050 and to do so with low cost as well as with low-carbon and renewable energy sources.

If we have to replace the existing energy system, it is important to clarify what is meant by this term. The word ‘system’ is derived from Greek and means ‘an aggregation of parts’. Ever since the time of ancient Greece, the term has been used

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**Fig. 1** Schematic representation of a system

to describe any organisation as a structured set of parts. Physical, biological, but also social and commercial systems are all examples of this.

The fact that systems can be distinguished in various disciplines and worlds makes it possible to describe the word 'system' in abstract or even in mathematical terms. It is then a combination of systems or elements that interact with each other and that can, and mostly do, also interact as a whole with their environment, see Fig. 1. In this sense a system of systems is also a system.

We can also see such composite structures in the everyday energy systems that have been designed to provide energy services to end users. If we translate such an energy system into a scheme, we may produce a sketch like this, which displays the physical system and the many subsystems and interactions it comprises, see Fig. 2. In this figure we did not include heating and cooling systems, so only a part of the physical energy system is presented here.

This large physical system is complicated enough on its own, but it is important to realise that the economic systems (involving energy markets and transactions), and the social systems (involving multiple stakeholders) are not shown in this diagram. Adding those makes this whole system much more complex.

The physical system diagram presented in Fig. 2 shows an energy system that is a collection of physical flows and conversion processes. It comprises solely passive elements that can only follow the choices of the designers, system managers and other actors. There are no smart elements, smart subsystems or active elements (whereby an active element is one that can make decisions independently). These elements are first encountered in the *cyber layer*: the part of our energy system where data is collected, the communication between the system components is accommodated, the components themselves are controlled, and the security protocols are defined and activated when necessary, see Fig. 3. This is the domain of ICT, measurement and

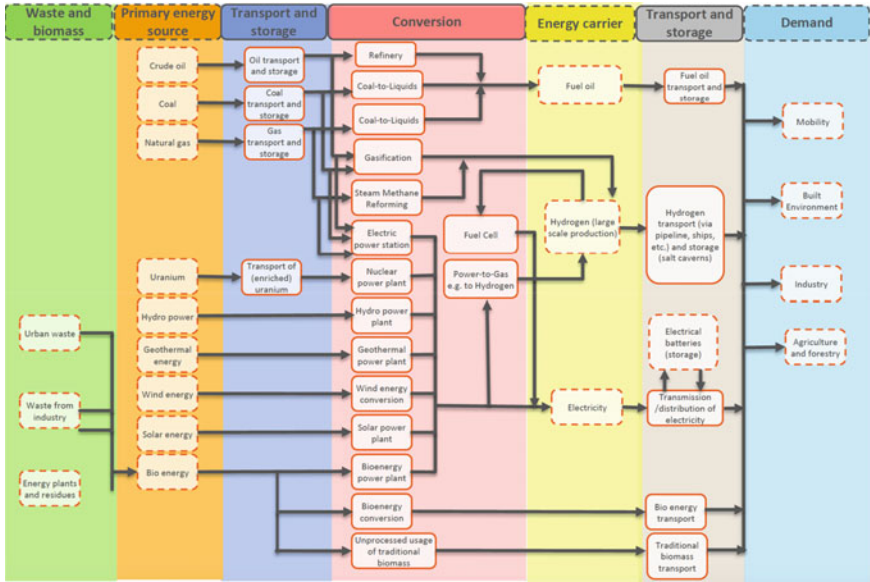


Fig. 2 Schematic representation of an energy system

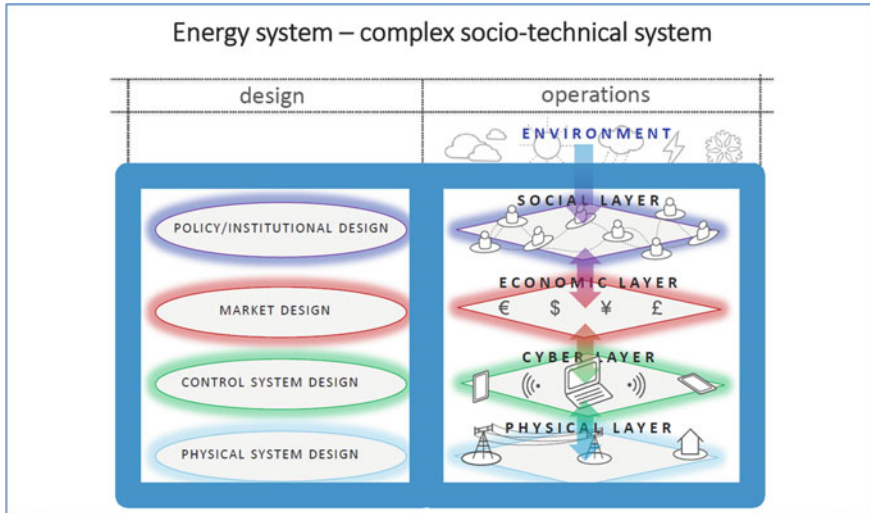


Fig. 3 Schematic representation of an energy system as a complex socio-technical system

control technology and smart algorithms. These advanced control systems calculate how to bring a system into a desired state, even in situations with lots of uncertainties; however, they cannot decide exactly what this desired state is. That decision is made by actors, such as system managers or other parties residing in the social domain. In other words, an energy system involves much more than only physical and control layers representing physical and control systems. In addition to these, such a system also contains a social and an economic layer that interact with each other. All these four interrelated layers interact with an external environment. This environment contains those elements that are not part of the system, but can either affect it or are affected by the system.

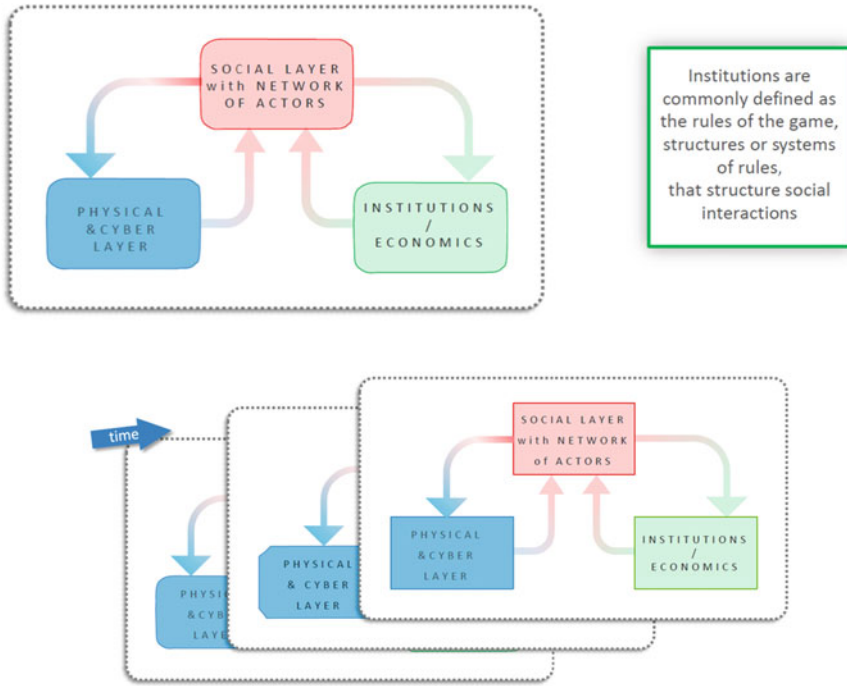
Using the term “layer” might be to some extent confusing, as it not only suggests that each layer has a different functionality, but also that each layer can only interact with the layer above and below. Since the latter is not the case, we will hereafter not use the term *layers*, as is often done in literature (see, for example, (Mittal et al., 2020; Sosa et al. 2003)), but we will talk about *domains* that interact with each other, see Fig. 3. These domains interacting with each other, across different time scales and geographical scales, result in an energy system that can be seen as a large-scale complex socio-technical system.

## Systems Thinking and Complex Adaptive Systems

(Re-)designing such a complex socio-technical system calls for a coherent design involving not only physical components and control mechanisms on the one hand and energy markets on the other, but also institutions taking into account social acceptance, market dynamics, social routines and the interests of all stakeholders in the economy and society. It is impossible to quickly sketch all these complexities in a simple diagram. To perceive and understand the whole, we need Systems Thinking and a systems perspective.

Systems Thinking helps us to see the energy system as a whole, constructed by different domains operating on various scale levels in the system, with various time constants, and, most importantly including their interconnectedness and the interrelationships between elements and subsystems (Moncada et al., 2017; Senge, 1990). Only by applying Systems Thinking, i.e., by analysing the whole system, understanding interconnections, considering multiple perspectives and values of actors operating in the social domain, we can realize appropriate institutions and rules of play to support the energy transition.

Figure 4 shows schematically that in (re-)designing future energy systems a whole system perspective, including the technical, cyber, economic and social domain, the latter including the individual behaviours of actors, and their interactions with institutions as well as with the physical and cyber domains, is necessary to understand, analyse and steer this complex socio-technical energy system in the desired direction of sustainability, affordability, reliability and safety. However, knowing which domains should be taken into account is not sufficient to design possible pathways



**Fig. 4** Systems thinking for the (re-)design of energy systems and time dependent adaptation. The top figure shows a static socio-technical system, which should be replaced in the analysis and design by the bottom figure to be adaptable to changing conditions in the system environment

for the energy transition. Besides Systems Thinking, theories of Complex Adaptive Systems (CAS) are helpful. CAS are seen as non-linear, dynamic systems with the ability to adapt to changing conditions in the environment, and they often show unexpected (emergent) behaviour and a strong path-dependency (Amer Power Plant, 2020). The time dependent adaptation of CAS is shown schematically in the lower part of Fig. 4 where the domains and interactions constantly adapt themselves to dynamic changes in the environment, and therefore, proposed solutions should also be adaptable.

### Complex Socio-Technical Systems Engineering

Many international educational programmes and research groups have made Systems Thinking a cornerstone of their research and education, and are often viewed—and consider themselves—as multidisciplinary, interdisciplinary or transdisciplinary groups. To name a few of these programs contributing to complex systems engineering education, one could mention:

- Delft University of Technology (TUDelft); Faculty of Technology, Policy and Management (TPM)
- Massachusetts Institute of Technology (MIT); Technology and Policy Program (TPP)
- Carnegie Mellon University (CMU); Engineering and Public Policy (EPP)
- Stanford University; Management Science and Engineering (MS&E).

Over the years, and initiated by Systems Thinking, these programs have developed their own discipline. For instance, the faculty of TPM has applied this to the energy and telecommunications industries and to transport systems. These programs have been started as multidisciplinary faculties with a wide variety of academic backgrounds: engineering scientists, economists, mathematicians, psychologists, physicists and ecologists, to name just a few. Just as physics has many interfaces with chemistry, biology, mathematics, etc., so have these programs countless interfaces with other disciplines. Meanwhile, these faculties are by themselves independent scientific disciplines that focus on major societal challenges with their specific social and technological complexities. We call this discipline *Complex Socio-Technical Systems Engineering*, or shortly *Comprehensive Engineering*. It is a discipline that recognises the social, economic and technical complexities of major dynamic systems, studies how these systems interact with each other and how they need to be designed and/or operated to satisfy desired states and/or values.

The question that is relevant for this chapter is: How can we deploy the scientific discipline of *Complex Socio-Technical Systems Engineering* to facilitate the inclusive energy transition? An inclusive energy transition is a shared goal of the entire international community and entails switching from fossil to renewable energy sources. This transition is needed to secure our energy supply for the future and to mitigate climate change. A consequence of the transition is that, by 2050, the share of renewable energy in the power sector will increase to 85%, compared to 25% in 2017 (IRENA, 2018). To reach this goal, countries all around the world have started changing their energy production policies to move towards more renewable energy resources.

While many countries are mainly focused on replacing coal in their energy system, some go even further and plan to replace natural gas as well. Netherlands is a good example of the latter-mentioned countries. In late January of 2018, the House of Representatives in the Netherlands passed a bill to accelerate the energy transition (Electricity Act Amendment, 2018). The new law aims to remove existing barriers to the energy transition in the Netherlands and adapt the Electricity Act and Gas Act to adequately meet the new policy targets. The most important changes involve:

- a broader experimentation provision with a reference framework for grid operators who have to choose between strengthening the grids or deploying the flexibility of market parties (so-called demand response)
- scrapping the gas connection obligation for new-built homes and for small businesses (gasless new-builds are now the norm, unless there are serious public interests that make it strictly necessary to provide a gas network).

Further, it has been decided in 2019, among other things, to convert the two oldest coal-fired power plants in the Netherlands, i.e., the Amer and Hemweg plants, by using a more sustainable fuel (Amer Power Plant, 2020; Decision of the Dutch Government, 2020). The new coal-fired plants in the Maasvlakte and Eemshaven are to undergo the same treatment, only a few years later. But that is still not enough to achieve the carbon-reduction targets. The changes in the Dutch law are intended to facilitate new developments that will help accelerate the energy transition. However, the energy system for which we are developing legislation and regulation stops at the country's borders, while in the physical reality our national energy system is interconnected with the European gas and electricity networks. Having a comprehensive approach here, would help to connect and align the new policies and regulation with European and international new policies; and this will accelerate the energy transition as well as result in a more coherent energy system—both physically and institutionally—worldwide. Our scientific research of *Complex Socio-Technical Systems Engineering* contributes significantly to this comprehensive approach as it transcends the scale levels of districts, cities, countries and continents to consider other boundaries as well.

Finally, we would like to draw attention to one of the 17 Sustainable Development Goals (SDGs): ensure access to affordable, reliable, sustainable and modern energy for all. The European Pillar of Social Rights, which was established by the European Parliament at the end of 2017, declares that all European citizens are entitled to reliable and affordable energy services (The European Pillar of Social Rights, 2020). We take this for granted in the developed countries, but it is by no means a given fact in many countries in the world. Researchers of the University of Oxford have shown that (Ritchie, 2019):

- nearly 13% of the world's population still have no access to electricity
- energy consumption is not evenly distributed and varies more than tenfold across the world, and electricity consumption more than 100-fold
- energy access is strongly related to income.

To what extent do we need to accept responsibility for this inequality? We will leave this question open; it is the question we ask ourselves frequently when looking for smarter and more effective solutions for the energy transition in the Dutch and European context.

In the next section, we discuss one of potentially effective solutions for the energy transition and for enabling access to reliable and affordable energy services, based on using hydrogen as a main energy carrier in our energy system. *Complex Socio-Technical Systems Engineering* teaches us that the rapid emergence of the hydrogen economy requires concerted action amongst the stakeholders along the hydrogen value chain, shifting from local to regional to international perspective. Large-scale deployment of renewable power needs to be followed by large-scale conversion, transport and storage from source to use. From a western European viewpoint, this involves both local production and remote import through gas pipe infrastructures and through shipping. The end users need to invest in ways of adopting large-scale hydrogen for energy and feedstock sources in a cross-sectoral context of industry,

mobility and the built environment. The roles of the many actors involved in the value chain should be investigated to understand how individual decision making of the actors can be influenced to result in rigorous actions towards a trans-national, high-impact, adaptive investment and policy agenda to develop an inclusive, fair, reliable, affordable and sustainable hydrogen economy.

## Hydrogen's Role in the Energy Transition

As van Wijk emphasises in the first chapter of Part II, hydrogen can play an important role in the global inclusive energy transition. Hydrogen offers both flexibility and reliability of energy supply when being used as a means of storing solar and wind energy, and as a means of transporting energy to the demand location, anywhere in the world, by using the existing gas networks (after some adjustments have been made), by constructing new hydrogen networks, or by ships and trailers.

In this vision of the future energy system, green hydrogen produced using renewable energy sources could well prove to be an essential building block of this transition. To achieve the Paris climate targets, we definitely need to investigate to what extent priority should be given to hydrogen applications (Hydrogen Council, 2020).

To achieve energy transition aimed at decarbonising energy demand and energy production, a complementary energy system based on hydrogen can be developed to provide the necessary flexibility by:

- enabling cost-effective energy storage both in the short- and long-term;
- allowing energy and, more specifically, electricity consumption and production to be decoupled both geographically and temporally;
- helping to stabilise energy prices in the face of variable wind and solar power production;
- facilitating cost-efficient bulk transport over long distances using pipelines, ships and trucks.
- making energy sector and regional coupling possible.

Next to these roles, hydrogen can be used to decarbonise hard to abate energy use in the transport sector, industrial energy consumption, feedstock for industry and heat and power generation in the built environment. The Hydrogen Council has defined seven roles that hydrogen can play in the energy transition (Hydrogen Council, 2020) (Fig. 5).

As presented in the European Green Deal in December 2019 (European Green Deal, 2020) and later in the Hydrogen Strategy for Europe in July 2020 (European Commission, 2020), there is more research and innovation on clean hydrogen needed to tackle climate and environment-related challenges.



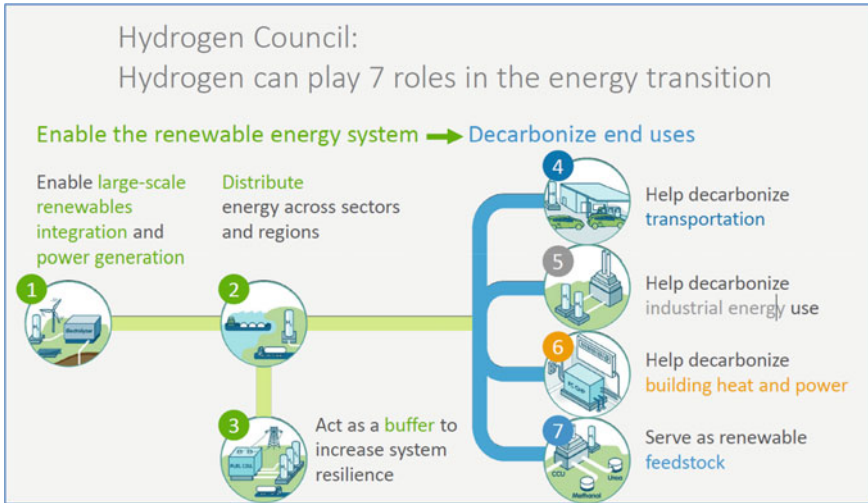


Fig. 5 Roles of hydrogen in the energy transition (Hydrogen Council, 2020)

### Car as Power Plant—An Integrated Energy and Mobility System

Many research groups worldwide have been actively researching how to efficiently deploy hydrogen to make the energy, industry, built environment and transport sectors more sustainable. In the transition towards a low carbon energy system, next to finding new energy carriers and sources as well as improving the energy efficiency in different parts of the energy system, *sector coupling* is one of the important aspects. Sector coupling refers to joining efforts between different sectors to support each other and improve overall efficiency and services. In this context, hydrogen can be used to strengthen the integration between energy (electricity, gas, heat) and transport sectors as well as to be deployed efficiently. It means that the system boundary is extended here to include the energy and mobility system with all their domains and interactions.

An example of such an integrated system is shown in the *Car as Power Plant (CaPP)* project, in which hydrogen fuel cell vehicles (FCEVs) are used in the vehicle-to-grid mode to support the energy system (Farahani, 2019). In such a system, the FCEVs do not only provide clean transportation; they can also feed-back electricity to the grid at the times the vehicles are parked. As such, the energy flexibility of hydrogen cars can be cleverly deployed to decouple electricity production and consumption. In short, the CaPP project investigates the potential impacts and feasibility of an integrated energy and transport system consisting of a power system based on wind and solar power, conversion of renewable energy (surpluses) to hydrogen using electrolysis, hydrogen storage and distribution, and hydrogen fuel cell vehicles that provide mobility, electricity, heat and water.

In terms of technology, the energy production system can be envisaged as a fleet of hydrogen fuel cell vehicles, where cars while parked (over 90% of the time) can produce (with their fuel cells) electricity, heat and fresh water, which will be fed into the respective grids. From a social perspective the stakeholders directly and indirectly involved in the design, building and operation of such a system, are car park operators, the local power, heat and water distribution companies, gas suppliers, H<sub>2</sub> producers, the equipment, system and software manufacturers but also municipalities, regulators, policy makers and not to forget the car owners/users. The CaPP system has been designed for several stand-alone, distributed, smart energy systems, such as in microgrids or an office building (Alavi et al., 2017; Farahani et al., 2020); also, it has been designed for smart cities (Farahani, 2019; Oldenbroek et al., 2017). The obtained results in different studies show that storage using hydrogen and salt caverns is much cheaper than using large battery storage systems; that the integration of electric vehicles into the electricity network is technically and economically feasible and that they can provide a flexible energy buffer; and that V2G is a promising technology and FCEVs give more flexibility than standard battery EVs since beside storage, they can operate as dispatchable power plants independent of the electricity grid. Ultimately, the results of these studies show that using both electricity and hydrogen as energy carriers can create a more flexible, reliable and cheaper energy system.

The CaPP system with the proposed multi-modelling framework is an example of a carbon-free energy system offering sector coupling and facilitating the penetration of 100% intermittent renewables without any compromise on reliability of energy supply for power, heat and transport and at the same time reducing system cost. Moreover, this approach will engage consumers to have a more active role in the energy transition as prosumers. However, realizing the CaPP concept cannot be done overnight. It requires combining different disciplines to provide comprehensive models and tools supported by real-life pilot projects. We need to provide a single comprehensive framework from different perspectives, such as technical, economic, operational, and social aspects, for designing such a complex socio-technical system (Alavi et al., 2017; Farahani, 2019; Farahani et al., 2020; Oldenbroek et al., 2017; Park Lee, 2019). The emphasis is on the fact that the system design and operation are deeply intertwined and that a stand-alone technical, economic, and social analysis is incomplete without the other ones. Furthermore, new policies to be defined for a carbon-free energy transition are manifold and policymakers require broader knowledge from different disciplines to address the challenges of such a system transition. The CaPP framework stresses the need to consider different aspects such as technology, economics, control, institutional and social perspectives in modelling energy systems. As such, it provides a clearer and more comprehensive insight into the realization of sustainable energy systems to policymakers, compared to the individual models.

Figure 6 shows the physical connection of a hydrogen fuel cell vehicle to the local electricity grid at the lab facility of The Green Village at Delft University of Technology, as part of the demonstration phase of the CaPP project.



**Fig. 6** The Europe's first Vehicle-to-grid connection using hydrogen fuel cell electric vehicle and the local electricity grid at The Green Village, Delft University of Technology

This innovative *Car as Power Plant* system can make an important contribution to the energy transition. However, to scale the research up to the level of the global energy transition, where hydrogen plays a prominent role, more research is needed. This does not only encompass technological innovation, but also:

- new hydrogen supply chains, from production to the end user
- new infrastructures
- new markets
- new legal and regulatory institutions, including new forms of energy contracts and incentives.

All these changes will not only need to help us to achieve our environmental targets, they will also need to do justice to social expectations and values. To make the realisation of such integrated complex systems possible, large-scale computational models are required. It is clear that these cannot be developed by a single research group alone. The modelling world needs to make a transition as well. We need to develop system models that do justice to many perspectives and many shades of complexity, such as:

- the social, economic and technical complexity of society's energy and mobility systems
- the geographical distribution of these systems
- the dynamic and adaptive behaviour of these systems.

We can meet this need by deploying a multi-modelling framework, whereby various models are developed by various research groups at different locations, and sometimes in different parts of the world, and combined to achieve a common goal. Now is the time for a paradigm change in modelling: A Multi-Modelling Framework for the energy transition, as is called for in (Bollinger et al. 2018).

## Conclusion

In this chapter, we have discussed the importance and necessity of a Complex Socio-Technical Systems Engineering approach to achieve an inclusive energy transition. A large network of actors is involved in the development and operation of the future carbon-free energy system, from its technical infrastructure and physical components to new institutions and regulations. New policies to be defined for carbon-free energy transition are manifold and policymakers require broader knowledge from different disciplines to address the challenges of such a radical system transition. The Complex Socio-Technical Systems Engineering framework stresses the need to consider different aspects such as technology, economics, cyber-physical, institutional and social perspectives in modelling energy systems. As such, it provides more comprehensive insight into the realization of new energy systems and richer evidence to inform policymakers, compared to the individual models. Moreover, to realize a low-carbon energy system, different sectors, such as energy (i.e., electricity, heat, gas) and mobility, must support each other to provide reliable services. This so-called sector coupling adds a new layer of complexity which can be tackled by the Complex Socio-Technical Systems Engineering framework.

To illustrate this framework, we have explained how the Car as Power Plant (CaPP) system works. This system is designed as a 100% renewable integrated energy and transport system based on wind and solar power, hydrogen and fuel cell electric vehicles (FCEVs). In the CaPP project, by using techno-economic analysis, we have shown that such a design is technically feasible. However, technical feasibility cannot be guaranteed without considering the controllability of the system. So, the next challenge was to maintain the supply–demand balance as well as to minimize the operational costs of the energy system, which we accomplished by using advanced control techniques. We stress that operation of the innovative CaPP concept should be accompanied by an institutional analysis and designing an organizational system structure. To this end, we have studied the system behaviour and analysed the interactions between different actors in such a system.

The CaPP system and our combined framework is an example of how a comprehensive engineering approach can be used to design an energy system offering sector coupling and facilitating the penetration of 100% intermittent renewables without any compromise on the reliability of energy supply for power, heat and transport, while at the same time reducing system cost. Moreover, this approach will engage energy consumers to have a more active role in the energy transition as well. Hence, by offering our students a program in Complex Socio-Technical System Engineering, not only we will make them smarter and more inclusive engineers and scientists, but also, we can show them the way to achieving an inclusive energy transition.

To conclude, we would like to cite the words of the famous economist John Maynard Keynes (John, 1842). Almost 100 years ago, he described the qualities of a good economist. We are convinced that this description also applies to the inclusive comprehensive engineers and scientists of today:

He must be mathematician, historian, statesman, philosopher—in some degree. He must understand symbols and speak in words... He must study the present in the light of the past

for the purposes of the future. No part of man's nature or his institutions must be entirely outside his regard.

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