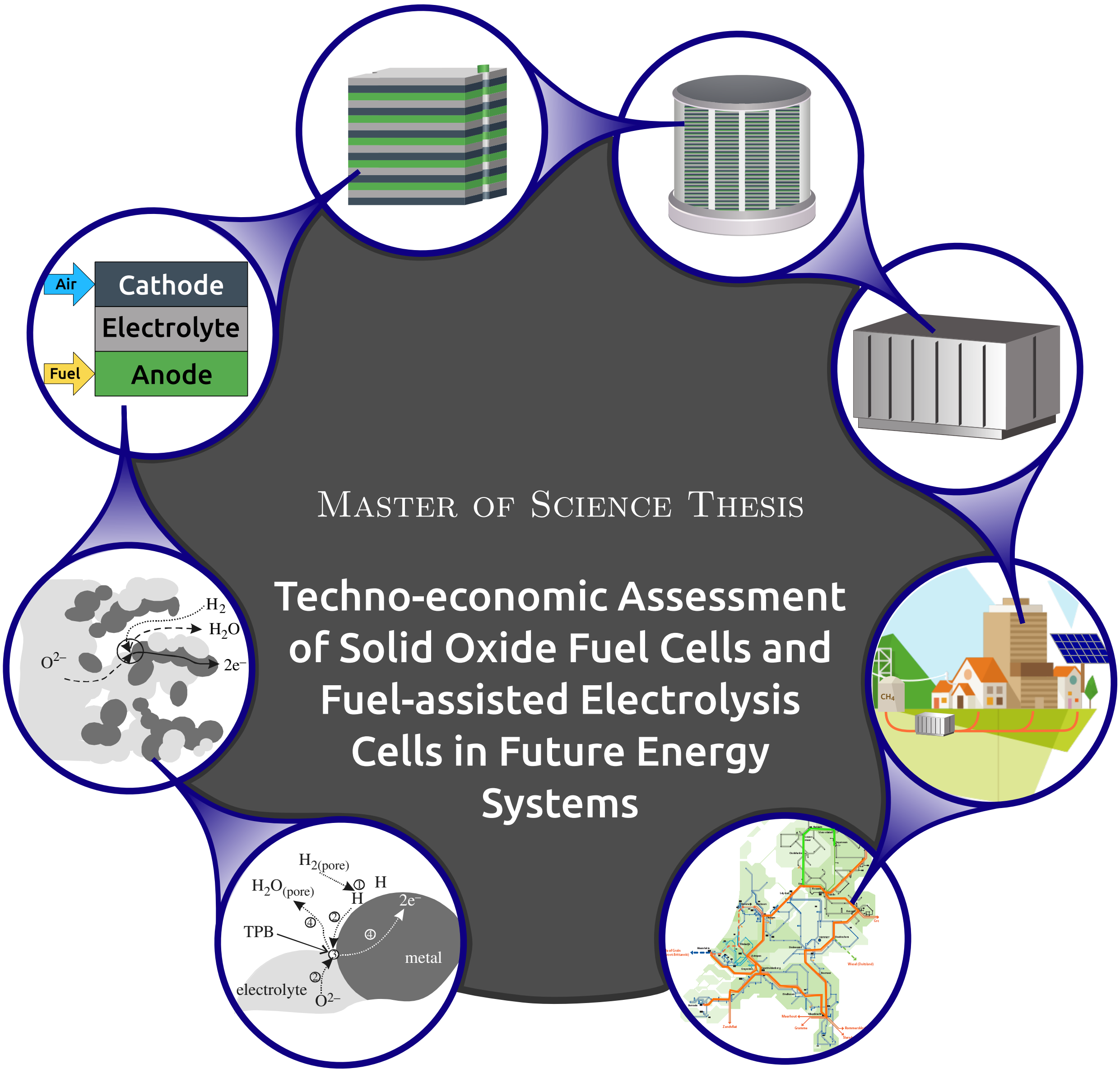
Master of Science Thesis

# Techno-economic Assessment of Solid Oxide Fuel Cells and Fuel-assisted Electrolysis Cells in Future Energy Systems





Sander van Nielen



TU Delft
Delft University of Technology

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INDUSTRIAL ECOLOGY
INNOVATIVE BY NATURE

# Techno-economic Assessment of Solid Oxide Fuel Cells and Fuel-assisted Electrolysis Cells in Future Energy Systems

Sander van Nielen
s1159615, 4174755

MSc *Industrial Ecology*
Leiden University, TU Delft

**Supervisors:**
Dr. K. Hemmes – TU Delft, Faculty of Technology, Policy & Management (TBM)
Dr. L.M. Ramírez-Elizondo – TU Delft, Faculty of Electrical Engineering, Mathematics and Computer Science (EWI)

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## Abstract

There is an increasing awareness in society of the problems and risks associated with climate change. In response, a transition from fossil to renewable energy sources is taking place. Meanwhile, there is an ongoing trend of increasing electricity demand for various applications. There is a growing number of electric appliances, as well as the electrification of heating, cooling, and transportation services. These changes provide a challenge when it comes to matching electricity production and consumption. The intermittent nature of wind and solar energy, combined with the large loads of heat pumps and BEVs, reduces the flexibility and robustness of the system in the future.

Solid oxide cells (SOCs) can contribute to solving the balancing problem of the electricity grid. SOCs perform electrochemical conversions and are developed for decentral energy conversion applications. A solid oxide fuel cell (SOFC) uses a fuel to produce electricity, hydrogen, and heat. Solid oxide fuel-assisted electrolysis cells (SOFECs) consume electricity and a fuel while producing hydrogen and heat. Gaseous fuels like natural gas, hydrogen, and biogas can be used. SOFCs have been under investigation for decades, and are mainly applied as backup power source. SOFEC technology, on the other hand, is rather unknown. Only a dozen of articles has been published, dedicated to theoretical models and small-scale lab tests. These SOCs are seen as promising technologies, because of the high energy efficiency, flexible operation, and ability to produce hydrogen.

The aim of this research is to assess whether it is feasible to introduce SOFCs and SOFECs in the (future) Dutch energy system. This research takes a broad perspective, by assessing the technological components in relation to the energy system as a whole. In addition, multiple aspects that determine the feasibility are assessed. These aspects are the technical possibilities and limitations of SOCs, their cost-effectiveness under different assumptions, the environmental implications, and societal drivers and barriers for the introduction in niche markets.

Existing literature shows that the commercial competitiveness of SOCs is currently limited because of high investment costs and a limited lifetime. The manufacturing costs can be decreased by learning through research and development, and higher production volumes. To prolong the service life, degradation of the electrodes at microscopic level should be minimised. Recent research indicates that regular switching between fuel cell and (fuel assisted) electrolysis mode can also prevent degradation. It is therefore recommended to further investigate how the service life is prolonged for a SOFC that is operated regularly as SOFEC.

A thermodynamic 1-D cell model was used to describe the inputs and outputs of a SOFC and a SOFEC. Based on this model, non-linear sets of equations with two degrees of freedom were derived for both technologies. These equations approximate the energy conversion by SOCs for different current densities and fuel utilisations. The level of complexity of these equations was suitable for the further analysis of the operation of the technologies.

The derived equations were used to implement SOFC and SOFEC technologies in oemof, an energy system optimisation framework. The framework was then used to model the energy system of the Netherlands, including all major energy carriers, i.e. fossil fuels, electricity, heat, biomass, and hydrogen. In the model, energy production, conversion, and consumption technologies are included, as well as corresponding hour-by-hour patterns. An optimisation algorithm is used to find the optimal combination of technologies and their optimal operation that results in a system that most effectively fulfils demand. The objective is to minimise the total system costs, excluding subsidies or taxes. Costs related to GHG emissions, carbon tax or emission certificates, are included. By doing so, it is the first optimisation model of its kind for the Netherlands. Not all aspects of the real energy system are represented in the model. Most notably, energy transport and demand response are not included.

The results clearly indicate that SOFCs can become an important part of the Dutch energy system if the costs decrease sufficiently and a longer lifetime of the stacks is achieved. The cost-effectiveness stems from the efficient co-production of three energy carriers and the low resource use. High GHG emission taxes are favourable for the diffusion of SOFCs. Their installation results in an emission reduction of around 5.2% (or 8 Mt$CO_2$-eq./a) compared to a system without fuel cells. No evidence

was found for the influence of SOFCs on the competitiveness of renewable electricity sources. Under some conditions, SOFCs can in fact squeeze solar and wind out of the electricity market.

If the costs of operating SOFCs remain high, then the installed capacity is limited to an extent for which high capacity utilisations can be achieved. The production of hydrogen is maximised to make expensive SOFCs profitable, indicating that this energy carrier is most important for a cost-effective introduction. If costs can be reduced, SOFCs prove to be a suitable technology for electricity production during periods of low renewable electricity production, while also responding to fluctuating $H_2$ demand. It becomes viable to operate the fuel cells with more flexibility when the technology is less expensive. The influence of the demand on SOFC operation is also considerable. In a scenario with a diverse demand for both heat, hydrogen, and electricity, a wide range of settings is used. In other scenarios, different operating strategies were more optimal. Only two or three operating points were used frequently, while other settings were applied seldom. For the requirements for SOFC technology, this implies that the preferred technical specifications depend on how the energy demand will develop.

The role that SOFECs can play in the Dutch energy system is much more limited than that of SOFCs. The conditions for cost-effectiveness are also stricter. A high level of renewable electricity production and/or high GHG emission taxes are required, on top of large cost reductions for SOC technology. Furthermore, its applicability is limited by the amount of biogas available. If SOFCs and SOFECs with the same costs are both available, a SOFC is often preferred, since it allows for much larger system cost reductions. The optimal operating strategy of SOFECs depends on their costs: if the technology becomes less expensive, it is cost-effective to operate at lower current densities with higher efficiency. Furthermore, SOFECs show a limited variation in the production rate over time. Unlike regular electrolysers, SOFECs are hardly operated to prevent electricity excesses. By operating almost continuously, a large fraction of biogas is utilised. A SOFEC profits from high GHG taxes, as it is (almost) carbon neutral.

The societal aspects of the development and potential of SOC technology were assessed using the multi-level perspective. This framework conceptualises a niche innovation as being nested structure within a socio-technical regime and a socio-technical landscape. Within the dominant regime of energy production and consumption, there is no fully developed solution to address the challenge of increased fluctuations of electricity demand and intermittent production.

Considerable research efforts in the field of SOC technology are undertaken. SOFC have received most attention, resulting in several pilot projects and growing production volumes. Few activities are taking place around SOFECs. A possible strategy is to focus on SOFC applications first, suspending efforts related to SOFECs. When lower electricity prices and lower SOC costs are achieved, it is more viable to introduce a SOFEC. Actors involved in the development of SOFCs are active, with several demonstration projects and market introductions in the area of micro-CHP applications. These dynamics could result in an uptake in the existing regime structure without exploiting and exploring the capability of SOFCs to co-produce hydrogen. Yet this study has shown the advantage of $H_2$ production for cost-effective SOFC applications.

It is deemed crucial that a user or market for the energy products of the SOFC or SOFEC is found. Therefore, the energy carrier markets for inputs and outputs form the starting point for identifying market niches, in which the SOC technology can be introduced first. Examples of identified niche applications include a farmer who uses biogas from manure digestion and supplies $H_2$ to trucks, or a neighbourhood community that invests in a common installation. A SOC provides heat to households in a neighbourhood, while $H_2$ is used for fuel cell vehicles or to provide electricity at peak demand. To convince potential users, these perceived barriers can be addressed or the advantages of SOCs can be emphasised. The high efficiency, low emissions, and importance for local grid balancing of SOFCs and SOFECs are arguments in favour of these technologies. In addition, the commitment of other stakeholders in pilot projects or through Green Deal agreements can stimulate the adoption.

## Highlights

- Co-production of $H_2$ is important for the cost-effectiveness of SOFCs.
- SOC costs should decrease significantly to become an attractive addition to the (future) Dutch energy system.
- SOFCs directly reduce GHG emissions and increase resource efficiency.
- SOFCs compete with renewable electricity sources and do not facilitate their introduction.
- SOFECs are economically less attractive than SOFCs, and their potential is limited by the availability of biogas.
- Ideal operating strategies for SOFC and SOFEC installations in the context of an energy system were assessed, and shown to depend on the demand composition and technology costs.
- Markets or consumers for heat and hydrogen are a key factor for first applications of SOC technologies.

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## Abbreviations

| | |
|---|---|
| AC | Alternating current |
| AGR | Anode gas recycling |
| BAU | Business as usual |
| BEV | Battery electric vehicle |
| BoP | Balance of plant |
| CAES | Compressed air energy storage |
| CCGT | Combined cycle gas turbine |
| CF | Capacity factor |
| CGR | Cathode gas recycling |
| CHHP | Combined heat, hydrogen, and power |
| CHP | Combined heat and power |
| CoP | Coefficient of performance |
| CRF | Capital recovery factor |
| CSP | Concentrated solar power |
| DC | Direct current |
| DSO | Distribution system operator |
| ECN | Energy Research Centre of the Netherlands |
| Eq. | Equation |
| ETS | European emission trading system |
| EU | European Union |
| FC | Fuel cell |
| FCEV | Fuel cell vehicle |
| FCH-JU | Fuel Cell and Hydrogen Joint Undertaking |
| GHG | Greenhouse gas |
| HHV | Higher heating value |
| IC | Installed capacity |
| ICE | Internal combustion engine |
| IR-FC | Internal-reforming fuel cell |
| IT | Intermediate temperature |
| JRC | Joint Research Centre |
| KNMI | Royal Netherlands Meteorological Institute |
| LCOE | Levelised cost of energy |
| LHV | Lower heating value |
| LP | Linear programming |
| LSM | Lanthanum strontium manganite |
| LT | Low-tempearture |
| MCFC | Molten carbonate fuel cell |
| MILP | Mixed-integer linear programming |
| MSW | Municipal solid waste |
| $n$-D | $n$-dimensional |
| NG | Natural gas |
| OCV | Open cell voltage |
| O&M | Operation and management |
| PCM | Phase change material |
| PEMFC | Proton exchange membrane fuel cell |
| PtG | Power-to-gas |
| PV | Photovoltaic cell |
| R-SOC | Reversible solid oxide cell |
| R&D | Research and development |
| SCR | Steam-to-carbon ratio |
| SOC | Solid oxide cell |
| SOEC | Solid oxide electrolysis cell |
| SOFC | Solid oxide fuel cell |
| SOFEC | Solid oxide fuel-assisted electrolysis cell |
| TNO | Dutch Organisation for Applied Scientific Research |
| TSO | Transmission system operator |
| VAT | Value-added taxes |
| WACC | Weighted average cost of capital |
| WWT | Waste-water treatment plant |
| YSZ | Yttrium-stabilised zirconia |

## Nomenclature

| Symbol | Meaning | Unit |
|---|---|---|
| $\alpha$ | Slope of $V_{\text{rev}}$ as a function of $U_f$ | V |
| ASR | Area specific resistance | $\Omega\text{cm}^2$ |
| $A$ | Active cell area | $\text{cm}^2$ |
| $C_{\text{fix}}$ | Fixed O&M costs | €/kW/a |
| $C_{\text{fuel}}$ | Fuel costs | €/MWh |
| $C_{\text{GHG}}$ | GHG emission costs | €/MWh |
| $C_{\text{inv}}$ | Investment costs | €/kW |
| $C_{\text{var}}$ | Variable O&M costs | €/MWh |
| CU | Capacity utilisation | |
| $D$ | Energy demand | PJ/a |
| $\Delta G$ | Gibbs free energy change | kJ/mol |
| $\Delta H$ | Enthalpy change | kJ/mol |
| $\dot{H}$ | Fuel flow rate | J/s |

| Symbol | Meaning | | Unit |
|---|---|---|---|
| $\Delta_c H$ | Heat of combustion; HHV | | kJ/mol |
| $\Delta S$ | Entropy change | | kJ/mol/K |
| $\eta$ | Efficiency | | |
| $E_{\text{inv}}$ | Initial GHG emission | | $tCO_2$-eq./kW |
| $E_{\text{var}}$ | Combustion GHG emission | | $tCO_2$-eq./MWh |
| $F$ | Faraday's constant | $96.485 \times 10^3$ | C/mol |
| $i$ | Current density | | $A/cm^2$ |
| $I$ | Current | | A |
| $J$ | Energy flux (flow rate per unit of cell area) | | $W/cm^2$ |
| $K_R$ | Equilibrium constant of reaction $R$ | | |
| $L$ | Lifetime | | a |
| $\nu_{S,R}$ | Stoichiometric coefficient of species $S$ in reaction $R$ | | mol/mol |
| $n$ | Stoichiometric coefficient of electrons in a redox reaction | | mol/mol |
| $\dot{n}$ | Molar flow rate | | mol/s |
| $P$ | Electric power output | | $W_e$ |
| | Electric energy | | $MWh_e$ |
| p | Pressure | | bar |
| $pS$ | Partial pressure of species S | | bar |
| $\dot{Q}$ | Heat flow rate | | J/s |
| $R$ | Gas constant | $8.314 \times 10^{-3}$ | kJ/mol/K |
| $r$ | Discount rate | | |
| T | Temperature | | K |
| $T$ | Time period length | | h |
| $t$ | Timestep | | |
| $tax_{\text{GHG}}$ | GHG emission tax | | €/$tCO_2$-eq. |
| $u$ | Local fuel utlisation | | mol/mol |
| $U_a$ | Air utilisation | | mol/mol |
| $U_s$ | Steam utilisation | | mol/mol |
| $U_f$ | Fuel utilisation | | mol/mol |
| $v$ | Wind speed | | m/s |
| $V_0$ | OCV under feed concentrations | | V |
| $V^\circ$ | OCV under standard concentrations | | V |
| $V^*_{\text{rev}}$ | Local Nernst potential | | V |
| $V_{\text{cell}}$ | Cell potential | | V |
| $V_{\text{rev}}$ | Nernst potential | | V |
| $\xi_R$ | Extent of reaction $R$ | | |
| $y$ | Fraction | | |

## Subscripts and superscripts

| | | | |
|---|---|---|---|
| add | Additional | inv | Investment, initial |
| c | Energy carrier | max | Maximum |
| cur | Curtailment | out | Output |
| e | Component | rated | Rated |
| exc | Excess | sho | Shortage |
| final | Final energy | tot | Total |
| fix | Fixed | useful | Useful energy |
| in | Input | var | Variable |

# Acknowlegements

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# Chapter 1

# Introduction

## 1.1 Introduction

Scholars, citizens, societal organisations and politicians are increasingly aware of the problems and risks associated with climate change. This awareness entails a growing sense of urgency to reduce greenhouse gas (GHG) emissions. An important measure to reach the targets of GHG emission reduction is the switch from fossil to renewable energy sources. Electric and thermal energy can be derived from wind and solar energy, and other renewable sources that are locally available. Meanwhile, a continuous trend towards a higher electricity demand is taking place. Fossil fuels are replaced by electricity as energy carrier by the electrification of heating, cooling, and transportation services. The growing number of electric appliances used by consumers also contributes to the trend.

These changes in production and consumption of electricity provide a challenge for the match between the two. On the one hand, the intermittent nature of renewable electricity sources causes periods of overproduction and shortage (Mulder, 2014). Fluctuations provide a challenge for conventional powerplants that have a limited output adjustment speed. On the other hand, heat pumps and battery electric vehicles (BEVs) provide considerable electric loads with the potential to cause major demand peaks. The challenge consists of filling up shortages in production, and handling excesses to ensure a balanced network at every moment in time. Solutions that are proposed include fossil fuel based backup plants, energy storage, and demand-response mechanisms. The effectiveness of these solutions depends on the configuration of the system. For example, backup plants work best with moderate or low renewable energy penetration (Schenk et al., 2007). Energy storage options such as batteries are attractive in systems with a high amount of renewable electricity production (Belderbos et al., 2015). The efficiency and costs restrain application in the current system.

An alternative solution to the balancing problem is provided by solid oxide cells (SOCs). SOCs are devices that perform electrochemical conversions. This developing technology is scalable from 1 kW to several megawatts (Energistyrelsen & Energinet.dk, 2015), and is therefore suitable for decentral applications. Solid oxide fuel cells (SOFCs) use a fuel to produce electricity, hydrogen, and heat (Hemmes, 2004). Solid oxide fuel-assisted electrolysis cell (SOFECs) consume electricity and a fuel while producing hydrogen and heat (Cinti et al., 2016). By operating in response to the electricity market, excess and shortage can be addressed by SOFCs and SOFECs. This would stimulate the growth of renewable electricity production (Vernay et al., 2008). In this respect, the concept of a reversible SOC (R-SOC) that can switch between fuel cell and fuel-assisted electrolysis mode is attractive. SOFECs and R-SOCs have been investigated to a limited extent, so there is little operational knowledge of these technologies.

Given the ability of SOCs to co-produce hydrogen, they could play a role in a transition towards a system with hydrogen as energy carrier. Besides, SOCs can use various gaseous fuels, among which natural gas (NG), hydrogen, and biogas (Van Herle et al., 2004; Ud Din & Zainal, 2016). Therefore, an opportunity to utilise a renewable fuel is provided.

In the past decades, large and growing efforts have been invested in the research and development (R&D) of SOFCs (Mahato et al., 2015). Applications are found in specific situations, such as remote areas or as subsidised installations for heat and power production in households (Hart et al., 2015). The scientific knowledge of SOFECs, on the other hand, is much more limited. A number of articles has been published, in which theoretical thermodynamic models are presented (Butler, 2010; Wijers, 2011; Luo et al., 2014; Patcharavorachot et al., 2016). Some experiments on a lab-scale have been published as well (Tao et al., 2006; Tao, 2007; Cinti et al., 2016).

Many questions related to the new SOC technology are yet unanswered, for example: At what costs are they competitive? To what extent do SOCs stabilise the electricity grid? What role could or should SOCs play on the energy market? How could they be operated in real-world market conditions? How do the answers change in a future energy system? Conventional assessment methods fall short in analysing SOCs, because of the complex input-output relations. The merit order is used to determine how often an electricity source is operated, but is hard to apply for multi-generation technologies. Hydrogen production alternatives can be compared by calculating the levelised costs of energy, but this is not straightforward if variable electricity prices apply for an electrolyser. Furthermore, technologies that have multiple inputs and/or outputs should somehow respond to the dynamics of all energy carrier markets to which they are connected. To conclude, more sophisticated and system-oriented tools are required to study SOCs.

A method that takes an integral approach, and is therefore able to answer most questions above, is energy system optimisation. Computational optimisation has been applied to many problems, and is also suitable for the assessment of energy systems. An energy system optimisation model can determine the optimal combination of technologies and/or their optimal operation, based on a given objective.

An energy system is defined as the collection of all socio-technical structures related to energy within a given geographic area. Energy systems include the supply chains of energy carriers. A typical supply chain consists of energy generation, conversion, transport, distribution, storage, and consumption units. Because of the wide variety of technical, financial, regulatory, institutional, and socio-cultural structures, actors, interactions, and dynamics involved in energy systems, they are complex systems.

Given the complexity of energy systems, it is not straightforward to evaluate the performance of a single component. The efficiency of the system as a whole does not only depend on the characteristics of single components, but also on how well they complement each other. When this complexity is acknowledged, the system should be assessed as a whole. To do so, computer models can be useful tools. By analysing a model of an energy system, valuable insights can be gained. Energy models can generate and quantify alternative energy system structures as part of the decision making processes of policy makers and business strategists.

## 1.2 Research questions

SOFCs and SOFECs are promising emerging technologies. They are claimed to be efficient in producing energy, flexible in their operation, and beneficial for the integration of renewable energy sources into the energy system. The latter two benefits can only be assessed properly from a systems perspective. Therefore, the aim of this research is to assess the sensibility of including SOFCs and SOFECs in a future national energy system. The feasibility depends on the technical feasibility, the effects on the energy system, its costs and its eco-efficiency, the required technical modifications of the energy system, and the societal acceptance of the technology.

To summarize, the research question is formulated as

> "Is it feasible to introduce SOFCs and SOFECs in the (future) Dutch energy system?"

The feasibility can be further specified by acknowledging that different aspects determine the feasibility. These aspects are taken into account in the subquestions:
Technical aspects:

- Is it technically possible to operate SOCs in both normal and fuel-assisted electrolysis mode?
- What is the optimal operating strategy for SOCs?

Economic aspects:

- Are SOCs a cost-effective addition to the current Dutch energy system?
- At what cost level are SOCs a cost-effective component of the future Dutch energy system?
- What effect do GHG emission taxes have on the economic feasibility?

Environmental aspects:

- How do SOCs affect the GHG emissions of the Dutch energy system?
- What changes in primary energy consumption result from the introduction of SOCs?

Societal aspects:

- How can the transition towards a system with SOCs take place in terms of technology replacement?
- What are potential niche markets, in which SOC technologies can be applied first?
- How can the development and diffusion of SOC technology in the Netherlands be promoted?

## 1.3 Relevance

SOFC and SOFEC are relevant for the field of Industrial Ecology, because of their contribution to resource savings, emission reductions, and ultimately a more sustainable energy system. Besides, SOCs can be operated using several fuel options and produce two or three energy carriers. These characteristics make that the technology can be relevant for *industrial symbioses* or *industrial ecosystems*, in which materials, energy, knowledge, and other resources are exchanged.

This research contributes to existing knowledge by deriving a model that describes the tri-generation of heat, hydrogen, and power by a SOFC as well as for the fuel-assisted electrolysis of water by a SOFEC. SOFC technology has been well-studied in the past, yet less development efforts are invested in its ability to produce $H_2$. Research on fuel-assisted electrolysis is limited to a number of studies on theoretical models and small-scale lab tests. Besides, the energy system of the Netherlands was modelled, while including all energy carriers and production and consumption patterns with a resolution of one hour. This integrated approach is relatively new, but is important to address the increasing conversions between different energy carriers. Energy system optimisation is applied to assess the feasibility in terms of economic and environmental aspects of SOFC and SOFEC technologies in the (future) energy system. This will provide new insights in the applications of both. SOFECs and SOFCs producing $H_2$ have not been investigated in this respect yet. Given the uncertainties related to future developments, it is relevant to determine the influences of SOC costs, GHG emission taxes, and demand composition on the feasibility of these emerging technologies. No studies have been conducted yet to investigate the ideal operating strategy of SOFCs and SOFECs. The optimisations of the present study allows to assess the operation in the context of realistic energy carrier markets.

## 1.4 Outline

The body of this thesis is structured as follows. Chapter 2 focusses on the technical aspects of SOFCs and SOFECs. By reviewing literature on the materials, operation and design of solid oxide cells, the characteristics and possible applications are assessed. Based on the insights gained from Chapter 2, Chapter 3 derives input-output relations that allow for the implementation of SOCs in optimisation frameworks. Next, Chapter 4 discusses the theory and practice of energy system modelling. The theoretical framework is discussed, as well as existing energy system models. Also, the modelling approach of this research is specified. Assumptions and scenarios related to the production and consumption of energy in the model are elaborated in Chapter 5, whereas data for specific technologies are presented in Chapter 6. In the next chapter, Chapter 7, optimisation outcomes are presented and discussed. These results are the key to answering the research questions related to economic and environmental aspects. Chapter 8 starts with the specification of an analytical framework based on literature study. The concepts of this framework are then applied to determine drivers, barriers, and niche markets for SOFC and SOFEC technology. The sensitivity and validity of the results are tested in Chapter 9. The final chapter provides conclusions, implications, and recommendations that follow from this thesis. In addition, possible directions for further research are recommended.

# Chapter 2

# Technical Aspects of Solid Oxide Cells

This chapter covers existing knowledge of the chemistry, materials, design, and operation of SOFCs. This information is needed to understand what the technical possibilities and limitations are for the application of SOFCs and SOFECs. Besides, the parameters that describe system operation and losses are important for the mathematical modelling of the cells.

## 2.1 Chemical principles

### 2.1.1 Fuel cell types

A fuel cell (FC) is an electrochemical device that converts chemical energy of a fuel to electric power and heat. The theoretical efficiency of a FC is higher than that of internal combustion engines. Fuel cells consist of an anode, where the fuel is supplied, a cathode, where the oxidant is supplied (usually air), and an electrolyte that transports ions between the electrodes. Various FC designs exist, differing in the choice of fuel and electrolyte (Giddey et al., 2012). FC types are usually named after their electrolyte. Hydrogen is the most common fuel.

Solid oxide fuel cells are named after their solid, ceramic, oxygen ion conducting electrolyte. SOFCs operate at high temperatures, that can range from 650 to 1000 °C (Mathiesen, 2008). These high temperatures entail several advantages. First, less or no precious metal catalysts such as platinum and palladium are required to drive the reactions at the electrodes. Second, higher efficiencies can be reached compared to low-temperature FCs. This is because electric losses, resulting from the internal resistance of a FC, decrease with temperature (Standaert, 1998). Third, any 'waste' heat that is recovered from the outflows has a high temperature and high exergetic value, allowing for reuse. Fourth, high-temperature FCs are capable of sustaining an endothermic internal reforming reaction with heat produced by the oxidation of fuel. If methane and steam are supplied to the anode, $H_2$ and $CO_2$ are formed. In that case, the FC is referred to as *internal reforming fuel cell* (IR-FC). Some of the generated hydrogen can be extracted from the cell as a product. By doing so, a very high efficiency for the conversion from fuel to energy products is realised (see § 3.4.1).

The disadvantage of high-temperature FCs is that all materials, including those of the support structure, have to be resistant towards high temperatures and temperature changes. Although the temperature is high in SOFCs, it is not as high as in conventional combustion engines. Therefore SOFCs cause, like other FCs, virtually no emissions of $NO_x$ and particulate matter (Giddey et al., 2012).

An advantage of FCs is their scalability. Even small stacks have a high efficiency, making them attractive for distributed combined heat and power (CHP) generation, or household-scale CHP (micro-CHP). Moreover, it is possible to build modular powerplants which can easily scale up when required by adding extra stacks. Furthermore, the energy production rate of FCs can be adapted quickly to the demand. An IR-FC installation can be ramped up in 15 minutes. A precondition for SOFCs is that temperature gradients are minimized to prevent degradation (Fardadi et al., 2016). Therefore, long start-up times are needed, unless the operating temperature can be maintained when the SOFC is not operated.

### 2.1.2 Solid oxide cells

The operation of SOCs is based on the principles of electrochemistry, which describes the conversion of electric energy to chemical energy and vice versa. A cell is composed of two electrodes, the anode and cathode, and an electrolyte sandwiched in between. An electric circuit connects the cathode and anode. Unlike batteries, the chemical reactants are not stored within the electrodes, but are continuously supplied to the cell during operation. The operational principles of SOCs are depicted in Figure 2.1.

At the oxygen electrode of a SOFC, oxygen from air takes up electrons from the external circuit and enters the electrolyte. The oxygen ions are transported between the electrodes via the electrolyte. At the fuel electrode, gaseous fuel is supplied and oxidised by the oxygen ions. To close the electrochemical cycle, an external load is connected to both electrodes.

A SOC can also be operated in reverse when steam is supplied to the fuel electrode. By applying an external voltage, hydrogen and oxygen are produced from the electrolysis of water. In this mode of operation, the cell is referred to as a solid oxide electrolysis cell (SOEC). Operating temperatures similar to that of SOFCs are applied. In a SOEC, voltages higher than the decomposition potential of water are required.

The high (over)potentials of a SOEC can be prevented in a third mode of operation, namely as solid oxide fuel-assisted electrolysis cell. Fuel (e.g. methane or syngas) is fed to the fuel electrode, where oxidation takes place. This reduces the operating voltage by about 1 V (Martinez-Frias et al., 2003), since the thermodynamically unfavourable formation of oxygen is prevented. Therefore, the electric power required to produce hydrogen from steam at the steam electrode decreases significantly.

### 2.1.3 Reactions

In a SOFC, chemical and electrochemical reactions are taking place. The operation of a SOFC can be described by three reactions: R1–R3. The overall reaction is identical to regular combustion, with the difference that fuel and air are never in direct contact as indicated by Figure 2.1a. The electrochemical fuel oxidation process has a higher exergy efficiency. The electrochemical redox reaction R1 of $H_2$ and $O_2$ to form water, with a half reaction at each electrode (Figure 2.1a), is responsible for the power generation. The hydrogen required for this reaction can be produced during two reactions: fuel reforming (R2) and water-gas shift (R3). Other reactions occur in parallel, but these have lower rates (Wendel et al., 2016) and are only relevant in detailed studies of kinetic effects at the fuel electrode (Hemmes, 2004). Reactions R2 and R3 together are referred to as steam methane reforming (SMR). The overall result of the three reactions is that methane is fully oxidised to $CO_2$ and $H_2O$ (R4), provided that all reactions are complete. For any practical application, R1 will never reach full conversion, as discussed in § 2.6.2.

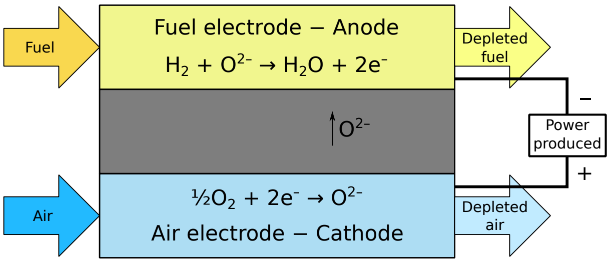
$$2\,H_2 + O_2 \longrightarrow 2\,H_2O \tag{R1}$$

$$CH_4 + H_2O \longrightarrow CO + 3\,H_2 \tag{R2}$$

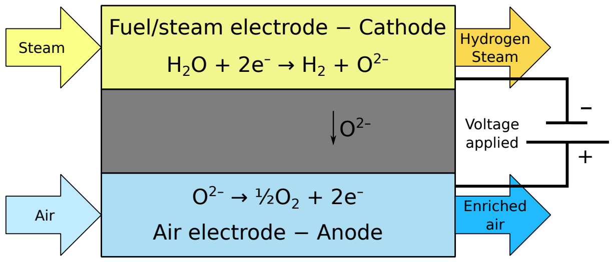
$$CO + H_2O \longrightarrow CO_2 + H_2 \tag{R3}$$

$$\text{Overall:}\quad CH_4 + 2\,O_2 \longrightarrow CO_2 + 2\,H_2O \tag{R4}$$

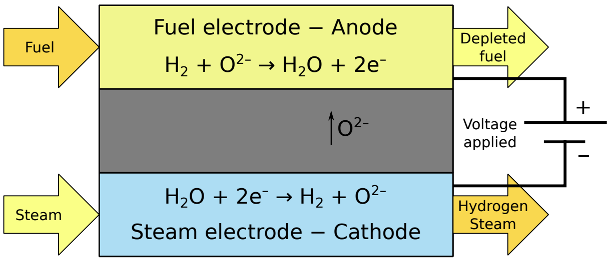
In a SOEC, the redox reactions proceed in the opposite direction compared to a SOFC. An applied voltage provides the driving force for the two redox half-reactions at the SOEC electrodes (Figure 2.1b). Oxygen is formed instead of consumed at the air electrode from $O^{2-}$ ions. The electrons released travel through the external circuit to the steam electrode, where $H_2$ is generated. In a SOFEC, $H_2O$ is reduced to $H_2$ at the steam electrode, identical to the SOEC cathode reaction. Instead of $O_2$ formation at the anode, a fuel is oxidised (e.g. $H_2$ or CO) in a reaction with $O^{2-}$. The fuel electrode reaction results in an overall cell reaction that is close to equilibrium, implying that an applied voltage close to zero is sufficient to drive the production of $H_2$.




(a) SOFC, in which a fuel, e.g. $H_2$, reacts electrochemically with $O_2$ to yield power.




(b) SOEC, where electricity is used for electrolysis, splitting $H_2O$ into $H_2$ and $O_2$.




(c) SOFEC, where electrolysis is performed, but with a fuel supplied at the anode as reducing agent.

Figure 2.1: Components and operating principles of solid oxide cells. Redox reactions at the electrodes are shown for all operating modes. The three main components of SOCs are illustrated in the figures. A cell has two porous electrodes, the anode and the cathode, which are separated by a dense electrolyte.

### 2.1.4 Fuel flexibility

Many hydrogen-rich fuels can be used as feed for the fuel electrode of a SOFC or SOFEC. Apart from methane, other hydrocarbons or hydrogen can also be used as a fuel. All of these compounds could be derived from biomass in the future. In the Netherlands, a limited amount of organic wastes is available, originating from agriculture, forestry, waste-water treatment, and households (Warmerdam et al., 2011; Ros & Prins, 2014). On a European level, the amount of available biowaste is estimated enough to run SOFCs with a total installed capacity of 12 $GW_e$ (Van Herle et al., 2004). Biomass can be converted to biogas by for example pyrolysis, thermo-chemical gasification, or fermentation. Combined with appropriate purification equipment and in some cases steam methane reforming, biogas is compatible with SOFCs (Ud Din & Zainal, 2016).

The advantage of using biogas is that fossil fuels are not depleted, and only biogenic $CO_2$ is emitted. Disadvantages of biogas include the higher costs of the plant due to contaminant removal equipment, and the limited supply of domestic biomass. Further issues and concerns arise if dedicated energy crops are used. The consequences include deforestation, the interference with food supplies, and fertiliser use (Ridjan et al., 2013).

SOFCs have been demonstrated to work well with CO-rich gases (Omosun et al., 2004; Penchini et al., 2013). These gases can be derived from municipal solid waste (MSW) incineration plants and steel production. Blast furnace gas, coke oven gas, or mixtures of these are presently used to generate electricity in conventional turbines (CBS, 2015b). Syngas (a mixture of CO and $H_2$) is another potential fuel derived from industrial processes. Higher hydrocarbons can be used by SOFCs (Murashkina et al., 2008).

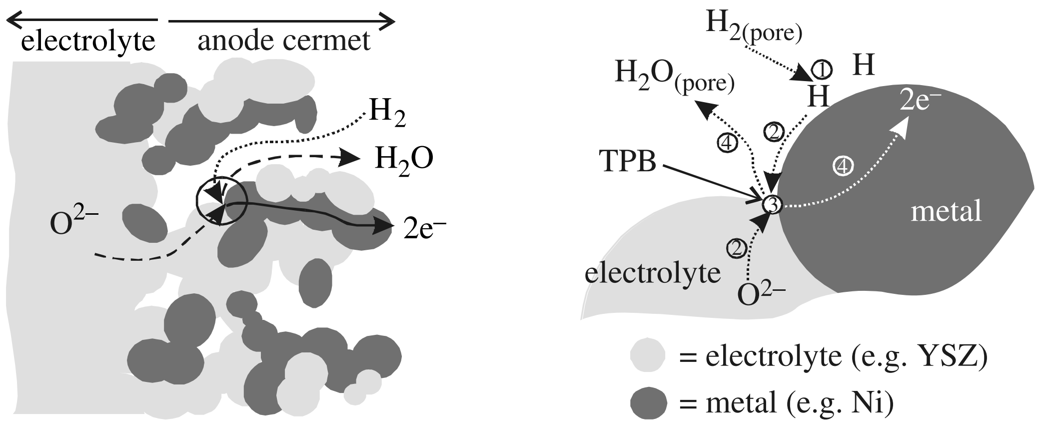
## 2.2 Materials used in SOFCs

The technical limitations and focus points for current research are closely connected to the materials that constitute the core parts of SOCs. Therefore, an overview of commonly used compounds for the anode, cathode, and electrolyte (see also Figure 2.1) is given below. Most materials discussed here can also be used in a SOFEC, as explained in § 2.3.6 in more detail.

### 2.2.1 Anode – fuel electrode

The fuel electrode is made of a porous material, connected to the electrolyte, as shown in Figure 2.2a. In almost all current SOFCs (Mahato et al., 2015), nickel–yttria-stabilized zirconia (Ni–YSZ) is the anode material. Ni–YSZ is a cermet, i.e. a material composed of both a ceramic and a metallic material. The metal ensures a high ionic conduction, while the ceramic material makes sure the cermet remains stable under high temperatures and provides ionic conductivity.

An important measure for the reactivity of the anode is the length of the *triple-phase boundary* (TPB). This interface between the Ni, zirconia, and gas phase (see Figure 2.2b) is the catalytically active part of the electrode. By optimising the TPB, high current densities and low losses can be achieved. Therefore, a great deal of research efforts have been invested in techniques to synthesize anode materials with longer TPBs. An evolution has occured from Ni patterns applied on the electrode, through screen printed or coated Ni anodes, to impregnated skeletons and cermets (Mahato et al., 2015; Irvine et al., 2016). The newest techniques give more precise control over the microstructure of the materials, leading to better performance.




(a) Schematic representation of a porous SOFC cermet anode.

(b) Detail of the triple phase boundary (TPB), where the metal, cermet, and gas phase are in contact.

Figure 2.2: Schematic depiction of a SOFC anode material. Reprinted from Brandon (2013).

### 2.2.2 Cathode – oxygen electrode

Metal oxides with a perovskite crystal lattice are important cathode materials. Perovskites have a general formula of $ABO_3$, in which A and B are metal cations. The most common cathode material for SOFCs is $La_{1-x}Sr_xMnO_{3-\delta}$ (LSM). The ionic conductivity of perovskites can be enhanced by doping the material with acceptor cations, resulting in vacant oxygen sites. In the case of LSM, $Sr^{2+}$ ions replace some of the lanthanum. The high operating temperatures increase electronic conductivity (Mahato et al., 2015).

### 2.2.3 Electrolyte

The function of the electrolyte is to transport oxygen ions ($O^{2-}$) from the cathode to the anode, thereby closing the electrochemical cycle of the fuel cell. A good electrolyte has high $O^{2-}$ conductivity, but does not conduct electrons. YSZ has these properties at high temperatures. Ceria-stabilized zirconia (CeSZ) is more attractive for intermediate temperatures (Marina et al., 2007).

Several designs and geometries of SOCs have been developed. As for the cell design, there are electrolyte-supported, anode-supported, and metal-supported cells. The geometry can be either planar or tubular. The most common planar design geometry is characterised by the 'sandwich' of anode, cathode, and electrolyte materials. This design allows to easily stack multiple cells in a fuel cell stack (Irvine et al., 2016).

## 2.3 Material stability

### 2.3.1 Degradation research

Better insights in how SOCs work and how they can be improved can be obtained through research on the chemical properties and mechanisms of fuel cell materials. As mentioned in § 2.2.1, the electrochemical interface or TPB is crucial for the performance of the cells. Damage done to the phase boundaries is the main cause of the short lifetime of most SOCs. Therefore, it is important to understand the mechanisms that cause passivation, activation, or degradation of the interfaces (Irvine et al., 2016). *Degradation* persistently damages the electrode, whereas *passivation* can be reversed.

Research conducted on SOCs is usually divided into three phases. In the first phase, small tubular button cells of typically 1-3 cm diameter are used. These cells allow researchers to investigate material behaviour and combinations and optimize the compositions. Second, design alternatives are compared using single cells with their intended dimensions (around 100 $cm^2$ of active area). Finally, a stack of cells is build and tested for contact issues and other problems occurring only at full system level (US Fuel Cell Council, 2007).

### 2.3.2 High temperatures

While the high operating temperature provides several advantages (internal reforming, more efficient electrolysis, redundancy of precious catalysts), it also poses a strict constraint on possible materials to used. Minimum requirements for all SOC materials are stability under high temperatures and the capability to withstand thermal stress caused by thermal gradients within the cell. This requirement does not only apply to the electrodes and electrolyte, but also holds for housing and interconnecting materials.

An example of a temperature-induced degradation effect is chromium poisoning. This effect occurs at the air electrode, where chromium present in interconnect materials or in steel housing, blocks the electrode active sites (Irvine et al., 2016). Gradients induce cracking of electrode materials. To minimise detrimental effects of thermal gradients as a result of heating and cooling of the cell, steep load changes should be avoided. In practical applications, the load-following capability of a SOFC is therefore limited. Transport phenomena add to the inertia of the cell (Napoli et al., 2015). Thermal management strategies (possibly using an external heat source) can increase the dynamic response of SOFCs (Fardadi et al., 2016; Komatsu et al., 2014).

The transient behaviour of a SOFC stack in response to a change in current density was examined by Komatsu et al. (2014). A sudden change results in an overshoot of the cell voltage, followed by stabilisation within 30-60 minutes. A ramping rate of 3 $W_e/s$ was reported for a 1 $kW_e$ SOFC manufactured by Ceres Power (Brandon, 2013). This implies that a cell can switch between full and zero load in 6 minutes. These figures indicate that the load-following operation limitations are more important at short time intervals. For this reason, low-temperature fuel cells perform better in following the electricity demand of as single household Napoli et al. (2015).

### 2.3.3 Sulfur tolerance

The fuel electrode is sensitive to sulfur poisoning. Even small traces of $H_2S$ are adsorbed by nickel at the TPB, resulting in a smaller active area. At higher $H_2S$ concentrations or large overpotentials in electrolysis mode, degradation occurs due to the formation of NiS (Irvine et al., 2016). This fact is important, because untreated biogas and, to a lesser extent, NG, contain sulfur compounds. In biogas generated from sewage sludge and other organic origins, $H_2S$ and organic sulfur compounds are the most abundant contaminant (McPhail et al., 2011). Sulfur concentrations depend on the origin of the biomass source. Although naturally occurring sulfur compounds are removed from crude natural gas, sulfur-containing odorants are added to the gas (De Wild et al., 2002). The odorants give the gas a characteristic smell, allowing for the detection of potentially dangerous gas leaks. In the Netherlands, the odorant used is tetrahydrothiophene, in a concentration of around 18 mg/m$^3$ (GTS, 2014).

A higher tolerance towards sulfur poisoning can be achieved by replacing YSZ by scandia stabilised zirconia (ScSZ) or gadolinia doped ceria (GDC) in the fuel electrode (Mahato et al., 2015). Experimental results indicate that a Ni–GDC electrode remains stable during operation with biosyngas as fuel (Ouweltjes et al., 2006; Ud Din & Zainal, 2016).

### 2.3.4 Electrolysis mode

The electrolysis mode seems to pose the largest challenges for electrode material stability. Typically, SOECs show higher degradation rates than SOFCs (Graves et al., 2015). Some of the mechanisms are discussed below.

A main source of degradation is the high overpotential applied during electrolysis. One possible consequence is crack formation in the anode material due to the growth of oxygen bubbles. The increasing pressure of these bubbles destabilises the electrode, resulting in disintegration or delamination in the long run (Graves et al., 2015). Meanwhile, $ZrO_2$ reduction can occur at the cathode. This mechanism eventually leads to passivation of the interface too. Yet, cycling between fuel cell and electrolysis mode can reverse the damage to a certain extent, since Zr can be oxidised again (Irvine et al., 2016).

Finally, as a consequence of the high steam pressures typically applied in SOECs, Ni particles can aggregate and coarsen at the Ni–YSZ electrode. This decreases the length of the TPB.

### 2.3.5 Material purity

Electrode materials should be able to withstand high temperatures, sulfur traces, and the reactants flowing through it, as discussed in the previous sections. An additional prerequisite is that the materials should not react in the presence of each other or under the applied redox atmospheres. Degradation of the Ni–YSZ electrode seems to be heavily influenced by the type and level of impurities not only in the fuel gas, but also in the electrode material itself. This could explain differences in performance of several orders of magnitude as reported for otherwise identical electrodes (Irvine et al., 2016).

### 2.3.6 Materials for reversible cells

As discussed above, degradation and passivation occur after prolonged operation in a single mode. Sometimes, this can be prevented by operating a fuel cell in a cyclic way, i.e. switching between SOFC and SOEC or SOFEC mode. For instance, Graves et al. (2015) show that after reversible cycling between electrolysis and fuel-cell mode, the microstructure of the electrodes is still intact. The test setup used cycles of 5 h in each mode. After 4000 h of operation, the power output was almost identical to the initial value (Graves et al., 2015).

The biggest challenge for the development of a R-SOC is to design electrode materials that are both stable and efficient under a range of redox environments. The electrolysis mode is still a major bottleneck (§ 2.3.4, Gómez and Hotza (2016)). New perovskite materials are investigated for their performance. For example, a $La_{0.3}Ca_{0.7}Fe_{0.7}Cr_{0.3}O_{3\text{-}\delta}$ air electrode (Molero-Sánchez et al., 2015) and a $La_{1\text{-}x}Sr_xCr_{1\text{-}y}Mn_yO_3$ (LSCM) fuel electrode (Tao, 2007) were developed. Both were shown to be stable and efficient in both fuel cell and electrolysis mode.

In 2016, a commercial, 50 kW R-SOC was installed by Sunfire (Fuel Cells Bulletin, 2016). This module can help to find optimal operating parameters and to identify bottlenecks in robustness. Tao (2007) has tested the use of SOCs in fuel-assisted electrolysis mode with positive results. Cells with 100 cm$^2$ active area each were combined in short stacks of 2 to 10 cells. These stacks were able to produce hydrogen in SOFEC mode at an overpotential of around 1 V lower than regular electrolysis. Both $CH_4$, $H_2$, and CO were tested as fuel, but only at low current densities (<0.5 A/cm$^2$).

## 2.4 System design

### 2.4.1 SOFC

Although the fuel cell is the core component of a combined heat, hydrogen, and power (CHHP) system, other components are needed as well to complete the system. A possible layout of an entire system is provided in Figure 2.3. Fuel gas entering the system is desulfurised before it is mixed with steam in the pre-reformer. The gas mixture now consists of mostly $H_2$, $H_2O$, CO, $CO_2$, and some unreacted $CH_4$. At the SOFC anode, $H_2$ is oxidised, and the SMR reactions proceed further. Hydrogen is separated from the cathode off-gas as a product. The remainder of the mixture is directed to the afterburner, where it reacts with partly depleted air from the SOFC anode. Heat released during the combustion reactions is exchanged with the pre-reformer. The temperature of the afterburner flue gases is decreased in a series of heat exchangers that heat up reactant flows. To reuse the remaining waste heat, another heat exchanger connected to an external circuit is included. Depending on the desired temperature of the external heat demand, it is possible to position this heat exchanger before or after the others. For maximum water and energy recovery, steam is condensed from the flue gas and re-used in the process.

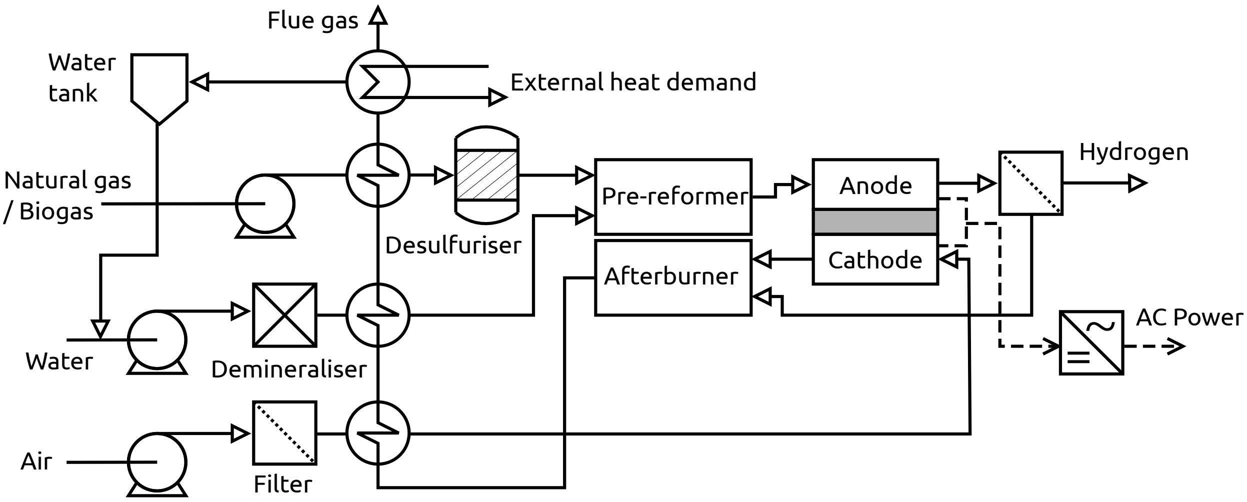



Figure 2.3: A possible SOFC system design. Similar drawings are published in Arduino and Santarelli (2016); Braun (2002); James et al. (2012); Scataglini et al. (2015).

The flowchart of a micro-CHP SOFC is very similar to the design in Figure 2.3. A difference is that $H_2$ leaving the cathode is not collected, but combusted in the afterburner together with the other off-gases (Pfeifer et al., 2013).

Some designs deviate from the one given in Figure 2.3. The pre-reformer can be excluded, or exhaust gas recycling of either the anode or cathode is included. Besides, the size of the stack is a relevant design parameter. The considerations for each of these decisions are discussed in § 2.4.2–2.4.5.

### 2.4.2 External reforming

An important design decision is whether (partial) external reforming is used, or that the SMR reactions (R2 and R3) occur internally, i.e. at the fuel electrode. In a fuel processor, external reformer or pre-reformer (as shown in Figure 2.3), the preheated fuel mixture is brought into contact with a Ni catalyst. Nickel, which is also present in the fuel electrode, catalyses SMR. Whether or not to include a pre-reformer depends on several considerations. Firstly, the choice affects the thermal management strategy. While the exothermic oxidation reaction (R1) releases heat, the reforming reaction R2 is highly endothermic; $\Delta_r H = 225.6$ kJ/mol at 800 °C(Wendel et al., 2016). On the one hand, this means that an IR-FC needs less cooling, which is an advantage. On the other hand, this does result in large temperature gradients in the cell, which accelerates degradation of the materials (Braun, 2002; Aguiar et al., 2002). Secondly, the cell efficiency depends on the way of reforming. External reforming results in a high hydrogen concentration at the inlet, which makes the fuel cell more efficient (Janardhanan et al., 2007). However, the overall system efficiency decreases by applying external reforming. These conclusions are supported by the model of Braun (2002). Braun shows that pre-reforming has only a very small effect on the power production, because most methane is reformed within a small distance from the fuel inlet of an IR-FC. Thirdly, the costs of the system are affected by the decision. An external reformer requires additional investments and maintenance compared to internal reforming (Braun, 2002; Janardhanan et al., 2007). Moreover, the reduced cooling requirements allow for smaller air pumping equipment (Staffell & Green, 2013).

### 2.4.3 Anode gas recycling

Instead of using pure steam as input to the pre-reformer, anode gas recycling (AGR) can be applied. This means that the anode exhaust gases, that have a high water content, are directly recycled. AGR reduces heat transfer efforts, because less or no steam preheating is required. Besides, the system fuel conversion is higher since unreacted $CH_4$ and $H_2$ are also recycled. Systems with AGR make less use of the afterburner. Because hydrogen output is minimised by AGR, it is not suitable if hydrogen is seen as a product.

### 2.4.4 Cathode gas recycling

Similar to AGR, cathode gas recycling (CGR) involves the recycling of hot fuel cell exhaust gases to the inlet. In the case of the cathode, the recycled stream partly replaces fresh air feed. Less energy is needed for air pumping and heating. A drawback is the lower oxygen concentration in the cathode feed, which reduces the fuel cell efficiency.

### 2.4.5 Stacks

Fuel cells are combined in a *stack*, which is a series of connected cells. The stack voltage is equal to the sum of the single cell voltages. The current is the same in each cell. Therefore, the number of cells in a stack determine the voltage that is produced. The stack size also has implications for the operator of the system. For maintenance or inspection, a single stack can be turned off, while the other stacks continue to operate.

### 2.4.6 SOFEC

A SOFEC system contains the same elements as a SOFC, but there are four differences in the connections between the components (see Figure 2.4). Air is no longer fed to the fuel cell, but directed directly to the afterburner. Steam replaces air as the feed of the anode. The fraction of steam that is not converted to hydrogen, is separated from the rest of the anode off-gas, and recycled to the water feed. The cathode is still fed by a steam–methane mixture. The reacted mixture is conveyed to the afterburner, without extracting any hydrogen present.

By comparing Figure 2.4 and 2.3, it can be concluded that in principle it is possible to design a reversible SOFC/SOFEC system. Extra connections (the blue lines) are required, as well as several switching mechanisms to open and close valves.

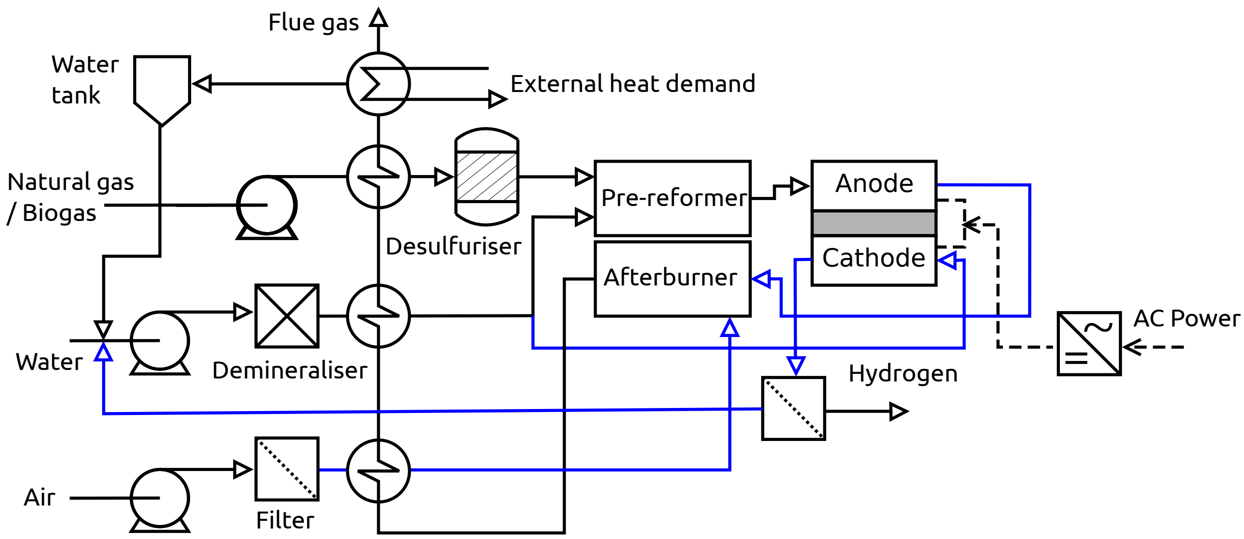



Figure 2.4: A possible SOFEC system design. Blue lines indicate connections that are not present in a SOFC system.

## 2.5 Losses

The low efficiencies of fuel combustion in regular engines is caused by the high entropy production during the reaction. From a thermodynamic point of view, there are two ways to reduce the irreversible losses of fuel oxidation: operate at higher temperature, or reduce the chemical driving force (Dunbar and Lior in Braun (2002)). This is why SOFCs have such a high efficiency: the operating temperature is high, and the oxidation reaction is controlled because oxidant and fuel are not in direct contact.

For conventional electrolysis of water, there are two main sources of losses: a high overpotential stemming from the large activation energy of the oxygen reduction redox half reaction, and loss of entropy (Cinti et al., 2016).

An important property of a SOFC is the current-voltage relation. Once this relation is obtained, the inputs and outputs can be derived. The most general relation is

$$V_{\text{cell}} = V_{\text{rev}} - i \cdot \text{ASR} \tag{2.1}$$

In Eq. 2.1, ASR is the area-specific resistance, and the reversible voltage $V_{\text{rev}}$ is the Nernst potential of the reactants, defined as:

$$V_{\text{rev}} = \frac{\Delta G}{nF} \quad \text{with} \quad \Delta G = \Delta H - T\Delta S + RT \ln \left( \frac{p\text{H}_2\text{O}}{p\text{H}_2 \cdot \sqrt{p\text{O}_2}} \right) \tag{2.2}$$

As Eq. 2.2 suggests, $V_{\text{rev}}$ depends on the concentration of species involved in the reactions. Moreover, since the concentrations change as the fuel gas flows through the electrode, $V_{\text{rev}}$ is a function of the fuel utilisation. Towards the outlet of the electrode, the fuel gas is depleted of hydrogen, thus lowering the cell potential compared to the initial OCV (see Figure 2.5). The losses that occur because of this effect are called Nernst losses. Nernst losses are reversible and cannot be prevented. A first order approximation of the reversible cell voltage is given by:

$$V_{\text{rev}} \approx V_0 - \alpha U_f \tag{2.3}$$

$V_0$ is the approximate OCV at the feed concentrations. This relation gives a rather accurate approximation of the reversible SOFC voltage (Hemmes, 2004). Eq. 2.3 also applies to SOFECs, although different values of $V_0$ and $\alpha$ apply.

Irreversible losses are captured in the internal resistance term ($i\cdot$ ASR) in Eq. 2.1. The irreversible overpotential is caused by three mechanisms (Park et al., 2012):

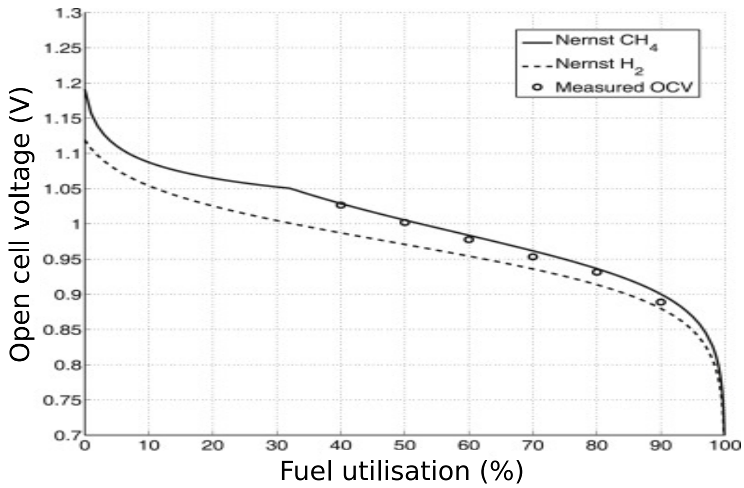



Figure 2.5: Decrease in the local Nernst potential as a function of fuel utilisation. The fuel is a mixture of $CH_4$ or $H_2$ mixed with 3% steam. Measurements were performed at 700 °C. Reprinted from Kuhn and Kesler (2015).

**Activation polarization** is the result of kinetic effects. The collection of electrochemical reactions taking place at both electrodes provide activation barriers that should be overcome. The Butler-Volmer equation describes the resulting overpotential. To lower the activation losses, it is crucial to have suitable catalysts and a large TPB. The active area can be increased if the microstructure of the electrode materials is controlled (Irvine et al., 2016; Mahato et al., 2015).

**Ohmic polarization** originates from the finite ionic conductivity of the electrolyte. Oxygen ions that migrate through the electrolyte experience a resistance. These losses can be minimised by operating at higher temperatures, decreasing the electrolyte thickness, or increasing the number of vacancies in the electrolyte material. The latter can be achieved by using dopants. The electrical resistance of the electrodes can also contribute to ohmic losses, but is often small compared to the electrolyte resistance.

**Concentration polarization** occurs because concentration gradients exist at the electrodes. Close

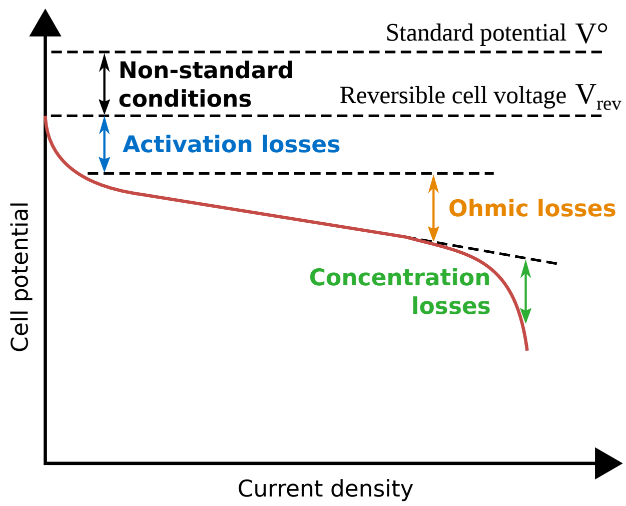



Figure 2.6: Decrease in cell potential due to polarisation losses, as a function of current density (Nagle, 2008).

to the active sites (the triple-phase boundaries, see § 2.2.1), the reactant concentrations are lower than in the bulk because of mass transport limitations. Especially at large current densities, diffusion of reactants limits reaction rates and cause concentration polarisation. To reduce concentration losses, the electrodes, especially the fuel electrode, are made porous.

These three polarisation mechanisms can be further classified as anode and cathode polarisation, since the losses are electrode-dependent.

Figure 2.6 indicates that each polarisation mechanism dominates the voltage loss in a distinct region of current densities. As soon as current is drawn from the cell, activation losses occur. Ohmic losses are responsible for the linear decrease of the voltage in the mid-range of $i$. Concentration losses induce additional losses at high current densities (Wijers, 2011).

## 2.6 System operation

During operation of a SOFC or SOFEC, three parameters should be taken into account: the steam-to-carbon ratio (SCR), and fuel and air utilisation. These parameters affect the performance of the fuel cell in different ways, which are discussed below.

### 2.6.1 Steam-to-carbon ratio

Carbon deposition is an unwanted side reaction that can occur at the fuel electrode. This negatively affects the cell performance, since solid carbon can block the active sites of the catalyst (Mahato et al., 2015). It can be prevented by mixing steam with the fuel gas up to the point that carbon deposition becomes thermodynamically unfavourable. If a perfect equilibrium between the chemical species is assumed, the carbon deposition potential depends on the ratio of C, H, and O in the mixture. As shown in the ternary diagram of Figure 2.7, the carbon deposition region also depends on temperature and pressure. The possibility of carbon deposition decreases for high temperatures and low pressures (Wendel et al., 2016). At atmospheric pressure and 800 °C, a SCR of 2 should be sufficient to prevent deposition (Mahato et al., 2015). Higher SCRs have a negative effect on the overall system efficiency, because steam dilutes the hydrogen at the anode and because of the larger flows involved (Braun, 2002; Janardhanan et al., 2007).

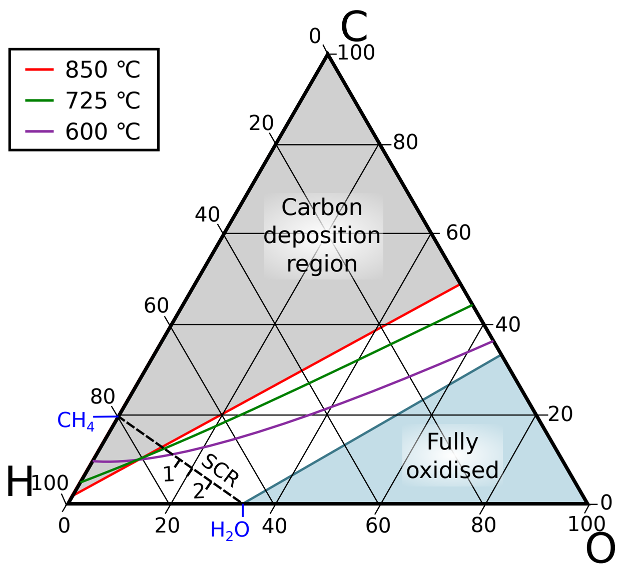



Figure 2.7: Ternary diagram, showing the carbon deposition region for different fuel gas compositions and temperatures. The pressure is 1 bar. The dashed line indicates a mixture of only $CH_4$ and $H_2O$. SCR: steam-to-carbon ratio. Adapted from Wendel et al. (2016).

### 2.6.2 Fuel utilisation

The driving force for electricity generation in a fuel cell is the electrochemical potential of R1, as given by Eq 2.2. This relation implies that the SOFC's cell potential is higher for higher concentrations of $H_2$ at the fuel electrode. If no $H_2$ is present at all, then the cell potential is not defined. Reaching a fuel utilisation of 100% is both unachievable and undesirable in practice, since the cell potential approaches 0 (see Figure 2.5). The sharp decline in OCV for high $U_f$ is due to reversible losses stemming from reactant concentration differences (see § 2.5).

The fuel utilisation is defined as the fraction of the fuel inflow that is converted to electrical energy. In the case that $CH_4$ is the only fuel supplied, $U_f$ can be expressed as:

$$U_f \equiv \frac{\Delta \dot{n}_{\mathrm{CH}_4}}{\dot{n}^{\mathrm{in}}_{\mathrm{CH}_4}} = \frac{\dot{n}^{\mathrm{in}}_{\mathrm{CH}_4} - (\dot{n}^{\mathrm{out}}_{\mathrm{CH}_4} + \frac{1}{4}\dot{n}^{\mathrm{out}}_{\mathrm{H}_2} + \frac{1}{4}\dot{n}^{\mathrm{out}}_{\mathrm{CO}})}{\dot{n}^{\mathrm{in}}_{\mathrm{CH}_4}} \tag{2.4}$$

If $U_f$ is low, a larger amount of $CH_4$ leaves the fuel cell unreacted, reducing the efficiency. To put it differently, a larger capacity of balance of plant (BoP) components is needed to achieve the same electricity output of a system with higher $U_f$. At the same time, a higher amount of $H_2$ is produced at low $U_f$. But if $U_f$ is lowered too much, the heat produced by the electrochemical reaction (R1) is insufficient to sustain hydrogen formation (R2–R3). There is also an upper limit to the fuel utilisation. If $U_f$ is too high, the fuel cell is said to suffer from *starvation*, i.e. a lack of hydrogen to drive R1 (Fang et al., 2015). Starvation negatively affects the cell voltage, and should therefore be prevented.

In this research, it is assumed that the region of safe operation lies between a $U_f$ of 0.6 and 0.95. In recent cell tests, significant starvation was observed at 90% $U_f$ (Fang et al., 2015), so this is a positive assumption.

### 2.6.3 Air utilisation

The concentrations of oxygen and hydrogen at both electrodes determine the driving force of the fuel cell (Eq. 2.2). A higher excess of air results in a higher average oxygen concentration at the air electrode, and therefore a higher cell voltage. SOFCs are often designed to operate at low air utilisations, since the air flow also provides cooling to the fuel cell stack (Wendel et al., 2016). Similar to the fuel utilisation, there is a trade-off between a low utilisation and BoP costs; large air flows require substantial investments in pumps and heat exchangers (Strazza et al., 2015).

Air utilisation is defined as the ratio of oxygen consumed (defined by R4) to the supplied amount of oxygen:

$$U_a = \frac{2 \cdot \Delta \dot{n}_{\mathrm{CH}_4}}{\dot{n}^{\mathrm{in}}_{\mathrm{O}_2}} = \frac{2 \cdot \dot{n}^{\mathrm{in}}_{\mathrm{CH}_4} U_f}{\dot{n}^{\mathrm{in}}_{\mathrm{O}_2}} \tag{2.5}$$

## 2.7 Concepts

Building on the technology of SOCs, several applications have been proposed. The most well-known application is the SOFC, followed by the SOEC. These and other concepts discussed in literature are shown in Figure 2.8. Six concepts are explained in more detail below.

Other concepts not treated here are the integrated gasification fuel cell powerplants, tri-generation of electricity, heating and cooling, and SOFCs applied in fuel cell electric vehicles (FCEVs) (Wachsman et al., 2012).

### 2.7.1 Superwind

The Superwind concept (Vernay et al., 2008) builds upon the capability of IR-FCs to co-produce hydrogen. Not only SOFCs, but also molten carbonate FCs (MCFCs) can perform CHHP production. The business model of Superwind is intended for wind park owners, who can complement the fluctuating electricity production using a fuel cell. The fuel cell has extra operational flexibility, because it can

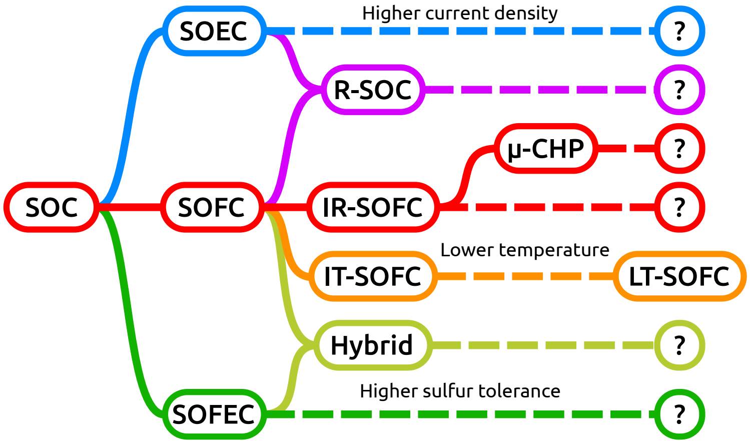



Figure 2.8: Development directions of solid oxide cell technology. Current and possible future applications are shown. R-SOC: reversible SOC, IR: internal reforming, IT: intermediate temperature, LT: low temperature.

operate in different modes with other product ratios. The produced amounts of its three outputs can be controlled by changing the fuel inflow and cell voltage (Hemmes et al., 2005). When the wind turbines generate ample electricity, the fuel cell will switch to a mode with low fuel utilisation. This results in a higher rate of hydrogen production relative to electricity. When less electricity is needed, the fuel supply can be lowered, leading to a reduction in the sum of outputs. The concept is also applicable in combination with other intermittent power sources.

Various studies have addressed the feasibility of Superwind in technological, social, and economical terms. Vernay et al. (2008) have experimentally demonstrated that a MCFC is capable of operating under a changing fuel supply and/or voltage. A technical limitation is the somewhat slow rate of power output increase. Operation with high power output was not tested. Manné (2009) argues that Superwind can be accepted by the public if it becomes better known, and if fears considering the safety of hydrogen are taken away. From an economic point of view, the concept is most attractive in systems with a moderate renewable energy market share and a local demand for hydrogen (Van Leeuwen, 2015). The output of electricity is profitable because it prevents underproduction fines, or is produced during peak demand hours (Vernay et al., 2008). Injecting hydrogen in the NG distribution network is less profitable, since it then has no added value compared to NG. Instead, hydrogen can be sold to companies or hydrogen fuel stations (Van Leeuwen, 2015). In spite of these business opportunities, the feasibility study of Vernay et al. found that Superwind is not economically viable due to the high investment costs of the fuel cell. The latter fact is also a barrier for investments and experiments by organisations (Manné, 2009).

### 2.7.2 Fuel-assisted electrolysis

SOCs can be applied for electrolysis of water, thereby functioning as hydrogen source (Energinet.dk, 2011). In order to prevent high overpotentials due to the slow water reduction reaction, a fuel can be supplied to the anode of what is now called a SOFEC (Cinti et al., 2016). The idea of producing hydrogen by feeding electricity and methane to a SOFC was first described by Pham et al. (2000). This hydrogen production method is more efficient than regular electrolysis (Ewan & Adeniyi, 2013). If electricity is derived from coal powerplants, then it is not only more efficient, but also more environmentally friendly to use a SOFEC instead of SOEC. Furthermore, SOFECs can be used for peak shaving in electricity markets with a high penetration of intermittent power sources.

In theory, the electrolysis mode can be added to the options of the Superwind fuel cell. The current knowledge of and experience with SOFCs that can also run in reverse is limited, since the technology is in an early stage of development (Minh & Mogensen, 2013). More research is required to increase the durability of these devices and find the 'optimal' design parameters.

### 2.7.3 Reversible hydrogen production

The reversible hydrogen production concept addresses electricity excesses by storing the energy in the form of hydrogen. A R-SOC operates in electrolysis mode at low electricity prices, and in fuel cell mode with $H_2$ as fuel when electricity prices are high. This system would have a high storage capacity in the form of $H_2$ tanks. It is not yet cost competitive with other electricity storage systems, due to the low round-trip efficiency from electricity to hydrogen and back. An important barrier for higher electrolysis efficiency are high polarisation losses (Remick & Wheeler, 2011). Another challenge is provided by the considerable amounts of heat consumed and generated during charging and discharging (Gençer et al., 2014). As explained in § 2.4.2, the oxidation of $H_2$ in a fuel cell is an exothermic reaction, implying that heat is generated. In the reverse reaction, this amount of heat has to be provided. Thus, either a heat storage system is required, or the cell stack has to be connected to a (high-temperature) heat source and sink.

The largest R-SOC installation has a capacity of 50 $kW_e$ and was installed by Sunfire in 2016(Fuel Cells Bulletin, 2016).

### 2.7.4 Reversible fuel production

The setup introduced above involves the transfer of large amounts of heat. This can be prevented by using the reforming capability of SOFCs and performing co-electrolysis of $CO_2$ and $H_2O$ in SOECs (Ridjan et al., 2013). These reactions will compensate for the (reverse) $H_2$ oxidation reaction. For an efficient co-electrolysis reaction, a $CO_2$ source is needed. Wendel et al. (2016) propose a system where the exhaust gases from the SOFC mode are stored, and used for this purpose. In fact, a closed system can be designed, with storage tanks for fuel, exhaust gas, and oxidant (Bierschenk et al., 2011; Wendel et al., 2016). Alternatively, underground storage can be considered (Jensen et al., 2015). Mathiesen (2008) discusses SOECs and their ability to electrolyse water and $CO_2$. He emphasizes that the low efficiency makes other energy storage options more attractive.

### 2.7.5 Hybrid stack

Tao (2007) developed a SOC that is functional in both SOFC and SOFEC mode. He also demonstrated a hybrid stack. This is a SOC stack of which some cells operate in SOFC mode, and others in SOFEC mode. It is thus possible to operate reversibly on a stack level, but also on a cell level. The mode of operation for each individual cell is controlled by the choice of the cathode gas. Steam results in SOFEC behaviour, and air results in SOFC mode. This is possible when the direction of the current is aligned for the cells in a stack. A hybrid stack produces both hydrogen, heat and power, as long as there are not too few cells in fuel cell mode. When most cells are operated in SOFEC mode, the stack requires a supply of electricity to keep operating.

### 2.7.6 Micro-CHP

Since SOFCs can be downscaled without loss of efficiency, it is possible to design systems small enough to supply one household with heat and power (Pfeifer et al., 2013). SOFC-based micro-CHP systems are considered as an alternative for conventional boilers. The micro-CHP can be configured to respond to electricity price signals (such as in smart grid configurations) or follow the heat demand of the household. In *IDA's climate plan* (from the Danish Society of Engineers) (Mathiesen et al., 2009), fuel cells are introduced in decentralized and central CHP plants, as well as micro-CHP. Using NG, biogas, or synthetic fuel, the fuel cells provide a flexible and reliable electricity source to complement renewable electricity. In Kikuchi et al. (2014), the role of SOFCs as distributed CHP was suggested too.

Several large-scale pilot projects with micro-CHPs have been completed or are in progress in Europe. Examples include SOFT-PACT (2011–2015), ene.field (2012–2017), PACE (2016–2021) (European Commission, 2016), and Powermatching City (2009–2015) (Gerdes et al., 2014).

## 2.8 Conclusion

Strict requirements apply to the materials of which the electrodes, electrolyte, and housing of SOCs are made. All components have to be resistant towards high temperatures and thermal stress, traces of sulfur and other contaminants, and anticipated redox environments. Research has led to profound improvements on these aspects. The largest issues remaining are related to the high overpotential in electrolysis cells, degradation caused by sulfur, and stability in general over the lifetime of the stack. SOFECs have the advantage of lower overpotentials, but the experimental demonstration of larger stacks and long periods of time is still lacking.

To guarantee an efficiently operating SOC, it is important that polarisation losses are kept at a minimum, also after several years of operation. For ohmic, concentration, and activation losses, some mitigation strategies that can guide further research were discussed. The length of the TPB proves to be an important parameter related to losses. Therefore, preservation of the electrode microstructure throughout the lifetime of a SOC has a high priority when material selection is concerned.

It is known how SOFC systems can be designed and operated. Some modifications are needed to obtain a SOFEC. The system layouts in Figure 2.3 and 2.4 – with pre-reformer but without AGR and CGR – are assumed in the further modelling efforts of the next chapter. The operating conditions in this chapter (SCR, $U_f$, $U_a$) are important for the performance of a SOFC or SOFEC. In principle, reversible SOFC/SOFEC systems can be manufactured and operated, but experience is limited to lab-scale tests.

# Chapter 3

# SOC Input-Output Relations

## 3.1 Cell performance modelling

To derive a mathematical description of the relation between inputs and outputs of SOFCs, it is useful to have a model of a fuel cell. A range of mathematical models that describe SOCs have been proposed in literature. These models differ in complexity and level of detail, depending on the research objective. The similarity is their basis of physical principles. Examples of model types are static, dynamic, kinetic and lumped models (Yadav et al., 2015). Static or steady-state models assume a constant operation that does not change in time (Huo et al., 2008). Dynamic or transient models, on the other hand, incorporate changes in e.g. fuel supply or temperature changes. Kinetic models have a bottom-up approach. They intend to include all kinetic effects and transport phenomena that play a role at the electrodes. By doing so, Trendewicz and Braun (2013) derived an input-output model for a SOFC as CHP source. Lumped models are top-down oriented, and describe the fuel cell as if it were a black box. In a lumped model, thermodynamic laws are applied at the level of the whole cell, thus reducing complexity. By taking energy and mass conservation into account, the inputs and outputs can be calculated (Yadav et al., 2015). This approach was used by Wendel et al. (2016) to model a R-SOC.

Fuel cell models can also be classified based on the number of dimensions of the model. Two- and three-dimensional (2-D and 3-D) models allow to include transport phenomena. 0-D and 1-D modelling can be applied for control purposes on a system-level. Lumped models are 0-D by definition.

To evaluate a model, a numerical or analytical (exact) approach can be adopted. Simpler models can typically be solved using analytical methods. This is not always possible for more complex models. To simplify a numerical model, the cell can be conceptually divided into sub-units to discretise the problem (Hemmes, 2004). Finally, there is a great variety in the complexity of models. Dynamic and more-dimensional models tend to cost more computation time. Still, these models are useful to assess the potential for performance improvements and to explore different design options. Lumped or 0-D models typically have a much shorter computation time. These models approximate the input-output relations using a top-down approach and experimentally determined values.

Given the large amount of parameters that determine how a SOFC operates, it is inevitable to assume a fixed value for some of them in further analysis. For example, Trendewicz and Braun (2013) assume a fixed operating voltage and fuel utilisation in their economic assessment. In linear energy system models (§ 4.2.4), the complexity of fuel cells is reduced to a component that converts fuel to electricity and heat with a fixed efficiency. The model constructed by Steup (2014) features a fuel cell that co-produces heat, hydrogen, and power, implemented with non-linear equations. Only the applied voltage can be adapted during operation.

## 3.2 Operating conditions

As concluded in § 2.6, the selected operating conditions influence the performance of a SOFC or SOFEC. For the input-output models presented in the following sections, a set of operating conditions is selected and listed in Table 3.1. The composition of NG was derived by assuming that all hydrogen molecules in

Table 3.1: Operating conditions assumed for SOFC and SOFEC operation.

| | |
|---|---|
| Air composition | 79% $N_2$, 21% $O_2$ |
| NG composition | 95.81% $CH_4$, 4.19% $N_2$ |
| T | 1073.15 K (800 °C) |
| p | 1.013 bar (1 atmosphere) |
| SCR | 2 |
| $U_a$ (SOFC) | 50% |
| $U_s$ (SOFEC) | 25% |
| $U_f$ | 60–95% (SOFC); 80% (SOFEC) |

NG from Groningen are present in the form of $CH_4$, and the remainder is $N_2$ (see § 5.3.4). The inflow to the fuel electrode is a mixture of NG and steam, for which the SCR is 2. This ratio is assumed to be sufficient to prevent carbon deposition (see § 2.6.1). Normal air is used as oxidant flow in SOFCs. The choices for the utilisation of air, steam, and fuel $(U_a, U_s, U_f)$ are motivated in the following sections.

Furthermore, the area-specific resistance ASR is assumed to be independent of the current density. This is a reasonable assumption, as long as $i$ is not too high and not too low (see Figure 2.6). An experimentally determined value of 0.45 $\Omega\,\mathrm{cm}^2$ is used (Trendewicz & Braun, 2013; Tao et al., 2011) for both SOFCs and SOFECs.

## 3.3 Nernst losses

As discussed in § 2.5, the reversible cell voltage is reduced due to Nernst losses, and the dependence on $U_f$ can be approximated by Eq. 2.3. To obtain a relation that describes the cell voltage as a function of $U_f$, an analytical 1-D model of a fuel cell is used. The method is explained in this section.

To accurately describe reversible losses, the concentrations of each gas at each position in the fuel cell should be known. An approximate solution can be obtained by dividing the fuel cell in *hypothetical sub-cells*. For each of these sub-cells, the local Nernst potential can be calculated. The size of each sub-cell is chosen in such a way that the change in $U_f$ between them is fixed (Hemmes, 2004). Furthermore, it is assumed that the reaction rates for R2 and R3 are identical and much larger than the redox reaction rates. Therefore, SMR reactions have reached an equilibrium in each sub-cell. The corresponding equilibrium equation is:

$$K_{2+3} = \frac{p\mathrm{CO}_2 \cdot p{\mathrm{H}_2}^4}{p\mathrm{CH}_4 \cdot p\mathrm{H}_2\mathrm{O}^2} \tag{3.1}$$

The partial pressure of each species $(pS)$ can be expressed in terms of the initial amount present, the local fuel utilisation $u$, and the extent of reaction R2 $\xi_2$. The fact that $\xi_1 = 4u$ and the assumption that $\xi_2 = \xi_3$ are used to derive Eq. 3.3, which gives the number of moles $n_S$ for each species.

$$p\mathrm{S}(u) = \frac{n_S(u)}{\sum_s n_s(u)} \tag{3.2}$$

$$n_S(u) = n_S(0) + \xi_1\nu_{S,1} + \xi_2\nu_{S,2} + \xi_3\nu_{S,3} = n_S(0) + 4u\,\nu_{S,1} + \xi_2(\nu_{S,2} + \nu_{S,3}) \tag{3.3}$$

Here, $\nu_{S,R}$ is the stoichiometric coefficient of species $S$ in reaction $R$. Using these expressions, Eq. 3.1 can be rewritten as:

$$K_{2+3} = \frac{(n_{\mathrm{CO}_2}(0) + \xi_2) \cdot (n_{\mathrm{H}_2}(0) - 4u + 4\xi_2)^4}{(n_{\mathrm{CH}_4}(0) - \xi_2) \cdot (n_{\mathrm{H}_2\mathrm{O}}(0) - 2\xi_2)^2 \cdot 2\xi_2} \tag{3.4}$$

Since the value of $K_{2+3}$ is known (177.7 at 800 °C), Eq. 3.4 can be solved for $\xi_2$. It is advised to use a numerical method to find the solution of this non-linear equation. Once the extent of reaction is known, Eq. 3.2–3.3 can be utilised to calculate all concentrations in a sub-cell. Then, the local Nernst potential $V^*_{\mathrm{rev}}$ follows from Eq. 2.2 for a SOFC and, from an analogous equation for a SOFEC:

$$V_{\mathrm{rev}} = \frac{\Delta G}{nF} \quad \text{with} \quad \Delta G = \Delta H - T\Delta S + RT\ln\left(\frac{p\mathrm{H}_2[\mathrm{s}] \cdot p\mathrm{H}_2\mathrm{O}[\mathrm{f}]}{p\mathrm{H}_2\mathrm{O}[\mathrm{s}] \cdot p\mathrm{H}_2[\mathrm{f}]}\right) \tag{3.5}$$

where the Nernst potential difference of the reactants and products at the fuel electrode [f] and steam electrode [s] is calculated.

$$\text{SOFC}: \qquad V^*_{\text{rev}}(u) = V^\circ + \frac{RT}{4F} \ln\left(\frac{pH_2(u)\cdot\sqrt{pO_2(u)}}{pH_2O(u)}\right) \tag{3.6}$$

$$\text{SOFEC}: \qquad V^*_{\text{rev}}(u) = V^\circ + \frac{RT}{4F} \ln\left(\frac{pH_2O[\text{s}](u)\cdot pH_2[\text{f}](u)}{pH_2[\text{s}](u)\cdot pH_2O[\text{f}](u)}\right) \tag{3.7}$$

with $V^\circ$ the (open) cell potential under standard concentrations.

To obtain the Nernst potential of the whole cell, the sub-cell potentials should be averaged:

$$V_{\text{rev}}(U_f) = \frac{1}{U_f}\int_0^{U_f} V^*_{\text{rev}}(u)du \tag{3.8}$$

If it is assumed that $V^*_{\text{rev}}$ has a linear dependence on $u$, then the integral can be solved, yielding Eq. 2.3 again:

$$V_{\text{rev}}(U_f) \approx V_0 + \alpha\cdot U_f \quad \text{with} \quad 2\alpha = \frac{\partial V^*_{\text{rev}}}{\partial u} \tag{3.9}$$

The value of $\alpha$ and $V_0$ can now be found by fitting Eq. 2.3 to Eq. 3.8.

To calculate the reaction progress from Eq. 3.4, the initial amounts presented in Table 3.2 were used. The calculation is made on the basis of 1 mol $CH_4$, with the other amounts derived based on the assumed conditions (Table 3.1). For the case of a SOFC, a maximum air utilisation of 50% is assumed, whereas a steam utilisation of 25% is set for a SOFEC.

Table 3.2: Inital amounts of gases at the fuel and air electrode of a SOFC, and at the fuel and steam electrode of a SOFEC.

| | Fuel electrode (both) | | | | | Air el. (SOFC) | | Steam el. (SOFEC) | |
|---|---|---|---|---|---|---|---|---|---|
| | $CH_4$ | $H_2O$ | $N_2$ | $H_2$ | $CO_2$ | $O_2$ | $N_2$ | $H_2O$ | $H_2$ |
| $n_S$ (mol) | 1 | 2 | 0.0765 | 0 | 0 | 4 | 15 | 16 | 0 |

Proceeding as outlined above, it was derived that $\alpha = -53$ mV for a SOFC and $\alpha = -87$ mV for a SOFEC. Finding a linear fit for $V_{\text{rev}}(U_f)$ as determined from Eq. 3.8 in the range $0.60 \leq U_f \leq 0.95$, results in the following equations:

$$\text{SOFC}: \qquad V_{\text{rev}}(U_f) = 1.069 - 0.053\cdot U_f \tag{3.10}$$

$$\text{SOFEC}: \qquad V_{\text{rev}}(U_f) = 0.116 - 0.087\cdot U_f \tag{3.11}$$

These linear approximations are a very close to the real $V_{\text{rev}}$, as indicated by Figure 3.1.

Now that the reversible voltage is known, it is possible to calculate the voltage of a single cell from Eq. 2.1:

$$V_{\text{cell}} = V_0 - \alpha U_f - i\cdot \text{ASR} \tag{3.12}$$

This expression contains ASR, which accounts for all losses occurring due to the polarisation effects discussed in § 2.5.

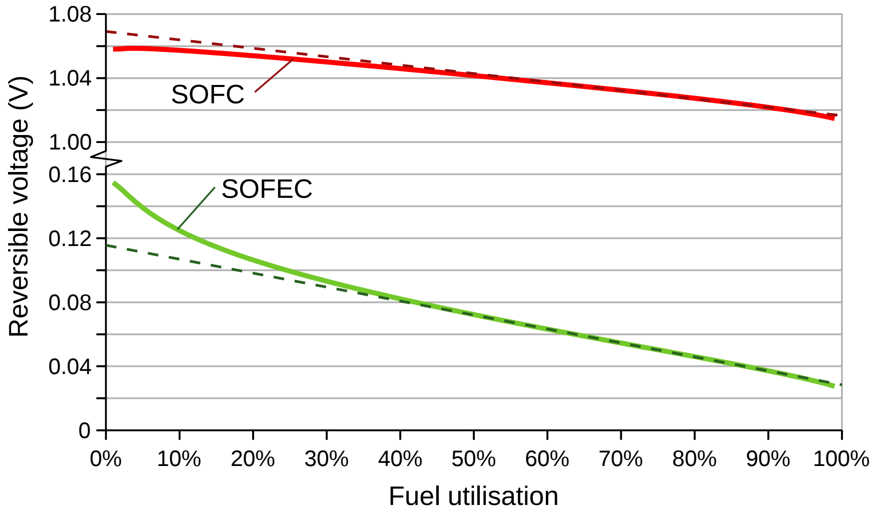



Figure 3.1: Reversible cell voltage of a SOFC and a SOFEC as a function of $U_f$, calculated from the local cell voltage $V^*_{\text{rev}}$. Linear approximations of $V(U_f)$ within the operating range are drawn.

## 3.4 Mass and energy balances

### 3.4.1 SOFC

Knowing $V_{\text{cell}}$, the next step is to relate it to the mass and energy flows through the cell. Since the mass and energy balances of SOFCs and SOFECs differ, those of SOFCs are discussed first. The case of SOFECs is treated in the next section.

Mass flows are expressed in units of moles per unit of cell area. The molar influx rate of methane ($J^{\text{in}}_{\text{CH}_4}$), to begin with, can be related to the current density by recognising that eight electrons are transferred per mole of $CH_4$ in R4.

$$i = 8FU_f J^{\text{in}}_{\text{CH}_4} \quad \text{or} \tag{3.13}$$

$$J^{\text{in}}_{\text{CH}_4} = \frac{i}{8FU_f} \tag{3.14}$$

Then, using Eq. 3.12 and 2.3, the power flux $J^{\text{out}}_P$ equals:

$$J^{\text{out}}_P = i \cdot V_{\text{cell}} = i \cdot (V_0 - \alpha U_f - i \cdot \text{ASR}) \tag{3.15}$$

The molar hydrogen outflux rate is based on the mole balance for $H_2$ and Eq. 3.13. A correction factor of 0.81 is applied here. This factor accounts for the fact that in equilibrium, the water gas shift reaction (R3) is not complete, so $\dot{\xi}_3 < J^{\text{in}}_{\text{CH}_4}$.

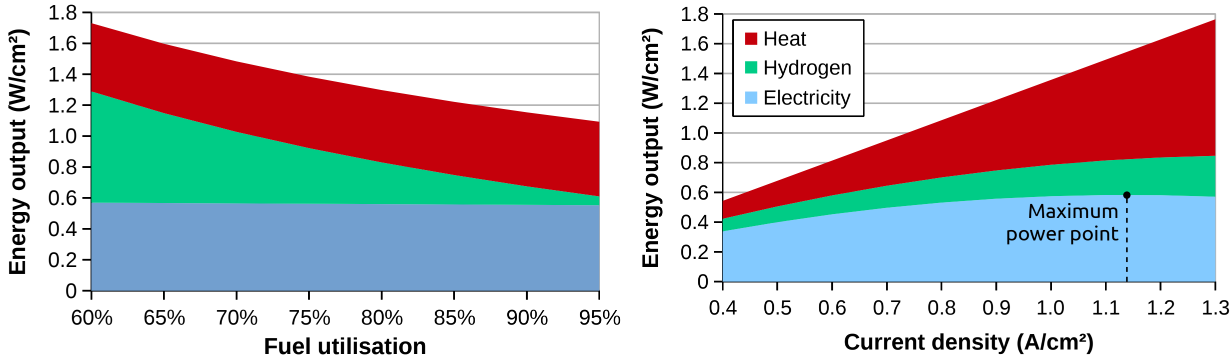
$$J^{\text{out}}_{\text{H}_2} = 0.81 \cdot (1 - U_f) \cdot 4J^{\text{in}}_{\text{CH}_4} = 0.81 \cdot (1 - U_f)\frac{4i}{8FU_f} = \frac{0.81i}{2F} \cdot \left(\frac{1}{U_f} - 1\right) \tag{3.16}$$

The heat flux calculation is based on the energy balance over the fuel cell and afterburner (see Figure 2.3), and assumes that any $CH_4$ or CO remaining in the exhaust gas is fully oxidised in an afterburner (after $H_2$ has been removed).

$$J^{\text{out}}_Q = J^{\text{in}}_{\text{CH}_4} \cdot \Delta_c H_{\text{CH}_4} - J^{\text{out}}_P - J^{\text{out}}_{\text{H}_2} \cdot \Delta_c H_{\text{H}_2} \tag{3.17}$$

Here, $\Delta_c H_s$ denotes the HHV of species $s$.

The resulting input-output relations resulting from the equations above are depicted in Figure 3.2. The stackplots show that hydrogen production is mainly determined by $U_f$. Furthermore, the highest electric efficiency occurs at low current densities. $i$ has a lower limit, below which the SOFC system is a net consumer of heat. In Figure 3.2, the maximum power point is indicated. If the current density exceeds the value belonging to this point, the electricity output no longer increases. During SOFC operation, the maximum power point should not be passed to prevent the unnecessary efficiency reduction.



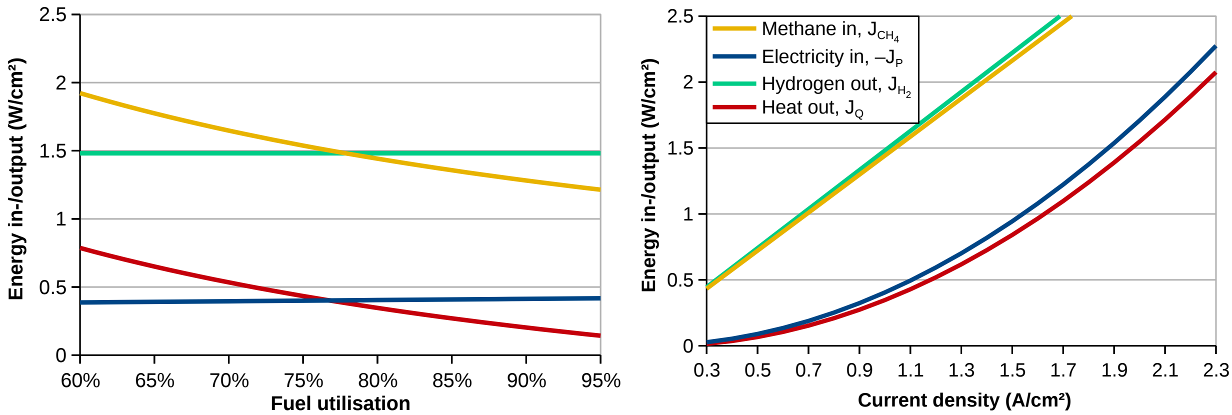

(a) At $i = 0.9$ A/cm$^2$. (b) At $U_f = 85\%$.

Figure 3.2: Outputs of a SOFC as modelled by Eq. 3.13–3.17. Note that, because of Eq. 3.17, the sum of the outputs equals the input of fuel. $\alpha = 0.053$ V, $V_0 = 1.069$ V, and ASR=0.45 $\Omega\,\mathrm{cm}^2$.

### 3.4.2 SOFEC

Many of the relations derived for a SOFC also apply to a SOFEC. Eq. 3.14, 3.15 and 3.17 are still valid. Note that $V_{\mathrm{cell}}$ – and therefore $J_P$ – is negative, reflecting the fact that a voltage is applied to instead of drawn from the cell. Another difference is the compositions of gases. In a SOFEC, the steam electrode gas is a mixture of $H_2O$ and $H_2$. This results in a radically different $V_{\mathrm{cell}}$ compared to a SOFC. Any $H_2$ or unconverted $CH_4$ in the fuel electrode flue gas is combusted in the afterburner (see § 2.4.6). Hydrogen generated at the steam electrode is directly related to the current (similar to an electrolyser), and provides the $H_2$ output:

$$J_{\mathrm{H}_2}^{\mathrm{out}} = \frac{i}{2F} \tag{3.18}$$




(a) At $i = 1.0$ A/cm$^2$. (b) At $U_f = 80\%$.

Figure 3.3: Input and outputs of a SOFEC, as described by Eq. 3.14, 3.15, 3.17, and 3.18. All functions are plotted as positive values.

The internal resistance is equal to that of a SOFC, provided that it is a property of the electrode and electrolyte materials. The fuel utilisation has a big influence on the amount of methane required to produce a given volume of hydrogen, whereas the cell potential is hardly affected (see Figure 3.3a). The SOFEC's $U_f$ was fixed at 80%, since this is the optimum (Wijers, 2011). A higher $U_f$ might lead to starvation, i.e. a lack of fuel, causing high overpotentials (Cinti et al., 2016; Fang et al., 2015). Lower utilisations reduce the efficiency of the conversion from $CH_4$ to $H_2$, as indicated by Figure 3.3a. Therefore, deviating from the optimum value has no clear benefits. The calculated SOFEC inputs and outputs are plotted in Figure 3.3b.

### 3.4.3 Scaling up

The balance of plant includes all auxiliary equipment needed for a correct operation of the SOC system. Heat losses occur throughout the system and via the exhaust. Electricity is lost in the DC/AC (direct to alternating current) inverter. Furthermore, electronic control systems, pumps, blowers, and compressors use some electric power. An efficiency of 96% is assumed for the DC/AC inverter (James et al., 2012). Parasitic loads are responsible for a reduction of 10% of the electricity output. Large contributors to BoP energy consumption are compressors and pumps (James et al., 2012). Based on these assumptions, it can be stated that the BoP efficiency $\eta_{\text{BoP}} = 96\% \times 90\% = 86.4\%$. The fraction of electricity that is 'lost' is converted to heat within the system, resulting in a lower power output of a SOFC, and a higher power demand for a SOFEC. It is assumed that only 5% of all heat is lost from the system, while the remainder of heat generated is transferred to an external heat demand.

The costs for a fuel cell system are very dependent on the scale of the system. A cost comparison performed by (James et al., 2012) indicated that a 100 kW SOFC system is around 13 times as expensive per kW as a 1 kW system. An other important factor for the production costs is the scale of the manufacturing facility. Both effects are not taken into account in the model.

Unlike conventional powerplants, fuel cells become more efficient when operating at partial load. As observed from Figure 3.2, a SOFC converts a higher fraction of the input energy to electricity at low current densities due to the lower overpotential. This is an advantage over conventional powerplants, such as gas turbines. Not only do gas turbines demand a minimum load of 40%, their efficiency at that point is almost 10% lower than the full-load efficiency (Figure 3.4). Besides, emissions of CO and $NO_x$ per $kWh_e$ tend to increase for lower loads (López, 2013).

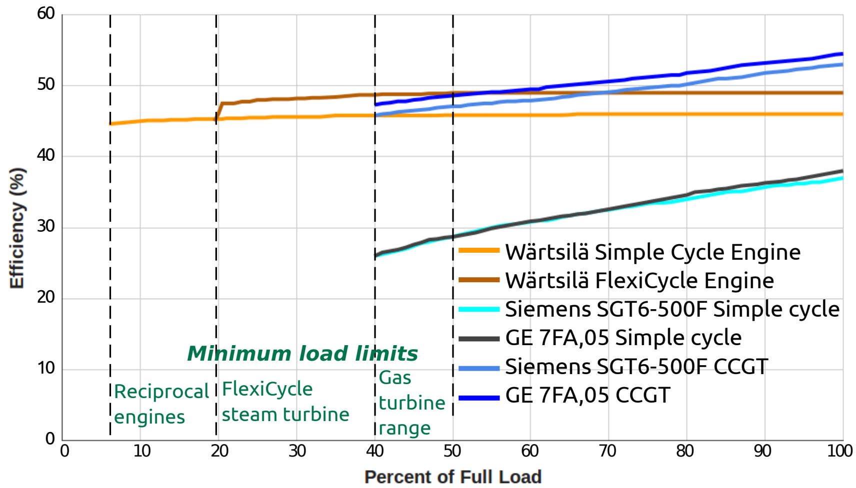



Figure 3.4: Partial load efficiencies of NG-fuelled combustion engine and gas turbine technologies in a 25 °C environment. Reprinted from López (2013).

In § 3.4.1, the energy flows per unit of active area were derived. In this section, the flows of interest are the total input or output of methane, electricity, hydrogen, and heat ($\dot{H}_{\text{CH}_4}$, $P$, $\dot{H}_{\text{H}_2}$, $\dot{Q}$), all in units of power. These will be expressed relative to the maximum input capacity for a collection of fuel cell stacks. The power output, to begin with, depends on the voltage of the single cells. The power output is determined using the equation for $V_{\text{cell}}$ (Eq. 3.12):

$$P = V_{\text{cell}} \cdot I = (V_0 - \alpha U_f - i \cdot \text{ASR}) \cdot I \tag{3.19}$$

The total current $I$ is determined straightforward from the methane inflow (either molar $\dot{n}^{\text{in}}_{\text{CH}_4}$, or energetic $\dot{H}_{\text{CH}_4}$) and fuel utilisation.

$$I = 8FU_f\dot{n}^{\text{in}}_{\text{CH}_4} = 8FU_f\frac{\dot{H}_{\text{CH}_4}}{\Delta_c H_{\text{CH}_4}} \tag{3.20}$$

The current density and total current are related to each other by the total active area $A$. In turn, $A$ is determined by the maximum $CH_4$ inflow allowed, which occurs at the maximum current density $i_{\max}$ and highest fuel utilisation. $i_{\max}$ is derived as follows:

$$\frac{\partial P}{\partial i}(i_{\max}) = 0 \tag{3.21}$$

$$\left.\frac{\partial P}{\partial i}\right|_{U_f=U_{\text{f,max}}} = V_0 - \alpha U_{\text{f,max}} - 2i \cdot \text{ASR} \tag{3.22}$$

$$i_{\max} = \frac{V_0 - \alpha U_{\text{f,max}}}{2\text{ASR}} \tag{3.23}$$

Using Eq. 3.23, $A$ is calculated by inserting the maximum current and current density.

$$\begin{aligned} A &= \frac{I}{i} = \frac{8FU_f\dot{H}_{\text{CH}_4}}{\Delta_c H_{\text{CH}_4} \cdot i} = \frac{8FU_{\text{f,max}}\dot{H}_{\text{CH}_4,\text{max}}}{\Delta_c H_{\text{CH}_4} \cdot i_{\max}} \\ &= \frac{8FU_{\text{f,max}} \cdot \dot{H}_{\text{CH}_4,\text{max}} 2\text{ASR}}{\Delta_c H_{\text{CH}_4} \cdot (V_0 - \alpha U_{\text{f,max}})} \end{aligned} \tag{3.24}$$

To find the ohmic loss term $i \cdot \text{ASR}$ in Eq. 3.19, the expressions for the total current and total area (Eq. 3.20 and 3.24) are subsituted to obtain Eq. 3.25. The result is that the ohmic loss does not depend on ASR any more. The only variables are $\dot{H}_{\text{CH}_4}$ and $U_f$.

$$\begin{aligned} i \cdot \text{ASR} &= \frac{I \cdot \text{ASR}}{A} = I \cdot \frac{\Delta_c H_{\text{CH}_4} \cdot (V_0 - \alpha U_{\text{f,max}})}{16FU_{\text{f,max}}\dot{H}_{\text{CH}_4,\text{max}}} = \frac{8FU_f\dot{H}_{\text{CH}_4}}{\Delta_c H_{\text{CH}_4}} \cdot \frac{\Delta_c H_{\text{CH}_4} \cdot (V_0 - \alpha U_{\text{f,max}})}{16FU_{\text{f,max}}\dot{H}_{\text{CH}_4,\text{max}}} \\ &= \frac{U_f\dot{H}_{\text{CH}_4}}{U_{\text{f,max}}\dot{H}_{\text{CH}_4,\text{max}}} \cdot \tfrac{1}{2}(V_0 - \alpha U_{\text{f,max}}) \end{aligned} \tag{3.25}$$

Although this substitution is useful for creating an input-output model, it should not be forgotten that ASR remains an important parameter in particular with respect to costs (Tao, 2007). If ASR can be reduced by 50%, then the same power can be produced using only half of the original cell area.

For a SOFEC, the maximum current density cannot be determined similar to that of a SOFC, because the current-power relation does not have a maximum. So instead of deriving $i_{\max}$ from the maximum power point, it is set to 2.3 A. As a consequence, a different expression for the ohmic loss term appears. By rearranging Eq. 3.24, we see that:

$$i = I \cdot \frac{i_{\max}}{I_{\max}} = \dot{H}_{\text{CH}_4} \cdot \frac{i_{\max}}{\dot{H}_{\text{CH}_4,\text{max}}} \tag{3.26}$$

## 3.5 Implementation

The implementation of a SOFC and a SOFEC component in an optimisation model (see Chapter 4) is based on the equations presented in § 3.4. The equations below define the inputs and outputs in terms of $I$, $i$ and $U_f$. $I$ and $i$ can be related to each other using Eq. 3.25 and 3.26 for SOFC and SOFEC, respectively. The unknowns in these equations are $\dot{H}_{\text{CH}_4}, P, \dot{H}_{\text{H}_2}, \dot{Q}, U_f, I, i$. For both SOFC and SOFEC, there are 4 input-output relations and one $I - i$ relation. Therefore, there are $7 - 5 = 2$

degrees of freedom in both cases. Note that $P$ and $\dot{Q}$ are defined to be positive if power or heat is produced by the SOFC or SOFEC.

$$\text{SOFC}\begin{cases}\dot{H}_{\mathrm{CH}_4} & = I\frac{\Delta_c H_{\mathrm{CH}_4}}{8FU_f}\\ P & = I\cdot(V_0-\alpha U_f - i\cdot\mathrm{ASR})\cdot\eta_{\mathrm{BoP}}\\ \dot{H}_{\mathrm{H}_2} & = I\cdot\frac{0.81}{2F}\Delta_c H_{\mathrm{H}_2}\cdot(\frac{1}{U_f}-1)\\ \dot{Q} & = 0.95\cdot(\dot{H}_{\mathrm{CH}_4}-P-\dot{H}_{\mathrm{H}_2})\end{cases} \tag{3.27}$$

$$\text{SOFEC}\begin{cases}\dot{H}_{\mathrm{CH}_4} & = I\frac{\Delta_c H_{\mathrm{CH}_4}}{8FU_f}\\ P & = I\cdot(V_0-\alpha U_f - \mathrm{ASR}\cdot I\cdot\frac{i_{\mathrm{max}}}{I_{\mathrm{max}}})\cdot\frac{1}{\eta_{\mathrm{BoP}}}\\ \dot{H}_{\mathrm{H}_2} & = I\cdot\frac{1}{2F}\Delta_c H_{\mathrm{H}_2}\\ \dot{Q} & = 0.95\cdot(\dot{H}_{\mathrm{CH}_4}-P-\dot{H}_{\mathrm{H}_2})\end{cases} \tag{3.28}$$

Apart from the equalities listed in Eq. 3.27 and 3.28, an inequality constraint applies to restrict the installed capacity. In energy converters, it is conventional to express the installed capacity is defined in terms of energy output. However, this is not useful for flexible multi-output technologies, with their fluctuating conversion efficiencies. Therefore, the installed capacity of SOFCs and SOFECs is expressed relative to the fuel input, yielding the following inequality:

$$\dot{H}_{\mathrm{CH}_4,e}(t) \leq \overline{IC}_e + \overline{IC}_e^{\mathrm{add}} \qquad \forall e,t \tag{3.29}$$

Here, $\dot{H}_{\mathrm{CH}_4,e}(t)$ is the input of methane for component $e$ at timestep $t$, and $\overline{IC}_e$ and $\overline{IC}_e^{\mathrm{add}}$ are the available and maximum additional installed capacity.

## 3.6 Nonlinearity

The relations that were derived to describe the inputs and outputs of a SOFC (Eq. 3.27) are nonlinear. Therefore, either the nonlinear problem has to be solved, or it has to be simplified to a linear problem. It is not possible to retain the dependence of the outputs as a function of both $I$ and $U_f$. This is because the expressions for the input of methane, and the output of power and hydrogen (Eq. 3.14–3.16) all contain terms featuring both of these variables.

A linear relation is obtained when the fuel cell operates at a fixed fuel utilisation, and when the power–current relationship is approximated by a linear function.

Alternatively, a linear mixed-integer relation can be formulated. For example by defining a number of states, characterised by their fixed fuel utilisation, between which the SOFCs can switch. Under this approach, an integer variable determines the fuel utilisation of *all* SOFCs in the model. The power–current relation is described by a slightly different linear equation for each state.

The fact that the efficiency of SOFCs decreases with their total output, allows for an easy linearisation with respect to the capacity. If for example ten individually controlled stacks are installed, the highest system efficiency is achieved when each of the stacks operates at $\frac{1}{10}$th of the total required load. Thus, the output is simply ten times the output of a single unit with the same capacity factor. In other words, an collection of many SOFCs has the same input-output relation as a single stack.

Provided that a linear problem can be solved faster, a trade-off has to be made between the accuracy of the model and computation time. For this research, the decision was made to retain the complexity of SOC operation, thereby accepting the additional time needed to solve the optimisation problems.

## 3.7 Summary

This chapter has employed a simple thermodynamic model to arrive at a set of equations that describe the inputs and outputs of a SOFC and SOFEC, namely Eq. 3.27 and 3.28. These equations have two degrees of freedom each, which is required to account for different ratios of outputs, and variation in the total throughput. The energy flows are expressed as a function of density and fuel utilisation, although other variables such as fuel input and cell voltage can also be chosen. This gives sufficient accuracy for the implementation in an energy system model. Yet, the implication is that a non-linear problem has to be solved.

# Chapter 4

# Energy System Modelling

## 4.1 Introduction

### 4.1.1 Energy systems

The aim of energy systems is to fulfil the need for energy by consumers. A good system solves the mismatch between energy supply and demand at three levels: time, place, and energy carrier (Hemmes, 2009). The technical components of a supply chain are operated to overcome these mismatches. Transportation networks address the spatial mismatch, storage deals with temporal variances, and converters ensure the desired energy carrier is delivered. The ensemble of components in not static; replacements and additions are occurring frequently.

The choice for a set of technologies is a trade-off between four parameters: affordability of energy, security of supply, sustainability (both GHG emissions, land use, and resource use), and social acceptability (safety concerns, perception of health impacts, comfort, etc.) (Mancarella et al., 2016). How these parameters are weighted is a normative judgement, and differs between actors. In the Netherlands, the liberalisation of the energy market has been completed to ensure affordability. The risk of supply failure is very low, which is managed by distribution system operators (DSOs) under strict regulation by governments. The societal attitude towards the social and sustainability aspects are subject to change. The acceptance of different sources of energy can increase or decrease within a few years time.

Currently, a transition towards more sustainable energy production is taking place. Mainly driven by governmental and societal pressure, the unpredictability of fossil fuel prices, and an expected cost reduction of emerging technologies, new energy production and consumption technologies are installed. This development is expected to require a drastic restructuring of the energy system (Bokhoven et al., 2015). Some of the entailed changes are a growing share of intermittent power sources and more decentralized generation. To retain the resilience of the system under these changes, it is expected that the energy production system will become increasingly complex in the future (Bourennani et al., 2015). To conclude, it seems inevitable that the importance of the energy system society will increase, while it is uncertain *how* it will develop.

### 4.1.2 Optimisation

Many choices are to be made regarding the design of energy systems. Multiple energy (re)sources are available, even more options to convert various energy carriers, and a number of options to use final energy to provide a certain service. This raises the question what combination of technologies is best suited to provide the energy services needed. Finding an answer to this question is in the strategic interest of all stakeholders involved in the energy supply chain. Energy users are best served by energy carriers that meet their needs in a comfortable, reliable and inexpensive way. For energy producers and distributors, the challenge is to know the demand for each energy form in time. Engineers who operate and plan energy infrastructure are interested in reliable technologies that can be operated flexibly. And policy makers are assigned to secure an affordable, reliable, sustainable, and safe energy supply (Mancarella et al., 2016).

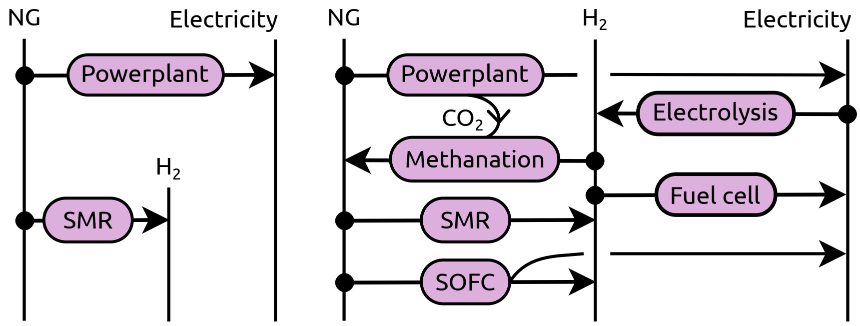


Figure 4.1: Schematic overview of energy conversion processes that connect electricity, hydrogen and natural gas (NG) in the current system (left) and future options (right).

Most models that were created in the past only address one energy carrier. Electricity is studied most often, because the balancing of the electricity grid is a delicate task. Models for other energy carriers also exist, for example to optimise hydrogen infrastructure (Strachan et al., 2009). Regarding the expected energy transition in the near future, interactions between the supply chains of different energy carriers can no longer be neglected. The markets for electricity, hydrogen, gas, heat, and liquid fuels will become increasingly interconnected (Bokhoven et al., 2015), creating the need for models that cover the whole energy system. It is not clear yet whether hydrogen will become a major energy carrier, but it could play a role as connecting element between methane and electricity. In Figure 4.1, the potential role of hydrogen is illustrated. $H_2$ can be produced by electrolysis of water from electricity, or by steam methane reforming (SMR) from NG. Fuel cells or combustion engines can (re)generate electricity. Methanation of $CO_2$, converts $H_2$ to methane. It is also possible to perform co-electrolysis of $H_2O$ and $CO_2$ to obtain methane directly (Ridjan et al., 2013).

### 4.1.3 Path dependence

Since energy infrastructure has a lifetime of several decades, decisions made in the past can have consequences reaching far into the future. This effect is called *path dependence*, and may lead to *lock-ins*, unfavourable system configurations that are hard to escape from. The existence of path dependence is one of the reasons to use energy system optimisation when planning new investments in the system. Since optimisation is an *exploratory* mode of research, it can generate unexpected system configurations. This type of research is relevant for decision makers because of four more reasons (Schenk et al., 2007):

- The high investment costs related to the energy system make that a large amount of money can be saved if a more optimal system is created.
- The long lifetime of energy technologies imply that decisions made now have implications for a long time period.
- There is a danger of creating lock-in situations, for which it is hard to move away from.
- The rapid development of novel technologies can have far-reaching impacts on the system, so the possible effects should be anticipated on.

When a future energy system configuration is determined by means of optimisation, a new question raises immediately: how can the current system be transformed into the optimal future system? The answer can be found by optimising longer time periods, taking the lifetime of existing installations into account.

## 4.2 Literature review

For conventional energy systems, the design and operation are of limited complexity. These systems are composed of generation technologies that produce one energy carrier, and sometimes waste heat is recovered. The problem of operational dispatch in these systems can be solved by using the *merit order* of the technologies. Demand is met by turning on as many plants as required, starting with those with the lowest operating and fuel costs. The investment decision for new plants can be made based on a LCOE analysis (4.5). Finding an optimum for a system containing multi-generation components is more complicated. Whether or not to operate depends on the costs and revenues of all inputs and outputs (Chicco & Mancarella, 2009). In the past decade, various models have been made that address the challenge of finding the optimal composition of energy systems. Existing literature describing these modelling efforts has been reviewed. The differences and similarities are discussed below. The focus is put on three parts of the modelling work: problem definition, implementation, and scenario construction. In addition, software tools used and relevant results are discussed.

### 4.2.1 Simulation vs. Optimisation

Considering energy system models, there is a big difference between simulation and optimisation – both conceptually and computationally. Simulation models are intended to study the performance of a certain system design. Each component of the energy system is represented in the model by a set of *heuristics* or rules, according to which the component behaves. There is no overall objective, as optimisation only occurs at the component level. It is possible that a simulation does not find the optimum solution, for instance when the heuristics of two components are contradictory. Also, the existence of a better heuristic is always present.

Simulations with pre-defined control strategies are useful to assess existing technologies, but they do not provide insight in the best way to operate or design a system. Additionally, simulations are used to predict system dynamics and the behaviour of its components. An example of a simulation tool is EnergyPLAN (Lund, 2007). For emerging technologies like SOCs, optimisations are more relevant, since the technology operation is determined by the algorithm. Optimisations help system developers to investigate the effects of design decisions and control constraints (Hawkes et al., 2009).

An optimisation model searches for the conditions, i.e. the set of values of variables, that give the best system performance. The performance is measured by the objective function, whose result is lowest or highest for the optimisation solution (Frangopoulos, 2003). Three types of optimisation can be distinguished: operation optimisation, system design optimisation, and system evolution optimisation. For the first type, the power generation equipment is fixed, but the dispatch is to be optimised. For example, Lozano et al. (2010) have studied a small system of one CHP plant that supplies heat and power to a collection of buildings with a given heating, cooling, and electricity demand. Notice the difference between operation optimisation and simulation: the former finds the optimal operating scheme, while the latter gives a *possible* option. The second optimisation type aims to find the optimal set of components and their optimal operation (Frangopoulos, 2003). The third type optimises the development of a system in time (e.g. Aki et al., 2005). Questions related to long-term strategies for installing and decommissioning energy infrastructure can be addressed. Usually, the operation is not part of the model in system evolution optimisation.

### 4.2.2 Problem definition

The formulation of the problem generally consists of determining the objective, scope, and restrictions. The objective specifies what should be optimised. This can for example be the total costs of the system, the net present value, or the GHG emissions. It is also possible to have minimum power outages as an objective, for which several indicators exist (Shahmohammadi et al., 2015). A single, or multiple objectives can be selected.

The scope sets the spatial and temporal boundaries and the available options for power generation. Ridjan et al. (2013) take a national scope with a few options for fuel supply, whereas Aboumahboub et al. (2010) have built a global model and a model describing Europe and North-Africa. For larger scopes, the importance of transport and associated losses increases. The temporal scope strongly depends on the optimisation type. Operation optimisation is short-term oriented, and should therefore have small timesteps (in the range of minutes to hours). On the other hand, system evolution optimisation has both larger timesteps and timespans. Differences also exist in the technology options that are used. The efficiency of either existing technology (e.g. Kamjoo et al., 2016; Kaviani et al., 2009) or expected future technologies (Kikuchi et al., 2014; Mathiesen et al., 2009; Aki et al., 2005) can be assumed. If the selected year is further in the future, technology assumptions become more uncertain.

Restrictions specify what conditions should be met by a solution. Most, but not all models feature the boundary condition that the energy demand should be met. If this condition is not present, the modellers have chosen to maximize the reliability of energy supply or set a lower bound for it (Shahmohammadi et al., 2015). Lozano et al. (2010) add legal constraints. In operation optimisation models, the number and size of components is fixed. But also in system design optimisations, it is possible to limit components to a maximum or minimum size. A minimum can for example be included to account for existing infrastructure (Belderbos et al., 2015). Upper bounds can reflect limitations for expansion, such as the limited space available for solar cells. Restrictions can also be defined for the energy storage and transport capacities. What restrictions apply in the model, depends on the assumptions made. These will be discussed in more detail in Section 4.2.5.

### 4.2.3 Mapping of energy systems

In order to map a system, a simplified representation is needed. Only the relevant dimensions of the real-world system are mapped. This reduces the complexity, while retaining sufficient detail to answer the research questions.

Biberacher (2004) describes a system mapping approach with two types of entities: commodities and processes. Commodities represent energy carriers. The conversion, transport, and storage of these carriers is undertaken by processes. The mapping approach can be applied for visualisation as well, as in Figure 4.2. This representation proves to be a powerful tool to conceptualise any existing or imaginary energy system, including all energy forms and technologies of interest.

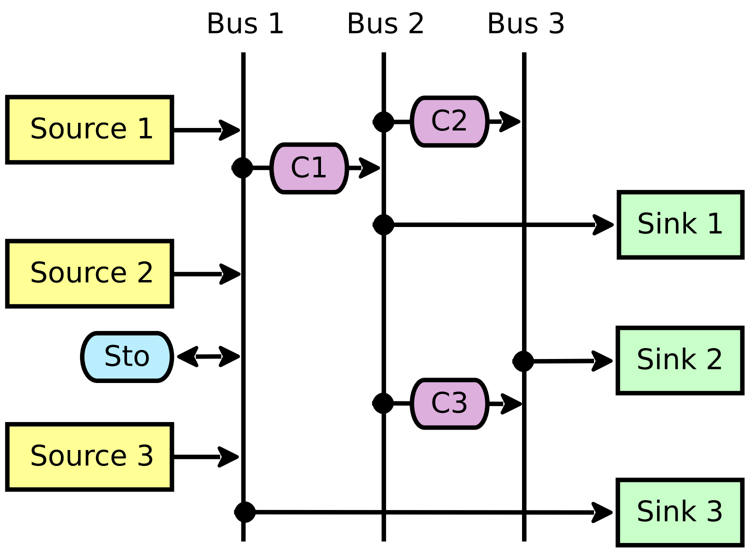



Figure 4.2: Representation of energy system components in a model. Three types of components are shown: sources, sinks, and converters. Storage is a special type of component. These components are connected via buses. Each bus represents a distinct type of energy carrier.

### 4.2.4 Implementation

Optimising an energy system requires the selection of an algorithm that efficiently and correctly finds the optimum. The solution space of the problem is determined by the set of variables that should be optimised. Given the infinite number of possibilities, it is not feasible to calculate the solution by exhaustive search. Therefore other, more sophisticated algorithms are needed (Geidl, 2007). For the implementation phase, the problem definition serves an an input.

First of all, a suitable spatial resultion can be derived from the scope definition. For a global scope, the world can be divided into regions. For a national model, smaller spatial units can be used. This spatial differentiation allows to model energy transport and exchange, and local differences in energy consumption and weather conditions. For small-scale cases, these factors do not play a role, so spatial divisions are not needed. The MARKAL model can be linked to GIS to study spatial developments (Strachan et al., 2009). The resolution in time has to be set too. Usually, timesteps of one hour are applied, because this is the timescale at which data on wind speeds and solar irradiation (for modelling solar and wind energy) are available (Aboumahboub et al., 2010; Kaviani et al., 2009). Shahmohammadi et al. (2015) have reduced the computation time of their case-study by taking one representative weekday and weekend day for each season.

Boundary conditions are important, because they formalize requirements and restrictions from the problem definition. Basic constraints like technological and physical limits are included in every model. Other conditions were discussed in the previous section. The objective function is the formalisation of the objective. The algorithm aims to minimize or maximize the outcome of this function. In their review, Chicco and Mancarella (2009) discuss the objective function used by several modellers. They note that sometimes, the emission of $CO_2$ is expressed in monetary value to obtain a single economic objective. In the case of multiple objectives, there is a trade-off, and the algorithm is referred to as multi-objective optimisation (Frangopoulos, 2003). This has been done by for example Kamjoo et al. (2016) and Aki et al. (2005), who present their results as a Pareto set. For the case of Kamjoo, the Pareto set describes the trade-off between the reliability of energy supply and the costs. Aki et al. present the trade-off between $CO_2$ and consumer costs. By doing so, the authors avoid judging the costs of power outages and climate change respectively.

During model formulation, a trade-off has to be made between computational burden and model accuracy. Real-world phenomena are often not fully linear, but in some cases a linear approximation is justified. When the optimisation problem is formulated as a linear programming (LP) problem, the solution can be found numerically. The ever increasing computation speed and capacity of computers opens up the road to more detailed and complex models (Erdinc & Uzunoglu, 2012). Often, the problem formulation contains a convex objective function, binary or integer variables, or nonlinear constraints. Integer variables (as opposed to continuous variables) describe for example start-up costs or the number of built installations. This results in a convex solution space. In these cases, numerical tools can still be used, but it is not guaranteed that the global optimum is found (Geidl, 2007).

Another approach is mixed-integer LP (MILP), which is a mix of LP and other algorithms such as *branch & bound*. It can be applied as long as both the objective function and the constraints are linear (Mathworks, 2015). An example of a model that uses MILP is the *Bing model* (Steup, 2014; Steup & Hemmes, 2015). In case of nonlinear problems, the solution can only be approximated, for which a number of dedicated algorithms exists. Advanced bio-inspired algorithms are becoming increasingly popular for solving non-linear problems. Among others, particle swarm optimisation, genetic algorithms, and simulated annealing are in use (Chicco & Mancarella, 2009; Bourennani et al., 2015). Other approaches that are promising, but have not yet been applied in energy system optimisation models, are ant colony and artificial immune system algorithms (Erdinc & Uzunoglu, 2012).

### 4.2.5 Scenarios

Before a model can run, the input parameters should be quantified. When dealing with future energy systems, high uncertainties are involved. This is because of the distant time horizon and long lifetimes, and because of the unpredictable dynamics of the energy transition. Therefore, the construction of explorative scenarios becomes important. Using scenarios, sets of input parameters are generated. The aim of explorative scenarios is to cover a wide range of possible future developments (Börjeson et al., 2006). Sørensen (2008) presents three steps to construct a renewable energy scenario:

1. Determine the end-use demand of energy by society.

2. Determine the potential energy supply of available resources.
3. Match supply and demand using intermediate conversions, storage, transmission, and possibly imports and/or exports.

Step 1 can be approached in two ways: taking the final energy or useful energy demand. Step 2 requires that energy production technologies are selected. Step 3 involves the definition of energy infrastructure and the simulation of supply and demand time series.

Predictions and/or assumptions have to be made for a wide range of input parameters and to set boundary conditions. Important factors as identified by existing literature are:

- The market share of renewable energy technologies (Belderbos et al., 2015).
- The supply of fossil fuels (Ridjan et al., 2013).
- Legislation in the form of taxes, subsidies, quota, obligations (Aki et al., 2005).
- Available technologies and their efficiencies. Both for generation, conversion, and storage of energy (Mathiesen et al., 2009).
- The demand for specific energy carriers (Kikuchi et al., 2014; Ridjan et al., 2013; Sørensen, 2008), depending on:
  - population size,
  - efficiency changes of existing technology, and
  - spread of new technology, like BEVs, FCEVs, electrification (heat pumps, electric stoves).

For many countries, national energy scenarios have been made. For the Netherlands, ECN has drawn up a possible energy future (Schoots & Hammingh, 2015). In Denmark, a '100% renewable energy scenario' was developed (Mathiesen et al., 2009). On a worldwide level, there are also several energy scenarios. See for example the IEA Outlook (IEA, 2015) and the Sustainable Global Energy Outlook (Teske et al., 2010).

### 4.2.6 Results

The most relevant outcomes of the reviewed papers are presented in this section. It should be noted that the conclusions drawn from the case studies are not always valid for other cases, in particular when assumptions and/or scope differ.

The acclaimed advantages of FCs for CHP production have been confirmed by several studies. For example, Aki et al. (2005) show that micro-CHP installations with PEMFCs can be effective to reduce $CO_2$ emissions. The penetration of FCs is accelerated by a price reduction of the devices (possibly with subsidies), and a lower price of NG relative to electricity. Kikuchi et al. (2014) also find that distributed co-generation systems such as SOFCs in the residential sector are part of an optimal energy system.

Aboumahboub et al. (2010) demonstrate the merits of international high-voltage electricity transmission. It is shown that transport infrastructure reduces the need for energy storage and vice versa. However, no capacity limits were considered, possibly yielding suboptimal results. Two other researches focussed more on storage technology. Power-to-gas technology (PtG, producing methane by electrolysis) is preferred over batteries, when renewable energy has a share of 80% (Belderbos et al., 2015). The researchers explain this observation by noting that gas is an attractive energy storage medium to handle seasonal energy availability. Batteries remain more efficient for short-term storage. Meibom and Karlsson (2010) calculated the configuration of an economically optimal energy system in 2060. Hydrogen storage was included in the solution even if there was no demand for it from transport. Under the technology assumptions made, the direct conversion of biomass to hydrogen is not attractive. Instead, biomass combustion followed by water electrolysis was selected. Hydrogen production could also serve as demand response mechanism (Kikuchi et al., 2014): by constructing more electrolysis facilities, the installed capacity of fossil-based powerplants can be reduced. No reports were found that described an optimisation model with SOFCs with the ability to produce hydrogen or operate at different fuel utilisations, as described in Section 2.7.1. or SOFECs

One of the first optimisation models with SOFCs was demonstrated by Hawkes et al. (2009). The model had a very limited set of components, and focussed on the degradation of the cells and the ideal moment of stack replacement. The impact of a number of operating constraints were also assessed. Hawkes et al. (2006) used an optimisation model to show that the rate of current density change of a SOFC stack in response to load changes is not important for the economic attractiveness. Therefore, a long lifetime should be preferred over ramp-up ability during the design phase.

### 4.2.7 Modelling software

The continued interest in energy system planning has resulted in a wide range of modelling and optimisation tools (Connolly et al., 2010). These software tools allow to model, optimise, and analyse (hybrid) renewable energy systems. Examples of packages with many users include energyPRO, HOMER, and LEAP. Connolly et al. (2010) identified 68 different tools, ranging from short-term dispatch optimisation software at the level of individual houses (HOMER), to models for long-term investment and replacement planning (Balmorel, MARKAL/TIMES). In recent years, an increasing number of free and open source models have been added to this collection (see Table 4.1). The wide variety is a result of the diversity in problem definitions (see § 4.2.2) and optimisation algorithms. Depending on the aim of a research, a different model will be most suitable to use.

Although EnergyPLAN is a popular tool, it is not designed for optimisations. Instead, the user should compose different sets of technologies, for which EnergyPLAN simulates the optimal dispatch using heuristic methods (Connolly et al., 2010).

Table 4.1: Open source renewable or hybrid energy system optimisation models (Schlecht & Davis, 2016).

| Name | Programming language |
|---|---|
| Balmorel | GAMS |
| Calliope | Pyomo (Python) |
| DIETER | GAMS |
| EMMA | GAMS |
| Ficus | Pyomo (Python) |
| Genesys | C++ |
| NEMO | Python |
| Oemof | Pyomo (Python) |
| OSeMOSYS | GNU MathProg |
| PyPSA | Pyomo (Python) |
| Renpass | R |
| Temoa | Pyomo (Python) |
| URBS | Pyomo (Python) |

The number and type of predefined technology options differs between the models. In some cases, a selection of cost and performance data is provided, while other models leave the definition of these characteristics to the user.

### 4.2.8 Models of the Netherlands

A limited number of models have specifically been designed to apply to the Dutch energy system. Netbeheer Nederland (2016) has listed 17 of these tools, of which six can handle multiple energy carriers on a national scale. The models that have a national scope are listed in Table 4.2. Most models are not publicly available, but are used and maintained by consultants and research institutes. Two example studies of the Netherlands are highlighted below.

Schenk et al. (2007) have designed a model that simulates the Dutch electricity system on an hourly basis. The simulation is employed to study the effect of different installed wind turbine capacities on the electricity network. The merit order approach is used to determine the operation strategy of conventional powerplants in this model. The research shows that hydrogen production via electrolysis can prevent start-up and shut-down costs or electricity excess. However, because of the energy losses

Table 4.2: Tools for modelling the Dutch energy system at a national level (Netbeheer Nederland, 2016).

| Model | Organisation(s) | Carrier(s) |
|---|---|---|
| Vesta | PBL | Heat |
| CEGRID | CE Delft | Electricity |
| Smart Grid Scenario Model (DSSM) | DNV GL | Multiple |
| Energy Transition Model (ETM) | Quintel Intelligence | Multiple |
| ETMoses | Quintel Intelligence; Alliander | Multiple |
| PICO | Geodan; TNO; Alliander; NRG31/Waifer; Geodan; Ecofys; Esri | Multiple |
| OPERA | ECN | Multiple |

associated with electrolysis, the total primary energy use was only reduced if the installed wind energy capacity exceeded 8 $GW_e$ in the Netherlands (Schenk et al., 2007).

This model has also been applied by De Boer et al. (2014) and Bellekom et al. (2012). The study by Bellekom et al. (2012) assessed the role of BEVs in compensating the fluctuating production of electricity from wind. It was concluded that charging BEVs at night contributes to a higher direct consumption of wind energy. The importance of appropriate load management strategies to prevent network problems was stressed. In De Boer et al. (2014), the effect of electricity storage options (compressed air energy storage (CAES), Norwegian pumped hydro storage and PtG) to compensate for wind energy fluctuations was simulated. The simulation heuristic did not always result in cost or emission reductions at low wind penetrations. At high installed capacities of wind turbines, pumped hydro storage was the most cost-effective technology to reduce electricity excesses and start-up costs of powerplants.

The first study has investigated the system costs of residential heat supply (Van Melle et al., 2015). The costs of energy distribution and local conversion to heat were analysed (not optimised) for different scenarios. Central energy conversion was excluded. Demand data of a year with an extremely cold were used to simulate high heat demands. The analysis has shown that most investments have to be made by households, for insulation, heat pumps and micro-CHPs. Insulation plays an important role in reducing the energy demand. The highest grid costs occur in full electric scenarios, in which case the electricity grid has to be expanded.

The second study of the energy system in the Netherlands is about the optimal sustainable heat provision (Schepers et al., 2015). The authors have divided all neighbourhoods in fifteen categories, and determined the most cost-effective heat supply alternative for each category. The alternatives are different combinations of energy generation, transport, and local conversion technologies. Instead of performing simulations, the required installed capacity per household were estimated. The importance of insulation is stressed here too. Although green gas is attractive for many locations, its availability restricted. In urban areas, sources of geothermal and waste heat are exploited whenever available. For rural areas, heat pumps are often the optimal choice.

While both studies are valuable because of the bottom-up approach of the energy demand, the restricted optimisation ignores unexpected solutions. It might for example be attractive to equip some households with electric boilers, that produce heat during cold days and/or oversupply of electricity. This option is, however, not considered by both models. Another limitation is the limited scope: energy demand by industry is excluded, as well as the demand of the transport sector. As discussed in § 4.1.2, the different energy carriers cannot be properly studied in isolation, in particular in future energy systems.

## 4.3 Modelling decisions

To assess the economic and environmental effects of SOCs on the energy system, a system design optimisation model will be used. This model calculates the optimal energy supply system for a given future energy demand, and is based on a framework called oemof (*oemof*, 2016). The following modelling decisions were made:

**Objective:** A cost objective is used, which means that the annualised costs of the total energy supply system are minimised. GHG emissions are expressed in terms of costs by multiplication with an emission tax to obtain a single objective function.

**Scope:** The national energy system of the Netherlands is considered. To get a good understanding of the role of components with multiple inputs or outputs, not only the market for electricity, but also for heat, hydrogen, and other fuels are included. Timesteps of one hour are used. No spatial resolution smaller than the country is applied, so transportation limits are absent.

**Restrictions:** The final energy demand of all included energy carriers should be met. The only exchanges with other countries are modelled as commodity markets for fossil fuels and biomass. It is allowed to 'dump' excess electricity, biogas, hydrogen, or heat.

**Model input:** The set of available generation technologies consists of currently used technologies (like fossil fuel powerplants and wind turbines), and some 'new' technologies like SOCs and electrolysers. Furthermore, components for storage, and conversions of energy are included (e.g. batteries and hydrogen tanks, electrolysers and heat pumps).

**Model output:** The calculations yield the amount of energy generating, converting, transporting, and storing devices that should be installed to achieve the optimal situation. The throughput of each component at each timestep is provided as well. From these data, detailed information on the GHG emissions and costs of the system can be derived.

**Scenarios:** Multiple scenarios will be explored to find under what developments fuel cell systems are favoured. The scenarios are constructed by making combinations of different demand compositions and levels of GHG emission taxes.

Important elements of the model as mentioned above are schematically represented in Figure 4.3. Each of the decisions is discussed and motivated further in Chapter 5.

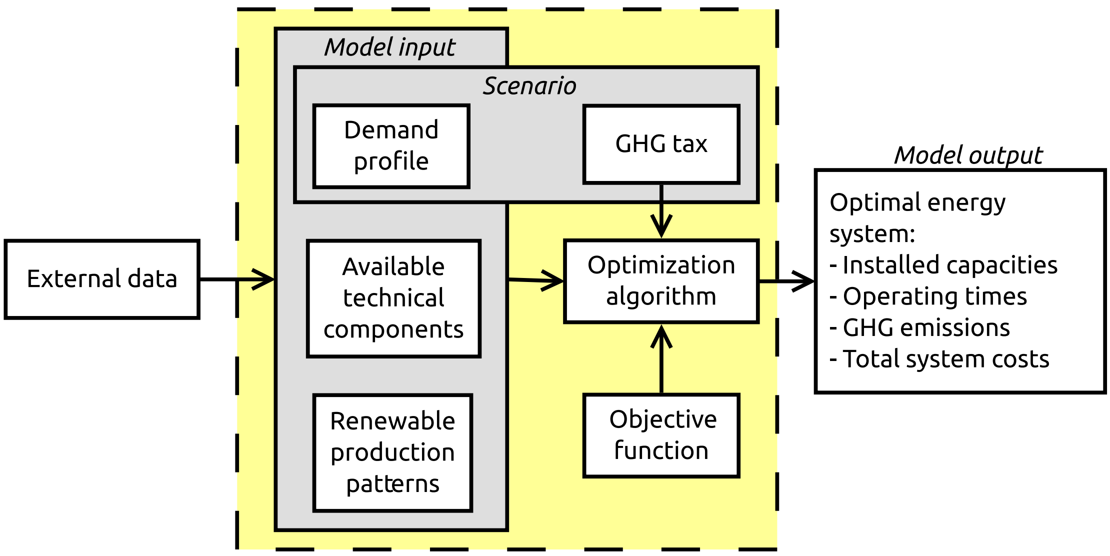



Figure 4.3: Structure of the energy system optimisation model, including inputs and outputs.

## 4.4 Model implementation

### 4.4.1 Software sources

The optimisation model implementation is based on the open-source modelling framework *oemof* (*oemof*, 2016). The framework, written in Python and dependent on Pyomo, was extended with additional functionalities to accommodate for SOFC and SOFEC components. The code is appended in Appendix C.

The Center for Sustainable Energy Systems (ZNES) together with the Reiner Lemoine Institute (RLI) in Berlin and the Otto-von-Guericke-University of Magdeburg (OVGU) have initiated the development of an *Open Energy System Modeling Framework* (oemof). Their ambition is to create a free and open-source software package that addresses the lack of transparency of many existing energy system models. The fact that both the source code and a clear documentation are freely accessible, improvement, debugging, and re-use of the software are stimulated (*oemof*, 2016). Oemof is under development, and anyone can propose changes or additions to the framework via the online software sharing platform GitHub.

Oemof is programmed in Python and uses several other Python packages. The most important dependency is Pyomo, which supports formulating, solving, and analyzing optimisation models. To solve an optimisation model, Pyomo passes the problem to a dedicated solver.

In this research, the GNU Linear Programming Kit (GLPK) solver was used for linear programming problems (Makhorin, n.d.). IPOPT (an interior-point optimisation algorithm) was used as a solver for non-linear problems (Wächter & Biegler, 2006). This software package depends on a number of libraries, among which the Harwell Subroutine Library (HSL) (*HSL*, n.d.) and AMPL Solver Library (ASL) (Fourer & Kernighan, 2002).

### 4.4.2 Energy system mapping

The system mapping that is applied in oemof, matches the concept of Figure 4.2. This concept dictates the basic structure of any energy supply system within the framework.

The system consists of two types of *entities*: *busses* and *components*. A bus is an imaginary reservoir of an energy carrier or resource. Components are entities that produce and/or consume energy carriers, such as sinks, sources, and converters. Components are always connected to one or several buses, but never to other components. The same holds for buses. To build an energy system, components and buses are combined and connected. An energy system can be conceptualised as a bipartite directed graph, in which all entities are interpreted as nodes and the directed edges are the in- and outputs of the components. An energy system instance is described by the nodes and edges present, while a possible solution is characterised by the weight of the edges (the energy flow) at each timestep.

In oemof, all entities are an instance of the class `Entity` or one of its subclasses. Figure 4.4 lists the classes that are predefined in oemof. Most energy system components can be modelled as one of these.

### 4.4.3 User input

The energy system optimisation in oemof is embedded in a sequence of steps, including model definition, result processing, and everything in between. Most of these steps require the user to decide what input is provided to the model, as indicated in Table 4.3. To clarify the process, a small code example is provided below. This is the code used for Test 3 discussed in § 7.2.

```
# Import software libraries (not shown here)

# Define logger that allows to print status information
logger.define_logging()

# Read data from file and set time index
```

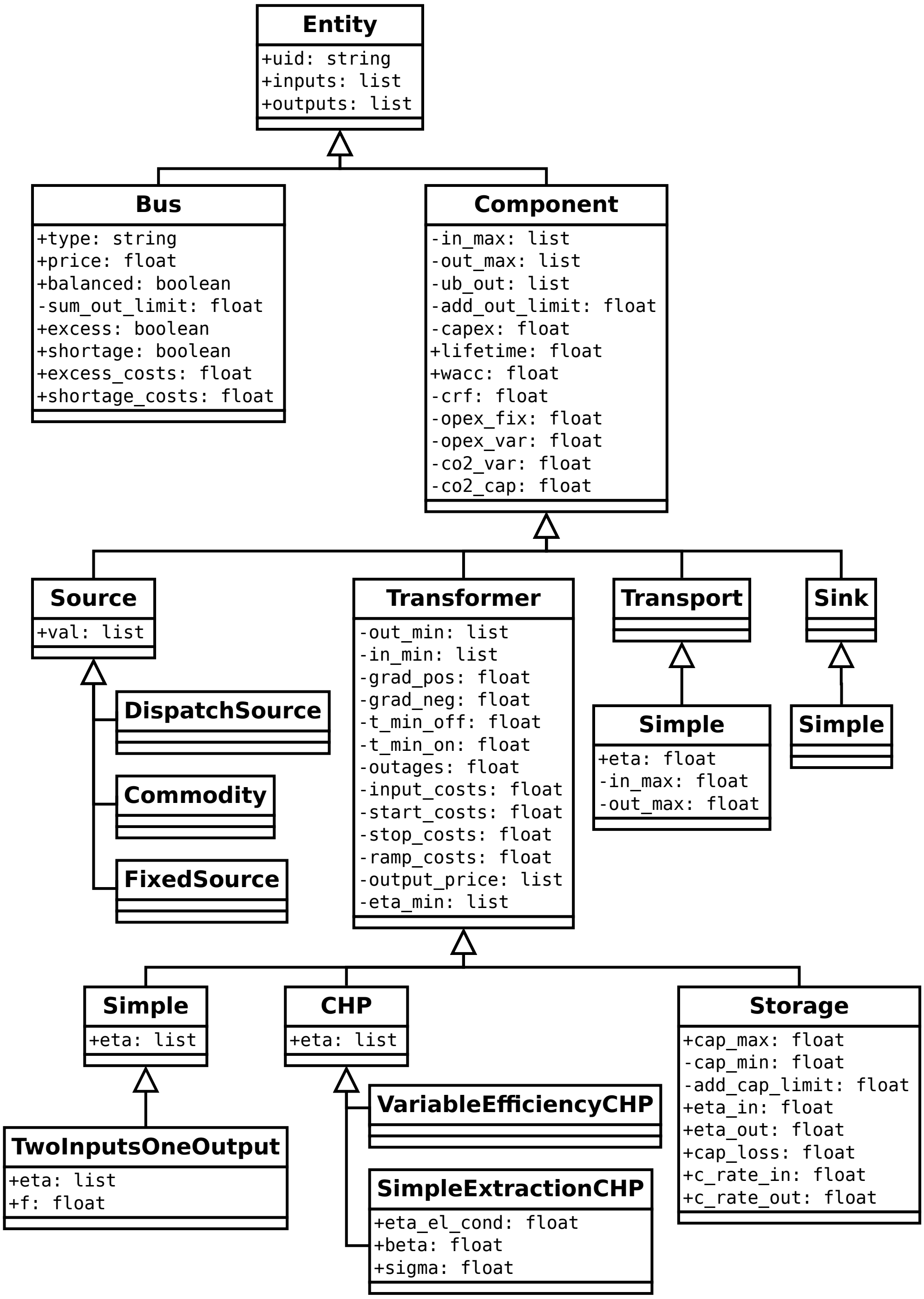



Figure 4.4: The `Entity` class, its subclasses, and their attributes as available in oemof. Attributes indicated with a plus sign (+) must be specified when an instance of the class is created. Others are optional attributes that are ignored or set to zero when not provided.

```
filename = ospath.normpath("/path/to/data/file.csv")
data = pd.read_csv(filename, sep="\t")
time_index = pd.date_range('1/1/2015', periods=8760, freq='H')

# Initialize the energy system and specify solver and objective
simulation = es.Simulation(
    timesteps=range(len(time_index)), verbose=True, solver='glpk',
```

Table 4.3: User input required for each step of the modelling process.

| | Model step | User input |
|---|---|---|
| 1. | Read energy production and consumption patterns | Specify data file(s) |
| 2. | Initialise the energy system | Specify the solver algorithm, objective function, and logging options |
| 3. | Create all entities that are part of the energy system | List the energy carrier buses, and whether excess or shortage is allowed<br>List all components and their characteristics (see Figure 4.4)<br>Specify which components' installed capacities can be increased |
| 4. | Calculate the optimal solution of the problem | – |
| 5. | Process the results | Functions to visualise, print, or save the results |

```
    objective_options={'function': ghg_objectives.minimize_cost, 'co2_tax': 0})

energysystem = es.EnergySystem(time_idx=time_index, simulation=simulation,
                               display=True)

# Set some or all components to investment mode
source.FixedSource.optimization_options.update({'investment': True})
transformer.Storage.optimization_options.update({'investment': True})

# Define entities and their characteristics
# Energy carriers
bele = Bus(uid="bele", type="el", excess=True)

# Sources
pv2 = source.FixedSource(uid="PV_comm", outputs=[bele], out_max=[0],
      add_out_limit=29757, capex=660, opex_fix=6.591, lifetime=40,
      wacc=0.08, co2_cap=1793.75e-3, val=data['solar'])

# Storage
battery = transformer.Storage(uid='Li_battery', inputs=[bele],
          outputs=[bele], eta_in=1, eta_out=0.85, cap_loss=6.94e-5,
          opex_var=0.001, capex=50, lifetime=10, cap_max=1,
          add_cap_limit=10e10, c_rate_in=1, c_rate_out=1)

# Demand
ele_dem = sink.Simple(uid="ele_dem_hh", inputs=[bele], val=data['el_dem_hh']*3)

# Optimise the energy system
om = OptimizationModel(energysystem=energysystem)
energysystem.optimize(om)
logging.info('Finished!')

# Plot and save the results
stackplots(energysystem.results, time_index, bele)
store_results (energysystem.results, time_index, "ResultsFile")
```

### 4.4.4 Implementation of SOC components

As depicted in Figure 4.4, each set of components that has different input-output relations is modelled by a unique sub-class of `Component`. SOFCs and SOFECs each have their own sub-class. These classes do not have additional parameters. The constraints that apply to instances of this class were implemented in accordance with § 3.5. The code that defines the SOC classes and the corresponding constraints are included in Appendix C.

## 4.5 Levelised costs of energy

Levelised cost of energy (LCOE) analysis is a rapid method to compare several options of energy production. The idea is that all costs involved in energy production using a technology – investment costs, fuel costs, fixed and variable operation and management (O&M) costs, and optionally taxes – are expressed in terms of costs per unit of energy (see Eq. 4.1). This approach ensures that technology options with very different cost structures can be compared on an equal basis, e.g. €/kWh$_e$.

An important aspect of a LCOE calculation is the *discounting* of investment costs. In economic analyses, the investment costs are annualised by multiplication with the *capital recovery factor* (CRF). The CRF accounts for the fact that the investment costs are discounted to the future. It is calculated by taking into consideration the expected lifetime of the technology and the *discount rate* $r$ (Eq. 4.2). The value of the discount rate is assumed equal to the weighted average cost of capital (WACC), which is the interest rate for loans or the desired interest for investors (Bruckner et al., 2014). In general, lower interest rates apply for conventional technologies, due to the higher reliability and demonstrated performance. New and unconventional energy transformers, however, can guarantee the profitability to a lesser extent, resulting in higher interest rates. In the present analysis, a WACC of 5% for proven, and 8% for unproven technologies is used.

The definition of LCOE is (Bruckner et al., 2014):

$$\mathrm{LCOE} = \frac{\mathrm{CRF} \cdot C_{\mathrm{inv}} + C_{\mathrm{fix}}}{8.76 \cdot \mathrm{CU}} + C_{\mathrm{var}} + \frac{C_{\mathrm{fuel}}}{\eta} + C_{\mathrm{GHG}} \tag{4.1}$$

$$\text{with} \quad \mathrm{CRF} = \frac{r}{1-(1+r)^{-L}} = \frac{r \cdot (1+r)^{L}}{(1+r)^{L}-1} \tag{4.2}$$

and with $C_{\mathrm{inv}}$, $C_{\mathrm{var}}$, and $C_{\mathrm{fix}}$ the investment costs, variable and fixed O&M costs, CU the capacity utilisation, and $L$ the lifetime of the technology.

The most used indicator is the levelised cost of electricity, but the levelised cost of hydrogen or any other energy carrier can be calculated too (Chen, 2006). Furthermore, the levelised cost of electricity storage can and has been assessed (Lazard, 2015b). The simplicity of LCOE analysis entails some limitations. To calculate the variable costs, a CU has to be assumed. Therefore, LCOE analysis is most useful to analyse a single technology in isolation from the rest of the energy system, or to evaluate different options for a specific application.

# Chapter 5

# Assumptions & Scenarios

## 5.1 Goal & Scope definition

### 5.1.1 Goal

The goal of the optimisation model is to find a combination of technologies that most cost-effectively meets the final energy demand throughout the year. The model should cover all relevant energy carriers, and be able to include any type of existing or future energy conversion, storage, and transport technologies. The model is intended to be used to study SOCs specifically. It is applied in Chapter 7 to see whether fuel cells can make the Dutch energy sytem more efficient, and what the effects of fuel cells on various aspects of the system are.

### 5.1.2 Timesteps

The dynamics of each energy carrier emerge at various temporal scales. For example, coal has to be ordered weeks or months before it arrives at a powerplant, while a cloud affects the electricity output of a solar panel within a minute. Since the model should cover all energy carriers, a timestep size in between these extremes is best. Therefore, the model consists of 8760 timesteps, i.e. one year divided in steps of one hour. This choice allows to include the effects of both short-term and long-term fluctuations. A model with only eight representative days as in (as in Shahmohammadi et al., 2015) would greatly reduce the computation time, but is not suitable to guarantee proper long-term performance of the energy system. Considering the balancing function of energy systems (see § 4.1.1), the balancing is not investigated at all timescales. Electricity grid balancing on the millisecond to minute scale is not considered. For other energy carriers, the dynamics that play a role in timescales shorter than hours are hardly important for the operational planning of the system.

No specific reference year is defined. But as explained in § 5.4, scenarios with an energy demand that largely differs from the current situation are included.

The demand and supply patterns used are intended to represent an average year. Thus, no conclusions can be drawn about the security of supply under extreme conditions, such as very cold periods (which was investigated by Van Melle et al., 2015). On the other hand, a full year features a broad range of weather conditions and combinations of solar and wind availabilities.

### 5.1.3 Constraints

A number of constraints is applied to the solution, such that it meets the requirements of being technically and thermodynamically possible. Constraints are associated with each entity.

### 5.1.4 Objectives

Two objectives are distinguished: cost minimisation and GHG emission minimisation. The former objective has an economic focus, but can also include environmental aspects by means of a weighting factor for GHG emissions. This weighting factor translates emissions to costs in order to obtain a single objective value. In this thesis, it will be referred to as emission tax. Yet, it can also be interpreted as the price that has to be paid on the European market for emission certificates within the emission trading system (ETS), or as an expression of societal costs associated with climate change.

The total annualised costs are a sum of investments, fixed and variable O&M, curtailment costs of dispatchable sources, costs for an excess or shortage of energy.

Investment costs:
$$C_{\text{inv}} = \frac{T}{8760} \sum_e IC_e^{\text{add}} \cdot \text{CRF}_e \cdot C_{\text{inv,e}} \quad \forall e \tag{5.1a}$$

Fixed O&M costs:
$$C_{\text{fix}} = \frac{T}{8760} \sum_e (\overline{IC}_e + IC_e^{\text{add}}) \cdot C_{\text{fix,e}} \quad \forall e \tag{5.1b}$$

Variable O&M costs:
$$C_{\text{var}} = \sum_e \sum_t \text{Output}_e(t) \cdot C_{\text{var,e}} \quad \forall e,t \tag{5.1c}$$

Curtailment costs:
$$C_{\text{cur}} = \sum_e \sum_t \text{Curtailment}_e(t) \cdot C_{\text{cur,e}} \quad \forall e,t \tag{5.1d}$$

Excess costs:
$$C_{\text{exc}} = \sum_e \sum_t \text{Excess}_e(t) \cdot C_{\text{exc,e}} \quad \forall e,t \tag{5.1e}$$

Shortage costs:
$$C_{\text{sho}} = \sum_e \sum_t \text{Shortage}_e(t) \cdot C_{\text{sho,e}} \quad \forall e,t \tag{5.1f}$$

GHG costs:
$$C_{\text{GHG}} = tax_{\text{GHG}} \sum_e \left[ IC_e^{\text{add}} \cdot E_{\text{inv,e}} + \sum_t \text{Output}_e(t) \cdot E_{\text{var,e}} \right] \quad \forall e,t \tag{5.1g}$$

Annual costs:
$$C_{\text{tot}} = \frac{8760}{T} \cdot (C_{\text{inv}} + C_{\text{fix}} + C_{\text{var}} + C_{\text{cur}} + C_{\text{exc}} + C_{\text{sho}} + C_{\text{GHG}}) \tag{5.1h}$$

For storage components, the $IC^{\text{add}}$ factor is expressed in units of storage capacity.

Similarly, but with less terms, the GHG emissions can be calculated by summing the emissions during construction and operation of components:

Construction:
$$\sum_e IC_e^{\text{add}} \cdot E_{\text{inv,e}} \quad \forall e \tag{5.2}$$

Operation:
$$\sum_e \sum_t \text{Output}_e(t) \cdot E_{\text{var,e}} \quad \forall e,t \tag{5.3}$$

## 5.2 Energy conversions

The energy system can be conceptualised as a series of energy conversions, as illustrated by Figure 5.1. Inputs of the system are forms of primary energy: solar, nuclear, and chemical energy. The purpose of the system is to provide energy in a useful form ('useful energy'), such as light, sound, heating, cooling, and work. The energy carrier that is bought by consumers ('final energy') often undergoes a final energy conversion to obtain useful energy. The end-use of energy by society can be characterised as the demand for either final or useful energy. In the first case, the demand for specific energy carriers should be known. In the second case, the demand for services should be known, including the efficiencies of the appliances that provide these services (Deng et al., 2012).

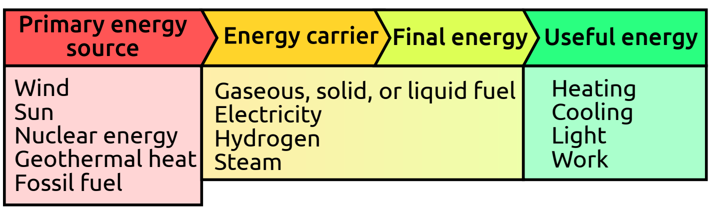



Figure 5.1: Energy flows through an energy system, including some examples of carriers.

Determining the demand for useful energy can be a challenge, since statistics offices only record final energy demand. If the final conversion options were included in the boundaries of the energy system, demand would be optimised too. Implicitly, ideal consumer behaviour is assumed in this manner, because consumers are 'allowed' to only use the devices that are most effective according to the optimisation objective. Although companies and the government can to some extent stimulate desirable consumption patterns, full consumer control would be an unrealistic assumption. From a computational point of view, the final conversion options would increase the number of variables of the model, thereby increasing the calculation time. Based on these considerations, the approach used here is to specify final energy demand. Instead of optimizing the final conversion, leading to one optimal consumption pattern, multiple possible consumption scenarios will be used (see § 5.4).

Throughout this thesis, amounts and flows of energy carriers will be quantified in terms of their energy content. For fuels, the higher heating value (HHV) is used. See Appendix A.1 for the conversion factors to calculate the mass of a given fuel.

## 5.3 Current energy demand

Before constructing scenarios of future energy demand, it is instructive to first analyse the current consumption of energy carriers in the Netherlands. Official statistics for the year 2014 are used here (CBS, 2016b). The *national energy balance* maps all energy-related flows. The final energy demand per sector is the relevant part of the balance in this analysis. Energy consumption by the energy sector itself and transmission losses are not included. Some fuels are used for applications other than energy production, such as the synthesis of plastics and other chemicals from oil. These applications are categorised as non-energy use. The data are visualised in Figure 5.2.

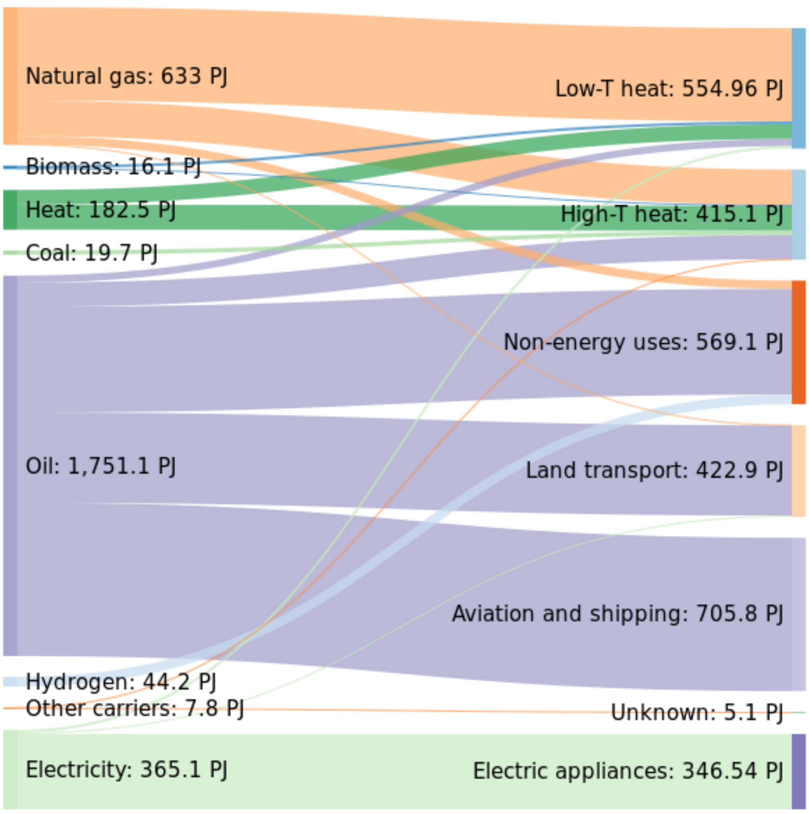



Figure 5.2: Energy demand of the Netherlands in 2014, grouped by energy carrier (left) and final energy demand (right).

From Figure 5.2, a number of conclusions can be drawn. Oil and oil products represent the biggest fraction of final energy demand, followed by NG. Electricity also has a big share of the demand. Because of high conversion losses in power plants, the share of primary energy used for electricity production is larger than the share in final energy.

### 5.3.1 Electricity consumption

Electricity is used predominantly for lighting and electric appliances, but some of it is used to produce heat. Electric boilers, cooking stoves, microwaves, and heat pumps can perform this conversion. For instance, around 1.75 GJ/a electricity was used for cooking in 2012 (Gerdes et al., 2014). 15% of electricity consumed by households is used for heating: 3% for cooking, 7% for space heating, and 5% for hot tap water) (Gerdes et al., 2014).

### 5.3.2 Heat demand

Heat demand is split into two categories: low-temperature (<100 ºC) and high-temperature (>100 ºC) heat demand. It is assumed that households and businesses only consume low-temperature heat, and industries only high-temperature heat. Concluding from the heat demand per temperature interval as shown in Figure 5.3, this approach slightly overestimates the high-temperature heat demand.

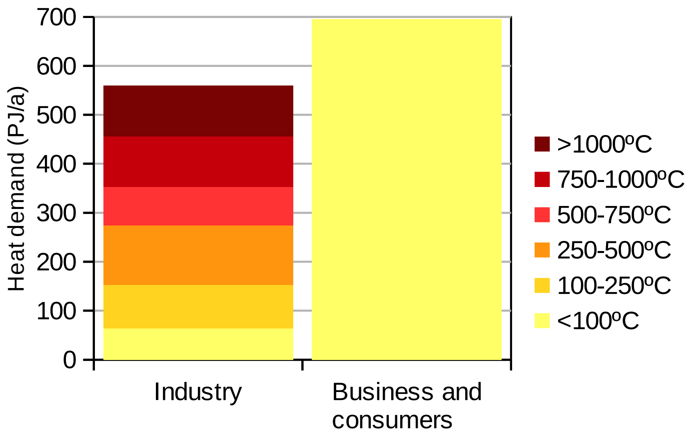



Figure 5.3: Heat demand by the residential and industrial sector in the Netherlands in 2006, divided in temperature intervals (S. Spoelstra, 2008).

### 5.3.3 Hydrogen consumption

Hydrogen does not occur in the energy statistics. This does not mean that it is not produced or consumed. In fact, large quantities of hydrogen are consumed by the ammonia and petrochemical industry (Sveshnikova, 2015).

Ammonia ($NH_3$) is produced from $H_2$ and $N_2$ in the Haber-Bosch process. The total production of ammonia in the Netherlands amounted to 2.6 Mt in 2014. Most of this is used for fertilizer production (Beljaars, 2015). The required hydrogen gas originates from NG; 91 PJ of NG was consumed by Dutch ammonia plants in 2014. Two thirds of this (61 PJ) is directly needed to produce hydrogen, while the remainder is combusted to provide heat to drive the endothermic reaction (Beljaars, 2015). 44 PJ of hydrogen would be sufficient to replace the methane feed. An additional amount of 17 PJ heat input is then required to compensate for the reduced methane input.

In the petrochemical industry, hydrogen serves as a reactant for hydrocracking, a process used in the production of oil-based fuels (Citizendium, 2013). However, this application falls outside the scope of the analysis, since it can be classified as energy use by the energy sector. Therefore it is not included as final demand, leaving the hydrogen demand calculated above as the single current demand.

### 5.3.4 Natural gas consumption

The composition of NG is assumed to be that of Groningen gas, which has a low caloric value. This is the mixture that is delivered by the gas distribution network of the Netherlands. The composition is given in Table 5.1.

Table 5.1: Average composition of gas from the Groningen gas field (Wikipedia, 2012).

| Component | volume% | mol% | mass% |
|---|---|---|---|
| Methane | 81.30 | 81.29 | 69.97 |
| Ethane | 2.85 | 2.87 | 4.63 |
| Propane | 0.37 | 0.38 | 0.90 |
| Butane | 0.14 | 0.15 | 0.47 |
| Pentane | 0.04 | 0.04 | 0.16 |
| Hexane | 0.05 | 0.05 | 0.23 |
| Nitrogen | 14.35 | 14.32 | 21.52 |
| Oxygen | 0.01 | 0.01 | 0.02 |
| Carbon dioxide | 0.89 | 0.89 | 2.10 |

## 5.4 Demand Scenarios

Building on the insights from § 5.3, this section discusses what factors influence the energy demand, and how to make scenarios based on these factors.

### 5.4.1 Possible developments

The final energy demand $D_{\text{final,c}}$ of an energy carrier depends on the magnitude of a useful energy demand $D_{\text{useful}}$ and on the fraction $y_c$ of that demand derived from the carrier:

$$D_{\text{final,c}} \propto D_{\text{useful}} \cdot y_c \tag{5.4}$$

Both aspects are subjected to change over time. For example, the demand for rail transport as a form of useful energy has grown (more passenger kilometres are consumed), while the form of final energy has changed from coal to electricity. Both developments influence the demand for the energy carriers coal to electricity. There mare many of such developments taking place, or expected to take off in the future. By considering these developments, scenarios for future energy demand can be constructed. A good starting point is provided by the six useful energy categories depicted in Figure 5.2. Below, the available energy carrier options to meet each demand are discussed briefly, providing guidance with respect to the values of $y_c$.

#### Electric appliances

Currently, electricity constitutes about 15% of the final energy demand (see Figure 5.2). It is consumed in all sectors of industry, business, and households. The majority of electricity is used to operate all kinds of appliances, such as computers, machines, lights, etc. In these applications, electricity cannot be replaced by other energy carriers.

#### Low-temperature heat

Households and business consume a considerable amount of NG to produce low-temperature heat. Some heat is derived from oil and biomass combustion in stoves, electric heaters, and district heating systems. Low-temperature heat has three main purposes: space heating, hot tap water delivery, and cooking. In the future, NG could be replaced by electricity in all these applications. Electric or induction cooking stoves, microwaves, heat pumps, and electric boilers can be installed in such a scenario. Other options for future heating include direct heat from solar thermal panels, the expansion of district heating systems, or stoves fired with wood. The attractiveness of these options depend on the specific local situation (Schepers et al., 2015).

### Aviation and shipping

The transport sector is dominated by several types of fossil fuels as energy carrier. Oil products are used to propel air planes, ships, trucks, cars, and trains. Aviation and shipping are grouped in a separate category, because there are very few commercially attractive alternative energy carriers available. This is because it is hard to approach the energy density of kerosene and fuel oil currently used for these modes of long-distance transport., and it is expected that these fuels will not be replaced in the coming decades.

### Road and rail transport

Road traffic is mostly relying on fossil energy carriers, whereas rail traffic is to a large extent electrified in the Netherlands. can be electrified. Especially BEVs have the potential to drastically increase electricity demand. Hydrogen is another possible future energy carrier for transport. Since it does not (yet) function as an energy carrier, hydrogen is not included in official energy statistics. This can change if the technology of FCEVs spreads.

### High-temperature heat

The final energy demand by industry (excluding the energy industry) amounted to 1108 PJ in 2014 (about one third of the total). Around 415 PJ is used to produce heat for industrial processes. The remainder of energy carriers are for electric appliances and non-energy uses. Figure 5.3 illustrates that most heat is high-temperature heat, as opposed to the low-temperature heat demands discussed earlier. A few options exist to obtain high-temperature heat: one can burn coal, oil, gas, or biomass in a furnace, use concentrated solar power (CSP), or connect to an industrial district heating system. CSP is not as attractive as in countries in the south, because the efficiency drops sharply when no direct sunlight is available (MacKay, 2009).

### Non-energy uses

Half of the final energy demand by industry is not needed for energy purposes, but to make products. Most importantly, plastics and polymers are derived from oil. The synthesis of $NH_3$ is another example. And coal can be used as reducing agent in some processes.

### Translation to scenarios

To keep the number of scenarios low, only developments with a big impact on the demand are considered here. Out of the six useful energy categories discussed above, three are regarded as most relevant here: low-temperature heat, high-temperature heat, and land transport. The mix of final energy forms used for these demands is much more flexible than that of the other three.

The magnitude of all six demand categories ($D_{\mathrm{useful}}$ in Eq. 5.4) is likely to change over time too. On the one hand, the globally growing population and affluence are drivers for increasing energy consumption: more goods are manufactured and transported, longer distances are travelled, more buildings have to be heated, etc. On the other hand, higher technological efficiencies, better insulation, and dematerialisation of the economy can induce lower energy demands (Chertow, 2000). For the present study, the magnitude of the demand is of lesser importance. A higher or lower total demand presumably results in accordingly scaled installed capacities of technologies. Therefore, no variations in the magnitude of demand are included in the scenarios.

### 5.4.2 Efficiency factors

To calculate the final demand for an energy carrier starting from the fraction and magnitude of a useful energy demand, the efficiency of the final conversion needs to be taken into account. For example, to drive a given distance, a BEV requires less electricity than a gasoline car requires gasoline when both carriers are expressed as energetic values. Therefore, Eq. 5.4 can be extended, yielding:

$$D_{\text{final,c}} = D_{\text{useful}} \cdot y_c \cdot \eta_c \tag{5.5}$$

In Eq. 5.5, $\eta_c$ is the efficiency factor that applies to the conversion of energy carrier $c$ to a given form of useful energy. The assumed efficiencies are tabulated in Table 5.2. Using Eq. 5.5, it is possible to calculate the useful energy demand in the current situation. What is more, the final energy demand for a given energy carrier can also be calculated.

Table 5.2: Efficiency factors for the delivery of three useful energy forms.

| Heat <100 ºC | kJ/kJ | Heat >100 ºC | kJ/kJ | Land transport | kJ/km |
|---|---|---|---|---|---|
| Gas; condensing boiler | 0.96 | Oil; industrial furnace | 0.8 | Gasoline/diesel; ICE | 2320 |
| Electric; heat pump | 4 | Coal; industrial furnace | 0.85 | BEV | 576 |
| Hot water; district heat | 1 | Gas; industrial furnace | 0.75 | FCEV | 130 |
| | | Steam | 1 | | |

The remainder of this section aims to explain the derivation of the efficiency factors from Table 5.2.

**Low-temperature heat** can be derived from three energy carriers: (natural) gas, electricity, and hot water from a district heating system. For simplicity, only space heating is considered, since it provides the largest heat demand from households and business.

Small boilers cannot convey all heat of combustion to the water that has to be heated. Part of the energy is lost with the exhaust gases. The highest performance is achieved when condensing the steam from the exhaust. By doing so, a residential gas-fired condensing boiler can have an efficiency of up to 96% of the HHV (Wikipedia, 2016b). This corresponds to 104% of the lower heating value (LHV).

Two types of heat pumps exist: ground source and air source heat pumps (De Swardt & Meyer, 2001). Although heat pumps can also cool a house, here only their heating capacity is considered. Ground source heat pumps have a coefficient of performance (CoP) of 3.2, whereas air source heat pumps operate at a CoP of 2.6 (Mathiesen et al., 2009). The Dutch heat pump association even mentions a CoP of 4, with the expectation of 5 to 6 in the near future (DHPA, 2010). Therefore, heat pumps are assumed to have an average CoP of 4, which would be a heat pump with energy class A/A+ (Daikin UK, 2012).

**High-temperature heat** is assumed to be produced by industrial boilers. Since the technologies that are currently state-of-the-art will in the future become mainstream, the efficiency of new boilers is used as efficiency factor. The data are provided in Table 5.3.

Table 5.3: New industrial boiler efficiencies (Van Wortswinkel & Nijs, 2010).

| | Coal | Oil | Gas | Biomass |
|---|---|---|---|---|
| Full load efficiency | 85% | 80% | 75% | 70% |
| Low load efficiency | 75% | 72% | 70% | 60% |

**Land transport** efficiencies are based on the fuel consumption of different passenger vehicles, see Table 5.4. It is assumed that the relative efficiencies are comparable for rail transport.

Table 5.4: Comparison of fuel economies of six vehicle types (Verbeek et al., 2014). LPG: liquefied petroleum gas; CNG: Compressed NG.

| Vehicle | Fuel | Unit ($X$) | Energy density (MJ/$X$) | Fuel economy ($X$/100 km) | (MJ/100 km) |
|---|---|---|---|---|---|
| Conventional | Gasoline | L | 34.8 | 6.67 | 232 |
| | Diesel | L | 38.6 | 5.48 | 212 |
| | LPG | L | 33.1 | 8.89 | 295 |
| | CNG | kg | 55 | 6.67 | 367 |
| BEV | Electricity | $kWh_e$ | 3.6 | 16 | 57.6 |
| FCEV | Hydrogen | kg | 130 | 1.0 | 130 |

### 5.4.3 Scenarios quantified

To cover the range of directions of demand development introduced in § 5.4.1, four scenarios are constructed:

- Business as usual (BAU),
- Diversity,
- Full electric, and
- High hydrogen.

These scenarios differ in how the demand for each of the three 'variable' useful energy demand categories is met. Table 5.5 gives a quantitative definition of each scenario, and the figures are plotted in Figure 5.4. The calculations are made using Eq. 5.5. Further explanation of each scenario will now be given.

Table 5.5: The definition of four energy demand scenarios in terms of the demand (in PJ/a) for each energy carrier. The amount of useful energy demand is specified in the leftmost column.

| Useful energy | Scenario | Coal | Hydrogen | Heat | Electricity | Gas | Oil |
|---|---|---|---|---|---|---|---|
| Low-temperature heat | BAU | | | 68.7 | 2.6 | 431 | |
| 528.7 | Diversity | | | 176 | 44.1 | 169 | |
| | Full electric | | | 0 | 132.2 | 0 | |
| | High Hydrogen | | | 529 | 0 | 0 | |
| High-temperature heat | BAU | 17.8 | | 115 | | 91.4 | 72.4 |
| 348.1 | Diversity | 74.0 | | 87.0 | | 65.3 | 69.6 |
| | Full electric | 17.8 | | 115 | | 91.4 | 72.4 |
| | High Hydrogen | 17.8 | | 115 | | 91.4 | 72.4 |
| Land transport | BAU | | 0 | | 1.2 | | 434 |
| 438.5 | Diversity | | 79.9 | | 41.5 | | 146 |
| | Full electric | | 0 | | 124.6 | | 0 |
| | High Hydrogen | | 239.6 | | 0 | | 0 |
| Electric appliances | All | | | | 346.5 | | |
| Aviation & shipping | All | | | | | | 706 |
| Non-energy uses | All | 1.7 | 44.2 | | | 38.5 | 486 |

In *BAU*, the final energy mix as reported for 2014 is reproduced. This scenario therefore represents a situation where very few changes in energy demand have taken place. The *Full electric* scenario is characterised by a high degree of electrification. All low-temperature heat is derived from electricity, and all road and rail transport is fully electrified too. *High hydrogen* is a scenario that features a high demand for hydrogen, with all land transport equipped with fuel cells for propulsion. Both low-and high-temperature heat demands ask for steam or hot water. This is expected to provide a sink for heat produced by SOCs. To complete the list, the *Diversity* scenario represents a situation in which each

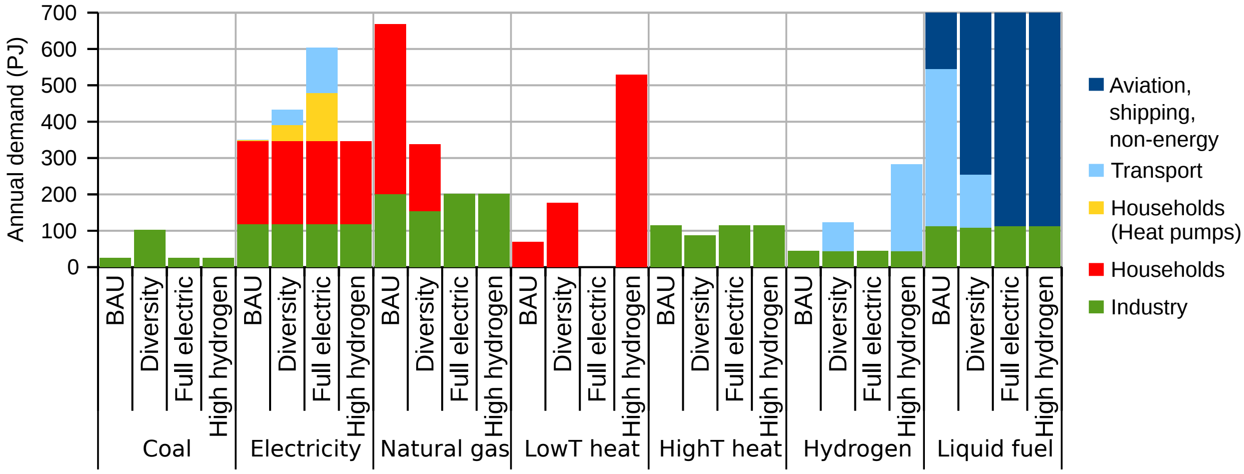



Figure 5.4: Energy demand per scenario by each sector. The liquid fuel demand of aviation, transport and non-energy uses adds up to 1192.2 PJ in all scenarios, but is not fully plotted. The numbers belonging to this figure are displayed in Table 5.5.

useful energy demand is met by a balanced mix of energy carriers. This means that equal fractions $y_c$ of each useful energy category are derived from the respective carrier options listed in Table 5.2.

## 5.5 (Environmental) constraints to energy production

In the present analysis, economic costs are used as indicator. Costs are important, because energy carriers constitute a significant part of the economy. Therefore, the consequences of changes in the energy supply system can be profound. Besides, providing affordable energy is one of the desired energy system properties. By minimising the energy system costs, the extent of competitiveness of emerging technologies is demonstrated. Yet there are many other aspects impacts related to energy supply. Air pollution and climate change are arguably the most important impacts of fossil-fuel based energy. For renewable technologies, the land use impact can be a limiting factor. Resource availability can constrain large-scale application of some technologies (Kleijn & Van der Voet, 2010). Resources and their distribution and scarcity also have social and geopolitical effects. Consequently, the choice for specific energy sources is a trade-off between these impacts. Depending on the prioritisation of each impact, a different set of technologies is preferred.

It falls outside the scope of this research to collect data on all impacts of all technologies and develop a prioritisation method. Therefore, air pollutant emissions and resource constraints are not considered. All GHG emissions are taken into account. Whenever data was available, the emission of $CO_2$, $CH_4$, and $N_2O$ during combustion or construction processes were assigned. Table 5.6 presents the conversion factors applied to each GHG. To express these emissions in monetary terms, the total amount is multiplied by a price per tonne $CO_2$-equivalent (t$CO_2$-eq.).

Table 5.6: Three important greenhouse gases and their conversion factors (IPCC, 2007).

| | $CO_2$ | $CH_4$ | $N_2O$ |
|---|---|---|---|
| Conversion factor (t$CO_2$-eq./t) | 1 | 25 | 298 |

In the case of biomass, it is highly uncertain what amount can be made available for energy uses. Dedicated energy crop farming faces competition with food production. Organic residues from forestry and agriculture are usually cheaper, but are a much more diffuse source of biomass. The extent to which imports can fulfil the demand for biomass is another source of uncertainty. The amount of biomass available for the Netherlands under different assumptions of the global production potential and allocation method are shown in Table 5.7 (PBL, 2011). The lower end estimate of 470 PJ per year is used. The biomass supply is assumed to consist of equal amounts of residues and energy crops, which in in agreement with Lamers et al. (2015).

Table 5.7: Annual availability of biomass for energy production in the Netherlands, based on different allocation methods (PBL, 2011).

| | Global production | |
|---|---|---|
| Allocation method | 150 EJ | 400 EJ |
| Based on population | 284 PJ | 760 PJ |
| Based on GDP | 735 PJ | 1960 PJ |
| 50% of global trade based on GDP plus 50% of domestic production | 470 PJ | 1080 PJ |

In principle, any form of biomass can be converted to biogas or green gas. Several techniques are under development to perform the gasification process (IEA-ETSAP & IRENA, 2013a). Given the limited amount of biomass, it makes sense to only use wet biomass streams, that are suitable for gasification but not applicable for other uses such as biodiesel production (Van Melle et al., 2015). Anaerobic digestion is typically used to convert moist biomass to biogas. A typical composition of the combustible gas mixture is 50–70% $CH_4$, 20–35% $CO_2$, 0–10% $H_2O$, with a dependence on the source (D'Appolonia, 2016). It is thus assumed that biogas is only derived from wet biomass streams such as manure and waste-water treatment sludge (Bergsma & Croezen, 2011). Landfills and food processing industries might also be a source of wet biomass (D'Appolonia, 2016). Imports are not considered, given that transport is costly because of the high water content of suitable streams.

The estimated future potential for biogas production of three different sources is compared in Table 5.8. The range of 20–77 PJ is rather broad, indicating that this source of biomass involves a high uncertainty. Much like the biomass residues and products described above, the potential that can be realised depends on the development of e.g. collection systems. 48 PJ is used as the limit for annual biogas production.

Table 5.8: Potential annual biogas production according to different sources. [a]

| Source | PJ | bcm [b] NG equivalents |
|---|---|---|
| Bergsma and Croezen (2011) | 30–48 | 1–1.5 |
| Van Melle et al. (2015) | *53* | 1.5 |
| Schepers et al. (2015) | *77* | 2.2 |
| D'Appolonia (2016) | 20 | *0.56* (0.92 bcm) |

[a] Numbers in italics are calculated using an energy density of 35.17 MJ/m$^3$ natural gas equivalent.
[b] Billion cubic meter. 1 bcm = $10^9$ m$^3$

The boundaries for the installed capacity of biomass sources, wind turbines, and solar thermal and photovoltaic (PV) cells are summarised in 5.9.

Table 5.9: Boundary conditions applied to the scale of implementation of various renewable energy technologies.

| Energy source | Production limit [a] (PJ/a) | (GW) | Source |
|---|---|---|---|
| Biogas | 48 | *1.52* | (Bergsma & Croezen, 2011) |
| Biomass residues | 235 | *7.45* | (PBL, 2011) |
| Biomass products | 235 | *7.45* | (PBL, 2011) |
| Onshore wind | | 8 | (PBL, 2011) |
| Offshore wind | | 34 | (PBL, 2011) |
| Residential PV | | 52.5 | (Veenstra, 2015) |
| Commercial PV | | 29.8 | (Veenstra, 2015) |
| Solar thermal [b] | | 260 | (PBL, 2011) |

[a] Numbers in italics are calculated assuming a constant production.
[b] 400 km$^2$ $\cdot$ 65% $\cdot$ 1 kW/m$^2$

## 5.6 Supply patterns

### 5.6.1 Fossil fuels

It is expected that the three main fossil fuels that are used nowadays (natural gas, oil, and coal) will still be available in the future. What is highly uncertain is the price at which these goods can be purchased on the international energy market.

The Netherlands traditionally has a strongly developed gas infrastructure. The majority of the resource is extracted from gas fields in Groningen and under the North Sea. After 2025, a sharp decrease in domestic extraction is expected, because the reserves are almost depleted around that time (Schoots & Hammingh, 2015). Developments in technology can possibly allow extraction after that time, but with much lower rates. Consequently, a large dependence on imports seems inevitable for NG. Imported gas is expected to be more expensive, partly because of the considerable energy losses during transport.

For oil, the Netherlands is dependent on imports already. The price of oil on the international market thus determines the economic attractiveness of using this fuel. Many factors influence the oil price, and these complex interactions have resulted in unexpected price fluctuations in the past. In the future, prices can rise as a consequence of growing demand or depletion of easily accessible reserves. If a rapid shift towards other energy carriers is made, prices can drop because of overproduction.

Like oil, coal is also traded on a global market. Long-term predictions assume a modest growth in the price levels (Schoots & Hammingh, 2015). Since the coal reserves are large and no unconventional technologies are needed to extract it, the supply risks are limited. Combustion of coal yields the highest emission of $CO_2$ per Joule, so GHG taxation policies will have the strongest impact on coal use.

Gas, oil, and coal are commodities, and it is assumed that they are available whenever there is a demand. Because of the assumption of a perfect match between demand and supply, storage is neglected. In reality, there are a number of storage facilities along the fuel supply chain. However, the costs of and losses during storage are negligible.

### 5.6.2 Renewable sources

For most renewable energy sources, the supply pattern is important for two reasons. Firstly, the amount of a renewable energy source available for conversion depends on external factors. For example biomass and solar radiation have predictable, seasonal variations in availability, while wind speed and cloudiness introduce more irregular fluctuations in the yield of wind turbines and PV cells. Secondly, a majority of renewables generate electricity, which cannot be readily stored. At the same time, a tight balance has to be maintained between supply and demand of electricity at all times.

#### Wind

The output capacity of wind turbines can be related to the wind speed. Therefore, wind speed data for two locations were retrieved from the Royal Netherlands Meteorological Institute (KNMI, 2005). Wind measurement station K13 (on the North Sea) is used for offshore turbines, while measurement station Lelystad will provide wind profiles for onshore turbines. For both locations, data from the year 2004 are used. The reported data are adjusted wind speeds at a height of 10 m. To calculate wind speeds at the height of a wind turbine, the wind power law is used (MacKay, 2009, p. 266):

$$\frac{v}{v_0} = \frac{log(h/l)}{log(h_0/l)} \tag{5.6}$$

With $v$ and $v_0$ the wind speeds at height $h$ and $h_0$, respectively. Parameter $l$ is the roughness length, and depends on the roughness of the surrounding land. For Lelystad $l = 0.03$ m, and for K13 $l = 0.002$ m (KNMI, 2005).

The capacity factor (CF) of a wind turbine is the ratio of delivered power to the rated maximum power output. To obtain the capacity factor at a given wind speed, the following relation is used:

$$\text{CF} = \frac{P}{P_{\text{max}}} = \left(\frac{v}{v_{\text{rated}}}\right)^3 \tag{5.7}$$

The rated output speed (the wind speed at which the power is rated; $v_{\text{rated}}$) for all wind turbines in the model is 14 m/s (Bradbury, 2009). This means that the power production will not increase further above that wind speed. The cut-in speed is set at 3.5 m/s. The cut-out speed (where the turbine is shut down for security reasons) of 25 m/s is not reached in the dataset, so the drop of all power above that speed is not modelled. These assumptions result in the capacity curve shown in Figure 5.5. When the KNMI data are combined with Eq. 5.7, an example of the resulting pattern is shown in Figure 5.6.

In the Netherlands, the yearly averaged capacity factors were 21.5% in the period 2003–2007 (Boccard, 2009). For offshore installations, it can reach values as high as 25–30%. The approach described above yields a capacity factor of 21.3% onshore and 46.5% offshore. Therefore, the offshore wind production could be overestimated.

#### Solar

From Elia, the Belgian transmission system operator (TSO), data about the power generated by PV cells during 2015 were obtained (Marsboom, 2013). The dataset represents all PV installations in Belgium

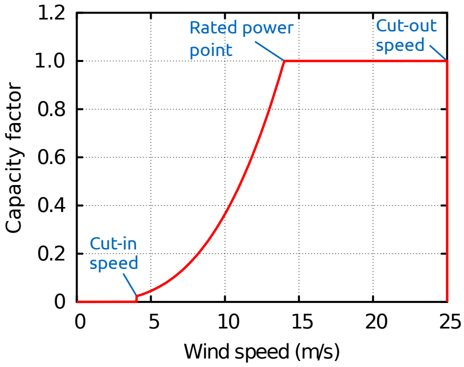



Figure 5.5: Capacity curve for wind turbines.

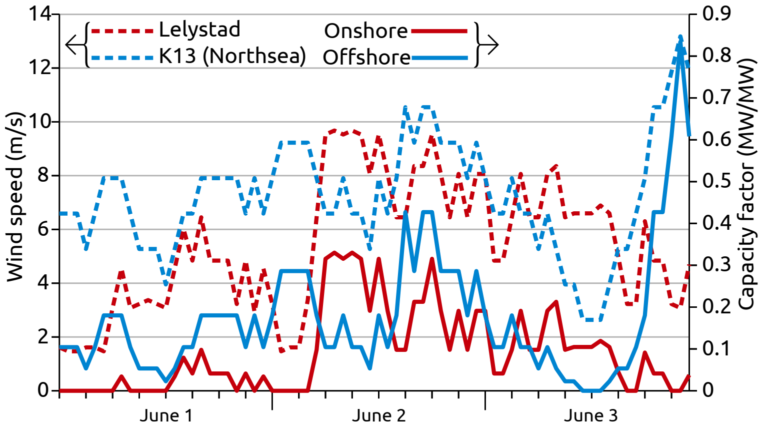



Figure 5.6: The wind speed patterns for three consecutive days, and the resulting capacity factors.

that are registered at Elia, and is considered to be representative for the pattern in the Netherlands. It is applied to both PV and solar thermal panels.

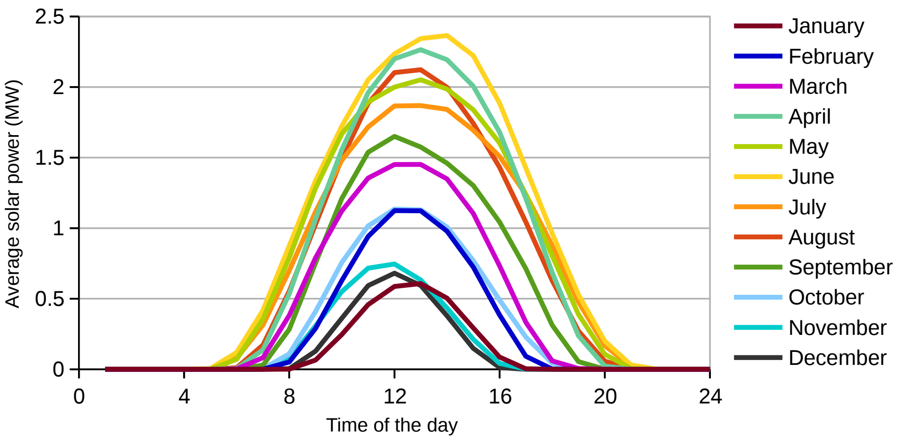
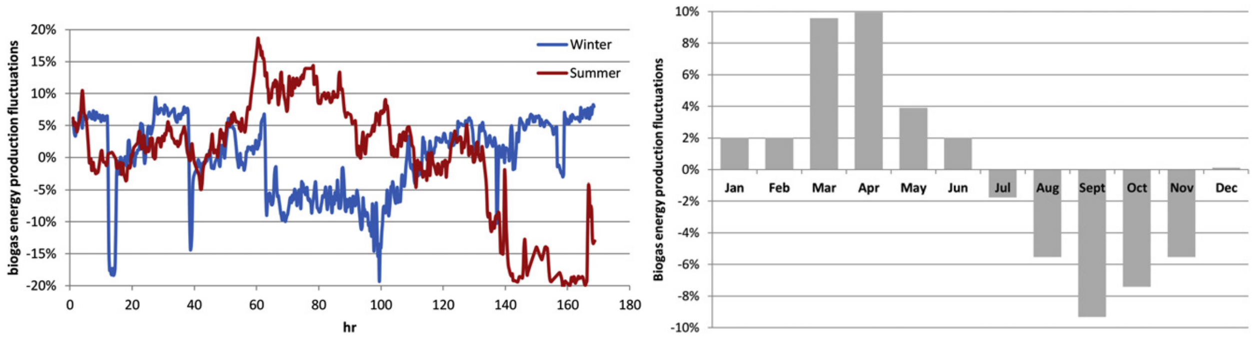



Figure 5.7: Average electricity production by PV for each month in 2015. Data from Marsboom (2013).

### Biogas

The availability of biomass suitable for gasification (see § 5.5) is subjected to seasonal variations. The bio-organisms responsible for methane production in digestion tanks cannot be controlled precisely. Therefore, the output of biogas exhibits irregularities. Very few data on the production is made public. Here, the pattern of a waste-water treatment plant in Denver is used, see Figure 5.8 (Trendewicz & Braun, 2013). The yearly pattern is produced by repeating the patterns for a week in summer and in winter 26 times each. The pattern is scaled to ensure that the monthly produced amounts match. The monthly average production has a variability of less than 10% of the output, which is smaller than the weekly variations.




(a) Weekly variations during winter and summer.

(b) Monthly variations.

Figure 5.8: Biogas production of a waste-water treatment plant in Denver. Reprinted from Trendewicz and Braun (2013).

## 5.7 Demand patterns

For each of the demand categories and energy carriers (see § 5.4), a pattern for demand will be specified. No demand-response mechanisms are included. The patterns described in this section serve as input to the optimisation model (see Figure 4.3). To facilitate scaling of the data to a given annual energy demand (in PJ), the patterns are normalised to an annual total of 1 PJ.

### 5.7.1 Electricity

Electricity consumption shows a rather regular pattern, with peaks in the morning and afternoon, and troughs during night-time. The data for the full year 2015 are obtained from TenneT (TenneT, 2016). It is assumed that businesses and households are responsible for the fluctuations, whereas the industry and trains provide a constant load. To extract the load profile of the variable demand, 3973 MW is subtracted from the total load on each hour of the day. The 3973 MW correspond to the averaged electricity demand of the industrial and transport sector.

### 5.7.2 Low-temperature heat

The demand for low-temperature heat is currently fulfilled mostly by NG. No hourly consumption data for gas were found. Therefore, the hourly demand pattern is assumed to be identical to that of electricity. Since gas demand is highly dependent on the season (E.ON, 2014)(see Figure 5.9), a correction is made for the monthly average demand.

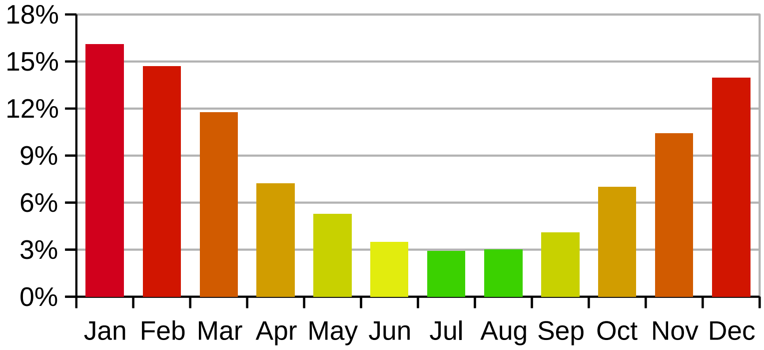



Figure 5.9: The average gas demand per month in the Netherlands (E.ON, 2014).

### 5.7.3 Land transport

The demand for energy in transport consists mostly of privately owned cars. The charging or refuelling behaviour of car owners is very dependent on the type of fuel. Conventional combustion engine cars are exclusively refuelled at a gas station during a trip. BEVs are sometimes charged at the office or at home (J. C. Spoelstra, 2014). But high-speed charging facilities at fuel stations are also an option. For hydrogen cars, these three options are open too. If hydrogen in produced centrally, it makes sense to refuel at fuel stations. If micro-CHP fuel cells are widespread, it is more likely that hydrogen cars are refuelled at home or at the office. Either way, some sort of hydrogen storage and transport infrastructure is required.

Refuelling at a gas station is done during a trip. Therefore, the demand is strongly coupled to the traffic density at a given moment. In general, more fuel is needed during the day than during the night. A demand curve of gasoline demand during an average week at a Chevron fuel station in the US (Chen, 2006) is used to represent fuel demand. The pattern is shown in Figure 5.11.

BEVs have not been used for a long time yet, but some studies have addressed the charging behaviour of this vehicle type (e.g. Schey et al., 2012; INL, 2015; J. C. Spoelstra, 2014). Schey et al. show that electricity pricing policies can strongly influence when vehicles are charged. For this study, it is assumed that in the future, charging during the night is stimulated. The pattern of San Francisco (see Figure 5.10) gives a good indication of how the demand pattern looks like in that case. The extremely steep increase in demand at midnight is the result of consumers that schedule the start of charging at that time, when they pay a lower tariff (Schey et al., 2012). This is seen as undesirable, and therefore it is assumed that a more smoothened demand pattern is established in the future. Figure 5.10 depicts a modified pattern with a parabolic shape of demand during the night. This pattern is used in this study.

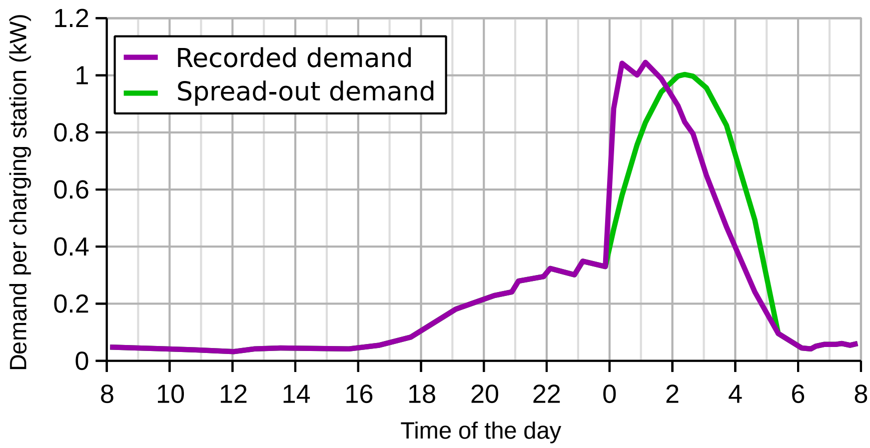



Figure 5.10: Median electricity demand at residential BEV charging units in San Francisco. The recorded data were obtained during a 3-week measurement period in October 2011 (Schey et al., 2012).

Similar to the research referenced above, the fuelling pattern of FCEVs has been studied. NREL has an extensive monitoring programme of hydrogen production, distribution, and usage for transport. The *Composite Data Products* that result from their analyses are publicly available (Sprik et al., 2015), and will be used here. Figure 5.11 depicts the distribution of hydrogen demand and number of fuelling events over the course of a day and a week. For comparison, the number of fuelling events at a regular gas station is shown, too. Hydrogen demand is highest in the morning, while gasoline shows a demand peak in the afternoon. A possible explanation is that FCEV owners try to minimise evaporation losses of hydrogen when the car is idle during the night.

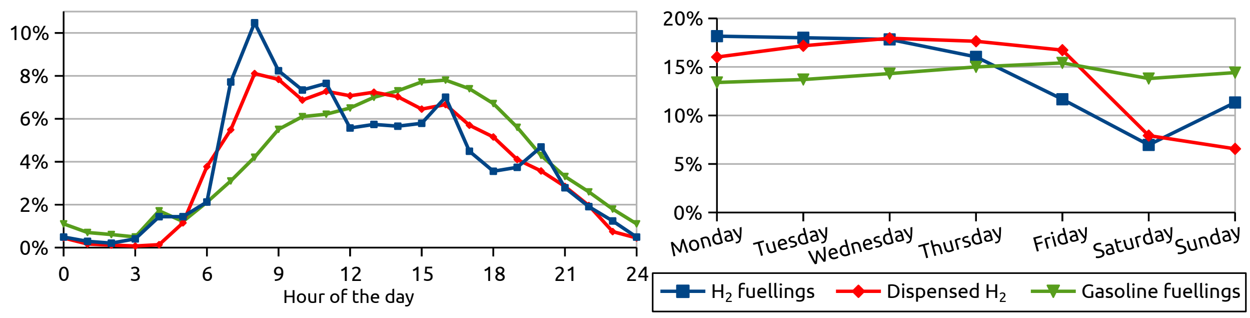



Figure 5.11: Average consumption pattern of $H_2$ at fuel stations during the course of a day and a week. For comparison, the pattern of gasoline demand is shown, too. Adapted from Sprik et al. (2015).

## 5.8 Final remarks

This chapter has specified the reasoning and data sources behind the assumptions used as input for the model. The most important simplifications are summarised here. Note that the effect of each simplification on the results depend on the configuration of the system that is modelled.

- It is assumed that technologies are available all the time. Scheduled maintenance or unexpected failures and crashes are not considered.
- The model is mostly linear, with an exception for the SOC components. Due to the linearity, the efficiency of transformers is constant, and independent of the capacity utilisation. As a consequence, the efficiency of fossil fuel powerplants is overestimated in the model.
- Another implication of the linearity is that economies of scale (see also § 8.1.3 are not taken into account. All costs have a linear dependence on the installed capacity or produced energy. The effect of this simplification becomes significant if the installed capacity of a technology differs a lot from the capacity for which the assumed costs hold.
- Transport losses are neglected, since the model has a country-wide spatial resolution. Therefore, no differentiation between locally and centrally produced energy can be made. This assumption affects the results in particular when an energy carrier has high transport losses, or when the distance between production and demand are large.
- Because of the lacking spatial resolution, aggregated patterns for supply and demand are used. Local effects, such as congestion on the electricity grid and differences in demand between regions, are not taken into account.
- The demand patterns, as introduced in § 5.7 are fixed. No demand-response mechanisms or price elasticity are taken into account.
- Fossil fuels are instantaneously available whenever there is a demand. This simplification removes the need to include storage components to the model for fossil fuels. Only for isolated systems with limited or intermittent access to continental or global commodity markets, this assumption is debatable.
- The optimum configuration for the system as a whole is to be found. From the perspective of individual organisations, the results can be sub-optimal.
- The solver has a perfect information position, since all patterns are known in advance. This is not the case in reality, where weather forecasts and demand predictions are never fully accurate. Due to this knowledge difference, there are backup power facilities or ‘spinning reserves’ in the real world, but not in the model.
- If the full complexity of the energy system were to be modelled, several second-order effects should be taken into account. To be precise, the costs of resources and technologies are not static, but depend on the composition of the system. A higher demand for e.g. coal results in a higher coal price. And the higher the installed capacity of a technical component, the lower the unit price

will be (see also § 8.1.2–8.1.3).

Finally, it is important to note that the *total system costs* considered by the model. Therefore, energy costs for consumers cannot be readily derived. The reason is that the amount consumers pay for an energy carrier consists for a large part of service fees, distribution network connection costs, value-added taxes (VAT), and other taxes (Schepers et al., 2015). These factors are dependent on policies and contracts, instead of on technologies, which is why they are not taken into account for this research. However, it can be expected that there is a positive correlation between system costs and energy consumer prices.

# Chapter 6

# Technology Options

## 6.1 General

Each technology that is considered in the model has characteristic properties. Three types of properties can be distinguised. Physical properties describe input-output relations such as efficiency, economic properties have to do with the costs entailed, and environmental properties determine GHG emissions. This chapter discusses the data inputs for each component, and the sources or calculations behind the numbers. A full overview of the data is provided in Appendix A.2.

A large set of economic properties are obtained from Energistyrelsen and Energinet.dk (2015). This is because the report contains an elaborate collection of cost predictions, and a high level of consistency is reached by using one source. If not specified, then the costs are derived from this report. The interest rate for conventional technologies is assumed 5%, whereas a rate of 8% is taken for emerging technologies. See § 4.5 for a more elaborate discussion.

Environmental properties are discussed separately in § 6.8.

## 6.2 Fossil fuels

### 6.2.1 Sources

Hard coal, crude oil, and NG can be extracted domestically or imported. The costs of the fuels are independent of the source, as they are traded on an (inter)national market. The prices of the fossil fuel commodities as predicted by Schoots and Hammingh (2015) for 2030 are used, see Table 6.1. Since the focus of this study is on the total system costs, the raw product prices are used, excluding taxes and subsidies.

Table 6.1: Fossil fuel prices in the Netherlands, in the past and predicted for the future. The type of fuels are North Sea Brent oil, Groningen gas, and steam coal, respectively. All prices apply to the wholesale market (Schoots & Hammingh, 2015).

| | Oil price | | NG price | | Coal price | |
|---|---|---|---|---|---|---|
| | ($/barrel) | (€/GJ) | (€/m$^3$) | (€/GJ) | (€/t) | (€/GJ) |
| 2000 | 39 | 4.82 | 0.16 | 4.55 | 52 | 1.99 |
| 2015[a] | 50 | 6.18 | 0.24 | 6.90 | 65 | 2.50 |
| 2020 | 89 | 11.00 | 0.28 | 7.96 | 81 | 3.10 |
| 2030 | 140 | 17.30 | 0.33 | 9.38 | 88 | 3.37 |

[a] Realisations for 2015 according to CBS (`http://statline.cbs.nl`).

### 6.2.2 Gas powerplant

Gas-fired powerplants are assumed to be of the type Combined Cycle Gas Turbine (CCGT). These plants operate gas turbines, in which NG is combusted. It is possible to operate at part-load, but this results in reduced efficiencies (see e.g. Figure 3.4), but this effect is not taken into consideration. The fixed efficiency is 60% (Energistyrelsen & Energinet.dk, 2015).

### 6.2.3 Coal powerplant

Electricity can be generated from coal in advanced pulverised fuel powerplants. The efficiency is assumed to be 43%, the highest efficiency of currently existing plants (Santoianni, 2015). This makes coal powerplants less efficient than CCGTs, but better than most current coal powerplants.

## 6.3 Renewable electricity

### 6.3.1 PV

Several material options exist for the production of PV cells. The most abundantly used material is high-purity silicon, which is included in PV panels as a mono- or multi-crystalline wafer. For simplicity, only silicon-based PV panels are considered here. Because of significant cost differences for large and small installations, differentiation between commercial and residential PV systems is applied. Utility-scale systems are not included. Although these systems could be more cost-effective (Energistyrelsen & Energinet.dk, 2015), the uncertainties related to the availability and costs of land are large.

### 6.3.2 Wind turbines

Electricity is generated from wind in large wind turbines. The height of these turbines has increased in the past, and is expected to rise some more in the future, to a height of 150 m. The investment and O&M costs are almost two times lower for onshore wind turbines (Energistyrelsen & Energinet.dk, 2015). On the other hand, there is more space and wind available offshore.

## 6.4 Energy storage

### 6.4.1 Lithium battery

Lithium-ion batteries are an important technology for energy storage in devices. The first commercial versions of larger battery systems are entering the market, although the costs are still high. Data on the characteristics of batteries are based on the Tesla Powerpack, a Li battery system intended for industrial-scale (100 kWh) energy storage. The round-trip efficiency under ideal conditions is 92% (Lazard, 2015a). However, during the assumed lifetime of 10 years, the performance will decrease. Therefore, the average efficiency is assumed to be 85% (Energistyrelsen & Energinet.dk, 2015). Besides, a self-discharge rate of 694 kW per MWh installed capacity is assumed, implying that 99.8% of the stored energy is lost during one day.

The claims made with respect to the investment costs of the Powerpack might be exaggerated, but do give an estimate of what battery storage can cost in the future. Thus, 250 $/kWh is used as investment cost. O&M costs are estimated at 10 $/kW (Lazard, 2015a).

Many other battery types exist, and redox flow batteries are also being developed. These will not be considered here.

### 6.4.2 Compressed air energy storage

CAES uses underground cavities, like depleted gas reservoirs and salt caverns to store air under high pressure. Electric compressors are used to fill the storage. When the air is released, it can drive a turbine to regenerate electricity. CAES is especially suited for the storage of large volumes of energy during long terms (Lazard, 2015b). Since the compression of a gas is an exothermic process, heat is released during the 'charging' process. It is considered unrealistic that this low-temperature heat is recovered. This implies that an external heat source is required during expansion. Often, the output power is increased by also burning NG to drive the turbine (Energistyrelsen & Energinet.dk, 2015). For simplicity, it is assumed here that the stored energy can be recovered without using a fuel. In that case, an efficiency of 43%

The investment costs for CAES are estimated at 171 $/kWh (Lazard, 2015a), which translates to 154 €/kWh.

### 6.4.3 Flywheel

A flywheel stores electricity as kinetic energy. It has a very fast response, so can be used to respond to sudden peaks of demand or production, and for frequency regulation (Lazard, 2015a). This technology is rather expensive, with O&M costs of 77 $/kWh and investment costs of 2070–9933 $/kWh. Therefore, the merit of flywheels can only be assessed with models with high temporal resolution.

### 6.4.4 Hot water tank

The storage of low-temperature heat is needed especially in houses. A low-cost solution is to employ sensible heat storage in a simple hot water tank. This technology costs only 3 €/kWh (IEA-ETSAP & IRENA, 2013b). No operational costs are assumed during the lifetime of 20 years. Hot water can be added to and extracted from the tank without loss. When stored, self-discharge with a rate of 13.6% of the capacity is assumed.

### 6.4.5 Phase change materials

High-temperature heat can be more challenging to store, partly because of heat losses over longer time periods. One of the promising options under development is latent heat storage in phase change materials (PCMs). By using thermal energy to induce a phase change instead of only heating up a material, the temperature difference between the PCM and its environment is much smaller. Therefore, heat losses are reduced to 3% and longer storage periods are possible. Besides, PCMs generally have a higher energy density compared to sensible heat storage options (IEA-ETSAP & IRENA, 2013b).

The investment costs of PCM thermal energy storage range between 10–50 €/kWh (IEA-ETSAP & IRENA, 2013b). While the raw PCMs are relatively cheap, substantial costs are involved with the BoP. Heat transfer technologies (heat exchangers) that provide sufficient (dis)charging capacity are expensive. To allow for storage of high-temperature heat, either materials with a suitable phase change point or extensive heat pump systems are needed (IEA-ETSAP & IRENA, 2013b). The heat exchange process entails some losses; both charge and discharge are assumed to be 80% efficient.

### 6.4.6 Hydrogen tank

The purpose of a hydrogen tank is to store $H_2$ for later use. Depending on the volume restrictions, the pressure of the tank can be higher or lower. At (very) high pressure and if the temperature is lowered, $H_2$ can be stored in liquid form, resulting in a high energy density. Few information on the costs of $H_2$ storage could be found. The assumptions made are therefore uncertain. The lifetime of the tank is assumed 15 years. The investment costs are 2.5 €/kWh, and the self-discharge rate is 7% per 24 hours (Schoenung, 2011). The operating costs are set at a low level of only 0.01 €/kWh.

## 6.5 Biomass

### 6.5.1 Sources

Many sources of biomass exists, with large local variation in quantity and nature. Here, two classes of biomass are distinguished: residues and products. Residues include organic byproducts from industries, wastes from agriculture, forestry, gardens, and food waste. Products are energy crops that are grown specifically for the application as energy carrier. The average costs of biomass residues and products are shown in Table 6.2. A range of organic waste streams was analysed by Koppejan et al. (2009). Biomass availability was discussed in § 5.5.

Table 6.2: Solid biomass supply costs for the European Union (EU), per resource category in € per GJ energy content (Lamers et al., 2015).

| | Agriculture | Forestry | Average |
|---|---|---|---|
| Residues (€/GJ) | 8.47–9.94 | 4.03–4.89 | 6.83 |
| Products (€/GJ) | 8.47–11.8 | 9.32–11.31 | 10.25 |

Not only the sources of biomass, but also the pathways towards usable energy products show a large diversity (IEA-ETSAP & IRENA, 2013a). Here, only a limited range of conversion technologies is included. The selection is made while taking the research questions into account.

### 6.5.2 Biogas

The production of biogas is assumed to proceed via the anaerobic digestion of moist biomass. Futher details were given in § 5.5. The costs and emissions for the production of biogas and green gas (see Table 6.3) were reported by Bergsma and Croezen (2011).

Table 6.3: Costs and emissions for the production of biogas for local use and green gas (Bergsma & Croezen, 2011).

| | Investment costs (€/kW) | | | Operating costs (€/MWh) | | | GHG emission |
|---|---|---|---|---|---|---|---|
| | Gasifier | Gas cleaning | Total | O&M | Electricity | Total | (kg $CO_2$-eq./MWh) |
| Biogas | 888 | 88 | 977 | 5.95 | 12.01 | 17.95 | -172 |
| Green gas | 888 | 162 | 1051 | 6.33 | 15.22 | 21.54 | -172 |

Storage of biogas provides two problems. First, it takes a considerable storage volume because methane is diluted with $CO_2$, leading to low energy densities. Second, traces of steam in the mixture can react with non-metal oxides to form corrosive acids, which can damage pipelines and tanks (Wiser et al., 2010). Therefore, a pretreatment is often applied when the biogas is not used immediately. In such a process, harmful contaminants are removed. The costs of a pretreatment system range between 500–3000 $/kW (Trendewicz & Braun, 2013). However, costs of only 88 €/kW are possible according to Bergsma and Croezen (2011).

### 6.5.3 Green gas

Biogas can be upgraded to the same quality as natural gas in the distribution network. It is then called 'green gas'. Sulfur compounds, ammonia, steam, and $CO_2$ are removed in the process. Desulfurisation, which has to be applied to NG too, costs \$4.71 per 1000 $m^3$ of processed NG (James et al., 2012). This translates to 105 €/GJ. Other values reported in literature are 162 €/kW (see Table 6.3 (Bergsma & Croezen, 2011)) and 300 €/kW (Mathiesen et al., 2009). The numbers from Mathiesen et al. (2009) were used: 300 €/kW investment costs, 56.25 €/kW fixed O&M costs, and an efficiency of 95%.

### 6.5.4 Biodiesel

Solid biomass can be converted to a liquid form, such as biodiesel or biogasoline. Liquid fuels are most convenient for combustion processes. Because of the high energy density, they are the dominant transport fuel. Here, the biomass-to-liquid (BtL) process is considered. This process can use a wide range of organic products and residues to produce biodiesel (Energistyrelsen & Energinet.dk, 2015). With an efficiency of 56%, these biomass streams are converted to fuel suitable for regular combustion engines (Boerrigter, 2006). The costs are high with an investment cost of 3393 €/kW and fixed O&M costs of 103 €/kW (Mathiesen et al., 2009).

### 6.5.5 Biomass powerplant

The ecomomic characteristics of a biomass powerplant are assumed to be identical to those of coal powerplants (§ 6.2.3). This is because biomass and coal are both solid fuels, for which the combustion process parameters are comparable. In the Netherlands, biomass is often co-fired in coal powerplants.

## 6.6 Fuel cells and hydrogen production

### 6.6.1 SOEC

A SOEC has heat and electricity as energy inputs. These are used to electrolyse water and produce hydrogen as output. The ratio between the inputs is fixed, but the rate of electrolysis can be changed. For each 100 J of electricity input, 20 J of heat with the same temperature as the cell (800–1000 °C) should be supplied. The process is assumed to have a heat loss of 10% (Mathiesen et al., 2009). Thus, the input-output relations can be written mathematically as:

$$\dot{Q} = \tfrac{1}{5} \cdot P^{\text{in}} \tag{6.1}$$

$$\dot{H}_{\text{H}_2} = 0.9 \cdot (P^{\text{in}} + \dot{Q}) \tag{6.2}$$

The cost parameters are as follows: $C_{\text{inv}} = 590$ €/kW, $C_{\text{fix}} = 11.8$ €/kW (2% of $C_{\text{inv}}$), and $C_{\text{var}} = 1.65$ €/MWh (Mathiesen et al., 2009). The investment costs estimated by Ridjan et al. (2013) are 210 €/kW$_\text{e}$ input, which is lower.

### 6.6.2 SOFC and SOFEC

Various sources have estimated current and future costs of SOFC systems. Differences in design choices, system size, production rate, etc. result in a wide range of cost estimates. The fact that not all studies include the costs of BoP manufacturing is responsible for some of the diversity encountered in general (Staffell & Green, 2013). In Figure 6.1, the investment and O&M cost estimates of four sources are compared. For both costs, there is an order of magnitude difference between the extremes. The estimates made by Energistyrelsen and Energinet.dk (2015) for SOFCs in base-load mode are used to make future cost predictions, shown in Table 6.4. The tabulated lifetimes correspond to the lifetime of the installation including BoP. The costs associated with the replacement of the SOC stacks due to degradation are included in the O&M costs.

Table 6.4: Cost parameters and levelised cost of electricity for SOFCs, based on (Energistyrelsen & Energinet.dk, 2015).

| | | 0 | I | II | III | IV | V | VI |
|---|---|---|---|---|---|---|---|---|
| Properties expected in year | | 2015 | 2019 | 2020 | 2022 | 2026 | 2030 | 2050 |
| Lifetime | (a) | 6 | 13 | 15 | 17 | 19 | 20 | 20 |
| Variable O&M costs [a] | (€/MWh) | 13.75 | 6.41 | 5.5 | 4.02 | 2.93 | 2.2 | 1.65 |
| Investment costs [a] | (€/kW) | 2750 | 1008 | 825 | 670 | 544 | 440 | 275 |
| LCOE [b] | (€/MWh) | 227.15 | 104.38 | 93.64 | 85.66 | 79.81 | 75.75 | 70.88 |

[a] Per unit of NG input.

[b] Per unit of electricity. Assuming an electric efficiency of 55%, 90% capacity utilisation, 8% discount rate, and neglecting taxes and the value of the co-products.

The economic properties of SOFECs are assumed to be identical to those of SOFCs. This is a reasonable assumption since both installations can be produced and maintained in a similar manner. The default fuel for SOFCs is NG, whereas SOFECs are assumed to be fuelled by biogas. No restriction in terms of ramping rates are applied, because this does not play a role at the timescale of hours.

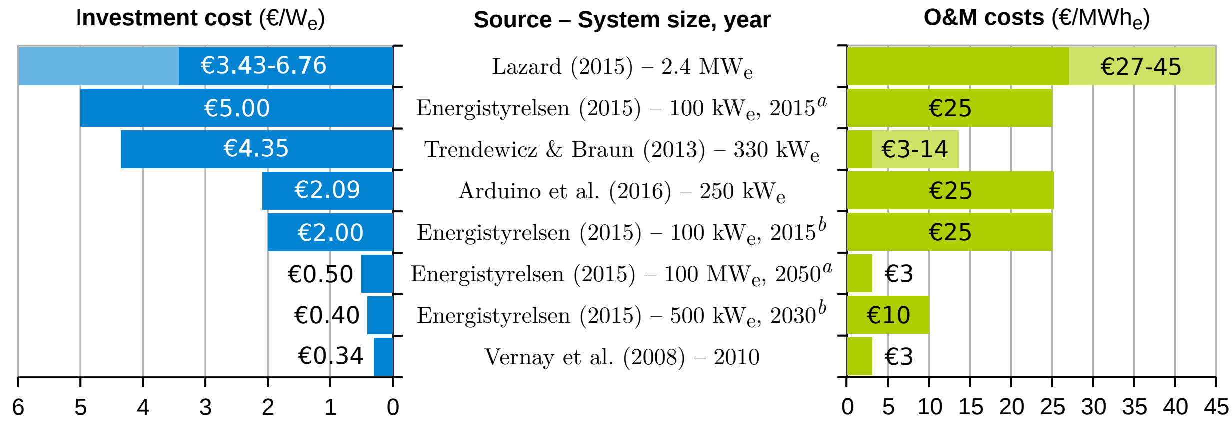



Figure 6.1: Comparison of investment and O&M costs for SOFCs from different sources. Amounts in Dollars were converted to Euros using the average exchange rate in the year of the publication. [a] Base-load operation. [b] Grid balancing operation.

### 6.6.3 PEMFC

Low-temperature PEMFCs can be used to convert hydrogen to electricity. Using data from James et al. (2012), the efficiency is 35%, and the investment costs are 207 €/kW. Note that the theoretical efficiency is lower than 100% due to thermodynamic limits. The oxidation of $H_2$ is exothermic, so heat losses are inevitable.

### 6.6.4 SMR

An alternative and most widely applied way to produce hydrogen is via steam methane reforming. The economic characteristics of SMR are adapted from Diakov et al. (2011), in which technology costs for 2025 are predicted. The efficiency of the conversion of NG to $H_2$ is assumed to be 80%. A lifetime of 20 years is assumed.

### 6.6.5 Methanation

The Sabatier process, also referred to as methanation, is a reaction between $CO_2$ and $H_2$, in which methane is produced:

$$CO_2 + 4\,H_2 \longrightarrow CH_4 + 2\,H_2O \tag{R5}$$

An installation that performs this process has a lifetime of 20 years and costs 900 €/kW. The process operates at 90% efficiency, while consuming some electricity (15 times less than the input of $H_2$). The fixed O&M costs amount 22.14 €/kW/a (Connolly & Mathiesen, 2014).

Methanation in combination with electrolysis of water (producing the required hydrogen) is called PtG.

## 6.7 Heat-related technologies

### 6.7.1 Solar thermal panels

Solar energy can be used to directly heat water in solar thermal panels. These systems are often installed on the roof of residential buildings. The investment costs associated with these panels are

$$\frac{£3300}{3.5\ \text{m}^2 \times 1\ \text{kW/m}^2} = 943\ £/\text{kW}$$

(Milieucentraal, 2016). Future cost reductions are expected to reduce the investments by 50%, backed by the estimate of 60% cost reduction in 2030 of Stryi-Hipp (2009). Thus, the investment costs are assumed to be 471 €/kW. The operating costs are estimated at 10 €/a per system, or 2.20 €/kW per year(Milieucentraal, 2016). A lifetime of 30 years is assumed (Energistyrelsen & Energinet.dk, 2015).

### 6.7.2 Boilers

The efficiencies of boilers fuelled with NG, coal, oil, or biomass are tabulated in Table 5.3.

Table 6.5: Economic properties of industrial boilers.

| | Coal | Oil | Gas | Biomass |
|---|---|---|---|---|
| Investment costs [a] (€/kW) | 800 | 100 | 100 | 800 |
| Variable O&M costs [a] (€/MWh) | 5.40 | – | – | 5.40 |
| Fixed O&M costs [a] (€/kW/a) | – | 3.7 | 3.7 | – |
| Economic lifetime (a)[b] | 25–40; average 32.5 | | | |

[a] (Energistyrelsen & Energinet.dk, 2015). [b] (Van Wortswinkel & Nijs, 2010).

### 6.7.3 Heat distribution

It is possible to convert high-temperature heat to low-temperature heat using heat exchangers or by dilution. The investment costs associated with this process are those of district heating system construction. This is because only central high-temperature heat production options and local low-temperature heat consumption are present in the model. Therefore, a heat distribution network is always required to deliver diluted heat. The installation are amount 1309 €/kW, which is an average of different neighbourhood types (Van Melle et al., 2015, p. 30).

## 6.8 Greenhouse gas emissions

### 6.8.1 Supply chain

The supply chain of fuels and energy conversion equipment should be taken into account when the impact on climate change is considered. The variable GHG emissions for the supply chain of fossil fuels, biomass and biogas are tabulated in Table 6.6. Biomass has a negative emission, since $CO_2$ is absorbed during its production. Two conversion processes are included in this table, whereas combustion processes are covered later. In Table 6.7, the fixed GHG emissions that occur during the production and construction of equipment needed for energy conversion. For solar and wind energy, these fixed emissions at the beginning of the life cycle are most important. For conventional energy supply, emissions from fuel combustion tend to dominate the life cycle impact.

Table 6.6: Emissions related to fuel production/supply and conversion.

| Fuel/Process | Emission (kg $CO_2$-eq./MWh) | Source |
|---|---|---|
| Coal | 56.4 | Edwards et al. (2014) |
| NG | 56.8 | Edwards et al. (2014) |
| Crude oil | 50.4 | Bergsma and Croezen (2011) |
| Biomass residues | -238 | Biomass Energy Centre (2004) |
| Biomass products | -341 | Biomass Energy Centre (2004) |
| Biogas | -172 | Bergsma and Croezen (2011) |
| Biogas upgrade | 10.1 | |
| SMR | 236 | Diakov et al. (2011) |
| Biodiesel | 183 | Edwards et al. (2014) |

Table 6.7: Emissions associated with the production and/or construction of energy conversion technologies (Bruckner et al., 2014).

| Technology | Emissions ($kgCO_2$-eq./GW) |
|---|---|
| Nuclear power | 3996 |
| Coal power | 2886 |
| NG power | 4829 |
| Wind onshore | 591 |
| Wind offshore | 975 |
| PV | 1794 |
| Solar thermal heat | 38 |

The production of solar thermal panels is associated with an emission of 38 $kgCO_2$-eq./GW (Lamnatou et al., 2015). This number was derived assuming a maximum solar irradiation of 1 kW/m$^2$, and 65% efficiency.

For biogas production, a negative emission of $-179.5$ kg $CO_2$-eq./kWh is assumed for the digestion process (Bergsma & Croezen, 2011). Some $CH_4$ leaks away during the production and processing of biogas. Expressed in $CO_2$-equivalents, there is a loss of 7.8 $kgCO_2$-eq./kWh biogas Bergsma and Croezen (2011). This translates to a loss of 1.7% of biogas throughout the chain. For validation, this figure is compared with the values from the Swedish voluntary agreement system for biogas producers (Holmgren, 2012). Their agreement states that a maximum of 2.5% is lost during production, and 2.1% during gas upgrading. The loss presented by CE Delft falls below this upper bound. Yet, the large gap between the numbers could indicate that one of them is an under- or overestimation.

The process to upgrade biogas to green gas has an efficiency of 95% (§ 6.5.3). The gas that is lost is assumed to be emitted as if it were combusted with emission of NG.

### 6.8.2 Combustion

The emissions of conventional electricity and heat sources were derived from Gómez et al. (2006). The emissions of $CO_2$ and other GHGs are listed in Table 6.8. For the combustion of biogas, the same emissions per unit of calorific value of NG are assumed. For SOFCs and SOFECs, an emission of $CO_2$ identical to that of NG combustion was assumed, along with zero emission of other GHGs.

Table 6.8: GHG emissions released during the combustion of the most common fossil fuels in different applications (Gómez et al., 2006), per GJ of fuel. Emissions of individual GHGs are expressed relative to the LHV of the fuel, whereas the total GHG intensity is expressed relative to the HHV.[a]

| Sector | Fuel | Assigned to | $CO_2$ (kg/GJ) | $CH_4$ (g/GJ) | $N_2O$ (g/GJ) | Total emission [a] ($tCO_2$-eq./MWh) |
|---|---|---|---|---|---|---|
| Energy industries | Natural gas | NG powerplant | 56.1 | 1 | 0.1 | 184 |
| | Coking coal | Coal powerplant | 94.6 | 1 | 1.5 | 326 |
| | Other primary solid biomass | Biomass boiler | 100 | 30 | 4 | 350 |
| Manufacturing & construction | Coking coal | Coal boiler | 94.6 | 10 | 1.5 | 327 |
| | Other primary solid biomass | Biomass boiler | 100 | 30 | 4 | 350 |
| | Natural gas | Gas boiler | 56.1 | 1 | 0.1 | 184 |
| Transport | Gasoline | Cars & aviation | 70 | 3 | 0.6 | 241 |

[a] The HHV is assumed to differ from the LHV by a factor of 1.1 for gaseous fuels, and 1.05 for solid or liquid fuels (Gómez et al., 2006).

# Chapter 7

# Optimisation Results

## 7.1 General

A number of experiments was conducted using the optimisation model described in § 4.4. By analysing the resulting optimal systems, questions related to the economic competitiveness of SOCs and the effect on the sustainability of the energy system can be answered. This chapter starts with three test cases to demonstrate the correctness of the optimisation model in § 7.2. Afterwards, the results of experiments addressing the effect of the costs of SOCs, the energy demand, and GHG emission taxes are presented. The chapter finishes with an optimisation of the transition pathway towards a future energy system.

The total system cost objective is used. A price for GHG emission is taken into account, but the emissions are never the only thing that is optimised. For each optimisation, the following information will be provided, to specify the input data used for that specific experiment:

- GHG emission tax
- Demand scenario
- Special restrictions on components
- The costs associated with SOCs

The demand and production patterns are the same in each experiment, and are introduced in § 5.6–5.7. The data cover one year, i.e. 8760 timesteps of one hour.

## 7.2 Tests

| GHG tax | Scenario | Restrictions | SOC costs |
|---|---|---|---|
| 0 €/t$CO_2$-eq. | Special (see below) | Limited set of components | – |

For the test cases in this section, the complexity of the models is low because the number of components is reduced. There is one energy source, i.e. natural gas. On the demand side, there is a 1 PJ/a electricity demand by households or 1 PJ/a consumption by BEVs. A time period of two weeks is considered, average summer and average winter week.

**Test 1:** Two identical powerplants
In this test model, there are two gas-fired powerplants that have to fulfil a demand for electricity only. Both plants have the same properties. As a consequence, it is indifferent which powerplant is installed and operated. The linear solver GLPK yields a solution with one of the two plants not used, while the solution of IPOPT features the two plant types with identical installed capacities and operating schemes. Both solutions are optimal given the assumptions made. These results are independent of the electricity demand profile selected.

**Test 2:** Two powerplants with different costs
Two plants are available, with the only difference being the fixed and variable O&M costs (Table 7.1).

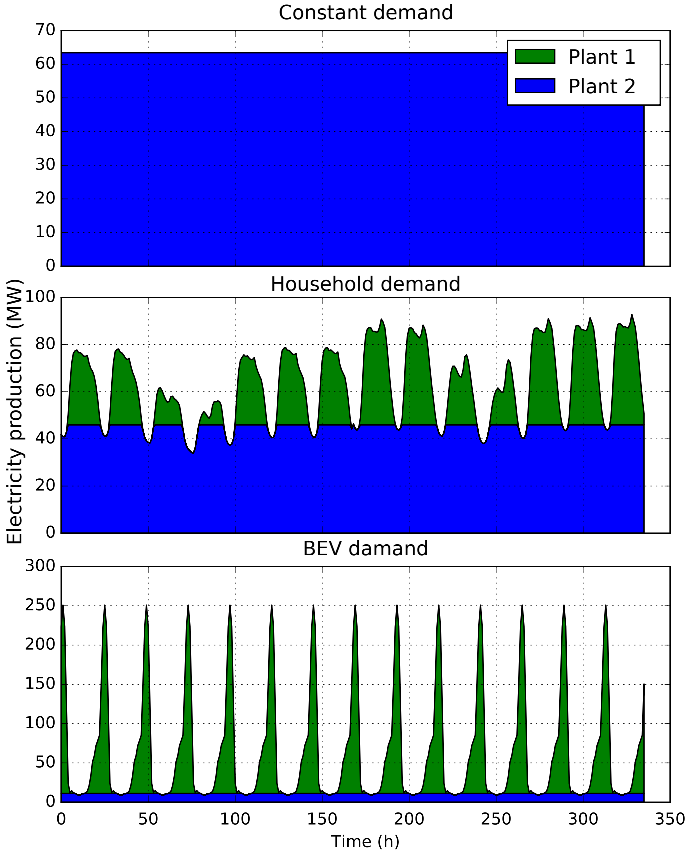



Figure 7.1: Electricity production by Plant 1 and 2 during two weeks, for three different demand curves.

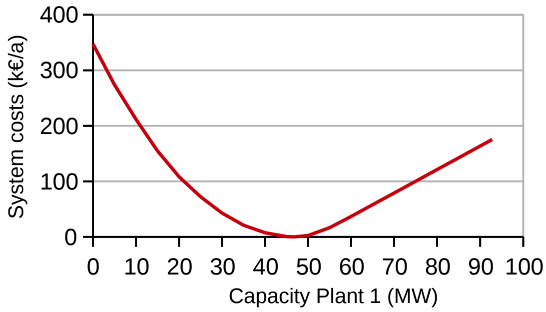



Figure 7.2: System costs relative to the optimum value for a system with two power-plants. The costs were calculated by fixing the installed capacity of Plant 1 at the given vale, and the capacity of Plant 2 at a size to complement Plant 1.

Table 7.1: Properties of Plant 1 and 2, and their levelised costs of electricity (LCOE) for different capacity utilisations. Fuel costs are included in the variable costs.

| | Lifetime | Investment | Variable O&M | Fixed O&M | LCOE (€/MWh) at CU | | |
|---|---|---|---|---|---|---|---|
| | (a) | (€/kW) | (€/MWh) | (€/kW) | 25% | 78% | 100% |
| Plant 1 | 25 | 790 | 58.80 | 15 | 91.24 | 69.20 | 66.91 |
| Plant 2 | 25 | 790 | 56.60 | 30 | 95.90 | 69.20 | 66.43 |

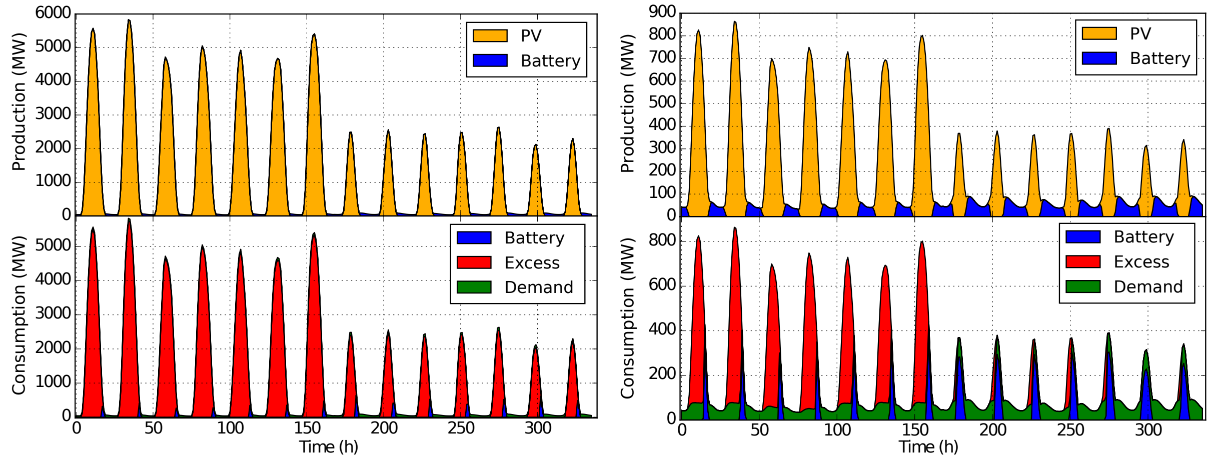
Further assumptions are 60% fuel efficiency, 5% discount rate, and NG costs of 33.78 €/MWh. If the capacity utilisation is set to 78%, then the LCOE is identical for both plants. At higher CUs, Plant 2 has the lower LCOE, while Plant 1 becomes more attractive at lower CU. In the optimal configuration, the installed capacity of Plant 2 is at least as big as the lowest demand of the time period. It also supplies each infinitesimal increase in demand above the base load, on the condition that the CU of *that part of the demand* is smaller than or equal to 78%. The remaining electricity demand peaks are met by Plant 1.

The optimisation results for three demand curves are plotted in Figure 7.1. In accordance with the expectation, Plant 2 is the only plant installed when there is a constant electricity demand. In case of very variable demand, as for example from BEVs, Plant 1 is the dominant type, since a high CU is only attained for a small fraction of the capacity. When the demand pattern of households is assumed, then both plants have a comparable installed capacity. The latter case was studied further by restricting the installed capacity of both plants. As shown by Figure 7.2, any deviation from the installed capacities in the optimum case result in higher system costs.

This test shows that the basics of energy economics are accurately reproduced in the model, provided that the installed capacities are continuous decision variables that can also assume non-integer values. In addition, the optimality of the solution for the test problem was demonstrated.

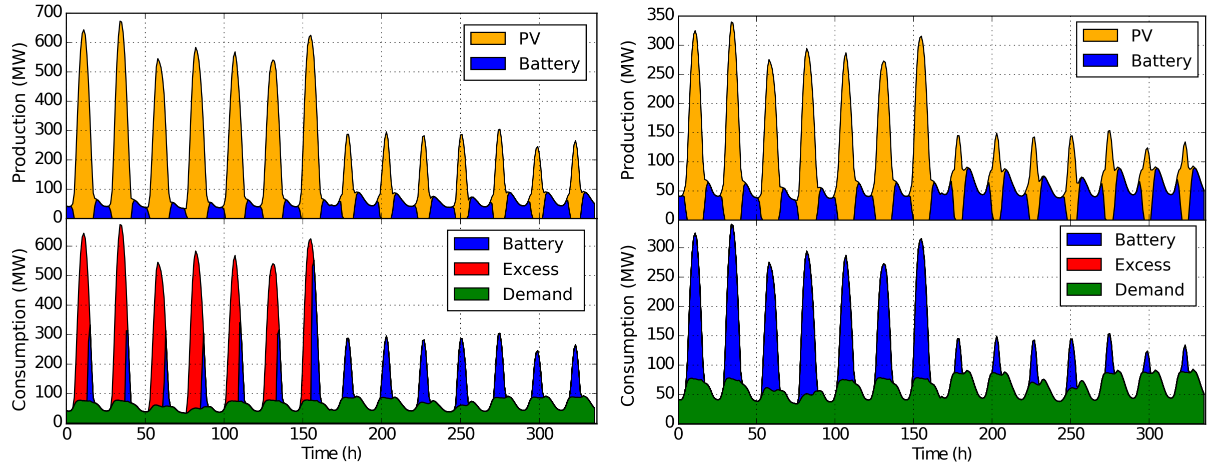
**Test 3:** Storage and excess

Fixed sources, such as PV and wind, do not produce sufficient energy to meet demand all the time. There are two options to guarantee all demand is met: temporary storage of energy, or the construction of more generation facilities in combination with curtailment of excess energy.




(a) 225 €/kWh investment costs, 9.015 €/MWh variable O&M costs.

(b) 225 €/kWh investment costs, no variable O&M costs.




(c) 50 €/kWh investment costs, 1 €/kWh variable O&M costs.

(d) No investment costs, 1 €/kWh variable O&M costs.

Figure 7.3: Optimised electricity production and consumption patterns in a simple energy system during an average summer and winter week. Demand consists of 1 PJ/a electricity by households. The characteristics of the components are those of a Li battery and commercial PV, except for the cost characteristics of the battery as specified below the graph.

To test whether these options are possible within the model, a simple system with three available components was constructed: PV, batteries, and electricity demand from households. Then, the optimal solution was calculated four times, each time with different costs associated with the battery. As Figure 7.3 shows, large-scale storage becomes attractive if the costs decrease significantly.

## 7.3 Nuclear energy

| GHG tax | Scenario | Restrictions | SOC costs |
|---|---|---|---|
| 5 €/t$CO_2$-eq. | Diversity | None | II, see Table 6.4 |

It turns out that nuclear energy is the most cost-efficient source of electricity. Without any restrictions on the number of nuclear powerplants, virtually all electricity is generated by these plants (see Figure 7.4). In such a system, electricity has a very low price, in particular in summer. Electrolysis

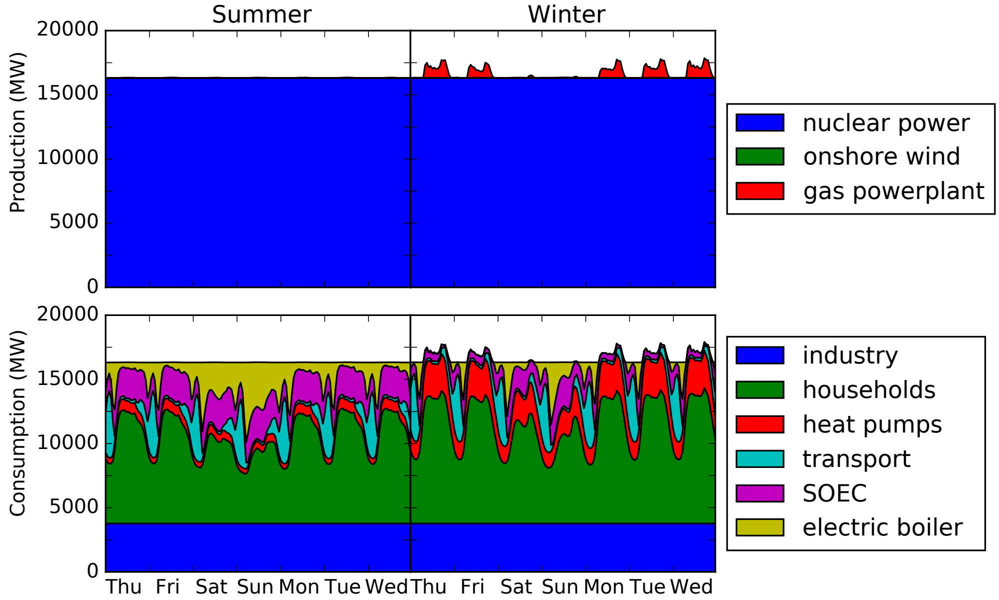



Figure 7.4: Optimal electricity production pattern when nuclear power generation is not constrained. The patterns are an average over a summer and winter week, for a diverse demand scenario.

therefore becomes an attractive method of hydrogen production. Since the output of nuclear plants cannot be regulated easily, the system features electric boilers that convert excess electricity to heat.

The resulting energy system configuration found here is far from the real-world situation. There are also several objections to such a system, among which safety concerns, the dependence on uranium producing countries, and the limited space for long-term storage of nuclear waste. To incorporate these considerations into the model, a constraint is added in addition to those presented in § 5.5. All following optimisations will be performed with 4 $GW_e$ as the maximum installed capacity of nuclear powerplants.

## 7.4 SOCs in the current energy system

### 7.4.1 Setup

| GHG tax | Scenario | Restrictions | SOC costs |
|---|---|---|---|
| 5 €/$tCO_2$-eq. | BAU | see Table 7.2 | VI, see Table 6.4 |

The question at hand is whether the (electricity) production system as it is currently in place, can profit from the installation of SOCs. To model the current energy system, the assumptions made are as follows. The installed capacity of electricity producing components in 2015 were obtained from ENTSOE (2016) and are listed in Table 7.2. The capacity of MSW powerplants is added to that of NG plants. Hydropower is not included in the model. It is assumed that the installed capacity of SMRs is 1402 MW, exactly enough to meet the demand for hydrogen. The demand for energy was set to the values of 2014, as identified in § 5.3. The prices of fossil fuels were set to the 2015 values as listed in Table 6.1. A model was constructed with these numbers included. Then, the system was optimised three times with different constraints on the installed capacity of electricity producing components:

**A** The installed capacity is fixed

**B** The installed capacity is fixed, except for SOFCs and SOFECs

**C** The installed capacity is not fixed.

Supply and demand of energy carriers other than electricity and hydrogen are still part of the model, but are not constrained and are not discussed here. Heat generation is not constrained, because there is no data on the installed capacity of heat-related equipment.

Table 7.2: Installed generation capacity of powerplants aggregated by type, in 2015 in the Netherlands (ENTSOE, 2016).

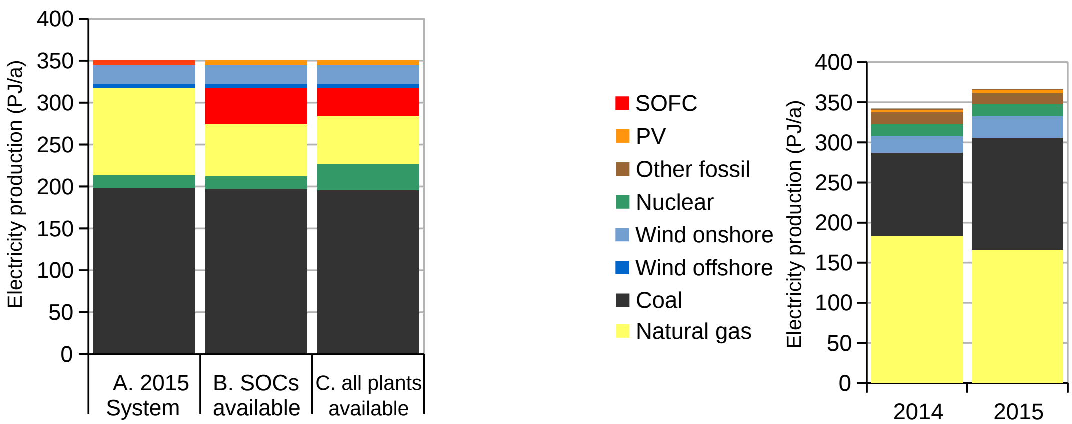
| Powerplant type | Capacity (MW) |
|---|---|
| Natural gas | 19914 |
| Hard coal | 5658 |
| Onshore wind | 3284 |
| PV | 1429 |
| MSW | 674 |
| Nuclear | 486 |
| Biomass | 398 |
| Offshore wind | 357 |
| Hydro | 38 |
| Total capacity | 32238 |

### 7.4.2 Validation

In case A, the optimisation problem reduces to an operation optimisation problem of electricity production. This setup can serve to validate the optimisation results by comparing them with energy production statistics. For this comparison, data on the real electricity and heat generation in 2014 and 2015 are presented in Table 7.3 and Figure 7.5–7.6. A major difference between statistical data and results from A, is the larger use of coal for energy production. Virtually all heat[1] originates from coal in the optimised system, whereas NG is the primary source in reality. To begin with, this is because no information about the installed capacity of NG furnaces was included in the model. Yet, the investment costs of furnaces are small compared to the fuel costs. This points to a second reason for the difference: in the model, coal is much less expensive than NG. Factors that are not accounted for are distribution costs (which are higher for coal than for NG), ease of use (a coal stock has to be maintained), and regulatory particulate matter emission limits.

The model correctly operates nuclear and coal powerplants as base load plants with 99–100% CU (Table 7.4), which is consistent with reality. Furthermore, gas plants are employed as peaking plants, as concluded from the CU of 38%. Interestingly, the installed capacity of gas powerplants is more than twice as big as the capacity that is actually used in the model. This is mostly explained by the fact that electricity production is shifted towards coal in case A compared to reality (Table 7.3). It is not clear what causes this difference.

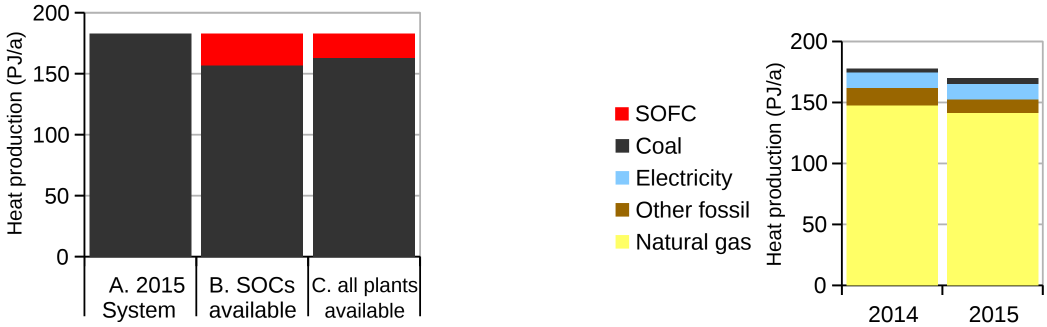
[1]Heat derived from fuel combustion in households and businesses is not considered here.




(a) Results of optimisation.

(b) Data from CBS (2015a).

Figure 7.5: Energy sources for electricity production in the Netherlands under the current conditions.




(a) Results of optimisation.

(b) Data from CBS (2015a).

Figure 7.6: Energy sources for heat production in the Netherlands under the current conditions.

Table 7.4 indicates that none of the biomass powerplants is being used in the model. This reflects the current situation, where electricity from biomass is only competitive if subsidies are granted, or if the price difference between biomass and coal were smaller.

### 7.4.3 Results

Case B is an extreme case where SOFCs and SOFECs are assumed to have reached low costs. The results show, that SOFCs have the potential to substitute a considerable fraction of the electricity currently generated by gas powerplants. An annual electricity production of 26 PJ/a by SOFCs is optimal. As a consequence, the CU of gas powerplants further decreases to 27%, while the CU of SOFCs is very high for both electricity and hydrogen production (see Table 7.4). The impact of SOFCs on the hydrogen market is even larger: over half of the SMR installations becomes redundant, while the remaining installations are used as a backup facility to provide only 6% of the demand. The effect on primary energy use compared to case A are significant. The total gas consumption (including non-energy uses) decreases by 9 PJ/a, while the use of coal is even 34 PJ/a lower. The former is due to the high efficiency of SOFCs, while the latter is because high-temperature heat from coal is partly replaced by heat from SOFCs. SOFECs are not installed, indicating that the technology is too expensive to compete with already installed SMR systems.

Under the assumption of case C, where any plant type can be installed, the following is observed. The installed capacity of SOFCs is the same as in case B, but less electricity is produced. The reason is that the capacity of nuclear powerplants doubles, now that investments are allowed. There are no other changes in installed powerplant capacities. Together with the electricity production, the hydrogen output of SOFCs also declines somewhat. Apparently, both products are strongly coupled in this system. Consequently, the required capacity and the CU of SMRs increases with respect to case B.

From these results, conclusions can be drawn only for the hypothetical situation that SOFCs with the costs expected in 2050 were available now. Under that assumption, it would be attractive to install a substantial amount of them from a systems point of view. SOFCs can become the main source of hydrogen for industry. SMRs are mostly replaced, and are used as backup technology. Furthermore, SOFCs can substitute some electricity from gas powerplants and heat from coal boilers. However, the current costs associated with SOCs are far from competitive, as will be shown in the next section.

Table 7.3: Energy sources for electricity and heat production in the Netherlands under the current conditions.

| | | Realisations (CBS, 2015a) | | Optimised system | | |
|---|---|---|---|---|---|---|
| | Energy source | 2014 | 2015 | A. Fixed | B. SOCs available | C. All available |
| Electricity | Natural gas | 184 | 166 | 104 | 62 | 56 |
| | Coal | 104 | 140 | 198 | 197 | 196 |
| | Wind onshore | 21 | 27 | 22 | 22 | 22 |
| | Wind offshore | | | 5.2 | 5.2 | 5.2 |
| | Nuclear | 15 | 15 | 15 | 15 | 32 |
| | Other fossil | 16 | 15 | | | |
| | Solar | 2.8 | 4.0 | 5.3 | 5.3 | 5.3 |
| | Fuel oil | 1.2 | 0.3 | | | |
| | Hydro | 0.4 | 0.3 | | | |
| | Biomass | | | | | |
| | SOFC | | | | 43 | 34 |
| | Other | | | | | |
| | Total | 343.5 | 366.9 | 350.4 | 350.4 | 350.4 |
| Heat | Natural gas | 148 | 141 | | | |
| | Other fossil | 15 | 11 | | | |
| | Electricity | 12 | 12 | | | |
| | Coal | 3.1 | 4.8 | 183 | 157 | 163 |
| | Fuel oil | 0.033 | 0.013 | | | |
| | Solar | | | 1.1 | 1.1 | 1.1 |
| | SOFC | | | | 26 | 20 |
| | Total | 177.7 | 169.9 | 184.2 | 184.2 | 184.2 |

Table 7.4: Capacity utilisation in three scenarios, all assuming the present installed capacities of powerplants. The capacity utilisation is calculated by dividing the average output by the maximum output.

| | A. fixed | B. SOCs available | C. free |
|---|---|---|---|
| *Electricity* | | | |
| Nuclear | 100% | 100% | 100% |
| Biomass | 0% | 0% | 0% |
| Coal | 99% | 99% | 98% |
| Gas | 38% | 27% | 26% |
| PV households | 15% | 15% | 15% |
| Offshore wind | 46% | 46% | 46% |
| Onshore wind | 21% | 21% | 21% |
| SOFC | 94% | 91% | |
| *Hydrogen* | | | |
| SMR | 100% | 12% | 19% |
| SOFC | – | 94% | 89% |

## 7.5 Effect of the costs of SOCs

### 7.5.1 Setup

| GHG tax | Scenario | Restrictions | SOC costs |
|---|---|---|---|
| 20 €/t$CO_2$-eq. | Diversity | – | I–VI, see Table 6.4 |

The current costs of SOCs are very high, and it is unlikely that they can compete with mature technologies at the present price level. However, the effects discussed in § 8.1.2 can cause major cost reductions. The change in the potential role of SOCs in the energy system is assessed based on an existing, approximately exponential, cost reduction prediction (Energistyrelsen & Energinet.dk, 2015). The properties of SOFCs in the future are given in Table 6.4. The composition of the LCOE is plotted in Figure 7.7.

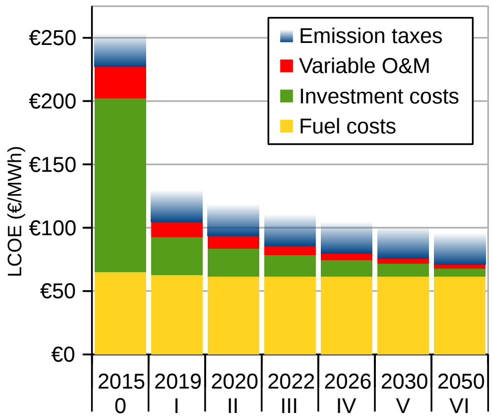


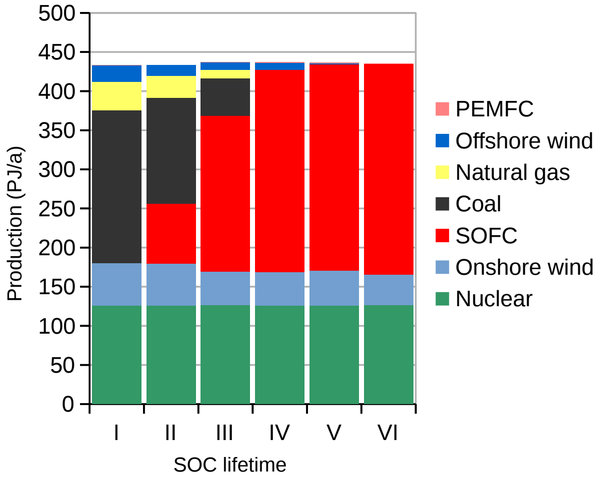

Figure 7.7: Levelised costs of electricity from SOFCs, based on the numbers in Table 6.4.

### 7.5.2 Installed capacities

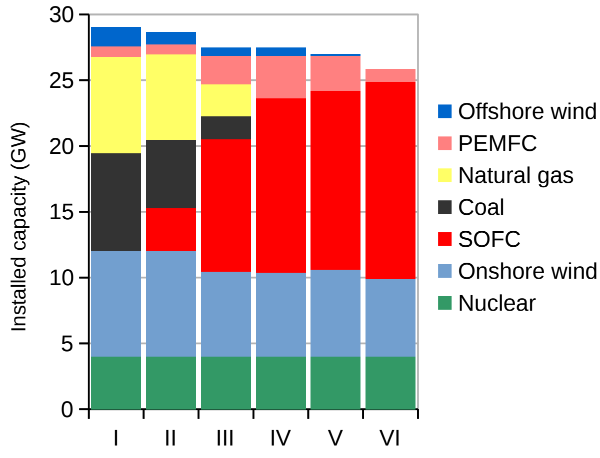
Using the diverse demand scenario and a GHG tax of 20 €/t$CO_2$-eq., the energy system was optimised for each of the sets of characteristics listed in Table 6.4 applied to both the SOFC and the SOFEC component. The contribution of the available technology options to the total production of electricity, hydrogen, and heat are show in Figure 7.8. As expected, the current costs prove to be too high to be competitive. This is why the results of scenario 0 are not plotted; they are identical to those of scenario I. With the predicted costs of 2020 (scenario II), SOFCs already start to play an important role. The main driver for their application appears to be the demand for hydrogen, since SMR as a $H_2$ source is replaced. SOFCs can be more cost-effective than SMR because of the co-production of heat and electricity. As a consequence, less coal-fired boilers and gas powerplants are installed, but also less wind turbines.

With the property set of scenario III, all SMRs are substituted by SOFCs. After decreasing the costs one step further (scenario IV), all coal and gas powerplants are replaced. Comparing scenario IV with I (a system without SOFCs), 30% less wind turbines are installed. Furthermore, a large fraction of coal heat plants is replaced. From these observations, it is deduced that the levelised costs of hydrogen production by SOFCs are competitive earlier than the costs of electricity production. A further reduction in costs, as seen under scenario V and VI, does not result in drastic shifts in production patterns.

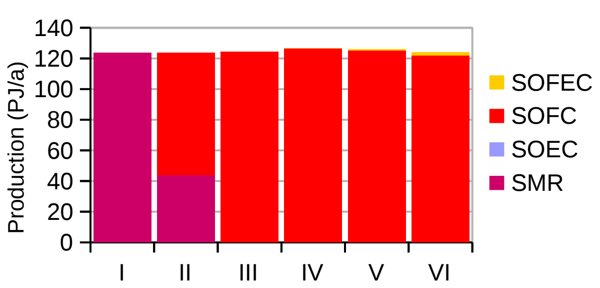
SOFECs play a much smaller role than SOFCs do. The highest production of hydrogen by SOFECs is 1.75 PJ/a in scenario VI, corresponding to 317 MW installed capacity. The low application of SOFECs is mostly due to the low amount of intermittent electricity production. Peaks in production are addressed by electric boilers, whereas fuel-assisted and normal electrolysis require more periods of low electricity prices. Under the assumptions made here, biogas is most cost-effectively used by upgrading it to green gas, and hydrogen is derived from SOFCs.



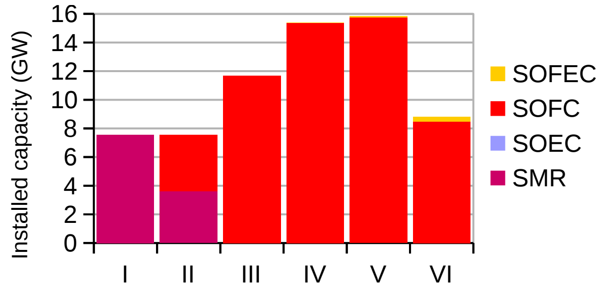

(a) Electricity



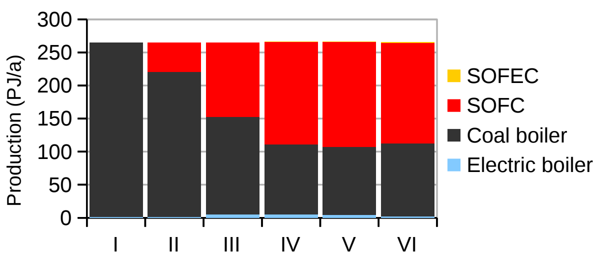

(b) Electricity



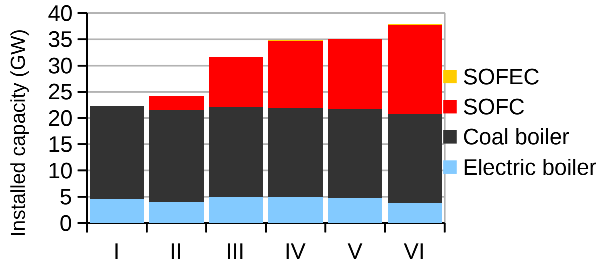

(c) Hydrogen




(d) Hydrogen




(e) Heat




(f) Heat

Figure 7.8: Total annual production (left) and installed capacities (right) of transformers under different SOC cost assumptions (see Table 6.4).

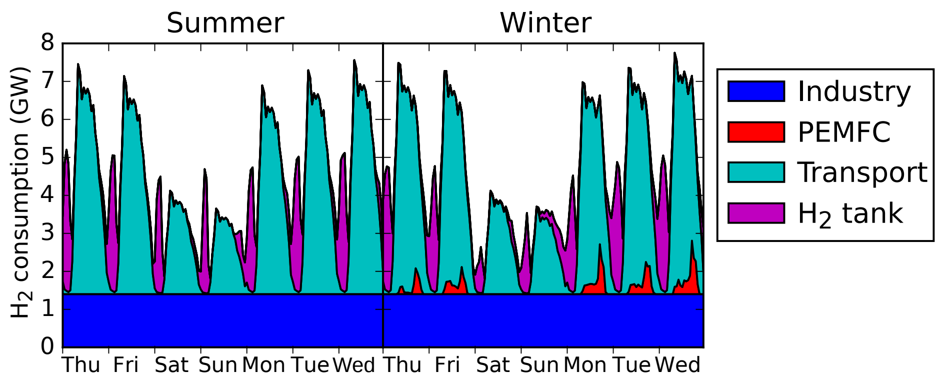



Figure 7.9: Hydrogen demand during an average summer and winter week, with SOFC properties from scenario III (Table 6.4).

The annual production of hydrogen in scenario IV is around 3 PJ larger compared to scenario I (see Figure 7.8c). Also, high peaks in $H_2$ production by SOFCs occur. A closer look at the hydrogen demand patterns in Figure 7.9 learns that this is because PEMFCs play a role in this system as peak electricity production technology. These situations occur almost exclusively during weekdays in winter months, when much electricity is required for among others heat pumps. In summer, there are some occasions where PEMFCs are operated to address the electricity demand peak caused by BEV charging. It is unexpected that this phenomenon does not occur in scenario VI, but this observation can be explained. In scenario VI, the investment costs of SOFCs are sufficiently low to allow the installation of some systems that are unused most of the time. These systems help to address the high electricity demand peaks, making the PEMFCs redundant. In scenarios III-V, the installed capacity of SOFCs is lower. To still meet electricity demand, the hydrogen output is increased and converted to electricity by PEMFCs.

Figure 7.8f shows that the installed capacity of coal boilers remains more or less constant in all scenarios, while its production decreases. This indicates that SOFCs do provide heat, but it is mainly a by-product. Therefore, the coal boilers remain necessary as load-following technology.

### 7.5.3 Costs

The cheaper the SOFCs are, the more of them are installed, and the lower the total system costs are. This effect is illustrated by Figure 7.10. In scenario II and III, the energy system as a whole has higher investment costs due to the SOFCs. O&M costs slightly increase, too. But the reduced emission tax burden outweights these effects at a given point. In the case of a 20 €/t$CO_2$-eq. tax, the tipping point lies between SOFC property sets I and II (Figure 7.10). Presumably, higher GHG taxes can make SOFCs attractive at an earlier stage (see also § 7.7.2). Most system-wide O&M costs originate from fossil fuel production. When less expensive SOFCs are available, they replace coal and gas powerplants in the optimal energy system. The resulting replacement of coal by NG as energy input increases the resource costs of the system. This is partly compensated by the shift from coal powerplants with high O&M costs to SOFCs with lower O&M costs.

Consistent with the similarity in energy production patterns of scenario IV–VI, the emission taxes are virtually identical for these scenarios. Further cost reductions originate from the lower technology costs, while GHG emissions do not decrease further from scenario IV onwards (Figure 7.10).

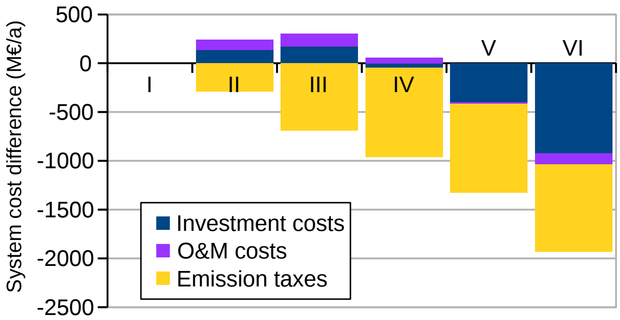



Figure 7.10: Change in system costs for scenario II–VI compared to scenario I.

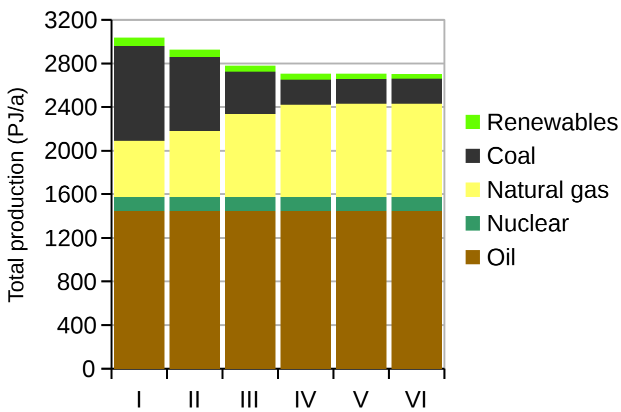



Figure 7.11: Primary energy use for scenario I–VI.

The primary energy use of the six scenarios, depicted in Figure 7.11, is compared. A larger utilisation of SOFCs has two effects. The total primary energy use is reduced, coal is replaced by NG as energy sources. As a consequence of these changes, the annual GHG emissions decline by 34.6 Mt$CO_2$-eq. between scenario I and III. Both effects can be fully assigned to the efficiency of SOFCs, since only SOC costs are different between the scenarios and SOFECs are only added at lower costs (Figure 7.8d). The addition of SOFCs does not, however, promote the use of renewable resources. So from a financial perspective, it does not become more attractive to operate intermittent energy sources because of the diffusion of SOFCs. No conclusion can be drawn on the reverse effect: whether SOFCs are more appealing if more renewable energy is produced.

It should be noted that the results presented in this section depend on the GHG emission tax that is applied. The effect of this assumption is investigated further in § 7.7.

### 7.5.4 SOFC operation

Comparing the results of scenario II and V, there are more differences than the installed capacity of SOFCs. The optimal operation of the fuel cells differs in the two cases, as illustrated by Figure 7.12 a and b. In this representative part of the year, $U_f$ changes much more for scenario V. It takes all values within the allowed boundaries (0.60–0.95). In scenario II, however, $U_f$ equals 0.60 most of the time. This results in a high hydrogen production relative to electricity. The NG input of the SOFCs shows a similar difference between the scenarios as $U_f$ (not shown). For scenario II, the input is often high, while it fluctuates much more in scenario V.

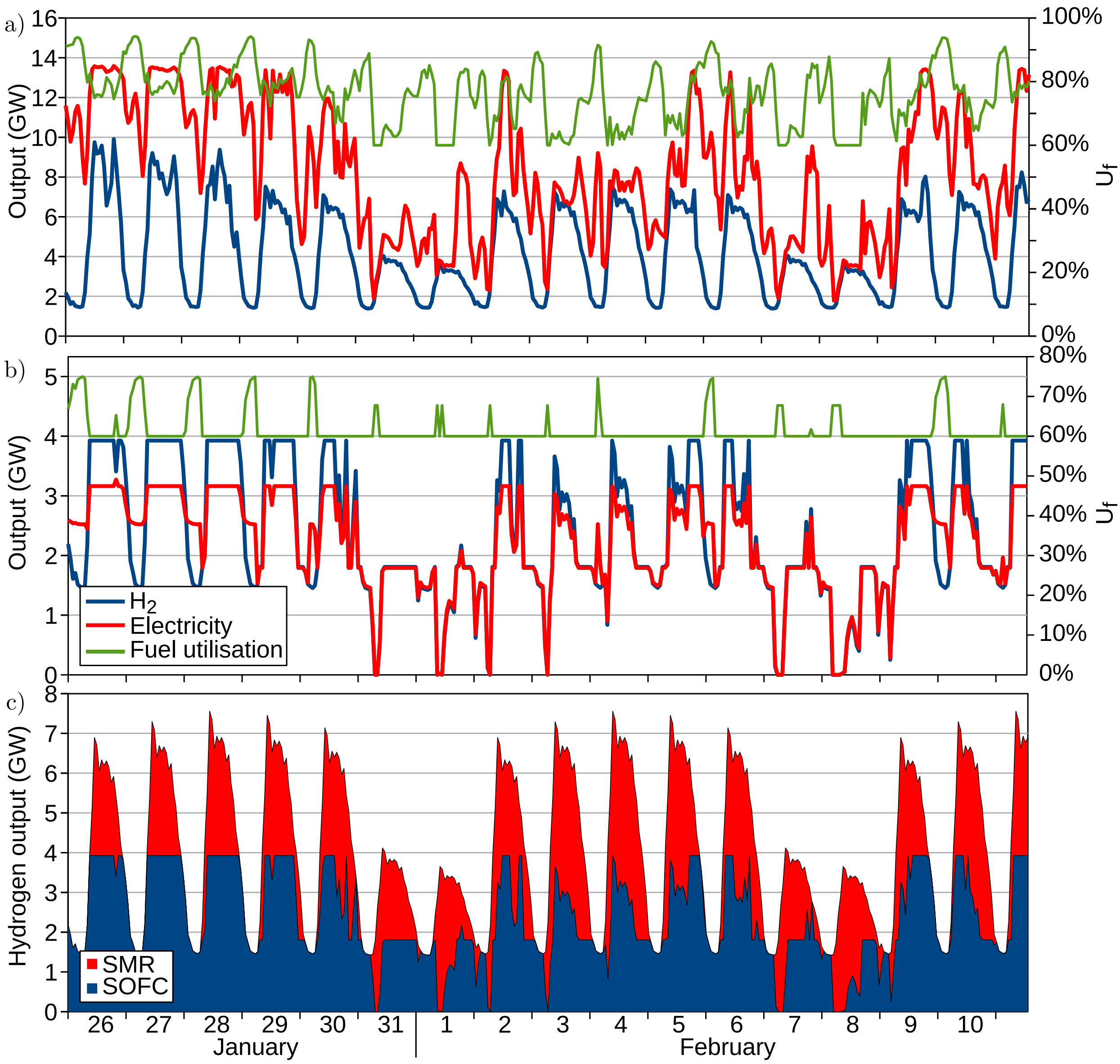
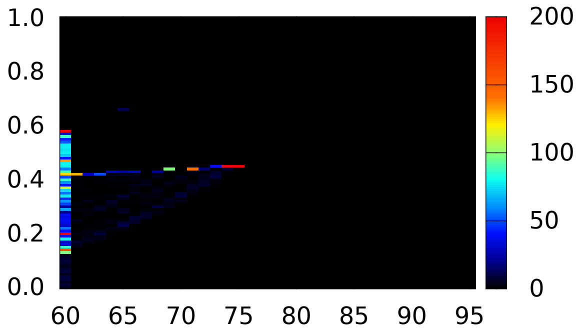



Figure 7.12: Optimised operation of SOFCs. Fuel utilisation and hydrogen and electricity production of SOFCs for Diverse demand scenario and costs a) V and b) II. c) Cumulative hydrogen output of SOFCs and SMRs in scenario II.

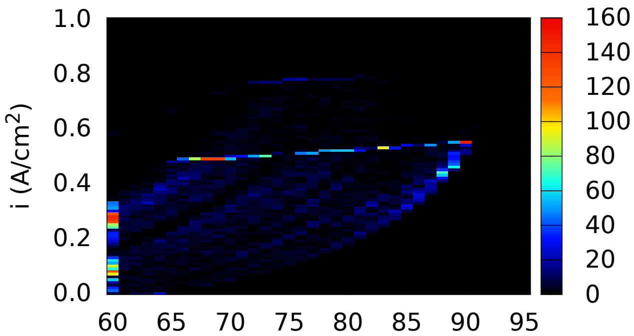
These observations can be explained by taking the installed capacity of SOFCs into account. The hydrogen production curve of SOFCs in scenario V is dictated by demand, since SOFCs supply virtually all hydrogen. In scenario II, supplementary hydrogen is produced by SMR (Figure 7.12c). This allows to operate the SOFCs in the most profitable way: with high hydrogen production and high capacity utilisation. This is not possible when the installed capacity is as high as in scenario V.

No SOFCs

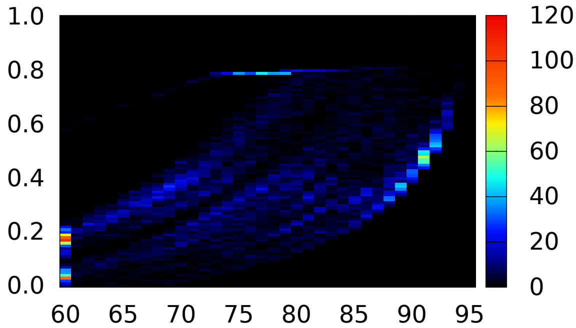
(a) Scenario I, 0 $GW_e$.



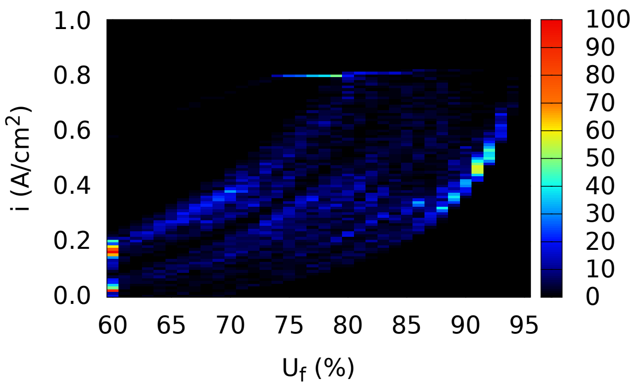

(b) Scenario II, 3.3 $GW_e$.



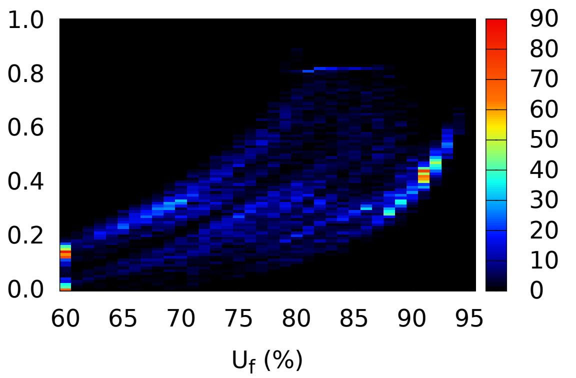

(c) Scenario III, 10 $GW_e$.




(d) Scenario IV, 13 $GW_e$.




(e) Scenario V, 14 $GW_e$.




(f) Scenario VI, 15 $GW_e$.

Figure 7.13: Heat map plots of optimal operation of SOFCs under different cost assumptions. The electric installed capacity is reported below each figure. The intensity refers to the frequency (h/a) of operation in each state.

To find out more about how SOFCs with different cost characteristics are operated, the operating parameters ($i$ and $U_f$) were compared for scenarios I–VI. Figure 7.13 shows how often a SOFC operates with each combination of $i$ and $U_f$. These plots show that less expensive fuel cells operate in a more flexible way, while expensive SOFCs are limited to only a few spots. This change in operation is related to the installed capacity. At higher costs, the capacity of SOFCs is small, and a high production of $H_2$ is possible. When larger number of SOFCs are installed while $H_2$ demand is unchanged, the cells are operated to produce more electricity.

Figure 7.13 also indicates that the current density in scenario II and III is limited, which results in a higher efficiency. The single most used setting in scenario II is at $U_f = 60\%$ and $i = 0.2$ A/cm$^2$, entailing a low total output, but a high yield of hydrogen, and low heat production. In scenario IV–VI, three areas of frequent operation can be discerned: high efficiency hydrogen production (low $U_f$, low $i$), maximum power production (high $U_f$, intermediate $i$), and maximum total output (intermediate $U_f$, high $i$). At lower SOFC costs, operation between these spots occurs more often, indicating a behaviour responsive towards market circumstances.

The current density does not exceed 0.9 A/cm$^2$ in all scenarios, which is somewhat below the maximum power point of 1.13 A/cm$^2$ (Figure 3.2). This should not be seen as a guideline for SOFC design. In fact, $i_{\max}$ depends on the assumed ASR value (Eq. 3.23). New cell designs with a lower ASR can make higher current densities possible. What can be concluded by comparison with Figure 3.2, is that a further increase of $i$ towards $i_{\text{max}}$ is not attractive due to the limited gain of hydrogen and power output.

## 7.6 Comparison of concepts

### 7.6.1 Setup

| GHG tax | Scenario | SOC technologies | SOC costs |
|---|---|---|---|
| 20/100 €/tCO$_2$-eq. | Diversity | SOFC | I–VI, see Table 6.4 |
| „ „ | „ „ | SOFEC | „ „ |
| 20 €/tCO$_2$-eq. | „ „ | SOFC+SOFEC | „ „ |
| „ „ | „ „ | Biogas-fuelled SOFC | „ „ |
| „ „ | „ „ | NG-fuelled SOFEC | „ „ |
| „ „ | „ „ | Hybrid SOC | „ „ |

In § 7.5, SOFCs and SOFECs compete with each other as hydrogen production technologies. To assess the role of each of these technologies separately, the energy system was optimised in absence of the competing technology. The other parameters settings were identical to those used in the previous section.

In addition, three alternative concepts for the application of SOCs were evaluated. One of the alternative setups is a SOFC with biogas as fuel. This is expected to be an advantage, since biogas is less expensive than NG. A NG-fuelled SOFEC was also tested next to the setup with a biogas-fuelled SOFEC. While it seems unattractive to replace the default and more intuitive biogas by NG to assist electrolysis, the application of SOFECs is no longer bound by the availability of biogas in this case. A third alternative is a hybrid SOC, which can switch between SOFC and SOFEC mode (§ 2.7.5).

Since it is expected that electrolysis is more attractive in systems with high renewable electricity production, the optimisation of the system with a SOFC or SOFEC is performed for a moderate and a high GHG emission tax.

### 7.6.2 Results

Analysis of the annual hydrogen production (Figure 7.14) confirms most expectations regarding SOFECs stated above. It is not feasible to use NG as a fuel for a SOFEC, since it negatively affects the break-even point. Competition with SOFCs indeed hinders the adoption of SOFECs. If the fuel cells are not available, SOFECs can be selected to produce around 48 PJ $H_2$, thereby using a large fraction of the available biogas. It is observed from Figure 7.14 that the cost reductions needed for SOFEC applications are larger than those needed for SOFCs. Assuming that costs for SOFC and SOFEC stack production and operation are tightly linked, SOFCs are the more attractive technology.

Additional evidence for the limited economic feasibility of SOFEC applications is provided in Figure 7.15, which plots the system cost reductions of the investigated scenarios. As would be expected, larger cost reductions are observed when SOC technologies are less expensive. The installation of SOFECs leads to negligible savings compared to SOFCs. SOFCs, on the other hand, reduce costs because they are more efficient, resulting in less resource consumption and less emissions. The same reduction in emission results in a larger saving at higher GHG taxes, which explains the significant difference between the graph of 20 and 100 €/tCO$_2$-eq..

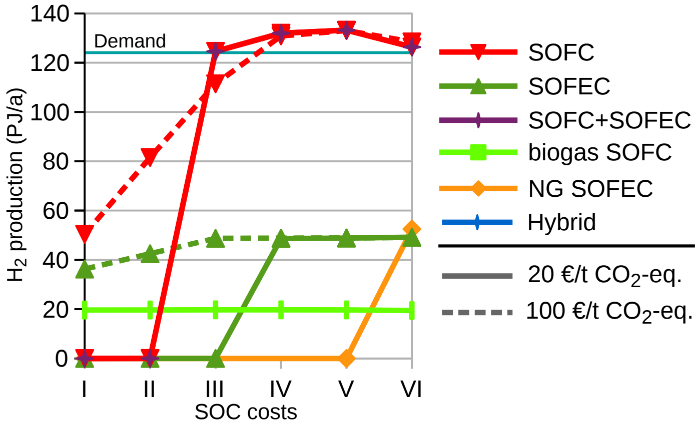



Figure 7.14: Annual production of $H_2$ by different SOC technologies and different cost characteristics of these technologies.

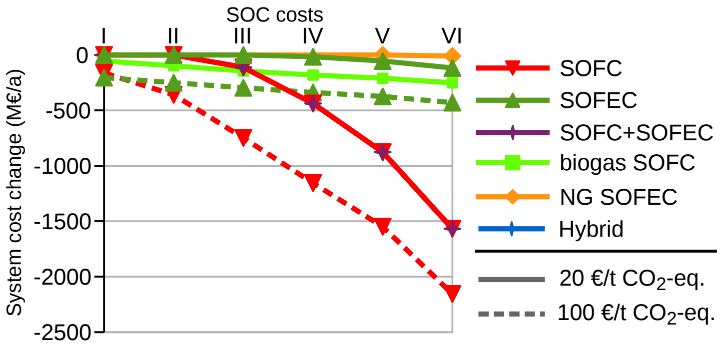



Figure 7.15: Change in total system costs for scenario I–VI compared to a system without SOCs, for systems with different SOC types.

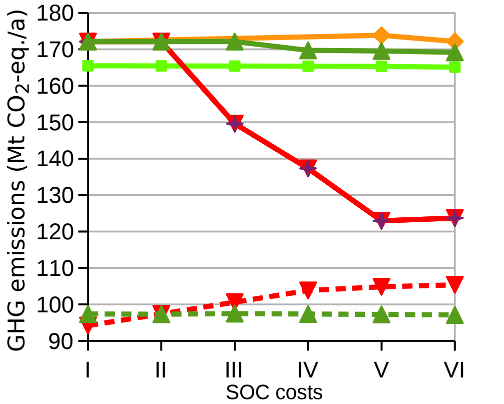



Figure 7.16: Annual GHG emissions for scenario I–VI and systems with different SOC types.

The results show that using biogas for SOFCs is feasible, and already at higher SOFC costs compared to the NG-fuelled concept. What is more, this application of biogas is more effective in reducing system costs and GHG emissions than fuel-assisted electrolysis. A drawback linked to the use of biogas is that the full potential of SOFCs cannot be realised. To conclude, using biogas to fuel SOFCs is attractive for the first installations. At lower cell costs, the number of SOFC can be increased by also employing NG.

Concerning the hybrid stack, a pattern very similar to systems with a SOFC emerges in Figure 7.15–7.16. In fact, the curves of a system with only SOFCs, with SOFCs and SOFECs, and with a hybrid SOC overlap in the plots. Further analysis learns that the hybrid stack is almost exclusively operated in fuel cell mode. There are no conditions that are favourable for NG-assisted electrolysis, even when it can be performed by an already installed SOFC. This implies that the capability of reversible operation is not effective in the investigated energy system.

The GHG emission reductions induced by the different SOC options shows diverging results, in line with the system cost. Figure 7.16 indicates that the use of biogas by SOFCs or SOFECs induces an emission reduction of 7 and 2 $MtCO_2$-eq. respectively. The use of SOFCs, although consuming NG, has a much larger effect. When a SOFC (or a hybrid stack operating in fuel cell mode) is present, the emission of up to 50 $MtCO_2$-eq. can be prevented on a yearly basis. At least when compared to the emissions of a system with 20 €/$tCO_2$-eq.. If the emissions are compared with a situation with high renewable energy shares, an *increase* is observed, indicating that SOFCs squeeze wind and solar energy out of the market. Under 100 €/$tCO_2$-eq. taxes, SOFECs have no noticeable effect on the GHGs emitted.

### 7.6.3 SOFEC operation

The optimisation algorithm yields the optimal operation of SOFECs based on the assumptions of costs and technical aspects. To gain insight in how a SOFEC is operated under the market conditions in the model, the state of SOFECs during a one-year optimisation was analysed. Figure 7.17 shows the number of hours that a given current density is used, for different SOFEC costs. It can be derived that the maximum current density is 1.03 A/cm$^2$. At the high cost level of II, this current density is applied often. In the other cases, $i$ fluctuates around lower values. The lower the costs, the lower the optimal

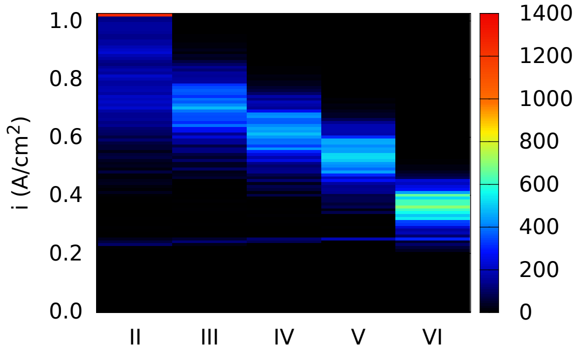
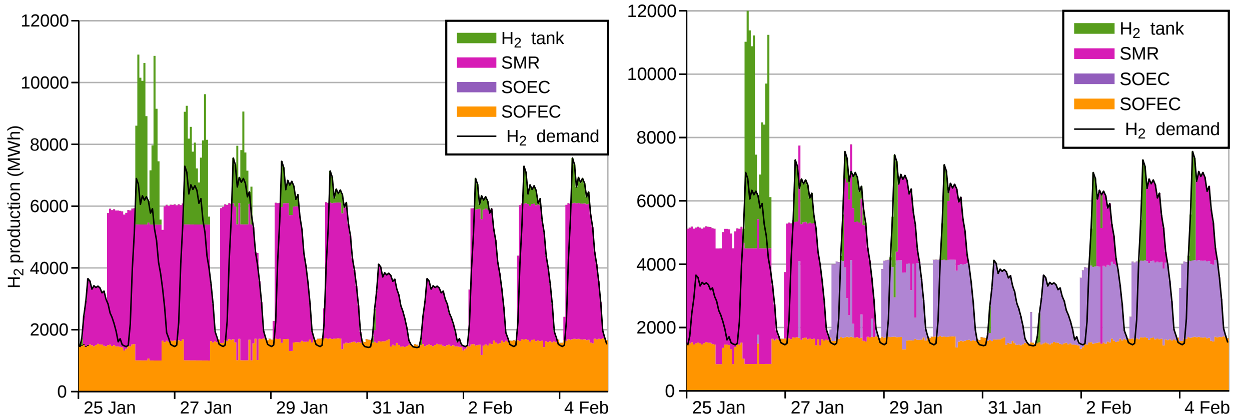



Figure 7.17: The frequency (in h/a) of operation at a given $i$ for different SOFEC cost scenarios. A GHG tax of 100 €/tCO$_2$-eq. and Diverse demand scenario apply.

current density range. Given that the $H_2$ production of SOFECs only increases (§ 7.14), a lower $i$ implies the total installed capacity is larger. This is because the higher efficiency of the SOFEC at lower $i$ can compensate for the higher initial investments. Higher investment costs require a higher annual production to recover these costs.

Comparison with a SOEC indicates that both technologies are employed rather differently, as illustrated by Figure 7.18. A SOEC is off for around two thirds of the time, and it is operated only when renewable energy production is high. SOFECs, on the other hand, are always on and supply the base-load of $H_2$ demand. The variation in output of SOFECs is more limited, and SOFECs are never turned off.




(a) 20 €/tCO$_2$-eq.

(b) 100 €/tCO$_2$-eq.

Figure 7.18: Hydrogen production and consumption during 11 days in an optimal energy system with SOFECs with characteristics IV. Overproduction is not lost, but stored in $H_2$ tanks or consumed by PEMFCs.

## 7.7 Effect of demand composition and GHG taxes

### 7.7.1 Setup

| GHG tax | Scenario | Restrictions | SOC costs |
|---|---|---|---|
| 5, 10, 20, 30, 40, 50, 75, 100 €/t$CO_2$-eq. | variable | – | II, see Table 6.4 |

In this section, the influence of demand composition and GHG taxes on the optimal energy system are investigated simultaneously. Both are expected to affect the system to a large extent. Energy demand, because it determines what amount of each energy carrier has to be delivered. And GHG taxes can shift the order of which technology is cheaper (merit order). It is expected that higher tax levels make efficient technologies and carbon-poor energy sources more competitive. SOFCs are expected to be more effective in some systems than in others. Some combinations of demand patterns of SOFC products might be more favourable than others. For example, a scenario with alternating peaks in the demand for hydrogen and electricity might provide opportunities. Yet it is hard to predict in which scenario the patterns are in favour of SOFCs. It is expectable that more SOFECs are installed in systems with high renewable electricity production, since there are high electricity production peaks that can be used.

The optimisation algorithm was run for 32 scenarios: all combinations of four demand scenarios (§ 5.4) and eight emission tax levels between 5 and 100 €/t$CO_2$-eq.. The costs of SOCs were fixed to those expected in 2020. The emission taxes works in advantage of less emitting technologies, while carbon-intensive fuels become less competitive. By comparing the primary energy inputs of the optimal system at different imposed taxes, the potential emission reductions and their cost-effectiveness can be assessed.

### 7.7.2 Effect of GHG taxes

#### Electricity

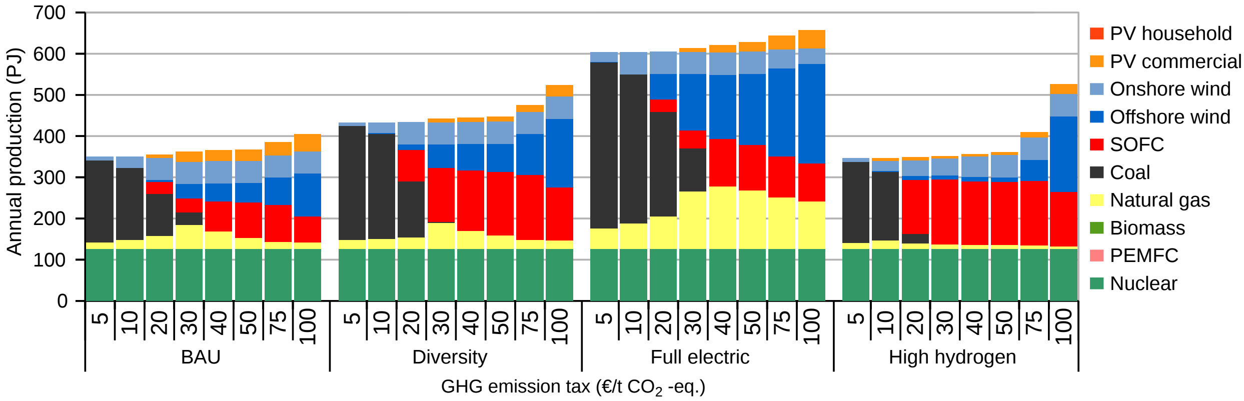
As expected, the use of coal – the most carbon-intensive fuel – for heat and power generation deceases rapidly for increasing taxes (Figure 7.19a and e). Coal powerplants are no longer favoured starting from 20 or 30 €/t$CO_2$-eq. (depending on the demand scenario), while a tax of at least 75 or 100 €/t$CO_2$-eq. is required to replace all coal-fired furnaces. The electricity originating from coal is replaced by a mix of technologies, among which PV and onshore and offshore wind. The latter technology has the highest potential (see § 5.5), and a large part of this potential is also used. For onshore wind, the maximum capacity of 8 $GW_e$ is reached in the majority of the scenarios (Figure 7.19b). Electricity derived from NG initially profits from higher taxes, but becomes less attractive when $CO_2$ is taxed even more. In particular in the Full electric scenario, a high fraction of electricity is produced by NG powerplants and SOFCs. The highest potential for gas powerplants is found around 30 to 40 €/t$CO_2$-eq., while the maximum SOFC electricity production occurs around 75 €/t$CO_2$-eq..

The capacity utilisation for three powerplant types is plotted in Figure 7.20. The utilisation of SOFCs is lies between 60%–80%, which is somewhat lower than that of coal powerplants. For gas powerplants, the capacity utilisation is much lower and does not exceed 30%. A general trend can be observed: when more SOFCs are installed, the capacity utilisation of the stacks decreases. In parallel, their role as flexible backup technology becomes more important.

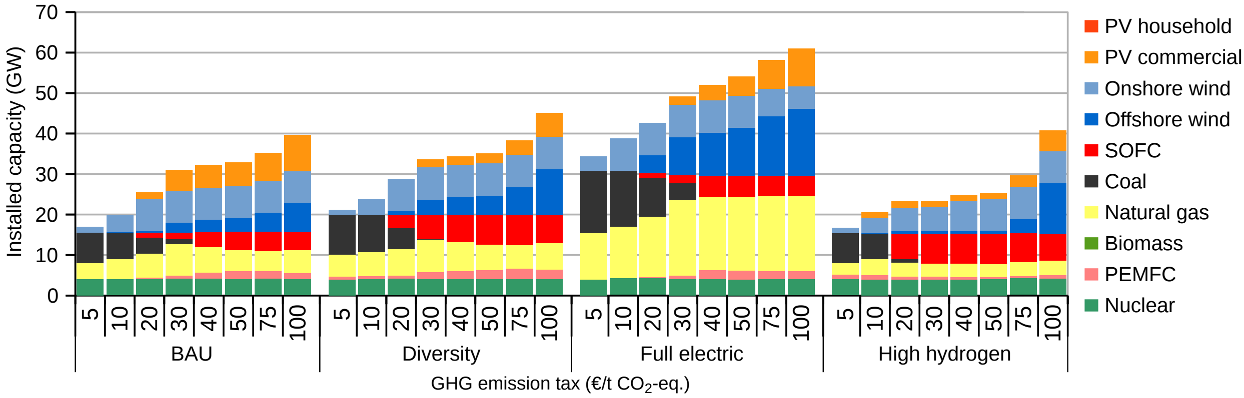
#### Heat

Heat derived from biomass has a very low GHG emission. Yet, the assumed costs of biomass technology restrain the use of biomass boilers up to a 50 €/t$CO_2$-eq. tax (Figure 7.19e). At that point, biomass is used to ensure heat supply during the winter months. Solar thermal is insufficient, and SOFCs are too expensive to be installed only for the peaks in winter.

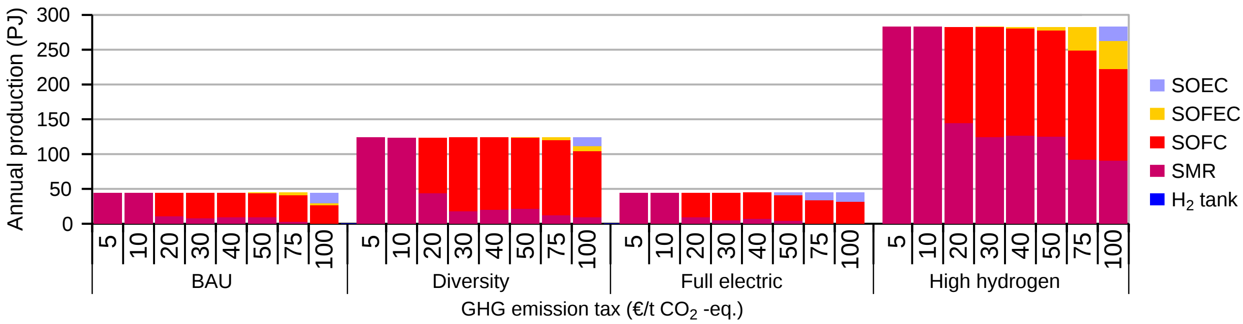
Considering electric boilers, it is observed that the installed capacity has the largest increase at low taxes. The capacity is related to the amount of intermittent electricity production. Interestingly, the total amount of heat produced by electric boilers becomes significant only at a tax level of 75 €/t$CO_2$-eq.. Below that, the boilers function mainly as a mechanism to get rid of excess electricity, while



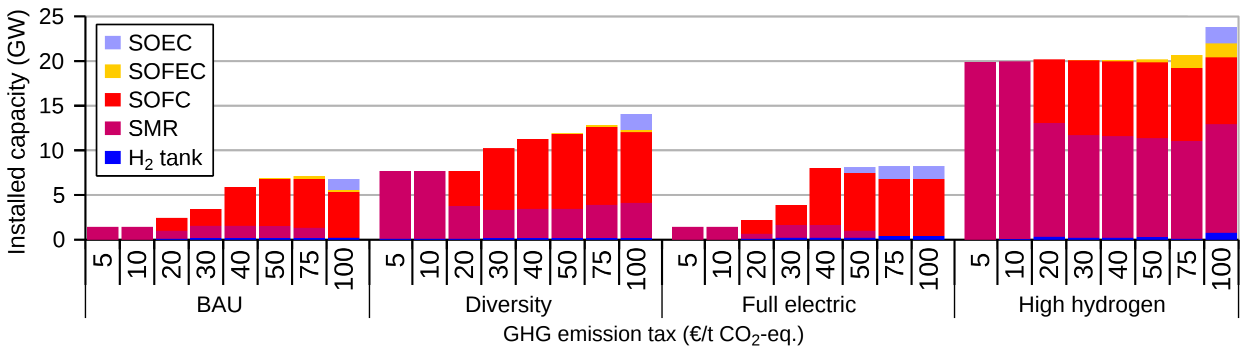

(a) Electricity production.



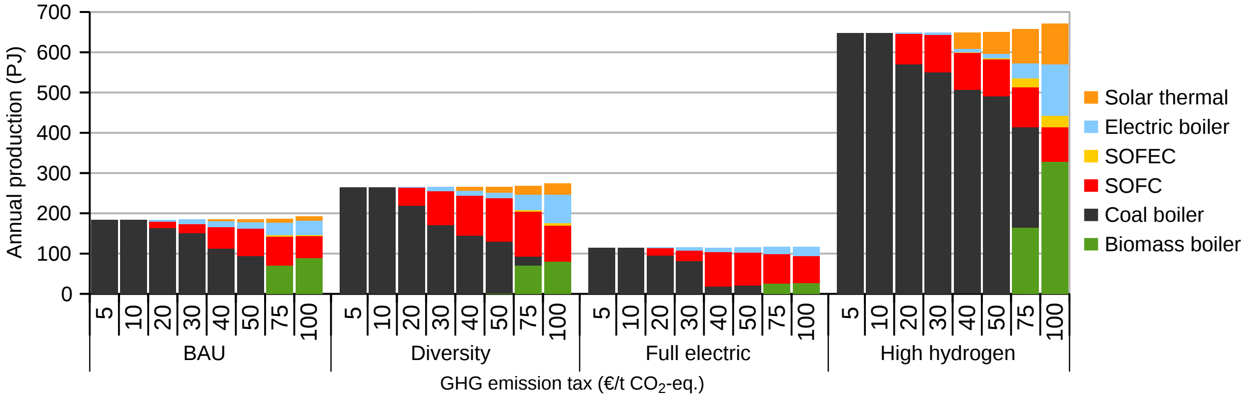

(b) Installed capacities for electricity production.



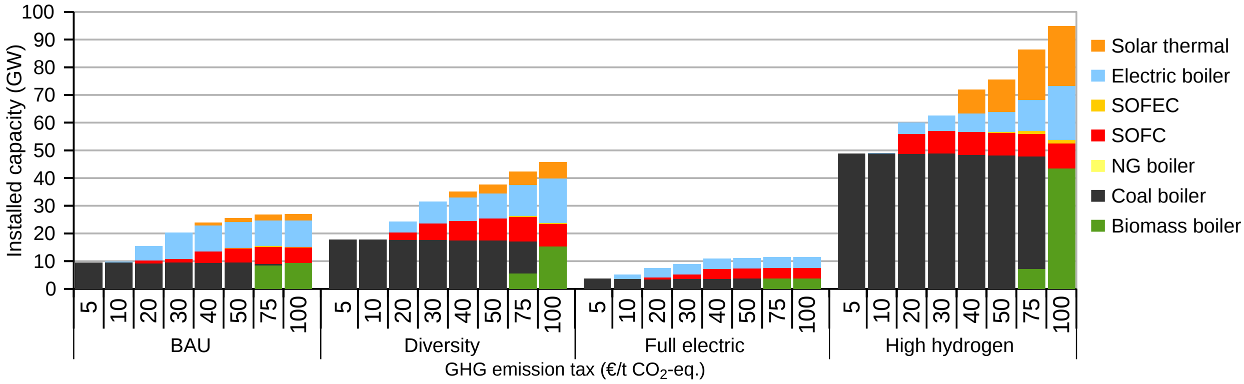

(c) Hydrogen production.




(d) Installed capacities for hydrogen production.

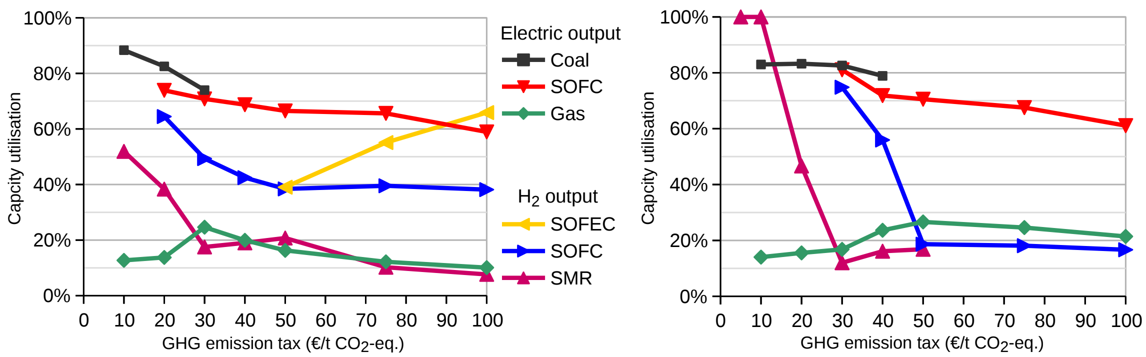



(e) Heat production.




(f) Installed capacities for heat production.

Figure 7.19: Annual production and installed capacity for electricity, hydrogen, and heat production. Scenarios are a combination of an emission tax and a demand scenario.




(a) Diversity

(b) Full electric

Figure 7.20: Capacity utilisations of three powerplants and three hydrogen production technologies, for different GHG emission taxes and two demand scenarios.

structural use for low-emission heat provision becomes attractive under high taxes. The total electricity production increases with higher GHG tax, because of the employment of electric boilers to convert cheap electricity to heat.

#### Hydrogen

The hydrogen market is affected most by SOCs. For low GHG taxes, $H_2$ is produced via SMR, but SOFCs can produce it cheaper starting from 20 €/t$CO_2$-eq. (Figure 7.19c). SMRs are still installed, and operate as backup facility. When there is an imminent excess of electricity, SOFCs are halted and $H_2$ production is taken over by SMR. SOFECs play a noticeable role only when taxes exceed 75 €/t$CO_2$-eq.. In the High hydrogen scenario, the number of SOFECs is sufficiently large that almost all biogas is used for fuel-assisted electrolysis. The High hydrogen scenario is also interesting because it shows the limit of cost-effective hydrogen production by SOFCs. In this scenario, SMRs are responsible for an important part of the hydrogen supply. Possibly, SOFCs are constrained by the market for electricity that is co-produced. Even when operated to maximise hydrogen output, SOFCs still produce a considerable amount of electricity. Therefore, at high shares of intermittent electricity production (as seen in the systems with 100 €/t$CO_2$-eq.), SOCs that are operated as electrolysers can replace some SOFCs. The results indeed show hydrogen production by SOEC and SOFEC components.

By comparing the results of the Diverse demand scenario with those in § 7.5, the effects of cost reduction and GHG taxes can be compared. The increase from 10 to 20 to 30 €/t$CO_2$-eq. results in comparable higher application of SOFCs as the change from characteristics I to II to III. So, a 10 €/t$CO_2$-eq. higher tax has a similar effect on the break-even point of SOFCs as a 9% lower LCOE.

The capacity utilisations of three hydrogen producing technologies, as plotted in Figure 7.20, show different patterns for the demand scenarios. These difference have to do with the hydrogen consumption of PEMFCs, as discussed in § 7.5.2. In the full electric scenario, the hydrogen demand peaks caused by PEMFCs are large compared to the total demand. Therefore, SOFCs have a low capacity utilisation, sometimes below 20%. In the diversity scenario, the capacity utilisation of SOFCs is around or above 40% for two reasons. There are SMRs to address hydrogen demand peaks, and the peaks occur more often, due to the hydrogen demand from FCEVs.

### 7.7.3 SOFC operation

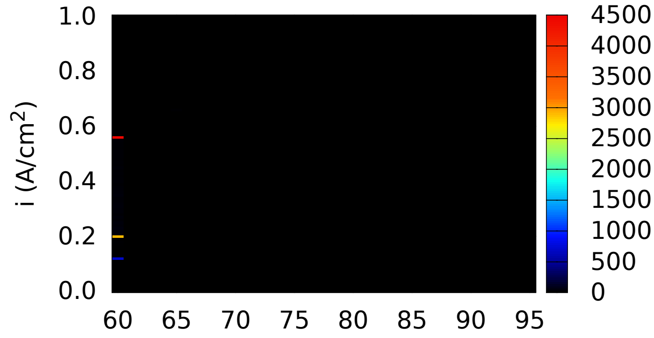
Heat map plots of SOFC operation in the scenarios treated here were made. A selection of these plots is provided in Figure 7.21. The most remarkable observation is that a wide range of settings is used in the Diversity scenario only. In the other scenarios, SOFCs are operated in one or a few settings most of the time. Regardless of the demand scenario, the fuel cells are operated at low $U_f$ for low GHG taxes. At the point of 20 €/t$CO_2$-eq., just past the threshold value for SOFC introduction, $U_f$ is almost exclusively 60%. This observation supports the hypothesis that $H_2$ production is a driver for the installation of SOFCs.

At a tax of 75 €/t$CO_2$-eq. and BAU demand, two states occur most frequently: high power output mode, and a high efficiency low $i$ mode. A curve of sparsely visited states in between these two modes is visible in Figure 7.21b. A similar pattern is seen in Figure 7.21f, although the high power mode is used more often. This reflect the situation with high electricity demand in the Full electric scenario. By contrast, in the scenario with High hydrogen demand and high GHG taxes (Figure 7.21h) modes with low $U_f$ dominate, in response to the need for hydrogen. The effects seen in the Diversity scenario are very similar to what was discussed in § 7.5.4. The wide range of operating conditions used in the Diversity scenario is partly due to the variability of the $H_2$ demand.

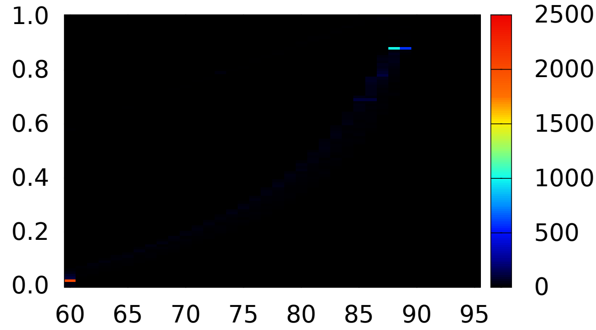
### 7.7.4 Sustainability

#### GHG emission reductions

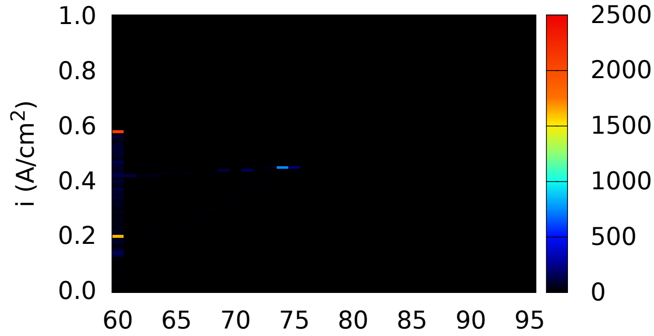
SOC technologies can cause direct GHG emissions reductions (by being more efficient than alternatives) or induce indirect changes (by changing the attractiveness of renewable energy). To determine what



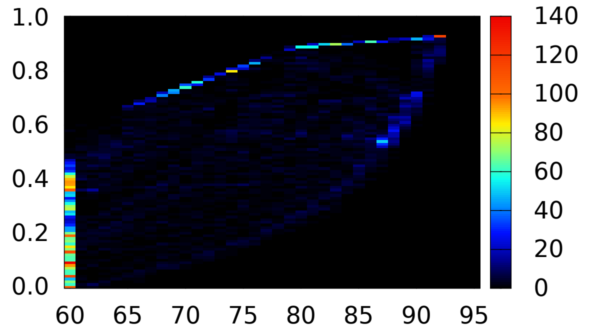

(a) BAU, 20 €/t$CO_2$-eq.



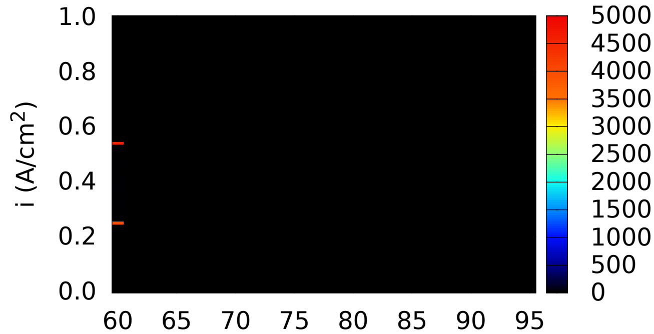

(b) BAU, 75 €/t$CO_2$-eq.



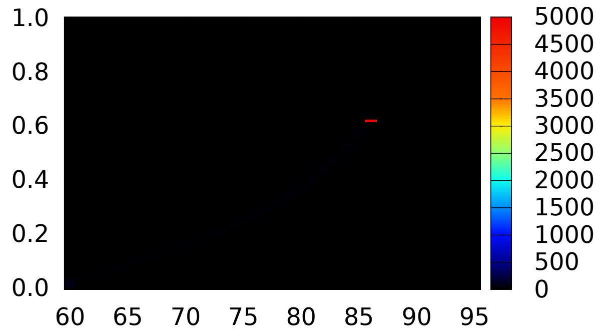

(c) Diversity, 20 €/t$CO_2$-eq.



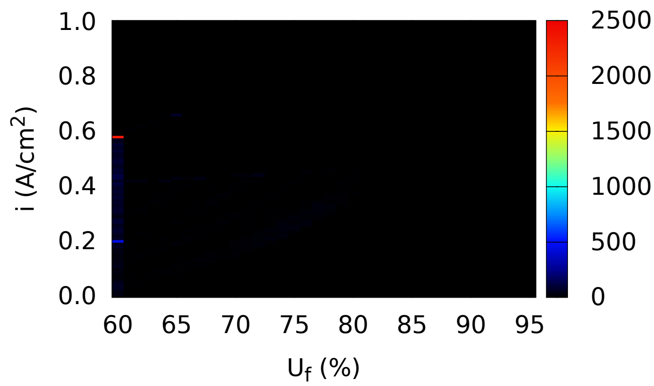

(d) Diversity, 75 €/t$CO_2$-eq.



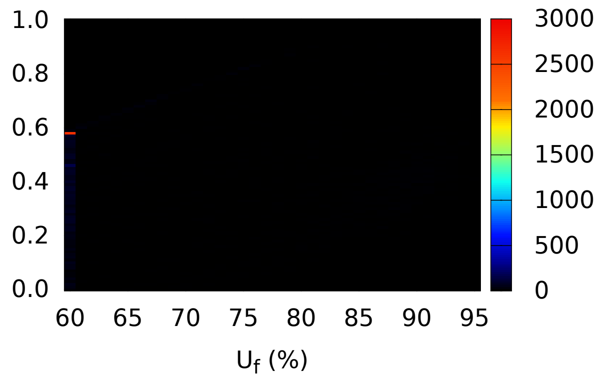

(e) Full electric, 20 €/t$CO_2$-eq.




(f) Full electric, 75 €/t$CO_2$-eq.




(g) High hydrogen, 20 €/t$CO_2$-eq.




(h) High hydrogen, 75 €/t$CO_2$-eq.

Figure 7.21: Heat map plots of optimal operation of SOFCs under different demand scenarios and GHG emission taxes.

emission reductions can be assigned to SOCs, the emissions of an optimal system with and without SOFCs and SOFECs are compared. Figure 7.22 shows the GHG emission savings of a system where SOCs are available relative to a baseline system without SOCs. The optimisation was performed for the BAU and Diversity scenario under different emission taxes. The absolute emissions decrease in a different pace in the different scenarios, due to demand definitions. Yet in both scenarios, the presence of SOCs reduce the annual emissions by 5.2% on average, corresponding to around 8 $MtCO_2$-eq. This amount is saved on top of the savings realised in the baseline case without SOCs.

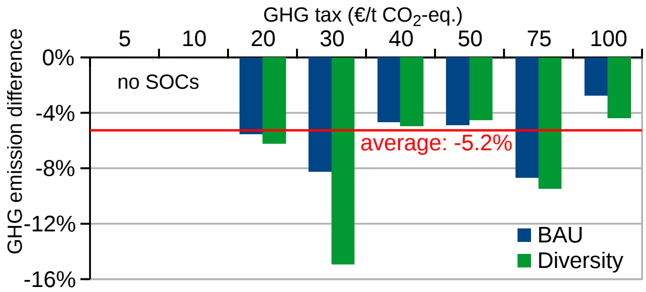



Figure 7.22: Difference in GHG emissions between an optimal system with and without SOCs.

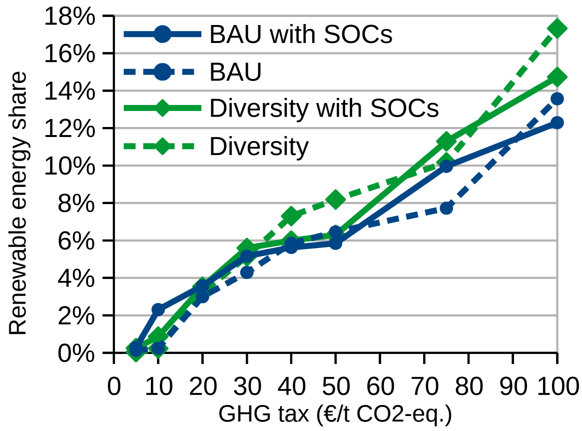



Figure 7.23: Share of renewable energy in the total primary energy consumption, for a BAU and Diverse demand with and without SOCs and different GHG taxes.

### Primary energy use

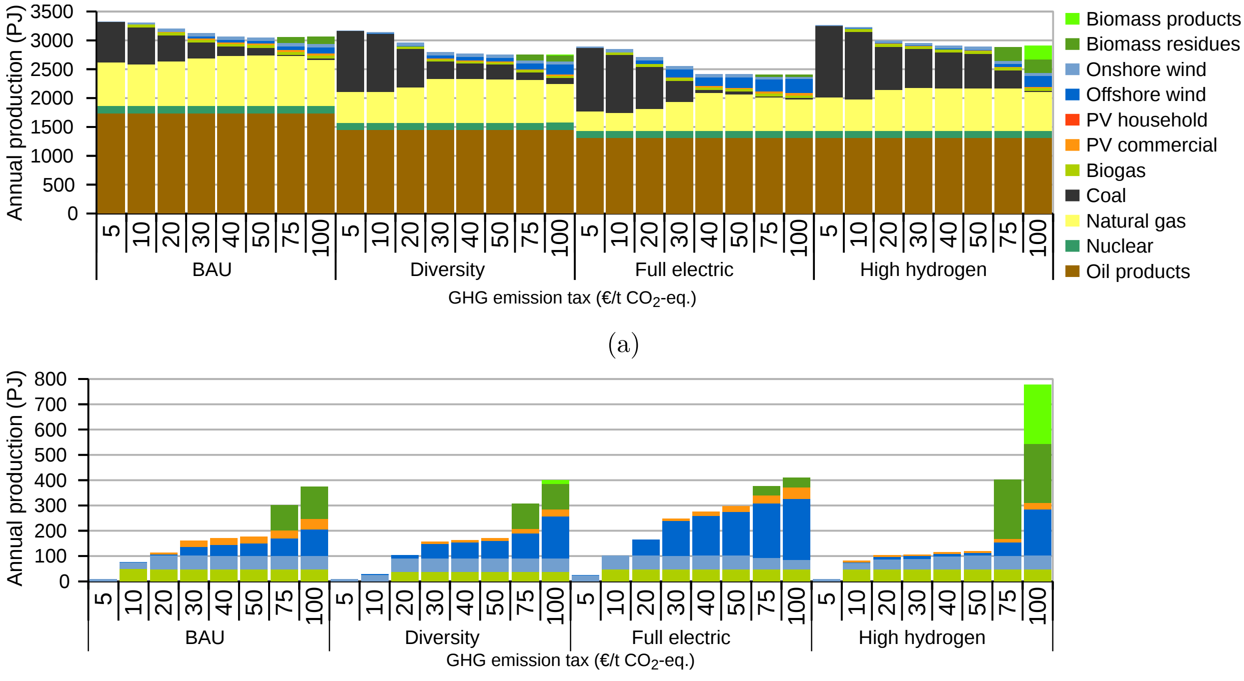
Only direct emission savings occur. As shown in Figure 7.23, the fraction of primary energy coming from renewable sources does not systematically increase when SOCs are in use. The share of renewables grows by 1.4% per €10 tax increase on average, independent of the demand scenario or the availability of SOCs. So, it can be concluded that SOFCs do not make renewable energy more attractive from a systems point of view. No evidence for indirect GHG emission reductions was found, consistent with the finding in earlier sections that SOFCs do not facilitate renewable electricity production.

It is not surprising that the share of energy obtained from renewable sources rises for higher GHG taxes, as confirmed by Figure 7.24. What was not foreseen, is that the highest share of biomass is achieved in the high hydrogen scenario. Examination of Figure 7.19c learns that the biomass is used for heat production. The production of biofuels does not become attractive, even at a tax of 100 €/$tCO_2$-eq..

Focussing on electricity (Figure 7.24), the highest share of renewable electricity is found in the Full electric scenario with the highest GHG tax. This scenario has an annual average of 49% renewable electricity. In the other scenarios, this fraction is similar, but the absolute amount of electricity is much smaller.

### Excess

Dumping of excess energy is allowed for electricity, biogas, hydrogen and heat. The latter two energy carriers are not wasted in any scenario. Excess electricity is clearly related to the amount of fluctuating electricity sources installed. It amounts to 9 PJ/a in the Full electric scenario, as visualised in Figure 7.25. Some biogas is dumped, indicating that the fluctuations in production are not always followed. This is because it is not economical to oversize the equipment for upgrading to green gas, and cheap electricity for fuel-assisted electrolysis is not always available.




(a)

(b)

Figure 7.24: Primary energy sources, a) total and b) renewable energy sources, for the four demand scenarios and different GHG taxes.

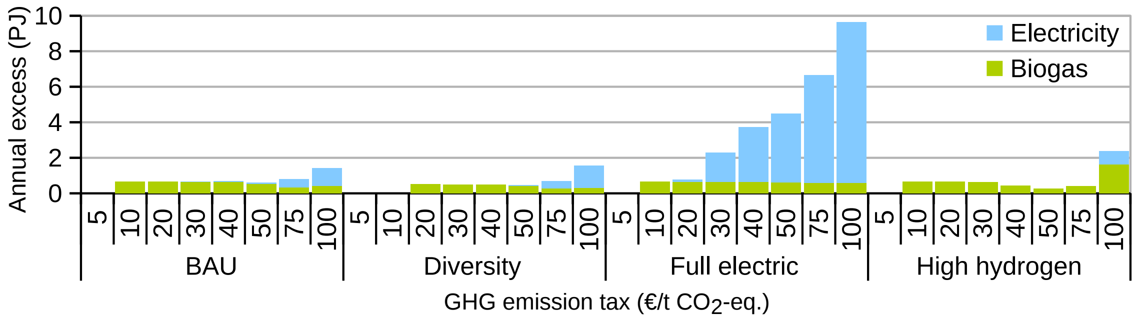



Figure 7.25: Total annual excess of biogas and electricity in scenario I–VI for different GHG taxes.

## 7.8 Transition optimisation

### 7.8.1 Setup

In § 7.4, the effect of introducing SOCs in the current energy system of the Netherlands was investigated, while in § 7.5–7.7, a completely new future energy system was optimised. This section aims to bridge the gap between the two, by sketching a pathway for the coming 35 years. Starting with the system and parameters of 2015, the time period was divided in timesteps of 5 years. After each timestep, the optimal energy system configuration and operation were determined as in the previous sections. The parameters related to costs, resource and emission prices, and demand compositions applied in each step evolve as given in Table 7.5. The assumptions with respect to resource prices are based on Schoots and Hammingh (2015), and the SOC costs are loosely based on Energistyrelsen and Energinet.dk (2015). The values of the other parameters in Table 7.5 are intended to represent a gradual, logistic growth-like, evolution towards a system with low fossil fuel demands and high GHG emission taxes. The only information exchange between subsequent optimisations concerns the installed capacities from the previous timestep.

Table 7.5: Assumed properties and values of parameters for each year in the transition.

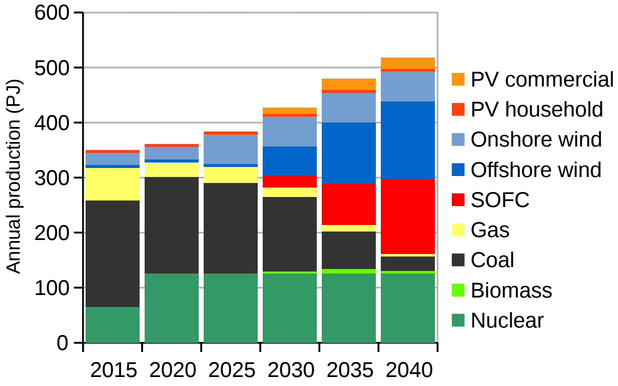
| | | 2015 | 2020 | 2025 | 2030 | 2035 | 2040 | 2045 | 2050 |
|---|---|---|---|---|---|---|---|---|---|
| SOC properties | Investment (€/kW) | 2750 | 1375 | 825 | 670 | 544 | 440 | 350 | 275 |
| | O&M (€/MWh) | 13.75 | 8 | 5.5 | 4.02 | 2.93 | 2.2 | 1.8 | 1.65 |
| | Lifetime (a) | 6 | 10 | 15 | 17 | 19 | 20 | 20 | 20 |
| GHG tax | (€/t$CO_2$-eq.) | 5 | 10 | 20 | 35 | 55 | 75 | 86 | 90 |
| Transport energy demand mix | Gasoline | 99% | 94% | 85% | 67% | 47% | 23% | 8% | 1% |
| | Electricity | 1% | 5% | 12% | 27% | 38% | 44% | 47% | 49% |
| | Hydrogen | 0% | 1% | 3% | 6% | 15% | 33% | 45% | 50% |
| Low-T heat demand mix | Total | 100% | 95% | 90% | 84% | 77% | 69% | 60% | 50% |
| | NG | 85% | 80% | 68% | 51% | 35% | 21% | 11% | 5% |
| | Electricity | 2% | 6% | 15% | 29% | 40% | 47% | 52% | 55% |
| | Heat | 13% | 14% | 17% | 20% | 25% | 32% | 37% | 40% |
| Resource prices (€/MWh) | Oil | 22.25 | 39.60 | 50.73 | 62.30 | 66.75 | 68.97 | 71.20 | 73.42 |
| | NG | 24.84 | 28.66 | 31.73 | 33.78 | 35.83 | 37.87 | 39.92 | 41.97 |
| | Coal | 9.00 | 11.15 | 11.70 | 12.12 | 12.53 | 12.94 | 13.36 | 13.77 |

To accurately model a transition over the timespan of several decades, it is important to know when powerplants are expected to be depreciated. Data from three sources (Wikipedia, 2016c; Davis et al., 2015; CBS, 2016b) were combined, resulting in the overview of Appendix A.3. Powerplants fuelled with coke oven gas, fuel oil or hydro-power sources were not included. These plants combined represent 1 $GW_e$, or 3.5% of the country-wide installed capacity. The installed capacity of MSW plants were added to the capacity of NG plants.

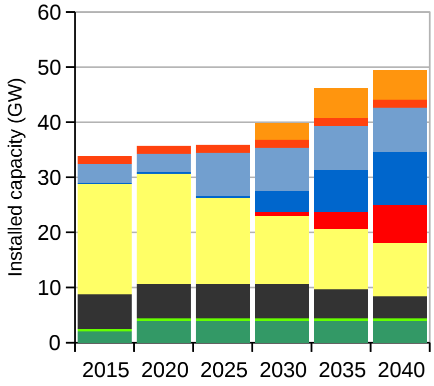
### 7.8.2 Results

In Figure 7.26, the annual production of electricity, hydrogen, and heat as found by the optimisations are presented. In the first 10 years, few changes occur in the energy system. In 2030, more wind turbines and PV panels are installed to replace old coal powerplants. The GHG tax of 35 €/t$CO_2$-eq. facilitates this shift. Around 940 kW of SOFCs and 150 kW SOFECs (kW $H_2$ output) are installed. Driven by the increasing $H_2$ demand, the installed capacity of SOFC and SOFEC installations expands rapidly in the years after that. In 2040, also 8.6 PJ of $H_2$ is produced by SOECs. With respect to heat production, it is observed that electric boilers gain importance over the years. These boilers are operated to limit electricity excesses.

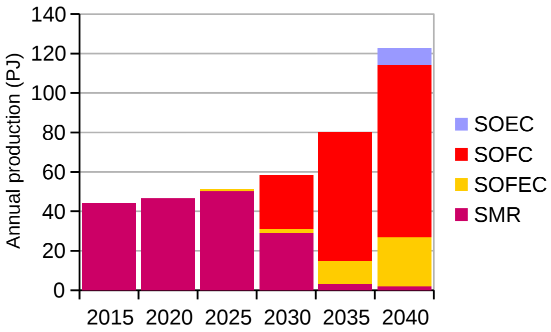
This optimisation shows how the initial diffusion of SOFC technology is hindered by existing technology. Although in the setup used here, SOFCs are competitive in 2025, their introduction starts only after that. SMR installations and powerplants that have not reached the end of their service life are more cost-effective than investments in construction of new SOFCs. These results thus indicate that a barrier for the adoption of SOFC technology exists, providing a dilemma. To be competitive at large scale, substantial cost reductions are needed. Yet for these reductions to occur, more systems have to be installed to gain experience. This dilemma and possible solutions are discussed in Chapter 8.



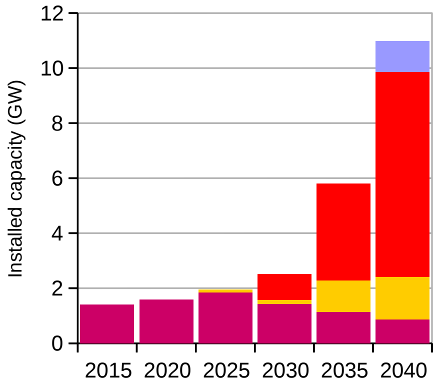

(a) Annual electricity production.



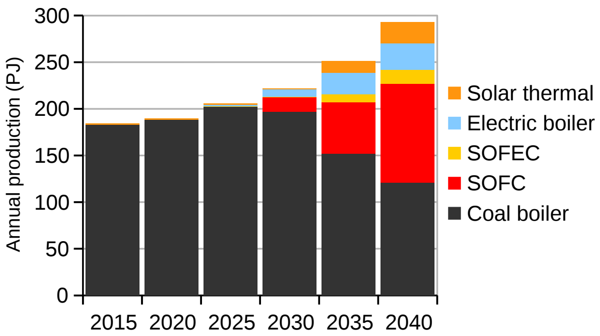

(b) Installed capacities of powerplants.



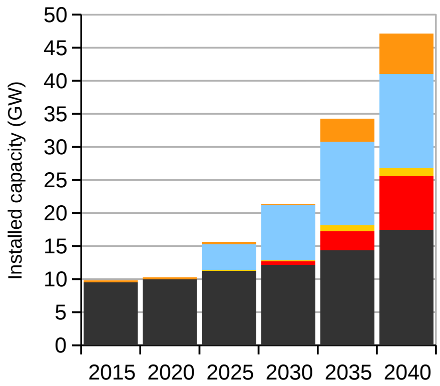

(c) Annual hydrogen production.




(d) Installed capacities of $H_2$ plants.




(e) Annual heat production.




(f) Installed capacities of heat generators.

Figure 7.26: Annual production of electricity, hydrogen and heat, and installed capacities of generation technologies during a transition path. Further assumptions: increasing emission taxes and demand from FCEVs and BEVs, decreasing heat demand and SOC costs; see Table 7.5.

## 7.9 Conclusion

The results clearly indicate that SOFCs can become an important part of the Dutch energy system if the costs decrease sufficiently and a longer lifetime of the stacks is achieved. An installed capacity of 7.5 $GW_e$ (High hydrogen, 50 €/t$CO_2$-eq.) to 15 $GW_e$ (Diverse demand, 20 €/t$CO_2$-eq.) is optimal. SOFCs are cost-effective because of the co-production of three energy carriers, of which $H_2$ is most valuable. The high efficiency, resulting in a lower resource use, also contributes to the effectiveness of SOFCs. The installation of SOFCs results an emission reduction of around 8 Mt$CO_2$-eq./a compared to a system without them. High GHG emission taxes promote fuel-efficient technologies, and therefore favour the diffusion of SOFCs. SOFC are especially good to facilitate a transition from coal to NG, at the same time decreasing the primary energy need. If GHG taxes are low, then renewable electricity sources become less attractive compared to SOFCs. At very high GHG taxes, the balance shifts towards renewables (see Figure 7.19b).

If the costs of operating SOFCs remain high, then the installed capacity is limited to an extent for which high capacity utilisations and a high production of $H_2$ can be achieved. If costs can be reduced, SOFCs prove to be a suitable technology for electricity production during periods of low renewable electricity production. Analysis of the operating parameters $U_f$ and $i$ indicated that expensive SOFCs are operated to maximise $H_2$ production, whereas cheaper cells are operated more flexible.

The conditions for which SOFECs can play a role in the Dutch energy system are more limited. A high level of renewable electricity production and/or high GHG emission taxes are required, on top of the cost reductions of SOC technology. Furthermore, the competition with SOFC and SOEC technologies as a $H_2$ source, and the limited availability of biogas further limit the application of SOFECs. If SOFCs and SOFECs with the same costs are both available, a SOFC is often preferred, since it allows for much larger system cost reductions. The operational dispatch of SOFECs shows a trend similar to SOFC operation. For expensive installations, the $H_2$ output is maximised, even though this entails a lower efficiency. At lower costs, a higher installed capacity is operated at lower rates. In general, a SOFEC is operated optimally with a high capacity utilisation. This has two important implications. First, the variations in current density during operation are limited, which is favourable for the thermal management. Second, a SOFEC shows a limited response to electricity prices. As opposed to SOECs, they are therefore not ideal to prevent electricity excesses. Nonetheless, SOFECs are more favourable under high GHG taxes. This is because the technology profits from low *average* electricity prices and it uses (almost) carbon neutral biogas.

The optimisation results of the last section indicate that the diffusion of SOCs is hampered initially by existing technologies. Over time, when some old installations are dismantled and SOC costs have decreased, SOFCs and SOFECs become cost-effective.

# Chapter 8

# Societal Aspects

## 8.1 Analytical framework

### 8.1.1 Socio-technical systems

The energy system was introduced in § 4.1.1 as a complex system composed of many technical components. Here, the perspective is broadened by acknowledging that also a wide variety of actors (organisations and individuals) is involved. The attitude of these actors, emerging network structures, and interactions such as learning processes influence how the system will evolve. In particular when transitions or transformations are considered, these social effects are of big importance for the outcomes. For SOC technology, this implies that social dynamics influence their development and diffusion in the Netherlands. To be able to understand the possible future developments around SOCs, it is instructive to use a number of concepts and an analytical framework. With respect to the future costs, learning curves and economies of scale are relevant concepts. The concepts of path dependence and actor perspectives are linked to the social side of the transition. The following sections will elaborate on these concepts. To analyse and asses the societal aspects of the adoption of SOFCs and SOFECs, the multi-level perspective (MLP) will be used. This analytical framework will be introduced in § 8.1.5.

### 8.1.2 Learning curves

One of the shortcomings of the optimisation model, is that it does not address the effect of learning, which is one of the major sources of cost reduction for emerging technologies. Learning curves describe the relation between cumulative installed capacity of a technology and the associated costs (Rivera-Tinoco et al., 2012). For other energy technologies, a linear relationship is often found between production cost and cumulative production on a double-logarithmic scale. This implies that the costs have decreased by a fixed fraction each time the cumulative output doubles (Staffell & Green, 2013). Experience can be gained through three processes, namely *learning-by-doing* (during production and installation processes), *learning-by-searching* (during R&D projects), and technology spillover (knowledge coming from other sectors) (Rivera-Tinoco et al., 2012). The learning rate of SOFC systems has been estimated by a few studies. Staffell and Green (2013) has determined the learning rate of micro-CHP SOFCs in the Enefarm pilot project in Japan (2004–2012) at 20.6% for the fuel cell stack and 11.7% for the BoP. Rivera-Tinoco et al. (2012) determined learning rates of the R&D phase in the range 13–17%, and 1–27% for the pilot and early commercial phase.

For comparison, the LCOE produced by wind turbines and PV have decreases by 61% and 82%, respectively, between 2009 and 2015 (Lazard, 2015a). These cost reductions are driven by the rapid increase of installed capacities of both technologies.

Since learning is only one of the mechanisms by which costs decrease, it can be difficult to distinguish its exact effect. Other cost reduction sources include economies of scale, automation, and raw material prices (Rivera-Tinoco et al., 2012). The former effect is discussed in the next section.

### 8.1.3 Economies of scale

The more fuel cell systems a factory produces, the lower the costs of each individual system. So by scaling up production, large cost reductions can be achieved. This can result in a positive feedback loop: lower prices will stimulate demand, which makes further upscaling possible. Besides, larger SOC systems are generally less expensive than small systems in a relative sense. The effect of economy of scale on SOFC production was quantified by (James et al., 2012). Table 8.1 and 8.2 illustrate the dependence of the fuel cell price on the production volume and the size of the fuel cell system itself. The data in the first table show a higher scale advantage than the second.

Table 8.1: SOFC system production costs in $\$/kW_e$ (James et al., 2012).

| Production | Fuel cell size ($kW_e$) | | | |
|---|---|---|---|---|
| (systems/a) | 1 | 5 | 25 | 100 |
| 100 | 11,830 | 3,264 | 981 | 532 |
| 1,000 | 6,786 | 2,168 | 671 | 440 |
| 10,000 | 5,619 | 1,862 | 599 | 414 |
| 50,000 | 5,108 | 1,709 | 570 | 402 |

Table 8.2: SOFC system production costs in $\$/kW_e$, excluding sales markup (Batelle, 2014).

| Production | Fuel cell size ($kW_e$) | | | |
|---|---|---|---|---|
| (systems/a) | 1 | 5 | 100 | 250 |
| 100 | 15,419 | 3,608 | 1,517 | 1,194 |
| 1,000 | 9,661 | 2,416 | 1,194 | 973 |
| 10,000 | 8,381 | 2,108 | 1,044 | 857 |
| 50,000 | 8,347 | 2,104 | 962 | 787 |

### 8.1.4 Actor perspectives

CE Delft has studied the transition pathways to a $CO_2$-emission free heat supply in the residential sector (Schepers et al., 2015). Some conclusions regarding the transition in heat supply are also applicable to the case of SOFCs. One important finding is related to the resistance to change of actors. In the study, a number of barriers were identified that constrain a transition. These barriers relate to how the system is perceived by the actors. First of all, stakeholders have a lack of information. It is not known throughout the sector which strategy is financially and technically most optimal. Secondly, there is a variety of perspectives among actors, in terms of scale and time horizon. Depending on their perception, each actor sets different targets. Thirdly, the ideal moment of making certain 'switches' (e.g. replacing a NG distribution network by a district heating system) is different for each stakeholder. These three challenges can be addressed by a close cooperation of the actors involved, a clear division of roles and responsibilities, and a shared vision of the aim of the transition (Schepers et al., 2015).

### 8.1.5 Multi-level perspective

The MLP was developed in the field of innovation studies, and it aims to guide the analysis of technological innovations and societal transitions (Geels, 2002, 2012). The framework distinguishes three analytical levels: socio-technical landscape, socio-technical regimes and niche innovations. Together the three levels can be understood as a nested hierarchy (Geels, 2002). The MLP acknowledges that the success of a new technology depends on processes at all three levels (Geels, 2002). Therefore, a better understanding of socio-technical changes can be achieved by assessing the dynamics of the landscape, regime, and niche. These concepts are elaborated below.

#### Socio-technical landscape

The socio-technical landscape refers to the deep structure of society in which niches and regimes are embedded. The landscape trends provides an environment and boundary conditions that are beyond the direct influence of niche and regime actors (Geels & Schot, 2007). Several examples of such landscape-factors are cultural and environmental patterns, economic paradigms, demography, wars and political developments. Landscape characteristics typically change at a slow pace, although sudden unexpected changes such as natural disasters can occur (Geels & Schot, 2007) or that. For the latter one, this means that this change in the landscape can put pressure on the existing regime creating windows of opportunity for niche innovations to break through into the regime and change (Geels, 2010).

**Socio-technical regime**

A regime is an established socio-technical system in which technologies, infrastructures, regulations, user patterns, knowledge, and cultural discourses are aligned. The actors that are embedded in a regime reproduce and maintain the rules and patterns of the regime. The stability of the regime is a result of coordination and alignment of orientation between actors. Changes do occur, but innovations often proceed slowly and in a predictable direction. Often, incremental improvements dominate (Geels, 2012). In spite of its stability, a regime can face pressure arising from developments at the other two levels (Geels & Schot, 2007)

**Niche**

Niches are the third and smallest level of the MLP. This is where radical innovations emerge and develop (Geels, 2002). A niche is a protected space, which is shielded from selection pressures governing dynamics at the regime level (Smith & Raven, 2012). Protection is provided by subsidies, demonstration projects, geographic conditions, or user groups with special needs. Within a niche, actors can learn in various dimensions, articulate expectations or visions, and build social networks (Kemp et al., 1998). These processes are important for growth of the niche. By voicing criticism on the structural problems of the regime and demonstrating alternative solutions, niche actors can exert pressure.

Both niches and regimes can be described by and are characterised by their nature in six socio-technical dimensions (Verbong & Geels, 2007; Geels, 2012; Smith et al., 2005):

- Industry structure
- Technology and infrastructure
- Knowledge base
- Markets and user preferences
- Policies and politics
- Cultural meaning

In a stable socio-technical regime, these dimensions are well-aligned, whereas they are subject to a dynamic co-evolution in niches. The characteristics that prevail in the regime form a selection pressure. Within niches, the selection pressures are less strict, which can be explained by an effect of *shielding* (Smith & Raven, 2012).

## 8.2 Actor identification

In Figure 8.1, the following (groups of) actors that are connected to the electricity and gas supply chain are identified.

**Energy producers** are companies that exploit an energy (re)source. Several powerplant operators are active in the Netherlands, such as Eneco, E.ON, and Essent. Some of them also own renewable energy plants, such as wind parks. Fossil fuels are mostly imported. An exception is NG, which is extracted from the domestic reserves by the Nederlandse Aardolie Maatschappij (NAM).

**TSOs** operate the national transmission systems. TSOs are monopolists, and are fully owned by the government. TenneT is the TSO of the high-voltage electricity network. Gasunie is the TSO of the high-pressure gas transmission network. Their task is to match supply and demand on both short and long term. Besides, TSOs are responsible for the maintenance and management of the transmission system infrastructure.

**DSOs** ensure that electricity and gas are distributed to all individual consumers. They operate, maintain, and expand the distribution systems of both electricity and gas, each in a designated area. It is enshrined in law that DSOs have to be independent organisations, without commercial connections

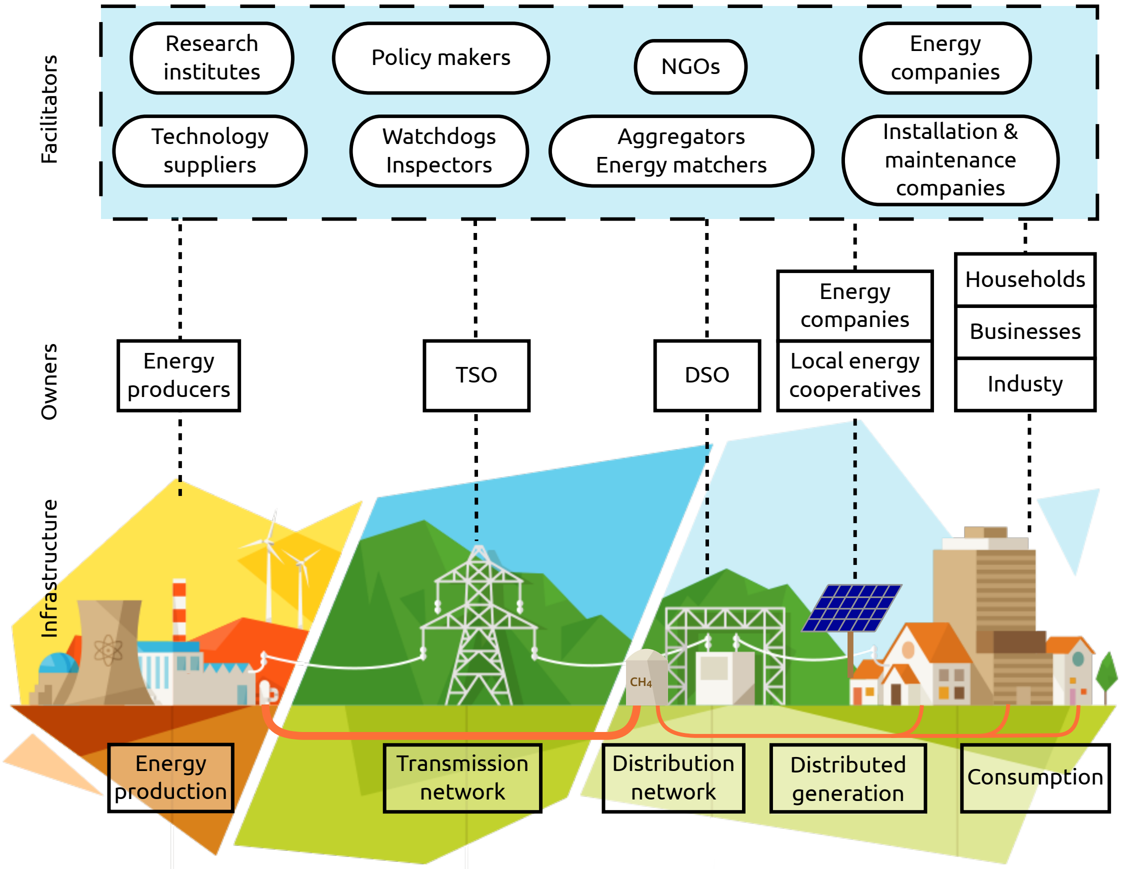



Figure 8.1: Physical energy infrastructure and connected actors. The figure applies to both electricity and natural gas supply chains. Illustration adapted from EDF Energy (2016).

with energy producers or retailers. The shareholders of all DSOs are municipalities and provinces. The main interest of DSOs is to guarantee safe and reliable energy distribution.

**Measurement and maintenance firms** perform repair and construction works, and are responsible for monitoring the consumption of energy users. These firms are typically part of the organisation of a DSO. During construction works, external companies and suppliers can be involved.

**Local energy initiatives** comprise various actors that own or operate distributed energy generation technologies. Examples are farmers, waste-water treatment plants (WWTs) or waste treatment companies that produce biogas or green gas for local use. Or solar farms and wind turbines owned by a community in the form of a cooperative (Van Bruggen et al., 2016). The installations used have a relatively small size.

**Energy consumers** include all entities that use energy. This diverse group of actors can be divided in three groups: households, businesses, and industries. The interaction of these consumers with the energy system depends on the type and amount of energy carriers they need and their demand pattern. Furthermore, local energy production, storage, or demand response at the consumer is expected to become increasingly important (Bokhoven et al., 2015).

**Energy retailers** are the intermediates between the energy wholesale market and the consumer market. They negotiate contracts with both energy producers and consumers. A number of retailers is also an energy producer itself.

**Energiekamer** is part of the Authority for Consumers and Markets (ACM), a governmental organisation that monitors market entities. The Energiekamer monitors energy market players to make sure that laws are adhered to.

**Governmental bodies** include the national administration, provinces, water boards, and municipalities. Their policies and regulations provide market actors and consumers with incentives, restrictions, and guidelines for their behaviour.

**Interest groups and NGOs** (non-governmental organisations) have the power to lobby and influence policies. They can play an important role in the mobilisation of resistance to a technology, or by providing legitimacy.

**Technology suppliers** and manufacturers develop and market technologies that are part of the energy system. For conventional technologies, suppliers are often large international companies. But also for emerging techniques, it proves important for companies to achieve substantial economies of scale (see § 8.1.3). An overview of SOFC technology suppliers is provided in Appendix B.1. Technology suppliers are interested in creating a large market share for their products.

**Research institutes** provide knowledge and new technological opportunities, which can form the basis of improved or new energy technologies. In the field of energy, the Organisation for Applied Scientific Research (TNO), the Energy Research Centre of the Netherlands (ECN), and the universities contribute significantly to the body of knowledge.

## 8.3 Regime description

In the MLP framework (§ 8.1.5), both niches and regimes can be characterised by taking six socio-technical dimensions into account, i.e. industry structure, technology and infrastructure, knowledge base, markets and user preferences, policies, and cultural meaning. This section focusses on the regime level.

The regime of the existing energy system in the Netherlands uses a linear model for the industry structure. Central production is connected with consumers via wholesale markets and energy retailers, as depicted in Figure 8.1. Consumers pay a fixed price for the consumed energy plus a fixed fee for using the transmission and distribution networks. Producers adapt to the demand in order to balance the grid. The paradigm of economies of scale ("bigger plants are more efficient") further governs policies, technologies, and knowledge base. R&D aims at gradual improvements. Energy is culturally seen as an unconditionally available commodity.

According to the MLP framework, pressures on the socio-technical regime arise from landscape and niche developments. Indeed, ongoing developments outside and within the energy system are exerting pressure on the dominant regime. These pressures affect the dynamics within the regime, as discussed below. It is relevant to discuss changes in the regime, since regime actors in turn influence niche dynamics, treated in the next section.

An important factor is the continuous trend of increasing renewable electricity production, supported by actors within the regime and several niches. As these fluctuating electricity sources become available, the flexibility of the electricity market is reduced. In fact, adjustable fossil fuel plants are replaced by sources with an uncontrolled output. The business case of remaining powerplants is undermined because the capacity utilisation declines and it is expensive to ramp the plants up and down frequently (Van den Bergh et al., 2013). From an infrastructural point of view, this means that other or new components of the energy system should compensate for the loss of flexibility. Examples include storage, demand response, etc. Taking a regulatory perspective, it might be needed to provide incentives for small actors to provide flexibility. Besides, the role of large players can be redefined by explicating their tasks and responsibilities under the new circumstances.

Currently, incumbents agree that structural changes are necessary, as witnessed by their commitment to the 'Energieakkoord' (Sociaal-Economische Raad, 2013) and a common position paper (Bokhoven et al., 2015). It is currently unclear who should take actions. DSOs see the urgency of system change most clearly, since they are aware of a changing energy demand and the impact on energy network capacity requirements. Grid refurbishments carried out now should be ready for the energy system in 2050 (Schepers et al., 2015). The question is whether DSOs should be the only actors that deliver flexibility services, and whether grid balancing fits in the role of a grid operator. Other organisations that could also bear (part of) the responsibility are energy producers and energy cooperatives. Both have operational experience and knowledge through their ownership of existing generation technologies. Therefore, they might also operate energy storage or additional conversion systems (batteries, fuel cells, PtG) to balance energy grids. Whereas energy producers have access to substantial resources to undertake this action, local cooperatives might be better geared towards the management of distributed technologies (Van Bruggen et al., 2016).

## 8.4 SOC niche innovation

### 8.4.1 Current status

Many resources are invested in research to improve SOC technology. An indication for this is given by the growing number of publications with the subject of SOFCs and SOECs, as presented in Figure 8.2. The R&D efforts have resulted in the sales of FCs growing almost every year (Figure 8.3). In 2015, 63.1 MW of SOFCs were sold. This amount is marginal compared to the terawatts of powerplants or billions of boilers installed globally. Looking in more detail at the capacity installed annually, it becomes clear that stationary FCs represent 60% of all FC types sold (Hart et al., 2015). Although small in capacity, the number of FCs applied in transport applications is big. The market for FCEVs is expected to continue growing in the near future (Hart et al., 2015), providing an increasing demand for hydrogen. Additionally, buses, trains, military vehicles, and material handling vehicles fuelled by $H_2$ have been demonstrated.

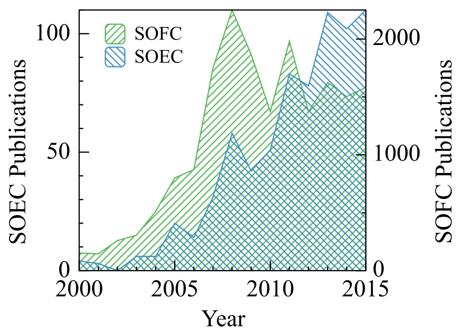



Figure 8.2: Number of articles published each year on SOFC and SOEC technology according to the Scopus ® database. Reprinted from Gómez and Hotza (2016).

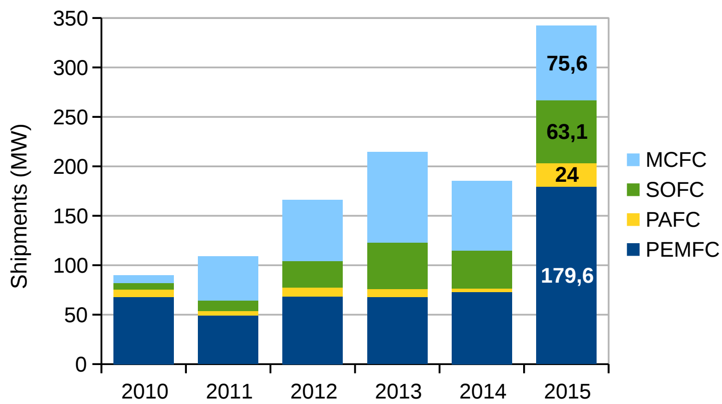



Figure 8.3: Annual fuel cell capacity shipped worldwide, in the period 2010–2015 (Carter et al., 2013; Hart et al., 2015). Amounts are decomposed into FC types: Molten carbonate FC (MCFC), Solid oxide FC (SOFC), Phosphoric acid FC (PAFC), Proton exchange membrane FC (PEMFC).

Half of the twenty SOFC manufacturers are located in Europe, while the other firms are based in Japan and the United States (Appendix B.1).

### 8.4.2 Potential system changes

Contrasting the characteristics of the existing regime with a system in which SOCs play a role, a number of differences can be identified. The most important difference is that SOCs are a distributed generation technology, for which other industry structures are more supportive than the current structure (Sauter & Watson, 2007). Central energy producers and TSOs play a much smaller role in distributed generation systems. This also affects retailers, as intermediate players between consumers and central producers. And the role of DSOs and energy retailers changes considerably if a distributed energy production structure is implemented.

New SOC technology involves new technology suppliers, and different requirements for the skills and knowledge offered by installation and maintenance firm. In terms of policy and technology, SOFCs and SOFECs profit when regulations and infrastructure accommodate for local grid balancing and exchange. Markets that are of interest are those where user preferences are focussed on energy savings, increased energy independence, and deployment of novel technology. User preferences with respect to the deployment model of SOCs are not yet clear. Possibly, consumers take care of their own device, or self-organise in local cooperatives to share responsibilities. For some consumers, the preference for energy as a service can prevail, in which case energy retailers can offer their services to operate and maintain SOC installations.

Finally, a certain alignment or cooperation with facilitating actors (see Figure 8.1) in the form of regulations and complementary technology can provide support. If distributed generation becomes the dominant practice in the energy system, a number of changes in the regulatory system should be accomplished. Energy taxation legislation has to be adapted to the new situation, taking into account the decline of tax incomes from energy retail. In addition, a coordination structure to control all distributed generation technologies should be implemented to prevent problematic system dynamics. For instance, price mechanisms or control via a central computer make sure that the energy networks are balanced properly.

## 8.5 Barriers & Drivers

This section discusses the drivers and barriers related to the diffusion and use of SOCs. Drivers can be internal strengths of the technology and niche, or opportunities provided by external regime or landscape dynamics. The same is true for barriers, which can be internal weaknesses or external threats.

### 8.5.1 Technology & infrastructure

SOCs are made of cheap and abundant raw materials. Traces of rare earth elements (La, Sc, Y, Ce) are needed for manufacturing, but the small quantities are unlikely to cause a scarcity, even at large-scale application of the technology (Thijssen, 2011). The reasons for most current customers to install SOFC products are the high reliability and low maintenance requirements. SOFCs are therefore an excellent choice at remote areas or as a backup power source (Curtin & Gangi, 2015; Carter et al., 2013). In applications for residential energy supply, the high efficiency conversion of fuel to high-value energy products is an additional strength of SOC technology.

Technological barriers that have to be overcome are degradation issues of stack materials. The effects of high temperatures and redox environments on materials within the cell are still considerable, resulting in short lifetimes. Another material-related weakness is the sensitivity to impurities, which is currently an important constraint for fuel selection. If SOCs with higher sulfur-tolerance are developed, the opportunity for efficient biogas use without cleaning processes in SOFEC or SOFC applications emerges. See also Chapter 2.

An important barrier is related to energy transport infrastructure. While the infrastructure to transport NG and electricity to and from most locations is well-established, possibilities for heat, $H_2$, and alternative fuel transport are much more limited. A fuel should be available at the location of the fuel cell installation. NG meets this requirement, since gas pipelines are present on many places, providing a reliable fuel source with a constant quality. As noted in § 2.1.4, biogas is another fuel option. Due to the limited technical possibilities for storage and transport, it is advised to convert or use biogas at its origin. Blast furnace or coke oven gas can serve as fuel too. Pipeline infrastructure for transport over small distances exists in some areas, or can be constructed. Given the limited importance of hydrogen in the current energy system, transportation infrastructure is limited. Users of small volumes of $H_2$ are supplied by trucks transporting compressed and/or cooled $H_2$. Large consumers usually own an on-site $H_2$ source. At fuel stations, $H_2$ has to be compressed before it is transferred to FCEVs. Therefore, it can be considered to compress the $H_2$ at its origin, allowing transport by truck (Chen, 2006). A distribution infrastructure to supply FCEVs is virtually non-existent.

### 8.5.2 Markets & user preferences

Although the high efficiency and cheap raw materials (see § 8.5.1) are financial drivers of SOC development, there are also a number of weaknesses. The capital-intensive production process of SOCs and the BoP (James et al., 2012), together with the limited quality in terms of service life, limit the number of current market applications. Furthermore, significant expenses must be made due to network connection fees paid to the DSO (Prag et al., 2016). Medium or large-scale installations require a special connection to the gas distribution network, unless local biogas is used and a backup fuel source is not desired. To deliver electricity to the grid, another grid connection fee has to be paid.

Market opportunities are provided by experiments with flexible electricity prices, to which SOCs can respond by changing the ratio of outputs or operate at lower rates. A R-SOC has the additional advantage of being able to switch from electricity producing to electricity consuming mode. In combination with storage of $H_2$, a reversible cell can respond to fluctuating electricity prices. Both the response time and operating window of the technology are important here.

In the future, market circumstances with high amounts of renewable electricity, combined with a flexible pricing mechanism, can provide a window of opportunity for SOCs. The same hold for feed-in tariffs, which could provide a substantial stimulant for the adoption of SOFCs.

Compared to conventional gas-fired technologies, SOCs have lower emissions, both because of the higher efficiency and the virtual absence of non-$CO_2$ emissions. Amongst some groups of users, there is a willingness to pay more for energy-saving devices. A bigger opportunity might be provided by technology frontrunners, for whom a novel device is an expression of their attitude, and costs are less important (Sauter & Watson, 2007).

### 8.5.3 Policy & politics

International agreements concerning climate change mitigation signed by the Dutch government indicate political commitment to stimulate technology with high energy efficiency and low emissions. Several (inter)national and regional subsidy options for research on and implementation of fuel cells exist. Examples include EU funding for research projects, the SDE+ subsidy, Green Deal agreements, and local stimulation policies. SOFEC projects can apply to existing subsidy programmes for renewable energy. SOFC installations can be supported by schemes for industrial efficiency improvement. Grants from the European Fuel Cell and Hydrogen Joint undertaking (FCH-JU) are available for both technologies. Another example of fuel cell-specific policy is the local stimulation of micro-CHP installations in Gelderland (Energy Company, 2015). Within Green Deals, the government helps to remove obstacles by bringing actors together and adapting legislation (Ministry of Economic Affairs, 2011).

Acquiring a permit for supplying electricity to the grid does not only involve paying a connection fee (§ 8.5.2), but also a lengthy and bureaucratic application procedure (Prag et al., 2016). In addition, SOC manufacturers, which are typically international companies, face a wide variety of standards and (safety) regulations. On a national level, not all regulations accommodate for fuel cells. A total of 13 norms were identified that apply to micro-CHP systems (Prag et al., 2016). When hydrogen is involved, an additional set of regulations apply to guarantee the safety of the installation.

Goals that guide the energy transition in the Netherlands were formulated in the 2013 agreement ‘Energy Agreement for Sustainable Growth’ (Sociaal-Economische Raad, 2013), which was supported by many (non-)governmental organisations and companies. The agreement aims to achieve a ‘climate neutral' energy supply of the built environment in 2050. This goal cannot be achieved when NG fuelled SOCs are installed at a large scale.

### 8.5.4 Cultural meaning

The cultural associations related to SOCs, and behavioural patterns can either constrain or support their diffusion. A distributed SOC system is a way of local energy production that reduces the need for centrally produced electricity. This idea appeals to several communities, and to energy production companies that seek to increase legitimacy in their customer relations. The use of biogas can increase the level of *autarky* (self-sufficiency) of a community. These considerations can prove to be an argument for households or energy cooperatives to choose for a SOC. On the other hand, an unknown new technology often faces the challenge of lacking awareness, proving its safety and demonstrating its merits to the general public. The high temperatures and the risk of hydrogen leaks make that SOCs could be perceived as an unsafe or risky technology.

The fact that SOFCs are a net emitter of $CO_2$ if NG is used as fuel is a potential threat. Life cycle assessment of SOFC use show that the largest impacts are linked to fuel supply (Strazza et al., 2015). If GHG emissions are an important criterion, then solar thermal or PV panels combined with energy storage could be a more attractive alternative for a household.

### 8.5.5 Industry structure

As discussed in § 8.3, the pressure to modify the structure of the energy supply chain is growing to achieve a more sustainable energy provision. If the industry structure is transformed, opportunities for the application of SOFC and SOFEC technology are created. SOFCs can fill gaps of low electricity production from wind and solar energy. SOFECs can respond to peaks in renewable electricity production. Furthermore, SOC installations are scalable sources of hydrogen, and can facilitate the development of $H_2$ as a transport fuel. Yet if the absence of hydrogen storage and dispensing infrastructure persists in the future, the exploitation of the full (flexibility) potential of SOCs is hampered.

The most successful business models featuring SOCs can be developed if the energy supply chains are decentralised more. This is because SOCs help to balance of production and consumption at a local level. What is more, SOC installations can maximise the useful application of energy products when they are distributed instead of located centrally. This requires an industry structure that differs from that of the current regime. For example, district heating systems are not open to heat suppliers other than the central CHP unit (Van Melle et al., 2015).

SOCs need a user of the produced hydrogen. If new applications for $H_2$ appear, this provides an opening for new technologies. This is because the existing industry structure does not provide an adequate solution for the supply to these new users.

### 8.5.6 Knowledge base

The complexity of the production process of SOCs makes that only specialised companies succeed in doing so. A considerable amount of theoretical and operational knowledge is vital for these firms. Since no manufacturers are located in the Netherlands, the knowledge base for SOC technology is assessed within the scope of Europe.

It is noted that several SOFC manufacturers are active in Europe (see Appendix B.1), all of which drive knowledge development by investing in research. As indicated by Figure 8.2, the scientific community contributes to knowledge development of SOC technology. Also in the Netherlands, there is a strong basis for R&D. Table 8.3 lists all organisations that have participated in research projects related to SOFC technology.

The expectations of stakeholders influence how much resources are invested in R&D and on what aspect the research is focussed. Currently, the majority of the European SOFC manufacturers see micro-CHP as the biggest potential application. At least six firms are actively marketing SOFC systems aimed

Table 8.3: List of Dutch organisations that participated in EU-funded research projects (as registered in Cordis (European Commission, 2016)) started between 1990 and 2016, on the topic of SOFCs. A full list of the projects in which these organisations participated is included in Appendix B.2.

| Organisation | Number of projects | Start of most recent project |
|---|---|---|
| ECN | 18 | 2010 |
| HyGear Fuel Cell Systems BV | 6 | 2015 |
| TNO | 4 | 1993 |
| Gastec NV | 3 | 1998 |
| Technische Universiteit Delft | 2 | 2015 |
| Technische Universiteit Eindhoven | 2 | 2015 |
| University of Twente | 2 | 2003 |
| Advanced Lightweight Engineering BV | 1 | 2002 |
| Brandstofcel Nederland BV | 1 | 1998 |
| Business Unit of TNO Built Environment and Geosciences | 1 | 1993 |
| Centre for Concepts in Mechatronics BV (CCM) | 1 | 2005 |
| DSM Resins NV | 1 | 1994 |
| Energy Matters BV | 1 | 2015 |
| Gasterra BV | 1 | 2015 |
| HOMA Software BV | 1 | 2011 |
| Micro Turbine Technology BV | 1 | 2015 |
| Netherlands Agency for Energy and the Environment (NOVEM) | 1 | 1998 |
| Shell Hydrogen BV | 1 | 2003 |
| Universiteit Utrecht | 1 | 2015 |

at small consumers: Sunfire, Viessmann[1], SOLIDPower, Ceres Power, Bosch and Elcogen (Hart et al., 2015). This trend affects the setup of recent research projects, such as ene.field, SOFT-PACT and PACE (European Commission, 2016), all aiming at the installation of SOFC-based micro-CHPs that replace a conventional boiler. This approach is supported by the EU, which subsidises all three projects. Another example of government support is the subsidy granted by the province of Gelderland to households that install a micro-CHP (Energy Company, 2015).

While the observed mobilisation of resources positively affects the development of SOC technology, the focus on micro-CHP instead of CHHP applications could hamper the latter. The pitfall exists that, under influence of regime actors, SOCs are used as a direct replacement of conventional heating systems. Consequently, less research efforts are invested in the capability to co-produce $H_2$, thereby cutting off the road to larger system changes.

## 8.6 Energy carrier markets

In addition to the identification of markets and user preferences in § 8.5.2, this section provides an analysis of the markets for energy carriers. When no or limited energy transport options exist, the presence of a nearby source or demand becomes a boundary condition for the application of SOCs.

To identify market niches where the application of SOFCs results in a viable business case, a range of cost aspects has to be considered. From the energy system perspective adopted in the optimisation model, only investment, O&M, and fuel costs are important. For specific applications, also taxes and sales prices have to be taken into account. These factors show large variations between cases. For instance, a lower percentage of taxes has to be paid if larger amounts of NG are consumed. And small

[1]Viessmann has acquired the SOFC manufacturer Hexis to safeguard its position in the fuel cell market (Hart et al., 2015).

consumers are willing to pay more for the SOFC products, because the alternative energy sources are more expensive for them than for large consumers (Van Leeuwen, 2016). The business case calculations done by Van Leeuwen (2016) will not be repeated here. Instead, the emphasis is put on the qualitative local market conditions of energy carriers and their role in creating a successful niche.

**Natural gas:** Large variations in NG costs exist. Bulk consumers pay much lower taxes per volume of the fuel than small consumers. Due to several developments, the price is expected to rise in the future (see Table 6.1).

**Biogas:** Possible sites for biogas-fuelled SOCs are at farms with a digestion tank, WWTs, or at organic waste treatment plants. The fuel cell can be operated to match the production of biogas, while maintaining some flexibility in the ratio of outputs. The price of biogas depends on the costs of the biomass source (or biomass collection) and the generation equipment. The latter costs can be reduced through learning and scaling up (Bergsma & Croezen, 2011), whereas both costs are dependent on the quality of the biomass.

**Industrial gas:** Blast furnace or coke oven gas can be derived from steel plants, and syngas from refineries. These industrial by-product gases are produced in large quantities in a continuous flow. Fuel cells directly compete with conventional turbines to convert the energy of the energy-rich gases.

**Electricity:** Because of its versatility, electricity is an energy carrier with a high value. The price is time-dependent, since the possibilities for storage are limited and entail losses. The production location is less important, since the extensive electricity grid allows for efficient transport. Electricity can be purchased from energy retailers. To sell electricity, a contract can be signed with large industrial users, or grid connection costs and electricity fees have to be negotiated with DSOs (see also § 8.5.2). In the future, renewable electricity sources can cause periods with very low or high electricity prices.

**Hydrogen:** There is a limited number of applications for hydrogen. In § 5.3.3, $H_2$ fuel stations and the fertiliser and petrochemical industry were identified. In general terms, larger users expect lower prices (Energinet.dk, 2011). A niche market not discussed before, are firms that need hydrogen in small amounts. Applications are found in industries producing among others food, semiconductors, electronics, and chemicals. Most of these users currently rely on centrally produced $H_2$, which is transported by truck or pipeline (Energinet.dk, 2011). Current costs of $H_2$ are substantially higher in this niche compared to the bulk consumers. The price is influenced by the transport distance from the central production site (Chen, 2006). Given that FCEVs are an emerging technology, the hydrogen market for this purpose is not fully established yet. Therefore, competing $H_2$ production options and the corresponding prices are to some extent uncertain. What can be said is that $H_2$ is produced either locally or centrally, can be transported by pipe or truck, and can be stored in a tank or other medium. At fuel stations, hydrogen has to be compressed before it is transferred to FCEVs. Therefore, it can be considered to compress the $H_2$ at its origin, allowing transport by truck (Chen, 2006).

**Heat:** Heat produced by SOCs can be most effectively used by industries that need high-temperature heat. Heat exchangers can convert the heat to lower temperatures, although this results in a loss of exergy. In that case, heat can be supplied to district heating systems. A third possible destination are greenhouses, which need heat to maintain the indoor temperature during winter. Although industrial and residential district heating systems are not open for competition (Van Melle et al., 2015), SOCs will face compete to some extent with industrial sources of waste heat and CHP plants. Heat users have local heat production technologies as alternative. The considerable investment costs for heat transport infrastructure makes them attractive only when a cluster of heat consumers is located nearby (Stryi-Hipp, 2009). This can be the case in industrial areas, densely populated cities, or greenhouse areas.

## 8.7 Niche strategies

Building on the analysis of drivers, barriers, and energy carrier markets, niches that are favourable for SOFC and SOFEC development can be identified. Niches that have a higher level of protection from regime selection pressures are generally more successful. Therefore, this section focusses on configurations that are passively shielded, and suggests options for active shielding.

An important decision parameter is the size of the system. This is a trade-off between investment costs (which are lower for larger systems; § 8.1.3) and the distance to suppliers and consumers (which tend to be higher for larger energy flows). The proximity is particularly important for biogas and industrial gas sources, and heat consumers. Micro-CHPs are positioned at the extreme end of the spectrum, with a size that matches the demand of a single household. While this seems attractive in terms of ownership and grid connection procedures, there are some disadvantages. When operated to follow the demand of heat or electricity of the household, only low capacity utilisations are attained. The optimisation results have shown how SOFC operation at high capacity utilisation is cost-effective for the system as a whole and for the SOFC installation. Therefore, it is a better strategy to install a somewhat larger fuel cell for a block of houses, an apartment building, or (part of) a neighbourhood. By supplying a group of households, the capacity utilisation is higher. Besides, the specific investment costs are lower, and the financial risks are shared.

Another trade-off concerns the flexibility in operation. The mode of operation of the installation can be adapted to match either the availability of resources, the need for products, or combinations of these. The optimisation results from Chapter 7 have shown that a SOFC has sufficient flexibility to respond to demand variations when NG is used as fuel. A source of flexibility not discussed before is the use of NG as a backup fuel to replace biogas.

### 8.7.1 SOFEC niches

From the considerations above, it becomes clear that the operation of a SOFEC is dictated by the availability of low-priced electricity and biogas or industrial gas from a nearby source. When located at a steel plant, a SOFEC can convert blast furnace gas streams to $H_2$ for a user in the same industrial area. In this application, SOFEC faces strong competition on price with SMR. Protection can be provided if the companies involved exempt the pilot project from profitability targets, and/or receive a subsidy for industrial efficiency improvement. The practise of continuous operation of steel plants on the one hand disables adaptive operation in response to electricity prices, but on the other hand ensures a high capacity utilisation. Similar reasoning applies to the use of syngas by a SOFEC at refineries.

Another site for SOFECs could be at a farm or WWT with a digester. For this setup, a conflict between the inputs arises. The SOFEC is either operated to profit from cheap electricity, or to operate continuously and use all biogas. The optimal choice is to adhere to the latter strategy, even if this means that some of the biogas is not used (§ 7.7.4). Therefore, a SOFEC provides a constant supply of $H_2$ and heat in this setup. In the case of a farm, trucks frequently deliver or collect goods. These trucks can be fuelled by hydrogen, providing a reliable consumer. As noted in a case study for a brewery, this project should be set up in collaboration with the involved transport companies (Van Leeuwen, 2016). When also greenhouses are located near the farm, the SOFEC installation represents an extra source of income.

What limits the attractiveness of this second option is the price of electricity, which is considerably larger than in the model because of taxes. In particular in the near future, with modest renewable electricity production, a SOFC can be a better alternative in terms of cost savings (see § 7.6). In the optimisation results, SOFECs only marginally help to reduce the pressure on the electricity distribution grid. Incentives to increase responsive operation can be provided by amplifying the price signals of the wholesale market.

Taking these considerations into account, the best strategy for SOFEC development seems to be diversification, i.e. by focussing on SOFC technology first. The knowledge and experience gained during SOFC development are to a large extent applicable to SOFECs. After 10 or 20 years, the decreased manufacturing costs provide SOFECs with a higher competitiveness. By that time, the share of renewable electricity production is likely to be larger, providing additional incentives for its introduction.

### 8.7.2 SOFC niches

A possible location for a SOFC is at a fuel station with a nearby heat consumer. The installation is sized to meet $H_2$ demand by FCEVs. An incentive for entrepreneurs to install a SOFC system, is to gain a market share in this developing market. Comparable to the market for BEV charging, investors are willing to make losses in the first years, as long as the market is expected to grow rapidly (Van Gurp, 2016). Even if the growth in $H_2$ demand does not meet expectations, the SOFC can still generate income from electricity production by operating at high $U_f$. Because of the low variable O&M costs, the installation has a low marginal electricity cost and therefore a high capacity utilisation.

As discussed for SOFECs, a SOFC can also be fuelled with blast furnace gas from a steel plant, or biogas from a digester. Again, $H_2$ can be used as truck fuel, while electricity is produced for individual use or feed-in to the grid. In this setup, higher electricity prices are favourable, as they cause the SOFC to pay of earlier. After all, electricity generated on-site becomes more attractive compared to taxed external power. Due to the centralised nature of steel plants and the segregated location of farms, it might not always be feasible to find a nearby destination for all heat produced.

Businesses with a small volume $H_2$ demand, for whom higher prices are acceptable, a SOFC system can be attractive. These users can save on transport by installing a small stack, operated to produce $H_2$ when needed. It is likely that most of these firms are located at industrial areas, so a customer for the co-produced heat is nearby. Electricity can be used by the company itself, or delivered to the grid. A profitable business case might not be a sufficient incentive for these actors, as the expenses on $H_2$ are small relative to the total turnover. To overcome the resistance to change, the process of financing, designing, installing, and certifying the system should be clear and straightforward. Installing a SOFC can also be a means to emphasise the role of the company as a frontrunner, and to distinguish itself from competitors.

A SOFC system can also be integrated in a local community energy system. Neighbourhoods that are conscious about energy and have an ambition to reduce their environmental impact are suitable communities (Van den Hil, 2015). People with this attitude are often willing to try new technologies and are less focussed on (short term) financial benefits (Sauter & Watson, 2007). By collectively investing in a SOFC installation, the members of of the community or cooperative have access to locally produced heat, electricity, and hydrogen. This setup can complement local renewable electricity and heat production. When some storage volume for heat and $H_2$ is included, it can be operated to primarily respond to electricity market fluctuations. A prerequisite for this niche is that a heat transport infrastructure is present or can be installed, and that at least some people drive in FCEVs. A lower carbon footprint can be achieved when a biogas source is near. Yet, there is a limited number of neighbourhoods with a manure or waste-water digester in the proximity. To guarantee security of supply NG can be used as backup. The chance for successful growth of the niche is increased if many stakeholders are involved. DSOs, energy retailers, and municipalities can provide expertise and support, as they also do in a dozen of other pilot projects (Gerdes et al., 2014).

Each of these applications can be facilitated by (local) governments through temporary subsidies or a Green Deal agreement. A better alignment of the practice of SOFC use and legislation can be accomplished by making a Green Deal. To convince policy makers of the need for stimulation, interest groups or individual actors can lobby and bring SOC technology under the attention.

## 8.8 Conclusion

This chapter has provided an overview of the socio-technical system related to the energy supply chain in the Netherlands. Learning effects and economies of scale determine how fast cost reductions of SOC technology will go. The technology development and its potential were assessed from a social point of view using the MLP. This framework features the concept of hierarchically nested levels, i.e. niche innovation, socio-technical regime, and socio-technical landscape.

Table 8.4: Potential niche markets for SOFCs and SOFECs and factors that influence chance of successful implementation.

| Niche | Boundary conditions | Motivation/Barrier | Suitable sites |
|---|---|---|---|
| All | Heat and $H_2$ consumers in proximity.<br>Electricity grid connection.<br>Gas network connection or near other fuel source. | | |
| **SOFEC** | | | |
| Refinery or steel plant | Subsidy to be competitive with SMR. | High capacity utilisation. | Many |
| Farm or WWT | Arrangement with $H_2$-fuelled trucks. | Generate income from by-product.<br>High electricity price. | Some |
| **SOFC** | | | |
| Fuel station | Produce sufficient $H_2$ to charge FCEVs. | Gain market share in $H_2$ for transport market. | Many |
| Farm or WWT | Biomass digester present.<br>$H_2$ trucks frequently pass. | Generate income from by-product.<br>Difficult to find heat users. | Some |
| Small industrial $H_2$ users | Meet own $H_2$ needs.<br>Guaranteed heat consumer. | Save on $H_2$ acquisition costs.<br>Complicated installation and regulation process. | Some |
| Energy cooperative | Dedication of most neighbours.<br>Presence of FCEVs and district heating system. | Energy independence.<br>Complement electricity and heat production.<br>Support from other stakeholders. | Limited |
| Sustainable community | As above.<br>Located near a biogas source. | Sustainable energy provision. | Few |

Within the dominant regime of energy production and consumption, there is no fully developed solution to address the challenge of increased fluctuations of electricity demand and intermittent production. From the perspective of regime actors, the roles should be redefined to provide flexibility and maintain the balance on the electricity grid. From the perspective of the SOC niche innovations, there are several drivers, but also barriers, that influence the development towards a role in a new regime. Few activities are taking place around SOFECs. It does not need to be problematic that efforts are suspended, given that SOFEC technology becomes more attractive in the future, with lower electricity prices and lower SOC costs. The SOFC niche is active, with several demonstration projects and market introductions in the area of micro-CHP applications. These dynamics could result in an uptake in the existing regime structure without exploiting and exploring the capability of SOFCs to co-produce hydrogen.

It is deemed crucial that a user for the energy products of the SOFC or SOFEC is found. Therefore, the energy carrier markets for inputs and outputs form the starting point for identifying market niches, in which the SOC technology can be introduced first. In these niches, the SOC need not be financially profitable from the beginning, since the involved actors are motivated by other aspects of the technology. The potential niche markets that were identified are summarised in Table 8.4. This table also lists expected motivations and barriers for the stakeholders. Barriers to be overcome include the high investment costs, regulations for equipment, and procedures and costs associated with NG and electricity grid connections. Drivers for the adoption of SOCs can be the high efficiency and low emissions of SOFCs and SOFECs, policies such as Green Deal agreements, and commitment of other stakeholders to learn from pilot projects.

# Chapter 9

# Discussion

## 9.1 Sensitivity analysis

### 9.1.1 Setup

| GHG tax | Scenario | Restrictions | SOC costs |
|---|---|---|---|
| 30 €/t$CO_2$-eq. | Diversity | see Table 9.1 and 9.2 | II, see Table 6.4 |

It should be kept in mind that the results obtained using the model – especially quantitative results – are dependent on the set of assumptions made. While it is impossible to assess the sensitivity of all assumptions listed in Chapter 6, the results described in Chapter 7 give incentive to investigate two technologies in more detail. These technologies are Li batteries and PV (see also § 6.4.1 and 6.3.1, respectively). Both technologies have shown a rapid cost reduction in the past decade, and it is assumed that this trend will continue (Lazard, 2015a, 2015b). Yet, even when assuming the costs for these technologies expected in the future, their role is of limited importance. The installed capacity is expected to be larger. Battery technology has a potentially important role in systems with large amounts of intermittent electricity sources (Mulder, 2014). At most 9 $GW_e$ of PV is installed in the most favourable scenario, but hardly any at a GHG tax of around 10 €/t$CO_2$-eq. (Figure 7.19b). Therefore, the effect of the costs assumed for both technologies on the optimisation results were investigated. The results are discussed below.

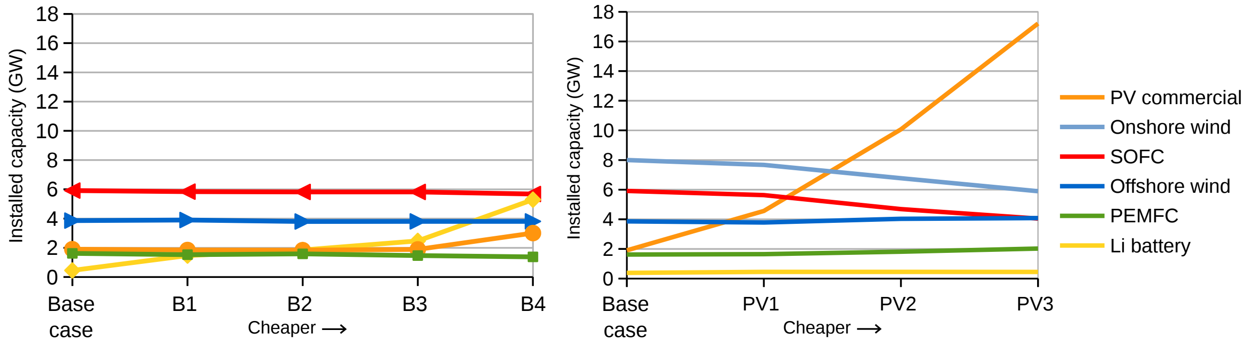
### 9.1.2 Cheaper batteries

As presented in Table 9.1, four scenarios with decreasing costs associated with batteries were optimised. The change to cheaper batteries for electric energy storage has only a modest effect on the other energy system components. The installed capacity of batteries increases from around 0.45 $GWh_e$ in the base case to 5.3 $GWh_e$ for the B4 scenario (Figure 9.1a). Cheaper storage has a positive effect on the penetration of PV, since the daily production peaks can be stored for later use. The results show that cost-effective batteries can replace some peak production powerplants. The installed capacity of SOFCs, PEMFCs, and hydrogen tanks marginally decreases with decreasing battery costs.

Table 9.1: Definition and optimisation outcomes of scenarios featuring Li batteries with different costs.

| | Base case | B1 | B2 | B3 | B4 |
|---|---|---|---|---|---|
| Investment costs (€/kWh) | 225 | 175 | 150 | 125 | 100 |
| Variable O&M costs (€/kWh) | 9.015 | 1 | 0.1 | 0.05 | 0.01 |
| Installed capacity (MWh) | 453 | 1473 | 1851 | 2473 | 5294 |
| Electricity production (TJ/a) | 1.39 | 6.27 | 9.87 | 29.2 | 1916 |

Although the use of batteries is affected by the large cost reductions studied here, the effect on SOFCs is small. It can be concluded that the two technologies do not compete, as they have different functions in the energy system. Therefore, the conclusions with respect to SOFCs are valid also when batteries are less expensive.




(a) Change of costs of Li battery component, see Table 9.1.

(b) Change of costs of PV commercial component, see Table 9.2.

Figure 9.1: Sensitivity analysis of the assumptions for two emerging technologies. Further assumptions: 30 €/t$CO_2$-eq. emission tax, diverse demand scenario, SOFC available with costs expected in 2020.

### 9.1.3 Cheaper PV

Commercial PV installations are cheaper than domestic ones. Since the limit to the installed capacity of commercial PV is not reached, domestic installations are not present in an optimal system. The effect of cheaper installations is considerable, as shown in Table 9.2 and Figure 9.1b. In the base case, 1.9 $GW_e$ of PV is installed, which increases to about 17 $GW_e$ in the PV3 scenario.

Table 9.2: Definition and optimisation outcomes of scenarios featuring commercial PV with different costs. The lifetime is assumed constant at 15 a.

| | Base case | PV1 | PV2 | PV3 |
|---|---|---|---|---|
| Investment costs (€/kW) | 660 | 600 | 500 | 400 |
| Fixed O&M costs (€/MW) | 6.591 | 6 | 5 | 4 |
| Installed capacity (GW) | 1.91 | 4.56 | 10.1 | 17.2 |
| Electricity production (PJ/a) | 8.94 | 21.4 | 47.2 | 80.7 |

Both the installed capacity and annual production of SOFCs decrease by about one third for decreasing PV costs. PV replaces the electricity, SMR produces the remainder of hydrogen, and electric boilers (indirectly using solar energy) fill the gap of decreasing heat production from SOFCs. Therefore, it is possible that a lower number of SOFC installations is optimal in the future energy system, compared to what was found in Chapter 7.

## 9.2 Break-even analysis

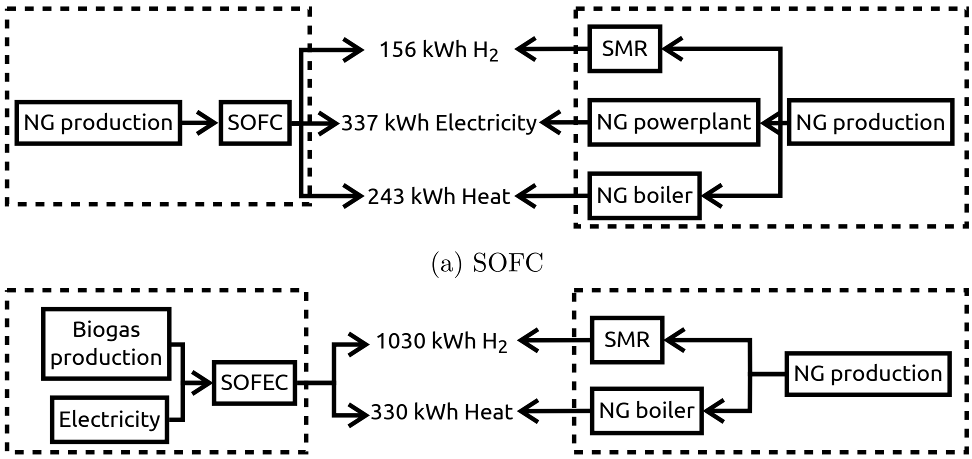
As can be concluded from Figure 7.7, the fuel costs are an important factor in the cost structure of SOFCs and SOFECs. The price of these resources was specified either directly (e.g. for NG) or indirectly by assuming costs of other technologies (e.g. for biogas). In either case, the results can be sensitive towards changes in these assumptions. Since the combination of many input parameters plays a role in establishing the energy prices, it laborious to assess each of them individually. Instead, the influence of the fuel prices on the levelised costs of energy from SOFC and SOFEC installations are assessed in a break-even calculation in this section. To do so, the levelised cost calculated for a SOFC and a SOFEC are compared with the costs of an alternative combination of conventional technologies. The comparison is made on a basis of equal energy outputs.

A SOFC operated at $U_f = 85\%$ and $i = 1.1$ A/cm$^2$ generates 0.156 MWh $H_2$, 0.337 MWh$_e$, and 0.243 MWh heat per MWh NG consumed (Eq. 3.27). An alternative pathway, also based on NG as energy source, is composed as depicted in Figure 9.2a. This alternative produces the same amounts of energy carriers by means of SMR, NG boiler, and NG powerplant. The break-even point can be found by comparing the levelised costs (expressed in Eq. 4.1) of the two alternative pathways:

$$\begin{aligned} \text{LCOE}_{\text{conv}} &= D_{\text{H}_2} \cdot \text{LCOE}_{\text{SMR}} + D_{\text{P}} \cdot \text{LCOE}_{\text{PP}} + D_{\text{Q}} \cdot \text{LCOE}_{\text{boil}} \\ &= \text{LCOE}_{\text{SOFC}} \end{aligned} \tag{9.1}$$

Most parameters are assumed fixed: the properties of the conventional technologies were adapted from Chapter 6, the CU is identical for all technologies, and for the SOFC we assume that $C_{\text{var}} = 5.5$ €/MWh and CRF=11.7%. Then, Eq. 9.1 can be rewritten to find the break-even investment costs of a SOFC:

$$C_{\text{inv,SOFC}} = 311 + (24.9\, C_{\text{NG}} + 11.9\, tax_{\text{GHG}} - 341) \cdot \text{CU} \tag{9.2}$$




(a) SOFC

(b) SOFEC

Figure 9.2: Reference systems for energy production by a SOFC or SOFEC (left) or conventional alternatives (right).

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This equation indicates that the capacity utilisation has a big influence on the break-even point. Higher SOFC investment costs are acceptable if a high CU can be realised. Higher NG prices and GHG taxes also positively affect the competitiveness of SOFCs. The effect of a 1 €/MWh increase of the NG price has roughly the same effect as a tax increase of 2 €/t$CO_2$-eq.. The break-even investment costs are plotted in Figure 9.3 as a function of CU and $C_{\text{NG}}$. In the upper right corner of the plot represents the most favourable set of conditions, where $C_{\text{inv}} \leq 1000$ €/kW makes the SOFC competitive. This value for the investment costs increases to about 1550 €/kW if a 50 €/t$CO_2$-eq. emission tax is applied. It should be kept in mind that this analysis is about the full replacement of one system by another (the alternatives in Figure 9.2a), by assuming an identical CU for both. Yet in practice, the alternatives can coexist and complement each other. For example, one technology fulfils a base-load function, while another operates for peak production. Consequently, SOFCs could already be introduced successfully with higher costs than calculated here.

A similar approach is used to assess the break-even point of a SOFEC. When operated at $U_f = 80\%$ and $i = 1.3$ A/cm$^2$, a SOFEC generates 1.03 MWh H2, 0.330 MWh heat, and consumes 0.433 MWh$_e$ per MWh biogas consumed (Figure 9.2a). A combination of an SMR and a NG boiler that together produce the same amounts of energy form the alternative. Most parameters are assumed fixed: $tax_{GHG}$=0 €/t$CO_2$-eq., CU=1, the properties of the SMR and boiler were adapted again from Chapter 6, and for the SOFEC we assume that $C_{\text{var}} = 5.35$ €/MWh, CRF=11.7%, and electricity consumed

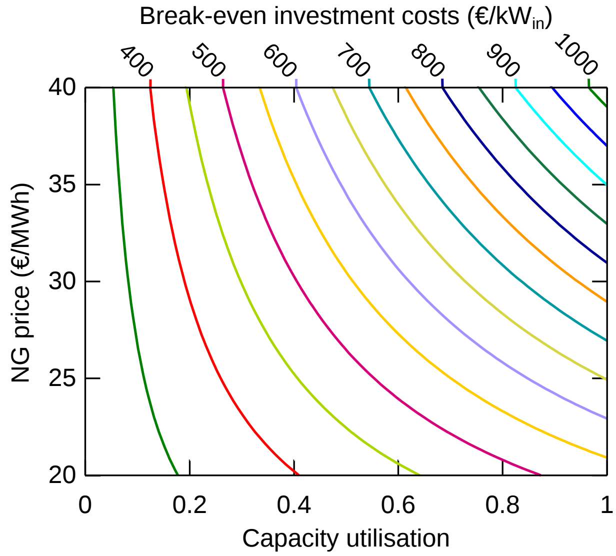


Figure 9.3: Investment costs of SOFC at which combined heat, hydrogen, and power production is equally expensive as the alternative of using SMR, a NG boiler, and a NG powerplant. The GHG tax is 5 €/t$CO_2$-eq.

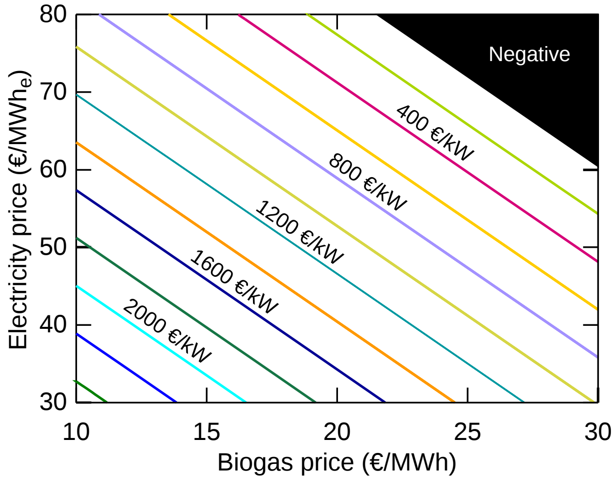


Figure 9.4: Investment costs of SOFEC at which combined heat and hydrogen production is equally expensive as the alternative of using SMR and a NG boiler. The capacity utilisation is 1.

has no GHG emissions. As above, $C_{\text{inv,SOFEC}}$ can be described by equating its LCOE to the alternative's LCOE:

$$\begin{aligned} \text{LCOE}_{\text{conv}} &= D_{\text{H}_2} \cdot \text{LCOE}_{\text{SMR}} + D_{\text{Q}} \cdot \text{LCOE}_{\text{boil}} \\ &= \text{LCOE}_{\text{SOFEC}} \end{aligned} \tag{9.3}$$

$$C_{\text{inv,SOFEC}} = 4212 - 75.0\ C_{\text{biogas}} - 32.5\ C_{\text{P}} + 26.4\ tax_{\text{GHG}} \tag{9.4}$$

Of course, a higher price of biogas and electricity decreases the break-even investment costs. The effect of both resources' prices are shown in Figure 9.4. A larger amount of biogas is used by a SOFEC, so the price of it is about twice as important as the electricity price. The biogas price estimated from the data in Chapter 6 is 28 €/MWh, which is somewhat higher than the current NG price. This price might decline due to efficiency improvements or through co-location with a cheap biomass source. Yet, increased competition for biomass or -gas could increase the price. As illustrated by Figure 9.4, the larger range of electricity prices provide opportunities. The higher the biogas price, the less electricity should cost to generate profit. There is also a relation with CU: lower electricity prices are low only a fraction of the time. Thus, the lower the required price, the lower the CU.

## 9.3 Validation

The calculations made in § 9.2 have demonstrated the influence of energy prices on the break-even point of SOCs. Combined with the variety of price levels (§ 8.6) for energy consumers, it is evident that the business case is dependent on the specific situation in which the SOC is implemented. To validate the results of the break-even calculation and the break-even costs found in § 7.5, a comparison with values obtained by other studies is made. No other optimisation models have studied the role of SOFCs with hydrogen co-production or SOFECs yet. Therefore, assessments of SOFCs used as (micro-)CHP are reviewed.

In the study of Pruitt et al. (2013), SOFCs for energy supply of various commercial buildings were considered. A hotel in California benefits from a SOFC CHP installation if it costs less than 4500 \$/kW$_e$, and 2500 \$/kW$_e$ for a hotel in Wisconsin. Whether GHG emission taxes support SOFC introduction or not depends on the situation. A comparison of a SOFC and a microturbine for the distributed generation of electricity was made by Strazza et al. (2015). Both alternatives have the same LCOE if the investment costs of the SOFC are 2450 €/kW$_e$ for households and 2300 €/kW$_e$ for industrial users. One reason why this break-even point is lower than that determined by Pruitt et al. (2013) is the fact that heat is not considered as a product. Hauptmeier et al. (2016) have assessed a SOFC system fuelled by biogas from a WWT. The results are highly dependent on the assumed electricity price and discount rate. The break-even point of the investment costs lies at 4500 €/kW$_e$ for the best or 1900 €/kW$_e$ for the worst case assumptions.

## 9.4 Cost reduction

For several experiments in Chapter 7, the SOC cost predictions from Energistyrelsen and Energinet.dk (2015) were used for guidance. One finding was that SOFCs become competitive starting from an investment cost of around 825 €/kW NG, or 1710 \$/kW$_e$. The question can be asked whether it is realistic that these cost target is reached in 2020, or else when it will be reached. To get an idea of the evolution of the investment costs in the future, the concept of learning rates introduced in § 8.1.2 is used. Considering the learning rate ranges found in literature (Rivera-Tinoco et al., 2012; Staffell & Green, 2013), a rate of 18% is used for the calculations following in this section.

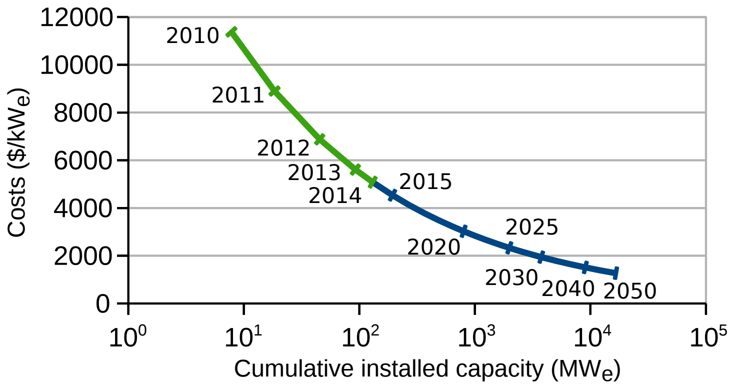


Figure 9.5: Possible cost reduction curve of the investment costs of SOFCs as a function of the cumulative installed capacity. The learning rate is 18%.

In Figure 9.5, the SOFC investment costs are plotted against the cumulative installed capacity. As a point of reference, the costs in 2014 are taken to be 5080 \$/kW$_e$ (Lazard, 2015a). To assign the year in which a cost level was reached in the past, the cumulative installed capacity in the period 2009–2014 was used (Hart et al., 2015). The capacity installed in the future was estimated by linear extrapolation of the shipped amount of SOFCs in the past five years (see Figure 8.3).

When Figure 9.5 is compared with the numbers from § 9.3, one would expect that the first applications of SOFCs become competitive within the coming five years. On the other hand, it might not be before 2040 that the point of 1710 \$/kW$_e$ is reached.

# Chapter 10

# Conclusion

## 10.1 Conclusion

The aim of this research is to assess the feasibility of including SOFCs and SOFECs in a future national energy system. Therefore, the technical feasibility, the effects on the energy system and its eco-efficiency, the required technical modifications of the energy system, and the societal dynamics of stakeholders were assessed. In this section, the answers to the research questions are summarised.

**Is it technically possible to operate SOCs in both normal and fuel-assisted electrolysis mode?**

By reviewing existing literature, the technical possibilities of SOFC and SOFEC technologies were assessed. SOFCs that co-produced heat and power have been extensively investigated at lab scale and in demonstration projects. Commercial installations are deployed as micro-CHP or as auxiliary power units. The possibility of hydrogen production by IR-SOFCs has been demonstrated in the lab. The same is true for the hybrid or reversible SOFEC concept. A reversible SOFC/SOEC system has been manufactured and employed at commercial scale.

A key limiting factor in the performance of SOCs is their limited lifetime. To address this issue, degradation of the electrodes at microscopic level should be minimised. This can be achieved by using other electrode materials or manufacturing methods. Recent research indicates that regular switching between fuel cell and (fuel-assisted) electrolysis mode can also prevent degradation.

To obtain a representation of the input-output relations of SOFCs and SOFECs, a 1-D model was used. In the SOFC model, hydrogen production was taken into account. Non-linear equations with two degrees of freedom were derived for both technologies. These equations have a suitable level of detail to represent the possible ratios of outputs and the freedom in the total throughput. In further analyses, this has proven useful for the assessment of technology operation.

The derived equations were used to implement SOFC and SOFEC components in oemof, an energy system optimisation framework. Then, the framework was used to model the energy system of the Netherlands in its current and possible future configurations. The model covers all major energy carriers, i.e. fossil fuels, electricity, heat, biomass, and hydrogen, allowing to assess technologies with multiple outputs. It models the system on an hourly basis during one year, taking into account the dynamic patterns of production and consumption. By doing so, it is the first optimisation model of its kind for the Netherlands. Not all aspects of the real energy system are represented in the model. Most notably, energy transport and demand response are not included.

**What is the optimal operating strategy for SOCs?**

The model was used to calculate the optimal set of technologies and their operation under different scenarios of SOC costs, demand compositions, and GHG emission taxes. The results allowed to study among other things the optimal operating strategy of SOFC and SOFEC installations.

Flexibility in the operation of SOFCs proves to be useful for responding to fluctuating hydrogen and electricity demand patterns. At low electricity demand, low fuel utilisations are used, whereas a setting with high $i$ and $U_f$ is used if the electricity demand is relatively high. The three factors investigated – emission tax, demand, SOFC costs – all influence the operation. When a small number of SOFCs is installed (because of high costs), operation with high $H_2$ output is optimal. At large-scale introduction, SOFC operate to produce more electricity and to be more flexible.

In the Diversity scenario (with high demands for both heat, hydrogen, and electricity), a wide range of settings is used. This requires a BoP design that can handle changes in mass and energy flows, plus an advanced control system that responds appropriately to changing market conditions. This control mechanism should take into consideration thermal gradients and temperature changes associated with this. The operation of a SOFC in the other demand scenarios displayed a different pattern. Only two or three operating points were used frequently, while other settings were applied seldom. Thus, the composition of the energy demand determines how SOFCs are operated optimally.

For SOFECs, the optimal operating strategy is also characterised by a high $H_2$ production. This is achieved by operating around a fixed, optimal $i$. Degradation due to temperature changes is therefore less of an issue in this application. There are also less restrictions on the ramping rate, since SOFECs are ideally operated almost continuously, contrary to regular electrolysers.

**Are SOCs a cost-effective addition to the current Dutch energy system?**
Both SOFCs and SOFECs with the current characteristics are not competitive as an additional component of the Dutch energy system. If significantly lower costs are assumed, SOFCs can play a role as a replacement for SMRs and NG powerplants as source of hydrogen and electricity. SOFECs are not effective in the current system.

**At what cost level are SOCs a cost-effective component of the future Dutch energy system?**
Since the costs of SOFC and SOFEC technologies are expected to decrease in the future, it was investigated at what point they become competitive. This was done by adapting the economic properties of SOCs in steps, and optimising their role in the Dutch energy system each time. The system was optimised without pre-defined installed capacities of existing technology. The LCOE of SOFCs should be reduced to 94–104 €/$MWh_e$ to be cost-effective in a future energy system with 20 €/t$CO_2$-eq.. This implies that investment costs of below 1000 €/$kW_e$ are required. Another important finding is that the production of $H_2$ increases the profitability of SOFCs, as witnessed by the potential to replace a major part of SMR installations.

SOFECs cannot realise significant energy system cost reductions, in particular in systems with limited renewable electricity. On the one hand, a SOFEC faces competition with other $H_2$ sources, and on the other hand upgrading to green gas is a good alternative application for biogas. Very low investment costs or high GHG emission taxes are required to make SOFECs attractive for the energy system. And even then, only part of the hydrogen demand is met by a SOFEC.

**What changes in GHG emissions and primary energy consumption result from the introduction of SOCs?**
A financial driver for the introduction of SOFCs is their resource-efficiency and low emission of GHGs. The life-cycle savings on fuel compensate for the high investment costs of SOFCs compared with competing technologies. SOFCs can support a transition from coal to NG as energy carrier. Additionally, the primary energy use and emissions of the energy system decrease when SOFCs are introduced. An average reduction in GHG emissions of 5% is achieved by adding SOFCs to the system. Yet, no supporting effect of SOFCs on the share of renewable energy was found. SOFCs with sufficiently low costs can even reduce the optimal capacity of solar and wind energy.

**What effect do GHG emission taxes have on the economic feasibility?**
Since SOFCs and SOFECs are more efficient and use less polluting fuels than alternative technologies,

higher GHG emission taxes are favourable for their deployment. SOFECs are almost carbon neutral due to the use of biogas as a fuel. Consequently, a SOFEC profits from the stimulation of renewable energy use. If NG were used, the technology is not attractive.

For SOFCs, a 10 €/t$CO_2$-eq. higher tax has a similar effect on the break-even point as a 9% lower LCOE. Also, the competitiveness of SOFCs increases for higher NG prices because of the efficiency. Only when very high taxes of around 100 €/t$CO_2$-eq. are applied, the attractiveness of SOFC technology starts to decline. Therefore, SOFCs can contribute to the first steps of GHG emission reduction at low societal costs. Taxation of either GHGs or fossil fuels directly are possible policies that promote SOFCs and SOFECs.

**How can the transition towards a system with SOCs take place in terms of technology replacement?**

Whether SOFC of SOFEC installations are a cost-effective addition to the energy system depends on the technologies that are already installed. As a consequence, the introduction of the new technologies was shown to occur somewhat later than expected purely based on costs. A growing demand for hydrogen by new (distributed) applications can provide opportunities for the installation of SOCs.

**What are potential niche markets, in which SOC technologies can be applied first?**

The optimisation model only selects technologies if they contribute to the effectiveness of the energy system. Therefore, no conclusion can be drawn for the economic feasibility of SOFC or SOFEC applications in specific market conditions or business cases. To give a better view on the possibilities for introducing the first SOC installations, potential niches were studied.

These first market applications are established through arrangements of involved stakeholders, who are interested in technology development and experimentation with less focus on short-term financial profit. The market and infrastructure for the involved energy carriers provide important conditions for possible applications. Electricity and NG can be exchanged with the distribution network at many locations. Alternative fuels can be supplied by WWTs, farms, steel plants, or refineries. There are often heat consumers nearby, but the transport infrastructure is not always present. Hydrogen can be supplied to firms with a small volume demand, to FCEVs parked in residential areas, or FCEV fuel stations. Examples of identified niche applications include a farmer who uses biogas from manure digestion and supplies $H_2$ to trucks, or a neighbourhood community that invests in a common CHHP installation.

**How can the development and diffusion of SOC technology in the Netherlands be promoted?**

The MLP framework was applied to analyse interactions and dynamics of the dominant regime and the SOC niche innovation. Existing barriers include the high investment costs, divergence of regulations for equipment, and procedures and costs associated with NG and electricity grid connections. To convince potential users, these perceived barriers can be addressed or the advantages of SOCs can be emphasised. The high efficiency, low emissions, and importance for local grid balancing of SOFCs and SOFECs are arguments in favour of these technologies. In addition, the commitment of other stakeholders in pilot projects or through Green Deal agreements can stimulate the adoption.

## 10.2 Recommendations

### 10.2.1 Energy consumers

The results of this study are of limited direct importance for consumers. This is because the total system costs are considered, ignoring any taxes, service fees, subsidies, and (in)variability of energy prices. Other studies, in which these factors were taken into account, suggest that the break-even investment costs are higher than those calculated here (see § 9.3). It is likely that a SOFC is financially attractive earlier than a SOFEC, in line with the total system results.

### 10.2.2 Policy-makers

As predicted by for example Schoots and Hammingh (2015), the NG reserves of the Netherlands will be depleted to a large extent around 2030. Therefore, policy-makers can ask the question whether it is worthwhile to invest resources in the development of SOFC technology, which relies on NG. In particular micro-CHPs do not comply with the goal of an emission-free residential sector (Sociaal-Economische Raad, 2013). There are several facts that make SOFCs fit to meet these policy goals. They can be switched to biogas or green gas as a fuel. For larger installations, it is relatively easy to apply carbon capture, since the flue gas has a very high $CO_2$ concentration. And as long as fossil fuelled electricity is produced, SOFCs are a highly resource-efficient option and can reduce the annual GHG emission by about 8 Mt/a. That being said, SOFC technology does not support solar and wind energy production. Therefore, GHG reduction policies cannot be replaced by the stimulation of SOFCs.

SOFCs are effective to achieve policy goals related to energy and resource efficiency. If cost reductions can be realised or subsidies are granted, the fuel cells can be applied for distributed CHHP for companies resulting in lower environmental impacts.

SOFEC technology should be critically evaluated, given its low cost-effectiveness. It might be more desirable to use the limited amount of biogas for applications other than fuel-assisted electrolysis. The options of upgrading to green gas or combustion for heat production can be more attractive, depending on the cost developments in the future.

### 10.2.3 System operators

DSOs should assess what organisations are willing and able to provide flexibility of consumption or production as a service. By comparing SOFCs and SOFECs with other strategies to accommodate for large amounts of intermittent electricity generation, a well-considered decision can be made. No available technology is currently mature enough, but SOCs can become a feasible option if the learning curve is continued. Under the assumptions made in this report, storage options (batteries and $H_2$ tanks) are best suited to address short-term fluctuations. SOCs, in particular SOFCs, are better geared towards mitigating imbalances on the timescale of months and seasons.

If SOFCs or SOFECs are considered to be useful in this respect, DSOs can stimulate their installation by providing favourable distribution network connection procedures and contracts. Besides, it is advised that a flexibility market that includes small consumers is established in cooperation with other stakeholders. Such a market creates the boundary conditions for the development of innovative solutions to maintain the electricity grid balance.

### 10.2.4 SOC manufacturers

SOC manufacturers benefit from a growing market share of SOC technologies. To achieve this, it is crucial to sustain R&D efforts. Therefore, manufacturers should aim for close cooperation with research institutes. As illustrated by Figure 2.8, various directions for future SOC applications have been identified. Efforts can be made to achieve miniaturisation of the BoP (for micro-CHP), biogas compatibility (for SOFEC), high conductivity at lower temperatures (for IT- and LT-SOFC), operation responsive to fuel variations (for fuel independence), safer $H_2$ handling equipment (for CHHP SOFC), reversible operation (for R-SOCs), or stability under high overpotentials and high current densities (for SOEC). Although divergence of R&D efforts can be beneficial, a common focus shared by multiple actors fosters learning through interaction resulting in fast progress. Besides, it is attractive to invest most in applications with the largest market potential. Based on the results of this research, some of the future SOC applications listed above appear more promising than others.

To begin with, it was concluded that the co-production of hydrogen increases the competitiveness of SOFC installations. Therefore, it is recommended that this capability is investigated and developed further, contrary to the current industry focus on CHP applications. The development of low-temperature SOFCs seems less attractive, since this creates the need for precious metal catalysts. Recent findings that demonstrate how reversible operation can prevent degradation give incentive to research R-SOCs further. It might not be economically attractive to switch between fuel cell and fuel-assisted electrolysis mode, but if regular operation as SOFEC prolongs the service life of the stack, there is a different situation. Furthermore, this study has revealed the limited potential market niche of SOFECs, in particular in the current system. It is recommended that development of this technology is not prioritised for now, but can be reconsidered in the future. Similarly, SOECs can become effective in systems with high renewable electricity production. SOC installations are preferably applied for distributed generation to minimise energy transport losses and maximise product utilisation. It is advised to install systems that supply several households. Smaller micro-CHP SOFCs are less attractive due to the relatively large investment costs.

## 10.3 Future research

### 10.3.1 Model refinement

Within oemof, the possibilities for further refinement of the details of the energy system model are infinite. Yet, the trade-off between model accuracy and calculation time should always be kept in mind. The enumeration of simplifications in § 5.8 can provide a starting point for model refinements. Some modifications to the model that are worth considering are discussed in this section.

To obtain a faster model, the linearisation options for SOC input-output relations proposed in § 3.6 could be considered. The effect of such a simplification has to be assessed by comparing the optimisation results with those of the nonlinear model. The deviation is probably significant, in particular if the costs of SOFCs are assumed to be low. In that case, nonlinear equations are needed to correctly describe the flexible behaviour as shown in the various optimisations.

On the other hand, it is also possible to increase the detail of the input-output relations of other components. The reduced efficiency at part load operation can be modelled by adding suitable (nonlinear) equations. Note that it should be specified how big all individual plants are for which efficiency reduction applies. This allows solutions where one or more plants are halted, to allow the remaining plants of the same type to operate at full load.

A useful refinement of the model can be the inclusion of energy transport infrastructure. This allows to account for losses that occur during transport, and costs associated to the infrastructure. If transport is included, the benefits of distributed energy conversion (close to the consumer) can be included better. This approach is also relevant for SOC technology, given their suitability for small-scale applications. To be able to model transport, it is necessary to apply some form of spatial quantisation to the model. A very basic form of quantisation can be achieved by defining two 'locations': central and local. All energy demand is located in the local space, while large-scale or remote generation occurs centrally. Any local energy source does not rely on transport, because it is situated locally. More 'realistic' quantisations can also be imagined. The country can be divided in regions, provinces, municipalities, or neighbourhoods, or in rectangles with desired dimensions. The more locations are added, the larger the optimisation problem becomes in terms of data input and computation time. For each location, buses and components, production and consumption, constraints and states have to be included.

The costs associated with the required transport infrastructure in a given scenario can also be estimated by recognising that these costs depend on the peak demand. If the highest expected consumption rate is known (for example by modelling a cold winter), the network capacity to distribute the energy carrier of interest can be calculated. This approach was applied by Van Melle et al. (2015).

If spatial quantisation is applied, then location-specific demand and production patterns have to be obtained or generated. Various options to obtain demand patterns of households are discussed in Van den Hil (2015). In the case of wind turbine power production, the database of KNMI (KNMI, 2005) features wind speeds for a wide range of locations. There are several more opportunities for the refinement of the input data. For example, the pattern for NG demand could be based on a dataset with hourly resolution. For this study, only a gas demand pattern with monthly resolution was found (see § 5.7.2).

Other data improvements can be implemented if more practical knowledge about new consumption and production technologies becomes available. For example, the behaviour of BEV and FCEV owners is not crystallised yet, and is therefore subject to change.

### 10.3.2 Innovation systems

To obtain a better understanding of the innovation niche around SOC technology, three aspects can be investigated further.

First, the attitude of the general public and the preferences of potential users can be assessed. This will provide insight into the differences between these groups, and into the perceived barriers for the adoption of SOCs. Also, the insights can be used to develop applications of SOC technology that match user preferences. Progress has been made in this area by Vernay et al. (2008) and Manné (2009). One step further could be the identification of deployment strategies, as introduced by Sauter and Watson (2007). They have explored possible company-consumer relations for distributed generation technologies.

Second, it is possible to elaborate further on the role of companies in the development of SOCs. The attitude towards SOC technology development, and the perception of the system and problems faced can be mapped for both companies within the SOC niche and organisations that are part of the socio-technical regime. These insights are valuable to better understand the dynamics and interactions of the niche and regime level.

Third, as demonstrated in § 9.2, energy carrier costs in specific market niches are the key determining factor for the viability of a business case including SOCs. Models or calculations that take into account local fuel costs, distribution network connection fees, VAT, and other taxes can give a verdict on the feasibility of SOCs in specific (niche) markets. An approach that can be taken is provided in planSOEC (Energinet.dk, 2011). This report assesses the value that different consumers assign to hydrogen, based on a cost calculation of the available alternatives.

# References

Aboumahboub, T., Schaber, K., Tzscheutschler, P., & Hamacher, T. (2010). Optimization of the utilization of renewable energy sources in the electricity sector. In *Proceedings of the 5th iasme/wseas international conference on energy & environment* (Vol. 11, pp. 196–204).

Aguiar, P., Chadwick, D., & Kershenbaum, L. (2002). Modelling of an indirect internal reforming solid oxide fuel cell. *Chemical Engineering Science*, *57*(10), 1665–1677. doi: http://dx.doi.org/10.1016/S0009-2509(02)00058-1

Aki, H., Murata, A., Yamamoto, S., Kondoh, J., Maeda, T., Yamaguchi, H., & Ishii, I. (2005). Penetration of residential fuel cells and CO2 mitigation–case studies in Japan by multi-objective models. *International Journal of Hydrogen Energy*, *30*(9), 943–952. doi: 10.1016/j.ijhydene.2004.11.009

Arduino, F., & Santarelli, M. (2016, jun). Total cost of ownership of CHP SOFC systems: Effect of installation context. *Energy Policy*, *93*, 213–228. doi: 10.1016/j.enpol.2016.02.053

Batelle. (2014). *Manufacturing cost analysis of 1 kW and 5 kW solid oxide fuel cell (SOFC) for auxilliary power applications* (Tech. Rep.). Columbus: Batelle Memorial Institute. Retrieved from http://energy.gov/sites/prod/files/2014/06/f16/fcto_battelle_cost_analysis_apu_feb2014.pdf

Belderbos, A., Delarue, E., & D'haeseleer, W. (2015). *Possible role of Power-to-Gas in future energy systems* (Working paper No. WP EN2015-09). Leuven: KULeuven Energy Institute, TME Branch. doi: 10.1109/EEM.2015.7216744

Beljaars, M. (2015). *Productie van minerale meststoffen in Nederland* (Tech. Rep.). Den Haag: Meststoffen Nederland.

Bellekom, S., Benders, R., Pelgröm, S., & Moll, H. (2012). Electric cars and wind energy: Two problems, one solution? A study to combine wind energy and electric cars in 2020 in The Netherlands. *Energy*, *45*(1), 859–866. doi: 10.1016/j.energy.2012.07.003

Bergsma, G. C., & Croezen, H. J. (2011). *Kansen voor Groen Gas: Concurrentie Groen Gas met andere biomassa opties* (Tech. Rep.). Delft: CE Delft.

Biberacher, M. (2004). *Modelling and optimisation of future energy systems using spatial and temporal methods* (Doctoral dissertation). University of Augsburg.

Bierschenk, D. M., Wilson, J. R., & Barnett, S. A. (2011). High efficiency electrical energy storage using a methane–oxygen solid oxide cell. *Energy Environmental Science*, *4*(3), 944–951. doi: 10.1039/C0EE00457J

Biomass Energy Centre. (2004). *Carbon emissions of different fuels.* Retrieved 2016-05-02, from http://www.biomassenergycentre.org.uk/portal/page?_pageid=75%2C163182&_dad=portal&_schema=PORTAL

Boccard, N. (2009). Capacity factor of wind power realized values vs. estimates. *Energy Policy*, *37*(7), 2679–2688. doi: 10.1016/j.enpol.2009.02.046

Boerrigter, H. (2006). *Economy of Biomass-to-Liquids plants* (Tech. Rep.). Petten: ECN. Retrieved from https://www.ecn.nl/docs/library/report/2006/c06019.pdf

Bokhoven, T., Fennema, H., Grünfeld, H., Jurjus, A., Miesen, R., Molengraaf, P., . . . Wagenaar, T. (2015). Nieuwe spelregels voor een duurzaam en stabiel energiesysteem. *Overlegtafel Energievoorziening*(September).

Börjeson, L., Höjer, M., Dreborg, K.-H., Ekvall, T., & Finnveden, G. (2006). Scenario types and techniques: Towards a user's guide. *Futures*, *38*(7), 723–739. doi: 10.1016/j.futures.2005.12.002

Bourennani, F., Rahnamayan, S., & Naterer, G. F. (2015). Optimal Design Methods for Hybrid Renewable Energy Systems. *International Journal of Green Energy*, *12*(2), 148–159. doi: 10.1080/15435075.2014.888999

Bradbury, L. (2009). Wind turbine power ouput variation with steady wind speed. In *WindPower Program* (chap. 14). Plymouth: PelaFlow Consulting. Retrieved 2016-03-25, from http://www.wind-power-program.com/turbine_characteristics.htm

Brandon, N. (2013). Recent Developments in Solid Oxide Fuel Cells. In *H2fc supergen.* London.

Braun, R. J. (2002). *Optimal design and operation of solid oxide fuel cell systems for small-scale stationary applications* (Doctoral dissertation). University of Wisconsin.

Bruckner, T., Fulton, L., Hertwich, E., McKinnon, A., Perczyk, D., Roy, J., . . . Wiser, R. (2014). Annex III: Technology-specific cost and performance parameters. In S. Schlömer (Ed.), *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (pp. 1329–1356). Cambridge; New York: Cambridge University Press.

Butler, B. J. (2010). *Energy balance in solid oxide fuel assisted electrolyzer cell modules* (Master thesis). University of Utah.

Carter, D., Ryan, M., Wing, J., Ryan, M., & Wing, J. (2013). The Fuel Cell Industry Review 2011, 2012, 2013. *Fuel Cell Today*, *56*(4), 1–56. doi: 10.1595/147106712X657535

CBS. (2015a). *Elektriciteit en warmte; productie en inzet naar energiedrager [Data set].* Retrieved from http://statline.cbs.nl/Statweb/publication/?DM=SLNL&PA=80030NED&D1=2,4-5&D2=1-2&D3=2-5,7-12&D4=16-17&HDR=T&STB=G1,G2,G3&VW=T

CBS. (2015b). *Energiebalans; aanbod, omzetting en verbruik [Data set].* Retrieved 2016-03-10, from http://statline.cbs.nl/Statweb/publication/?DM=SLNL&PA=83140NED&D1=a&D2=0-1,11,34-50&D3=l&HDR=G2,G1&STB=T&VW=T

CBS. (2016a). *Calorific value.* Retrieved 2016-02-10, from https://www.cbs.nl/en-gb/our-services/methods/definitions?tab=c#id=calorific-value

CBS. (2016b). *Hernieuwbare elektriciteit; productie en vermogen [Data set].* Retrieved 2016-09-26, from http://statline.cbs.nl/Statweb/publication/?DM=SLNL&PA=82610ned&D1=6-7&D2=a&D3=a&HDR=G2&STB=T,G1&VW=T

Chen, T.-P. (2006). *Hydrogen delivery infrastructure options analysis* (Tech. Rep.). Washington D.C.: Nexant.

Chertow, M. R. (2000, sep). The IPAT equation and its variants. *Journal of Industrial Ecology*, *4*(4), 13–29. doi: 10.1162/10881980052541927

Chicco, G., & Mancarella, P. (2009). Distributed multi-generation: A comprehensive view. *Renewable and Sustainable Energy Reviews*, *13*(3), 535–551. doi: 10.1016/j.rser.2007.11.014

Cinti, G., Bidini, G., & Hemmes, K. (2016, jun). An experimental investigation of fuel assisted electrolysis as a function of fuel and reactant utilization. *International Journal of Hydrogen Energy*. doi: 10.1016/j.ijhydene.2016.05.205

Citizendium. (2013). *Hydrocracking.* Retrieved 2016-09-05, from http://en.citizendium.org/wiki/Hydrocracking

Connolly, D., Lund, H., Mathiesen, B. V., & Leahy, M. (2010). A review of computer tools for analysing the integration of renewable energy into various energy systems. *Applied Energy*, *87*(4), 1059–1082. doi: 10.1016/j.apenergy.2009.09.026

Connolly, D., & Mathiesen, B. V. (2014). A technical and economic analysis of one potential pathway to a 100% renewable energy system. *International Journal of Sustainable Energy Planning and Management*, *1*, 7–28. Retrieved from http://journals.aau.dk/index.php/sepm/article/view/497 doi: 10.5278/ijsepm.2014.1.2

Curtin, S., & Gangi, J. (2015). *Fuel Cell Technologies Market Report 2014* (Tech. Rep.). Washington D.C.: Fuel Cell and Hydrogen Energy Association. Retrieved from http://energy.gov/sites/prod/files/2015/10/f27/fcto_2014_market_report.pdf

Daikin UK. (2012). *Seasonal efficiency – Energy labelling.* Retrieved 2016-05-23, from http://www.daikin.co.uk/seasonal-efficiency/energy-label/

D'Appolonia. (2016). *Analysis of market opportunities and legislative assessment* (Tech. Rep.). Genova: Bio-HyPP. Retrieved from http://www.bio-hypp.eu/wp-content/uploads/2016/05/D1.1-Market-opportunities-and-legislative-assessment.pdf

Davis, C. B., Chmieliauskas, A., Dijkema, G. P. J., & Nikolic, I. (2015). *Enipedia.* Delft.

De Swardt, C. A., & Meyer, J. P. (2001, aug). A performance comparison between an air-source and a ground-source reversible heat pump. *International Journal of Energy Research*, *25*(10), 899–910. doi: 10.1002/er.730

De Wild, P., Nyqvist, R., & De Bruijn, F. (2002). Removal of sulphur-containing odorants from natural gas for PEMFC-based micro-combined heat and power applications. In *Fuel cell seminar.* Palm Springs.

De Boer, H. S., Grond, L., Moll, H., & Benders, R. (2014). The application of power-to-gas, pumped hydro storage and compressed air energy storage in an electricity system at different wind power penetration levels. *Energy*, *72*, 360–370. doi: 10.1016/j.energy.2014.05.047

Deng, Y. Y., Blok, K., & Van der Leun, K. (2012). Transition to a fully sustainable global energy system. *Energy Strategy Reviews*, *1*(2), 109–121. doi: 10.1016/j.esr.2012.07.003

DHPA. (2010). *Veel gestelde vragen over warmtepompen.* Dutch Heat Pump Association. Retrieved 2016-05-23, from http://www.dhpa-online.nl/veel-gestelde-vragen/

Diakov, V., Ruth, M., James, B. D., Perez, J., & Spisak, A. B. (2011). *Technical breakthrough points and opportunities in transition scenarios for hydrogen as vehicular fuel* (Tech. Rep.). Golden, Colorado: NREL.

EDF Energy. (2016). *Electricity infrastructure.* Retrieved 2016-09-23, from https://www.edfenergy.com/sites/default/files/generation-and-supply-electricity_3.png

Edwards, R., Larivé, J.-F., Rickeard, D., & Weindorf, W. (2014). *Well-to-wheels analysis of future automotive fuels and powertrains in the European context* (4.a ed.; S. Godwin; et al., Eds.). Luxembourg: Joint Research Centre (JRC). Retrieved from http://iet.jrc.ec.europa.eu/about-jec/ doi: 10.2790/95629

Energinet.dk. (2011). *planSOEC* (Tech. Rep. No. May). Erritsø.

Energistyrelsen, & Energinet.dk. (2015). *Technology Data for Energy Plants – Generation of Electricity and District Heating, Energy Storage and Energy Carrier Generation and Conversion* (Tech. Rep.).

Energy Company. (2015). *HRe-ketels en brandstofcellen voor Gelderland.* Retrieved from http://energy-company.nl/hre-ketels-en-brandstofcellen-voor-gelderland/

ENTSOE. (2016). *Installed Capacity per Production Unit.* Retrieved from https://transparency.entsoe.eu/generation/r2/installedGenerationCapacityAggregation/show

E.ON. (2014). *Warme winter = lagere stookkosten.* Retrieved 2016-03-22, from http://magazine.eon.nl/media/11659061/20140428_Grafiek-energieverbruik-umbraco.jpg

Erdinc, O., & Uzunoglu, M. (2012). Optimum design of hybrid renewable energy systems: Overview of different approaches. *Renewable and Sustainable Energy Reviews*, *16*(3), 1412–1425. doi: 10.1016/j.rser.2011.11.011

European Commission. (2016). *Community Research and Development Information System.* Retrieved from http://cordis.europa.eu

Ewan, B. C. R., & Adeniyi, O. D. (2013). A Demonstration of Carbon-Assisted Water Electrolysis. *Energies*, *6*(3), 1657–1668. doi: 10.3390/en6031657

Fang, Q., Blum, L., Peters, R., Peksen, M., Batfalsky, P., & Stolten, D. (2015). SOFC stack performance under high fuel utilization. *International Journal of Hydrogen Energy*, *40*(2), 1128–1136. doi: 10.1016/j.ijhydene.2014.11.094

Fardadi, M., McLarty, D. F., & Jabbari, F. (2016). Investigation of thermal control for different SOFC flow geometries. *Applied Energy*, *178*, 43–55. doi: 10.1016/j.apenergy.2016.06.015

Fourer, R., & Kernighan, B. W. (2002). *AMPL: A Modeling Language for Mathematical Programming.* Duxbury Press.

Frangopoulos, C. A. (2003). Methods of energy systems optimization. In *Summer school: Optimization of energy systems and processes.* Gliwice.

Fuel Cells Bulletin. (2016). *Sunfire supplies Boeing with largest reversible solid oxide electrolyser/fuel cell system* (Vol. 2016) (No. 2). Elsevier. doi: 10.1016/S1464-2859(16)70002-2

Geels, F. W. (2002). Technological transitions as evolutionary reconfiguration processes: a multi-level perspective and a case-study. , *31*, 1257–1274.

Geels, F. W. (2010, may). Ontologies, socio-technical transitions (to sustainability), and the multi-level perspective. *Research Policy*, *39*(4), 495–510. doi: 10.1016/j.respol.2010.01.022

Geels, F. W. (2012). A socio-technical analysis of low-carbon transitions: introducing the multi-level perspective into transport studies. *Journal of Transport Geography*, *24*, 471–482. doi: 10.1016/j.jtrangeo.2012.01.021

Geels, F. W., & Schot, J. (2007). Typology of sociotechnical transition pathways. , *36*(August 2003), 399–417. doi: 10.1016/j.respol.2007.01.003

Geidl, M. (2007). *Integrated Modeling and Optimization of Multi-Carrier Energy Systems* (Unpublished doctoral dissertation). ETH Zurich.

Gençer, E., Al-musleh, E., Mallapragada, D. S., & Agrawal, R. (2014). Uninterrupted renewable power through chemical storage cycles. *Current Opinion in Chemical Engineering*, *5*, 29–36. doi: 10.1016/j.coche.2014.04.001

Gerdes, J., Marbus, S., & Boelhouwer, M. (2014). *Energietrends 2014* (Tech. Rep.). Petten: ECN, Energie-Nederland en Netbeheer Nederland.

Giddey, S., Badwal, S., Kulkarni, A., & Munnings, C. (2012, jun). A comprehensive review of direct carbon fuel cell technology. *Progress in Energy and Combustion Science*, *38*(3), 360–399. doi: 10.1016/j.pecs.2012.01.003

Gómez, D. R., Watterson, J. D., Americanohia, B. B., Ha, C., Marland, G., Matsika, E., . . . Treanton, K. (2006). Stationary Combustion. In *Guidelines for national greenhouse gas inventories* (2nd ed., p. 47). IPCC. Retrieved from http://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/2_Volume2/V2_2_Ch2_Stationary_Combustion.pdf doi: 10.1016/S0166-526X(06)47021-5

Gómez, S. Y., & Hotza, D. (2016). Current developments in reversible solid oxide fuel cells. *Renewable and Sustainable Energy Reviews*, *61*, 155–174. doi: 10.1016/j.rser.2016.03.005

Graves, C., Ebbesen, S. D., Jensen, S. H., Simonsen, S. B., & Mogensen, M. B. (2015). Eliminating degradation in solid oxide electrochemical cells by reversible operation. *Nature Materials*, *14*(2), 239–244. doi: 10.1038/nmat4165

GTS. (2014). *Safety sheet: Aardgas (geodoriseerd) met Tetra Hydro Thiofeen (THT)* (Tech. Rep.). Groningen: Gasunie Transport Services.

Hart, D., Lehner, F., Rose, R., Lewis, J., & Klippenstein, M. (2015). *The Fuel Cell Industry Review 2015* (Tech. Rep.). Lausanne: E4tech.

Hauptmeier, K., Penkuhn, M., & Tsatsaronis, G. (2016). Economic assessment of a solid oxide fuel cell system for biogas utilization in sewage plants. *Energy*. doi: 10.1016/j.energy.2016.05.072

Hawkes, A. D., Aguiar, P., Hernandez-Aramburo, C. A., Leach, M. A., Brandon, N. P., Green, T. C., & Adjiman, C. S. (2006, jun). Techno-economic modelling of a solid oxide fuel cell stack for micro combined heat and power. *Journal of Power Sources*, *156*(2), 321–333. doi: 10.1016/j.jpowsour.2005.05.076

Hawkes, A. D., Brett, D. J. L., & Brandon, N. P. (2009, dec). Fuel cell micro-CHP techno-economics: Part 1-model concept and formulation. *International Journal of Hydrogen Energy*, *34*(23), 9545–9557. doi: 10.1016/j.ijhydene.2009.09.094

Hemmes, K. (2004). Fuel Cells. In R. E. White, B. E. Conway, & C. G. Vayenas (Eds.), *Modern aspects of electrochemistry* (37th ed., p. 131). New York: Kluwer Academic; Plenum Publishers.

Hemmes, K. (2009). Towards multi-source multi-product and other integrated energy systems. *International Journal of Integrated Energy Systems*, *1*(1), 1–15.

Hemmes, K., Patil, A., & Woudstra, N. (2005). Internal reforming SOFC system for flexible coproduction of hydrogen and power. In *3rd international conference on fuel cell science, engineering and technology* (pp. 577–582). Ypsilanti, Michigan: ASME. doi: 10.1115/FUELCELL2005-74153

Holmgren, M. A. (2012). Methane emissions from biogas plants – The Swedish voluntary agreement system and sustainability criteria. In *Nordic biogas conference 2012.* Retrieved from http://www.slideshare.net/oznut/methane-emissions-from-biogas-plants-the-swedish-voluntary-agreement-system-and-sustainability-criteria

*HSL.* (n.d.). Oxford: STFC Rutherford Appleton Laboratory. Retrieved from http://www.hsl.rl.ac.uk/

Huo, H.-B., Zhong, Z.-D., Zhu, X.-J., & Tu, H.-Y. (2008, jan). Nonlinear dynamic modeling for a SOFC stack by using a Hammerstein model. *Journal of Power Sources*, *175*(1), 441–446. doi: 10.1016/j.jpowsour.2007.09.059

IEA. (2015). Energy and climate change. *World Energy Outlook Special Report*, 1–200. doi: 10.1038/479267b

IEA-ETSAP, & IRENA. (2013a). Production of Liquid Biofuels: Technology Brief. doi: 10.1111/j.1745-4514.2010.00447.x

IEA-ETSAP, & IRENA. (2013b). Thermal Energy Storage. Technology Brief.

INL. (2015). *Plugged In: How Americans Charge Their Electric Vehicles* (Tech. Rep.). Idaho National Laboratory.

IPCC. (2007). Climate Change 2007: Mitigation. In B. Metz, O. Davidson, P. Bosch, R. Dave, & L. Meyer (Eds.), *Contribution of working group iii to the fourth assessment report of the ipcc.* Cambridge; New York: Cambridge University Press.

Irvine, J. T. S., Neagu, D., Verbraeken, M. C., Chatzichristodoulou, C., Graves, C., & Mogensen, M. B. (2016). Evolution of the electrochemical interface in high-temperature fuel cells and electrolysers. *Nature Energy*, *1*(1). doi: 10.1038/nenergy.2015.14

James, B. D., Spisak, A. B., & Colella, W. G. (2012). *Manufacturing Cost Analysis of Stationary Fuel Cell Systems* (Tech. Rep.). Arlington: Strategic Analysis Inc.

Janardhanan, V. M., Heuveline, V., & Deutschmann, O. (2007, oct). Performance analysis of a SOFC under direct internal reforming conditions. *Journal of Power Sources*, *172*(1), 296–307. doi: 10.1016/j.jpowsour.2007.07.008

Jensen, S. H., Graves, C., Mogensen, M. B., Wendel, C. H., Braun, R. J., Hughes, G., ... Barnett, S. A. (2015). Large-scale electricity storage utilizing reversible solid oxide cells combined with underground storage of CO2 and CH4. *Energy Environ. Sci.*, *8*(8), 2471–2479. doi: 10.1039/C5EE01485A

Kamjoo, A., Maheri, A., Dizqah, A. M., & Putrus, G. A. (2016). Electrical Power and Energy Systems Multi-objective design under uncertainties of hybrid renewable energy system using NSGA-II and chance constrained programming. *International Journal of Electrical Power and Energy Systems*, *74*, 187–194. doi: 10.1016/j.ijepes.2015.07.007

Kaviani, A. K., Riahy, G. H., & Kouhsari, S. H. M. (2009). Optimal design of a reliable hydrogen-based stand-alone wind/PV generating system, considering component outages. *Renewable Energy*, *34*(11), 2380–2390. doi: 10.1016/j.renene.2009.03.020

Kemp, R., Schot, J., & Hoogma, R. (1998). Regime shifts to sustainability through processes of niche formation: The approach of strategic niche management. *Technology Analysis & Strategic Management*, *10*(2), 175–198. doi: 10.1080/09537329808524310

doi: 10.1080/09537329808524310

Kikuchi, Y., Kimura, S., Okamoto, Y., & Koyama, M. (2014). A scenario analysis of future energy systems based on an energy flow model represented as functionals of technology options. *Applied Energy*, *132*, 586–601. doi: 10.1016/j.apenergy.2014.07.005

Kleijn, R., & Van der Voet, E. (2010). Resource constraints in a hydrogen economy based on renewable energy sources: An exploration. *Renewable and Sustainable Energy Reviews*, *14*(9), 2784–2795. doi: 10.1016/j.rser.2010.07.066

KNMI. (2005). *HYDRA MetaDataConnection* (Tech. Rep.). DeBilt: Royal Netherlands Meteorological Institute. Retrieved from http://projects.knmi.nl/hydra/cgi-bin/meta_data.cgi

Komatsu, Y., Brus, G., Kimijima, S., & Szmyd, J. (2014). The effect of overpotentials on the transient response of the 300W SOFC cell stack voltage. *Applied Energy*, *115*, 352–359. doi: 10.1016/j.apenergy.2013.11.017

Koppejan, J., Elbersen, W., Meeusen, M., & Bindraban, P. (2009). Beschikbaarheid van Nederlandse biomassa voor elektriciteit en warmte in 2020. (November). Retrieved from http://edepot.wur.nl/51989

Kuhn, J., & Kesler, O. (2015, mar). Carbon deposition thresholds on nickel-based solid oxide fuel cell anodes I. Fuel utilization. *Journal of Power Sources*, *277*, 443–454. doi: 10.1016/j.jpowsour.2014.07.085

Lamers, P., Hoefnagels, R., Junginger, M., Hamelinck, C., & Faaij, A. (2015, jul). Global solid biomass trade for energy by 2020: an assessment of potential import streams and supply costs to North-West Europe under different sustainability constraints. *GCB Bioenergy*, *7*(4), 618–634. doi: 10.1111/gcbb.12162

Lamnatou, C., Notton, G., Chemisana, D., & Cristofari, C. (2015). The environmental performance of a building-integrated solar thermal collector, based on multiple approaches and life-cycle impact assessment methodologies. *Building and Environment*, *87*, 45–58. doi: 10.1016/j.buildenv.2015.01.011

Lazard. (2015a). Lazard's levelized cost of energy analysis. , *9.0*.

Lazard. (2015b). Lazard's levelized cost of storage analysis. , *1.0*.

López, J. (2013). *Combustion engine vs. gas turbine: Part load efficiency and flexibility.* Retrieved 2016-01-01, from http://www.wartsila.com/energy/learning-center/technical-comparisons/combustion-engine-vs-gas-turbine-part-load-efficiency-and-flexibility

Lozano, M. A., Ramos, J. C., & Serra, L. M. (2010). Cost optimization of the design of CHCP (combined heat, cooling and power) systems under legal constraints. *Energy*, *35*(2), 794–805. doi: 10.1016/j.energy.2009.08.022

Lund, H. (2007). EnergyPLAN–Advanced Energy Systems Analysis Computer Model. Documentation Version 7.0. *Aalborg University, Denmark*. Retrieved from http://www.energyplan.eu

Luo, Y., Shi, Y., Li, W., Ni, M., & Cai, N. (2014). Elementary reaction modeling and experimental characterization of solid oxide fuel-assisted steam electrolysis cells. *International Journal of Hydrogen Energy*, *39*(20), 10359–10373. doi: 10.1016/j.ijhydene.2014.05.018

MacKay, D. J. C. (2009). *Sustainable Energy–Without the hot air*. Cambridge: UIT Cambridge. Retrieved from withoutthehotair.com

Mahato, N., Banerjee, A., Gupta, A., Omar, S., & Balani, K. (2015). Progress in material selection for solid oxide fuel cell technology: A review. *Progress in Materials Science*, *72*, 141–337. doi: 10.1016/j.pmatsci.2015.01.001

Makhorin, A. O. (n.d.). *GNU Linear Programming Kit (GLPK).* Moscow: GNU Project. Retrieved from http://www.gnu.org/software/glpk

Mancarella, P., Andersson, G., Peças-Lopes, J. A., & Bell, K. R. (2016, jun). Modelling of integrated multi-energy systems: Drivers, requirements, and opportunities. In *2016 power systems computation conference (pscc).* Genoa: IEEE. doi: 10.1109/PSCC.2016.7541031

Manné, D. J. (2009). *The market introduction of Superwind in the Netherlands* (Master thesis). TU Delft.

Marina, O. A., Pederson, L. R., Williams, M. C., Coffey, G. W., Meinhardt, K. D., Nguyen, C. D., & Thomsen, E. C. (2007). Electrode performance in reversible solid oxide fuel cells. *Journal of The Electrochemical Society*, *154*(5), 452–459. doi: 10.1149/1.2710209

Marsboom, P.-J. (2013). *Forecast and actual solar-PV power generation* (Tech. Rep.). Elia.

Martinez-Frias, J., Pham, A.-Q., & Aceves, S. M. (2003). A natural gas-assisted steam electrolyzer for high-efficiency production of hydrogen. *International Journal of Hydrogen Energy*, *28*(5), 483–490. doi: 10.1016/S0360-3199(02)00135-0

Mathiesen, B. V. (2008). *Fuel cells and electrolysers in future energy systems* (PhD, Aalborg University). Retrieved from http://people.plan.aau.dk/~bvm/FinalWebVersion3.pdf

Mathiesen, B. V., Lund, H., & Karlsson, K. (2009). *IDA's climate plan 2050 – Background report.* Copenhagen V.

Mathworks. (2015). *Mixed-Integer Linear Programming Algorithms.* Retrieved 2016-01-02, from http://nl.mathworks.com/help/optim/ug/mixed-integer-linear-programming

-algorithms.html
McPhail, S. J., Aarva, A., Devianto, H., Bove, R., & Moreno, A. (2011). SOFC and MCFC: Commonalities and opportunities for integrated research. *International Journal of Hydrogen Energy*, *36*(16), 10337–10345. doi: 10.1016/j.ijhydene.2010.09.071
Meibom, P., & Karlsson, K. (2010). Role of hydrogen in future North European power system in 2060. *International Journal of Hydrogen Energy*, *35*(5), 1853–1863. doi: 10.1016/j.ijhydene.2009.12.161
Milieucentraal. (2016). *Kosten en besparing zonneboiler.* Retrieved 2016-07-01, from https://www.milieucentraal.nl/energie-besparen/energiezuinig-huis/energiezuinig-verwarmen-en-warm-water/zonneboiler
Minh, N. Q., & Mogensen, M. B. (2013). Reversible solid oxide fuel cell technology for green fuel and power production. *Interface*, *22*(4), 55–62. Retrieved from http://www.electrochem.org/dl/interface/wtr/wtr13/wtr13_p055_062.pdf doi: 10.1149/2.F05134if
Ministry of Economic Affairs. (2011). *Green Deal.* Retrieved 2016-11-20, from https://www.government.nl/topics/energy-policy/contents/green-deal
Molero-Sánchez, B., Prado-Gonjal, J., Ávila-Brande, D., Chen, M., Morán, E., & Birss, V. (2015). High performance La0.3Ca0.7Cr0.3Fe0.7O3–$\delta$ air electrode for reversible solid oxide fuel cell applications. *International Journal of Hydrogen Energy*, *40*(4), 1902–1910. doi: 10.1016/j.ijhydene.2014.11.127
Mulder, F. M. (2014). Implications of diurnal and seasonal variations in renewable energy generation for large scale energy storage. *Journal of Renewable and Sustainable Energy*, *6*(3), 33105. doi: 10.1063/1.4874845
Murashkina, A. A., Maragou, V. I., Demin, A. K., Pikalova, E. Y., & Tsiakaras, P. E. (2008). Hydrogen production aided solid oxide electrochemical reformer fed with octane: A theoretical analysis. *Journal of Power Sources*, *181*(2), 304–312. doi: 10.1016/j.jpowsour.2007.12.069
Nagle, A. (2008). Polarization curve of PEM Fuel Cell. *Roads2HyCom*. Retrieved from https://www.ika.rwth-aachen.de/r2h/images/thumb/c/cc/Polarization_curve_neu2.jpg/450px-Polarization_curve_neu2.jpg
Napoli, R., Gandiglio, M., Lanzini, A., & Santarelli, M. (2015). Techno-economic analysis of PEMFC and SOFC micro-CHP fuel cell systems for the residential sector. *Energy and Buildings*, *103*, 131–146. doi: 10.1016/j.enbuild.2015.06.052
Netbeheer Nederland. (2016). *Energietransitie Rekenmodellen.* Retrieved 2016-09-30, from http://nbn-assets.netbeheernederland.nl/p/32768//files/ETRM_Interactieve-Infographic_A.pdf
*oemof.* (2016). Retrieved from https://github.com/oemof (Open Energy Modelling Framework)
Omosun, A., Bauen, A., Brandon, N., Adjiman, C., & Hart, D. (2004). Modelling system efficiencies and costs of two biomass-fuelled SOFC systems. *Journal of Power Sources*, *131*(1–2), 96–106. doi: 10.1016/j.jpowsour.2004.01.004
Ouweltjes, J. P., Aravind, P. V., Woudstra, N., & Rietveld, G. (2006). Biosyngas utilization in solid oxide fuel cells with Ni/GDC anodes. *Journal of Fuel Cell Science and Technology*, *3*(4), 495–498. doi: 10.1115/1.2349535
Park, J., Li, P., & Bae, J. (2012). Analysis of chemical, electrochemical reactions and thermo-fluid flow in methane-feed internal reforming SOFCs: Part II-temperature effect. *International Journal of Hydrogen Energy*, *37*(10), 8532–8555. doi: 10.1016/j.ijhydene.2012.02.109
Patcharavorachot, Y., Thongdee, S., Saebea, D., Authayanun, S., & Arpornwichanop, A. (2016). Performance comparison of solid oxide steam electrolysis cells with/without the addition of methane. *Energy Conversion and Management*, *120*, 274–286. doi: 10.1016/j.enconman.2016.04.100
PBL. (2011). *Naar een schone economie in 2050: routes verkend.*
Penchini, D., Cinti, G., Discepoli, G., Sisani, E., & Desideri, U. (2013). Characterization of a 100 W SOFC stack fed by carbon monoxide rich fuels. *International Journal of Hydrogen Energy*, *38*(1), 525–531. doi: 10.1016/j.ijhydene.2012.09.060
Pfeifer, T., Nousch, L., Lieftink, D., & Modena, S. (2013, jan). System design and process layout for a

SOFC micro-CHP unit with reduced operating temperatures. *International Journal of Hydrogen Energy*, *38*(1), 431–439. doi: 10.1016/j.ijhydene.2012.09.118

Pham, A.-Q., Wallman, P. H., & Glass, R. S. (2000, apr). *Supplying natural gas to anode side of electrolyzer to lower electricity consumption by either providing an auxilliary source of hydrogen resulting from syngas formation and then water-shifting or by burning out oxygen by-product on anode.* Google Patents. (US Patent 6,051,125)

Prag, C. B., Hallinder, J., Nielsen, E. R., King, A., Santarelli, M., Drago, D., & Tudoroiu-Lakavičė, A. (2016). Non-economic barriers to large-scale market uptake of fuel cell based micro-CHP technology: preliminary report. *ene.field*.

Pruitt, K. A., Braun, R. J., & Newman, A. M. (2013, nov). Establishing conditions for the economic viability of fuel cell-based, combined heat and power distributed generation systems. *Applied Energy*, *111*, 904–920. doi: 10.1016/j.apenergy.2013.06.025

Remick, R. J., & Wheeler, D. (2011). Reversible Fuel Cells Workshop Summary Report. Arlington: U.S. Department of Energy.

Ridjan, I., Mathiesen, B. V., Connolly, D., & Duić, N. (2013). The feasibility of synthetic fuels in renewable energy systems. *Energy*, *57*, 76–84. doi: 10.1016/j.energy.2013.01.046

Rivera-Tinoco, R., Schoots, K., & Van der Zwaan, B. (2012). Learning curves for solid oxide fuel cells. *Energy Conversion and Management*, *57*, 86–96. doi: 10.1016/j.enconman.2011.11.018

Ros, J., & Prins, A. G. (2014, nov). *Biomass: Wishes and limitations.* Retrieved 2016-01-10, from http://infographics.pbl.nl/biomass

Santoianni, D. (2015). Setting the benchmark: The world's most efficient coal-fired power plants. *Cornerstone*, *3*(1). Retrieved from http://cornerstonemag.net/setting-the-benchmark-the-worlds-most-efficient-coal-fired-power-plants

Sauter, R., & Watson, J. (2007). Strategies for the deployment of micro-generation: Implications for social acceptance. *Energy Policy*, *35*(5), 2770–2779. doi: 10.1016/j.enpol.2006.12.006

Scataglini, R., Mayyas, A., Wei, M., Chan, S. H., Lipman, T., Gosselin, D., ... James, B. D. (2015). *A Total Cost of Ownership Model for Solid Oxide Fuel Cells in Combined Heat and Power and Power-Only Applications* (Tech. Rep.). Berkeley: Lawrence Berkeley National Laboratory.

Schenk, N. J., Moll, H. C., Potting, J., & Benders, R. M. (2007). Wind energy, electricity, and hydrogen in the Netherlands. *Energy*, *32*(10), 1960–1971. doi: 10.1016/j.energy.2007.02.002

Schepers, B. L., Naber, N. R., Rooijers, F. J., & Leguijt, C. (2015). *Op weg naar een klimaatneutrale woningvoorraad in 2050* (Tech. Rep.). Delft: CE Delft. Retrieved from http://www.ce.nl/?go=home.downloadPub&id=1638&file=CE_Delft_3A31_Klimaatneutrale_gebouwde

Schey, S., Scoffield, D., & Smart, J. (2012). A First Look at the Impact of Electric Vehicle Charging on the Electric Grid in The EV Project. In *International battery, hybrid and fuel cell electric vehicle symposium (evs26).* Retrieved from http://www.inl.gov/technicalpublications/Documents/5394115.pdf

Schlecht, I., & Davis, C. (2016). *Open models.* Retrieved 2016-06-01, from http://wiki.openmod-initiative.org/wiki/Open_Models

Schoenung, S. (2011). *Economic analysis of large-scale hydrogen storage for renewable utility applications* (Tech. Rep.). Albuquerque; Livermore: Sandia National Laboratories. Retrieved from http://prod.sandia.gov/techlib/access-control.cgi/2011/114845.pdf

Schoots, K., & Hammingh, P. (2015). *Nationale Energieverkenning 2015* (Vol. ECN-O-15-0; Tech. Rep.). Petten: Energieonderzoek Centrum Nederland (ECN), Planbureau voor de Leefomgeving (PBL), Centraal Bureau voor de Statistiek (CBS), Rijksdienst voor Ondernemend Nederland (RVO). Retrieved from http://www.cbs.nl/NR/rdonlyres/C0F1D74C-1EB1-4E3B-9A46-ECA28ABFED7E/0/2015nationaleenergieverkenning.pdf

Shahmohammadi, A., Moradi-Dalvand, M., Ghasemi, H., & Ghazizadeh, M. S. (2015). Optimal Design of Multicarrier Energy Systems Considering Reliability Constraints. *IEEE Transactions on Power Delivery*, *30*(c), 878–886. doi: 10.1109/TPWRD.2014.2365491

Smith, A., & Raven, R. (2012). What is protective space? Reconsidering niches in transitions to sustainability. *Research Policy*, *41*(6), 1025–1036. doi: 10.1016/j.respol.2011.12.012

Smith, A., Stirling, A., & Berkhout, F. (2005). The governance of sustainable socio-technical transitions. *Research Policy*, *34*(10), 1491–1510. doi: 10.1016/j.respol.2005.07.005

Sociaal-Economische Raad. (2013). *Energieakkoord voor duurzame groei* (Tech. Rep.). Den Haag. Retrieved from http://www.energieakkoordser.nl

Sørensen, B. (2008). A sustainable energy future: Construction of demand and renewable energy supply scenarios. *International Journal of Energy Research*, *32*(5), 436–470. doi: 10.1002/er.1375

Spoelstra, J. C. (2014). *Charging behaviour of Dutch EV drivers* (Master thesis). Utrecht University.

Spoelstra, S. (2008). *De Nederlandse en industriële energiehuishouding van 2000 tot en met 2006* (Tech. Rep.). Petten: ECN.

Sprik, S., Kurtz, J., Ainscough, C., & Peters, M. (2015). *Next Generation Hydrogen Station Composite Data Products* (Tech. Rep.). Columbus: NREL. Retrieved from http://www.nrel.gov/hydrogen/proj_infrastructure_analysis.html

Staffell, I., & Green, R. (2013). The cost of domestic fuel cell micro-CHP systems. *International Journal of Hydrogen Energy*, *38*(2), 1088–1102. doi: 10.1016/j.ijhydene.2012.10.090

Standaert, F. R. A. M. (1998). *Analytical fuel cell modelling and exergy analysis of fuel cells* (Doctoral dissertation). TU Delft.

Steup, B. J. (2014). *Design and Optimisation of Renewable Energy Systems using Matrices* (Master thesis). TU Delft.

Steup, B. J., & Hemmes, K. (2015, sep). *The Bing Model; Let the computer design the optimum energy system configuration.*

Strachan, N., Balta-Ozkan, N., Joffe, D., McGeevor, K., & Hughes, N. (2009). Soft-linking energy systems and GIS models to investigate spatial hydrogen infrastructure development in a low-carbon UK energy system. *International Journal of Hydrogen Energy*, *34*(2), 642–657. doi: 10.1016/j.ijhydene.2008.10.083

Strazza, C., Del Borghi, A., Costamagna, P., Gallo, M., Brignole, E., & Girdinio, P. (2015). Life Cycle Assessment and Life Cycle Costing of a SOFC system for distributed power generation. *Energy Conversion and Management*, *100*, 64–77. doi: 10.1016/j.enconman.2015.04.068

Stryi-Hipp, G. (2009). *Solar heating and Cooling for a Sustainable Energy Future in Europe (Revised)* (Tech. Rep.). Brussels: European Solar Thermal Technology Platform (ESTTP). Retrieved from http://www.estif.org/fileadmin/estif/content/projects/downloads/ESTTP_SRA_RevisedVersion.pdf

Sveshnikova, A. (2015). *Estimation of possibility to implement fuel cell technology for decentralized energy supply in Russia* (Master thesis, KTH Stockholm). Retrieved from http://kth.diva-portal.org/smash/get/diva2:852241/FULLTEXT01.pdf

Tao, G. G. (2007, mar). *A reversible planar solid oxide fuel-fed electrolysis cell and solid oxide fuel cell for hydrogen and electricity production operating on natural gas/biomass fuels* (Tech. Rep.). Salt Lake City: Materials and Systems Research, Inc. (MSRI). Retrieved from http://www.osti.gov/servlets/purl/934689-auwPAL/ doi: 10.2172/934689

Tao, G. G., Butler, B., & Virkar, A. V. (2011). Hydrogen and Power by Fuel-Assisted Electrolysis Using Solid Oxide Fuel Cells. *ECS Transactions*, *35*(1), 2929–2939. doi: 10.1149/1.3570292

Tao, G. G., Virkar, A., & Garland, R. (2006). A reversible planar solid oxide fuel-assisted electrolysis cell and solid oxide fuel cell for hydrogen and electricity production operating on natural gas/biogas. In *Fy annual progress report* (pp. 24–28).

TenneT. (2016). *Measurement data.* Retrieved 18-3-2016, from http://www.tennet.org/english/operational_management/export_data.aspx

Teske, S., Zervos, A., Lins, C., & Muth, J. (2010). *Energy (r)evolution; A sustainable global energy outlook* (3rd ed.). Retrieved from www.energyblueprint.info

Thijssen, J. (2011). *Solid oxide fuel cells and critical materials: A review of implications* (Tech. Rep.). Redmond: National Energy Technology Laboratory. Retrieved from https://www.netl.doe.gov/FileLibrary/research/coal/energysystems/fuelcells/Rare-Earth-Update-for-RFI-110523final.pdf

Trendewicz, A., & Braun, R. J. (2013, jul). Techno-economic analysis of solid oxide fuel cell-based combined heat and power systems for biogas utilization at wastewater treatment facilities. *Journal of Power Sources*, *233*, 380–393. doi: 10.1016/j.jpowsour.2013.01.017

Ud Din, Z., & Zainal, Z. A. (2016). Biomass integrated gasification-SOFC systems: Technology overview. *Renewable and Sustainable Energy Reviews*, *53*, 1356–1376. doi: 10.1016/j.rser.2015.09.013

US Fuel Cell Council. (2007). *Introduction to Solid Oxide Fuel Cell Button Cell Testing* (Tech. Rep.). Washington D.C.. Retrieved from `http://ftp.fchea.org/core/import/PDFs/TechnicalResources/SOFCFG-ButtonCellTesting-07-015.pdf`

Van den Bergh, K., Delarue, E., & D'haeseleer, W. (2013, may). The impact of renewable injections on cycling of conventional power plants. In *2013 10th international conference on the european energy market (eem)* (pp. 1–8). IEEE. doi: 10.1109/EEM.2013.6607322

Van den Hil, E. (2015). *Multi-objective optimisation of integrated community energy systems and assessment of the impact on households* (Master thesis). TU Delft.

Van Herle, J., Membrez, Y., & Bucheli, O. (2004). Biogas as a fuel source for SOFC co-generators. *Journal of Power Sources*, *127*(1–2), 300–312. doi: 10.1016/j.jpowsour.2003.09.027

Van Leeuwen, I. (2015). *Feasibility of combined heat, hydrogen and power production by molten carbonate fuel cells.*

Van Leeuwen, I. (2016). *Feasibility of combined heat, hydrogen and power production by molten carbonate fuel cells* (Master thesis). TU Delft.

Van Wortswinkel, L., & Nijs, W. (2010). Industrial combustion boilers. *Technology Brief* (1).

Van Bruggen, A., O'Connor, M., Ding, Z., Gao, Y., Paulina, A., Rojas, G., & Starmans, Z. (2016). *The role of the citizen-oriented initiatives in the dutch energy transition: Four archetypes.* Leiden.

Van Gurp, T. (2016). *Fastned: Laadstations bereiken medio 2017 break-even punt.* Retrieved 2016-10-01, from `http://www.tankpro.nl/ondernemen/2016/01/11/fastned-laadstations-bereiken-medio-2017-break-even-punt/`

Van Melle, T., Menkveld, M., Oude Lohuis, J., De Smidt, R., & Terlouw, W. (2015). *De systeemkosten van warmte voor woningen* (Tech. Rep.). Utrecht: Ecofys.

Veenstra, A. (2015). *Ruimte voor zonne-energie in Nederland 2020-2050* (Tech. Rep.). Utrecht: Holland Solar.

Verbeek, R., Van Zyl, S., Van Grinsven, A., & Van Essen, H. (2014). *Brandstoffen voor het wegverkeer. kenmerken en perspectief* (Tech. Rep.). Delft: CE Delft; TNO.

Verbong, G., & Geels, F. (2007). The ongoing energy transition: Lessons from a socio-technical, multi-level analysis of the Dutch electricity system (1960–2004). *Energy Policy*, *35*(2), 1025–1037. doi: 10.1016/j.enpol.2006.02.010

Vernay, A.-L., Manné, D. J., Steenvoorden, G., & Hemmes, K. (2008). *Superwind: A feasibility study* (Tech. Rep. No. NEOH02010). Delft: SenterNovem, TU Delft.

Wachsman, E. D., Marlowe, C. A., & Lee, K. T. (2012). Role of solid oxide fuel cells in a balanced energy strategy. *Energy & Environmental Science*, *5*(2), 5498–5509. doi: 10.1039/c1ee02445k

Wächter, A., & Biegler, T. L. (2006). On the implementation of an interior-point filter line-search algorithm for large-scale nonlinear programming. *Mathematical Programming*, *106*(1), 25–57. doi: 10.1007/s10107-004-0559-y

Warmerdam, J., Yildiz, I., & Koop, K. (2011). *Biomassapotentieel Provincie Utrecht* (Tech. Rep.). Utrecht: Ecofys.

Wendel, C. H., Kazempoor, P., & Braun, R. J. (2016, jan). A thermodynamic approach for selecting operating conditions in the design of reversible solid oxide cell energy systems. *Journal of Power Sources*, *301*, 93–104. doi: 10.1016/j.jpowsour.2015.09.093

Wijers, F. K. B. (2011). *Modeling a solid oxide fuel-assisted electrolysis cell in Cycle Tempo* (Master thesis). TU Delft.

Wikipedia. (2012). *Gronings gas.* Retrieved 2016-04-22, from `https://nl.wikipedia.org/wiki/Gronings_gas`

Wikipedia. (2016a). *Energy content of fuel.* Retrieved 2016-02-10, from `https://en.wikipedia.org/wiki/Fuel_efficiency#Energy_content_of_fuel`

Wikipedia. (2016b). *Hoogrendementsketel.* Retrieved from https://nl.wikipedia.org/wiki/Hoogrendementsketel

Wikipedia. (2016c). *Lijst van elektriciteitscentrales in Nederland.* Retrieved 2016-09-26, from https://nl.wikipedia.org/wiki/Lijst_van_elektriciteitscentrales_in_Nederland

Wiser, J. R., Schettler, J. W., & Willis, J. L. (2010). *Evaluation of Combined Heat and Power Technologies for Wastewater Facilities* (Tech. Rep.). Columbus: Brown and Caldwell. Retrieved from http://www.cwwga.org/documentlibrary/121_EvaluationCHPTechnologiespreliminary[1].pdf

Yadav, S., Singh, M. K., & Sudhakar, K. (2015). Modelling of a solid oxide fuel cell. *International Journal of Scientific & Engineering Research*, *6*(4), 834–841.

# Appendix A

# Data

## A.1 Conversion factors

| Energy carrier | Energy content (MJ/kg) | Energy density (MJ/L) | Source |
|---|---|---|---|
| Biodiesel | 39.9 | 35.1 | (Wikipedia, 2016a) |
| Crude oil | 41.9 | 38.5 | (Wikipedia, 2016a) |
| Diesel | 48 | 38.6 | (Wikipedia, 2016a) |
| Electricity | 3.6 $MJ/kWh_e$ | | |
| Heavy fuel oil | 43.05 | | (CBS, 2016a) |
| Hydrogen | 141.86 | | (Wikipedia, 2016a) |
| Jet fuel, kerosene | 47 | 37.6 | (Wikipedia, 2016a) |
| Liquefied hydrogen | 130 | 9.3 | (Wikipedia, 2016a) |
| Liquefied petroleum gas [a] | 51 | 27.1 | (Wikipedia, 2016a) |
| Natural gas | 42.2 | $35.17 \times 10^{-3}$ | (CBS, 2016a) |
| Steam coal | 24.9 | | (CBS, 2016a) |

[a] 60% propane and 40% butane

## A.2 Technology data

### A.2.1 Buses (Energy carriers)

| Energy carrier | uid | excess | shortage | balanced |
|---|---|---|---|---|
| Biogas | bbiog | True | False | True |
| Biomass | bbio | False | False | True |
| Coal | bcoal | False | False | True |
| Electricity | bele | True | False | True |
| Heat <100 °C | blowT | True | False | True |
| Heat >100 °C | bhighT | False | False | True |
| Hydrogen | bhyd | True | False | True |
| Natural gas | bgas | False | False | True |
| Oil | bfuel | False | False | True |

### A.2.2 Energy (re)sources

| | Class | uid | outputs | add_out _limit | capex | life-time | wacc | opex_fix | opex_var | co2_var | co2_cap |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | bus | MW | €/kW | a | | €/kW/a | €/MWh | kg$CO_2$-eq./MWh | g$CO_2$-eq./MW |
| Biomass products | Commodity | bio_prod | bbio | 7452 | | | | | 36.90 | -341.35 | |
| Biomass residues | Commodity | bio_res | bbio | 7452 | | | | | 18.88 | -237.81 | |
| Coal mine | Commodity | coal_prod | bcoal | | | | | | 12.72 | 56.412 | |
| NG source | Commodity | gas_prod | bgas | | | | | | 33.78 | 56.772 | |
| Oil well | Commodity | oil_prod | bfuel | | | | | | 51.61 | 50.4 | |
| Biogas | FixedSource | WWT | bgas | 1522 | 977 | 25 | 0.08 | | 17.95 | -172.145 | |
| Nuclear | FixedSource | nuclear | bele | 4000 | 3971 | 60 | 0.05 | 68.99 | 10.17 | | 9.18 |
| PV commercial | FixedSource | pv2 | bele | 29757 | 810 | 40 | 0.08 | 10.35 | 0 | 0 | 1793.75 |
| PV household | FixedSource | pv1 | bele | 52500 | 810 | 40 | 0.08 | 10.35 | 0 | 0 | 1793.75 |
| Solar thermal | FixedSource | solar_therm | blowT | 260000 | 471 | 30 | 0.08 | 1.428 | | | 38.46 |
| Wind offshore | FixedSource | wind_offshore | bele | 34000 | 2120 | 30 | 0.08 | | 15 | 0 | 975 |
| Wind onshore | FixedSource | wind_onshore | bele | 8000 | 900 | 30 | 0.08 | | 8 | 0 | 591.25 |

### A.2.3 Storage

For all: class=storage.Simple; wacc=0.05; cap_max=0; add_cap_limit=+inf; c_rate_in=1; c_rate_out=1.

| | uid | inputs/ outputs | capex | life -time | opex_fix | opex_var | cap_max | add_cap _limit | eta_in | eta_out | cap_loss |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | €/kWh | a | €/kW/a | €/kWh | MWh | MWh | | | MWh/h |
| Compressed air energy storage | caes | bele | 154 | 20 | 1400 | 3.6 | 0 | +inf | 1 | 0.43 | |
| Flywheel | flywheel | bele | 5410 | 20 | 69.41 | | 0 | +inf | 1 | 0.83 | |
| $H_2$ tank | h2tank | bhyd | 2.5 | 15 | 0.01 | | 0 | +inf | 1 | 0.98 | $8.93 \cdot 10^{-3}$ |
| Hot water tank | lowT_sto | blowT | 0.0015 | 20 | | | 0 | +inf | 1 | 1 | $1.36 \cdot 10^{-3}$ |
| Li-ion battery | battery | bele | 225 | 10 | 9.01 | 1.26 | 0 | +inf | 1 | 0.85 | $6.94 \cdot 10^{-5}$ |
| PCM | highT_sto | bhighT | 30 | 20 | 2100 | | 0 | +inf | 0.8 | 0.8 | 0.03 |

### A.2.4 Transformers

For all: out_max=0, add_out_limit=+inf.

transformer.Simple class

| | uid | inputs | outputs | capex €/kW | lifetime a | wacc | opex_fix €/kW/a | opex_var €/MWh | co2_var $kgCO_2$-eq./MWh | co2_cap $gCO_2$-eq./MW | eta |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Alkaline electrolyser | alkel | bele | bhyd | 0 | 10 | 0.05 | 0 | 0 | 0 | | 0.82 |
| Biodiesel production | biodiesel | bbio | bfuel | 3393 | 20 | 0.05 | 102.1 | | 183.1 | | 0.56 |
| Biomass boiler | bio_boil | bbio | bhighT | 800 | 32.5 | 0.05 | | 5.4 | 499.3 | | 0.70 |
| Biomass powerplant | pp_bio | bbio | bele | 1890 | 40 | 0.08 | 61.6 | 2.2 | 728.2 | 6.92 | 0.43 |
| CCGT | pp_gas | bgas | bele | 790 | 25 | 0.05 | 30 | 2.5 | 336.9 | 10.81 | 0.6 |
| Coal boiler | coal_boil | bcoal | bhighT | 800 | 32.5 | 0.05 | | 5.4 | 384.4 | | 0.85 |
| Coal powerplant | pp_coal | bcoal | bele | 1890 | 40 | 0.05 | 61.6 | 2.2 | 728.2 | 6.92 | 0.43 |
| Electric boiler | ele_boil | bele | bhighT | 75 | 15 | 0.05 | | 0.5 | | | 1 |
| Heat distribution | dilute | bhighT | blowT | 1309 | 40 | 0.05 | | | | | 1 |
| NG boiler | gas_boil | bgas | bhighT | 100 | 32.5 | 0.05 | 3.7 | 0.42 | 256.7 | | 0.75 |
| PEMFC | pemfc | bhyd | bele | 207 | 20 | 0.05 | | | | | 0.35 |
| SMR | smr | bgas | bhyd | 322 | 20 | 0.05 | 11.48 | 0.68 | 235.6 | | 0.80 |
| SOFC | sofc | bgas | bele; bhyd | 275 | 20 | 0.08 | | 1.65 | 183.6 | 36.72 | |
| SOFC | sofc | bgas | bele; bhyd | 275 | 20 | 0.08 | | 1.65 | 183.6 | 36.72 | |
| Upgrade | upgrade | bbiog | bgas | 300 | 15 | 0.08 | 56.25 | | 10.1 | | 0.95 |

transformer.TwoInputsOneOutput class

| | uid | inputs | outputs | capex €/kW | lifetime a | wacc | opex_fix €/kW/a | opex_var €/MWh | co2_var $kgCO_2$-eq./MWh | co2_cap $gCO_2$-eq./MW | eta | f [a] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Methanation | hydrogenation | bhyd; bele | bgas | 900 | 20 | 0.08 | 22.14 | | 48.36 | | 0; 0.9 | 15.75 |
| SOEC | soec | bele; bhighT | bhyd | 590 | 20 | 0.08 | 11.8 | 1.65 | 0 | 36.72 | 0.9; 0.9 | 5 |

[a] This parameter represents the ratio of the first and the second input of the process.

## A.3 Existing powerplants

Table A.1: Construction year and installed capacities (in MW) of powerplants that are currently in use in the Netherlands, per fuel type.

| Year built | Biomass | Coal | MSW | NG | Solar | Uranium | Offshore wind | Onshore wind |
|---|---|---|---|---|---|---|---|---|
| 1935 | | | | 80 | | | | |
| 1956 | | | | 81 | | | | |
| 1958 | | | | | | | | |
| 1960 | | | | | | 45 | | |
| 1969 | | | | | | | | 44 |
| 1972 | | | | 60 | | | | |
| 1974 | | | | 92 | | 485 | | |
| 1975 | | | | 332 | | | | |
| 1976 | | | | 332 | | | | |
| 1978 | | | | 638 | | | | |
| 1980 | | | | | | | | |
| 1983 | | | | 400 | | | | |
| 1985 | | | | 103 | | | | 6 |
| 1987 | | | | 1353 | | | | |
| 1988 | | 520 | | | | | | |
| 1989 | | 520 | | 282 | | | | |
| 1990 | | | 196 | 217 | 1 | | | |
| 1991 | | | 1 | | | | | 33 |
| 1992 | | | | 50 | | | | 18 |
| 1993 | | | 80 | | 1 | | | 30 |
| 1994 | | 1230 | | 130 | | | | 21 |
| 1995 | | | 48 | 58 | | | | 98 |
| 1996 | | | 62 | 1609 | 1 | | | 46 |
| 1997 | | | 7 | 924 | 1 | | | 28 |
| 1998 | | | | 460 | 2 | | | 39 |
| 1999 | | | | | 3 | | | 47 |
| 2000 | 25 | | | 231.9 | 4 | | | 37 |
| 2001 | | | | | 8 | | | 38 |
| 2002 | | | | 43 | 5 | | | 187 |
| 2003 | | | 6 | | 20 | | | 233 |
| 2004 | | | | 1017 | 4 | | | 170 |
| 2005 | 1.2 | | 29 | 5.8 | 1 | | | 149 |
| 2006 | 1.75 | | | | 2 | | 108 | 229 |
| 2007 | | | 77 | 410 | 1 | | | 188 |
| 2008 | 59 | | | 800 | 5 | | 120 | 280 |
| 2009 | | | 40 | | 10 | | | 73 |
| 2010 | | | 40 | 2175 | 21 | | | 15 |
| 2011 | 2.4 | | 63 | 870 | 59 | | | 79 |
| 2012 | | | | 2575 | 220 | | | 117 |
| 2013 | | | | 1320 | 377 | | | 280 |
| 2014 | 50 | | | | 302 | | | 152 |
| 2015 | | 2360 | | | 437 | | 129 | 394 |
| Total | 139 | 4630 | 649 | 16649 | 1485 | 530 | 357 | 3031 |

# Appendix B

# Companies

## B.1 SOFC manufacturers

The most important international SOFC manufacturers are listed below, in alphabetical order (Hart et al., 2015).

- Acumentrics SOFC (USA)
- Adelan Ltd. (UK)
- Bloom Energy Corporation (USA)
- Ceramic Fuel Cells Ltd. (Australia)
- Ceres Power Ltd. (UK)
- Convion Ltd. (Finland)
- Delphi Automotive plc (USA)
- Elcogen AS (Estonia)
- FuelCell Energy, Inc. (USA)
- Versa Power Systems, Inc. (USA)
- Hexis AG (Germany)
- Kyocera (Japan)
- NexTech Materials Ltd. (USA)
- Protonex Technology Corporation (USA)
- Rolls-Royce plc (UK)
- Sunfire GmbH (Germany)
- SOLIDpower (Italy/Switzerland)
- Topsoe Fuel Cell A/S (Denmark)
- Toto Ltd. (Japan)
- Ultra Electronics AMI (USA)
- Ztek Corporation (USA)

## B.2 List of European SOFC research projects

Table B.1: List of EU-funded research projects registered in Cordis (European Commission, 2016). Projects involving SOFCs, started between 1990 and 2016, are listed.

| Project | Dutch partners | Start | End |
|---|---|---|---|
| ACCEPT | Advanced Lightweight Engineering BV | 2002 | 2005 |
| | ECN | 2002 | 2005 |
| ASOF | TNO | 1990 | 1991 |

| Project | Dutch partners | Start | End |
|---|---|---|---|
| Bio-HyPP | Gasterra BV | 2015 | 2019 |
| | Micro Turbine Technology BV | 2015 | 2019 |
| | Technische Universiteit Eindhoven | 2015 | 2019 |
| BIOCELLUS | ECN | 2004 | 2007 |
| | Technische Universiteit Delft | 2004 | 2007 |
| BIOFEAT | ECN | 2003 | 2006 |
| CORE-SOFC | ECN | 2001 | 2004 |
| DESIGN | HyGear Fuel Cell Systems BV | 2011 | 2014 |
| Development of 50 kW class SOFC system and components | ECN | 1996 | 2000 |
| Development of a novel partial oxidation reactor for NG and integration into a micro-CHP SOFC system | Gastec NV | 1997 | 1999 |
| Development of a SOFC | ECN | 1990 | 1993 |
| Development of an advanced 1 kW SOFC prototype | TNO | 1992 | 1993 |
| Development of co fired ceramic cells for low temperature 800C SOFC operation | DSM Resins NV | 1994 | 1996 |
| | ECN | 1994 | 1996 |
| Development of SOFC flat plate reactor with metal separator plate for low temperature operation | ECN | 1993 | 1995 |
| DIAMOND | HyGear Fuel Cell Systems BV | 2014 | 2017 |
| FC CHAIN | HyGear Fuel Cell Systems BV | 2006 | 2010 |
| FC-DISTRICT | ECN | 2010 | 2014 |
| FELICITAS | Centre for Concepts in Mechatronics BV (CCM) | 2005 | 2008 |
| | Technische Universiteit Eindhoven | 2005 | 2008 |
| FLAME-SOFC | ECN | 2005 | 2010 |
| FlexiFuel-SOFC | HyGear Fuel Cell Systems BV | 2015 | 2019 |
| | Technische Universiteit Delft | 2015 | 2019 |
| | Universiteit Utrecht | 2015 | 2019 |
| Framework for system optimisation studies of integrated fuel energy systems | ECN | 1994 | 1995 |
| GREEN-FUEL-CELL | ECN | 2004 | 2008 |
| High temperature fuel cells use for the next ten years | Brandstofcel Nederland BV | 1998 | 2000 |
| | ECN | 1998 | 2000 |
| | Gastec NV | 1998 | 2000 |
| | Netherland Agency for Energy and the Environment (NOVEM) | 1998 | 2000 |
| Improving durability of SOFC stacks | ECN | 1996 | 1998 |
| INNO-SOFC | Energy Matters BV | 2015 | 2018 |
| IT-SOFC Technology | ECN | 1996 | 1998 |
| | Gastec NV | 1996 | 1998 |
| LOTUS | HyGear Fuel Cell Systems BV | 2011 | 2014 |
| Manufacturing techniques for components of flat plate SOFC reactors | ECN | 1991 | 1994 |
| New manufacturing technologies for advanced SOFCs | TNO | 1990 | 1992 |
| New SOFC materials and technology | TNO | 1993 | 1995 |
| Proof of feasibility of composite plate technology | Business Unit of TNO Built Environment and Geosciences | 1993 | 1994 |

| Project | Dutch partners | Start | End |
|---|---|---|---|
| SOFC600 | ECN | 2006 | 2010 |
| SOFCNET | ECN | 2003 | 2005 |
| | Shell Hydrogen BV | 2003 | 2005 |
| | University Of Twente | 2003 | 2005 |
| SOFT-PACT | Homa Software BV | 2011 | 2014 |
| SUAV | HyGear Fuel Cell Systems BV | 2011 | 2015 |
| Thin electrolyte layer for SOFCs and electrode materials | University Of Twente | 1991 | 1993 |

# Appendix C

# Source Code

This appendix displays the code that was added to oemof to allow for the optimisation of energy systems with SOC technologies. Modifications and additions were made for three purposes. First, objective functions were defined that take the emission of GHGs into account. Second, new classes of components were created to describe SOFCs and SOFECs. Third, sets of constraints are implemented to support the class definitions. These additions are displayed below. The full source code can be found on the following web pages: `https://github.com/oemof/oemof/` and `https://github.com/SanderNielen/oemof`.

## C.1 Objective functions

```
# -*- coding: utf-8 -*-
"""
This module contains a greenhouse gas minimisation objective.

@author: Sander van Nielen (sander.vannielen@planet.nl)
"""
import pyomo.environ as po
import oemof.solph as solph

from ..core.network.entities import Bus
from ..core.network.entities.components import transformers as transformer
from ..core.network.entities.components import sources as source

try:
    import objective_expressions as objexpr
except:
    from . import objective_expressions as objexpr

def set_ref(block):
    """Determine the type (capacity/input/output) of the first entity of
    'block', and return it.
    Detects the property 'cap_max' and 'in_max' to classify an entity.
    """
    for e in block.objs:
        try:
            if e.cap_max is not None:
                return 'capacity'
        except AttributeError: pass
        try:
            if e.in_max is not None:
                return 'input'
        except AttributeError: pass
        return 'output'

# @author: Sander van Nielen.
def minimize_ghg(self, cost_objects=None, revenue_objects=None):
    """ Builds objective function that minimises the total GHG emissions.
```

```
    Emissions to be included are:
                        Construction emissions
                        Operating/combustion emissions

    Parameters
    ----------
    self : pyomo model instance
    cost_objects : array-like list containing classes of
       objects of which GHG emissions should be included in
       terms of objective function (optional)
    revenue_objects: only included for compatibility reasons.
    """
    expr = 0
    ghg_blocks = cost_objects

    if ghg_blocks is None:
        ghg_blocks = [str(transformer.Simple),
                      str(transformer.CHP),
                      str(transformer.VariableEfficiencyCHP),
                      str(transformer.SimpleExtractionCHP),
                      str(transformer.TwoInputsOneOutput),
                      str(transformer.Sofc),
                      str(transformer.Sofec),
                      str(transformer.Hybrid),
                      str(transformer.Storage),
                      str(source.FixedSource),
                      str(source.Commodity),
                      str(source.DispatchSource)]
                      # add additional transformers if needed

    blocks = [block for block in self.block_data_objects(active=True)
              if not isinstance(block,
                                solph.optimization_model.OptimizationModel)]

    for block in blocks:
        if (block.name in ghg_blocks) and block.objs: #if block has emissions
            ref = set_ref(block)

            # variable emissions
            expr += objexpr.add_co2_var(self, block, ref)
            # fixed emissions
            # expr += objexpr.add_co2_fix(self, block, ref)
            # construction emissions
            if block.optimization_options.get('investment', False):
                expr += objexpr.add_co2_cap(self, block, ref)

    self.objective = po.Objective(expr=expr)

# @author: Simon Hilpert. Modified by Sander van Nielen.
def minimize_cost(self, cost_objects=None, revenue_objects=None):
    """ Builds objective function that minimises the total costs, including
    costs related to GHG emissions.

    Costs included are:
                        opex_var,
                        opex_fix,
                        curtailment_costs (dispatch sources),
                        annualised capex (investment components),
                        env_opex_var, env_capex
    Parameters
    ----------
    self : pyomo model instance
    cost_blocks : array like
       list containing classes of objects that are included in
```

```
            cost terms of objective function
revenue_blocks : array like
    list containing classes of objects that are included in revenue
            terms of objective function
"""
from ..core.network.entities import ExcessSlack, ShortageSlack

expr = 0
c_blocks = cost_objects
r_blocks = revenue_objects
tax = self.co2_tax

if cost_objects is None:
    c_blocks = [str(transformer.Simple),
                str(transformer.CHP),
                str(transformer.SimpleExtractionCHP),
                str(transformer.VariableEfficiencyCHP),
                str(transformer.TwoInputsOneOutput),
                str(transformer.Sofc),
                str(transformer.Sofec),
                str(transformer.Hybrid),
                str(transformer.Storage),
                str(source.FixedSource),
                str(source.Commodity),
                str(source.DispatchSource)]
if revenue_objects is None:
    r_blocks = []

blocks = [block for block in self.block_data_objects(active=True)
          if not isinstance(block,
                            solph.optimization_model.OptimizationModel)]

for block in blocks:
    if block.name in c_blocks and block.objs:
        ref = set_ref(block)

        # variable costs
        if ref == 'capacity':
            expr += objexpr.add_env_opex_var(self, getattr(self,
                    str(transformer.Storage)), 'input', tax)
            expr += objexpr.add_env_opex_var(self, block, 'output',
                    tax)
        else:
            expr += objexpr.add_env_opex_var(self, block, ref, tax)
        # fixed costs
        if block != str(source.Commodity):
            expr += objexpr.add_opex_fix(self, block, ref) * len(self.
timesteps)/8760
        # investment costs
        if block.optimization_options.get('investment', False):
            expr += objexpr.add_env_capex(self, block, ref, tax) * len(self.
timesteps)/8760
        if hasattr(block, 'z_start'):
            expr += objexpr.add_startup_costs(self, block)

        # revenues
    if block.name in r_blocks:
        expr += objexpr.add_revenues(self, block, 'output')

# costs for dispatchable sources
if hasattr(self, str(source.DispatchSource)):
    expr += \
        objexpr.add_curtailment_costs(self,
                getattr(self, str(source.DispatchSource)))
```

```
    # artificial costs for excess or shortage
    if hasattr(self, str(ExcessSlack)):
        expr += objexpr.add_excess_slack_costs(self,
                         getattr(self, str(ExcessSlack)))
    if hasattr(self, str(ShortageSlack)):
        expr += objexpr.add_shortage_slack_costs(self,
                         getattr(self, str(ShortageSlack)))


    self.objective = po.Objective(expr = expr * 8760/len(self.timesteps))
```

## C.2 SOC classes

```
from . import Transformer
import logging
import numpy as np
class Sofc(Transformer):
    # Added by Sander van Nielen
    """
    A SOFC transformer that produces three outputs

    Parameters
    ----------
    eta : list
      constant effciency for converting input into output. First element of
      list is used for conversion of input into first element of
      attribute `outputs`. Second element for second element of attribute
      `outputs`. E.g. eta = [0.3, 0.4]

    """
    optimization_options = {}

    def __init__(self, **kwargs):

        super().__init__(**kwargs)
        self.eta = kwargs.get('eta', [None, None, None])

class Sofec(Transformer):
    # Added by Sander van Nielen
    """
    A SOFEC consumes electricity and methane to produce H2 and heat.

    Parameters
    ----------
    eta : list
      constant effciency for converting input into output. First element of
      list is used for conversion of input into first element of
      attribute `outputs`. Second element for second element of attribute
      `outputs`. E.g. eta = [0.3, 0.4]

    """
    optimization_options = {}

    def __init__(self, **kwargs):

        super().__init__(**kwargs)
        self.eta = kwargs.get('eta', [None, None])

class Hybrid(Transformer):
    # Added by Sander van Nielen
    """
    A hybrid SOFC/SOFEC transformer can switch between two operation modes.

    Parameters
```

```
    ----------
    eta : list
      constant effciency for converting input into output. First element of
      list is used for conversion of input into first element of
      attribute `outputs`. Second element for second element of attribute
      `outputs`. E.g. eta = [0.3, 0.4]

    """
    optimization_options = {}

    def __init__(self, **kwargs):
        super().__init__(**kwargs)
```

## C.3 SOC constraints

```
"""
The nonlinear_contraints module contains the pyomo constraints wrapped in
functions. These functions are used by the '_assembler- methods
of the OptimizationModel()-class.

The module frequently uses the dictionaries I and O for the construction of
constraints. I and O contain all components' uids as dictionary keys and the
relevant input input/output uids as dictionary items.

*Illustrative Example*:

    Consider the following example of a chp-powerplant modeled with 4 entities
    (3 busses, 1 component) and their unique ids being stored in a list
    called `uids`:

    >>> uids = ['bus_el', 'bus_th', 'bus_coal','pp_coal']
    >>> I = {'pp_coal': 'bus_coal'}
    >>> O = {'pp_coal': ['bus_el', 'bus_th']}
    >>> print(I['pp_coal'])
    bus_coal

Sander van Nielen (s.s.vannielen@student.tudelft.nl)
"""

import inspect
import logging
import pyomo.environ as po
from pandas import Series as pdSeries
from . import pyomo_fastbuild as pofast

def add_sofc_relation(model, block):
    """Adds constraints for the relation between input and outputs of a
    SOFC component.
    Added by Sander van Nielen
    """
    if not block.objs or block.objs is None:
        raise ValueError("No objects defined. Please specify objects for \
                         which the constraints should be build")

    # Create fuel utilisation variable with bounds
    block.fuel_util = po.Var(block.uids, model.timesteps,
                        within=po.NonNegativeReals, bounds=(0.6,0.95))
    fuel_util = block.fuel_util
    add_out = getattr(block, "add_out", {obj.uid:0 for obj in block.objs})

    # Relation of outputs to input.
    def power_out_rule(block, e, t):
        OCV=1.0691993282
        alfa=0.0526705851
```

```python
        R=0.45; Ri={}
        I = model.w[model.I[e][0], e, t] * fuel_util[e,t] /1.1534914168
        for obj in block.objs:
            in_max = obj.in_max[0] + add_out[obj.uid]
            Ri[obj.uid] = 1.1534914168*I * (OCV-alfa*0.95)/(0.95*2*in_max)
        out = (OCV - alfa*fuel_util[e,t] - Ri[e])*I *0.96*0.9
        return(model.w[e, model.O[e][0], t] == out)
    def hydrogen_out_rule(block, e, t):
        I = model.w[model.I[e][0], e, t] * fuel_util[e,t] /1.1534914168
        out = I*1.199821776 * (1/fuel_util[e,t] - 1)
        return(model.w[e, model.O[e][1], t] == out)
    def heat_out_rule(block, e, t):
        # Energy balance: in - out = heat
        heat = (model.w[model.I[e][0], e, t] -
                model.w[e, model.O[e][0], t] - model.w[e, model.O[e][1], t])
        return(model.w[e, model.O[e][2], t] == 0.95 * heat)

    block.power_out = po.Constraint(block.indexset, rule=power_out_rule,
                      doc="Ele_out = i*(0.119 + (1.14-0.143)*U_f -0.2*i)")
    block.hydrogen_out = po.Constraint(block.indexset, rule=hydrogen_out_rule,
                         doc="H_2,out = i*1.199*(1/U_f -1)")
    block.heat_out = po.Constraint(block.indexset, rule=heat_out_rule,
                     doc="Heat_out = 0.95*(CH4_in - H2_out - Ele_out)")

def add_sofec_relation(model, block):
    """Adds constraints for the relation between input and outputs of a
    Solid Oxide Fuel-asissted Electrolysis Cell.
    Added by Sander van Nielen
    """
    if not block.objs or block.objs is None:
        raise ValueError("No objects defined. Please specify objects for \
                         which the constraints should be build")

    # Assumed constants:
    a = 0.08725 #alpha
    R = 0.45 #ASR
    Uf = 0.8 #Fuel utilisation
    OCV = 0.11564 #Open cell voltage
    add_out = getattr(block, "add_out", {obj.uid:0 for obj in block.objs})

    # Relation of outputs to input.
    def power_in_rule(block, e, t):
        Ri = {}
        I = model.w[model.I[e][0], e, t] * Uf /1.1534914168
        for obj in block.objs:
            Imax = (obj.in_max[0] + add_out[obj.uid]) * Uf /1.1534914168
            Ri[obj.uid] = R*I* 1.5 / Imax
        ele_in = -(OCV -a*Uf -Ri[e])*I /(0.9*0.96)
        return(model.w[model.I[e][1], e, t] == ele_in)
    def hydrogen_out_rule(block, e, t):
        Uf = 0.8
        I = model.w[model.I[e][0], e, t] * Uf /1.1534914168
        return(model.w[e, model.O[e][0], t] == I*1.4812614519)
    def heat_out_rule(block, e, t):
        heat = model.w[model.I[e][0], e, t] + model.w[model.I[e][1], e, t]
        heat -= model.w[e, model.O[e][0], t]
        model.w[e, model.O[e][1], t].setlb(0)
        return(model.w[e, model.O[e][1], t] == 0.95 * heat)

    block.power_in = po.Constraint(block.indexset, rule=power_in_rule,
                                   doc="Ele_in = i*(0.119 - 0.143*U_f -0.45*i)")
    block.hydrogen_out = po.Constraint(block.indexset, rule=hydrogen_out_rule,
                                   doc="H_2,out = i*1.199*(1/U_f -1)")
    block.heat_out = po.Constraint(block.indexset, rule=heat_out_rule,
```

```
                                 doc="Heat_out = 0.95*(CH4_in - H2_out -
    Ele_out)")

def add_hybrid_relation(model, block):
    """Adds constraints for the relation between input and outputs of a
    Solid Oxide Cell with a SOFC and a SOFEC mode.
    Added by Sander van Nielen
    """
    if not block.objs or block.objs is None:
        raise ValueError("No objects defined. Please specify objects for \
                         which the constraints should be build")

    # Create fuel utilisation variable with bounds
    block.fuel_util = po.Var(block.uids, model.timesteps,
                        within=po.NonNegativeReals, bounds=(0.6,0.95))
    fuel_util = block.fuel_util
    # Create variable for the fraction of cells operating in SOFC mode.
    block.y = po.Var(block.uids, model.timesteps,
                     within=po.Binary) #NonNegativeReals, bounds=(0,1))

    add_out = getattr(block, "add_out", {obj.uid:0 for obj in block.objs})

    # Relation of outputs to input as a linear combination of SOFC and SOFEC.
    def power_out_rule(block, e, t):
        OCV=1.0691993282; alfa=0.0526705851; R=0.45; Ri={}
        I = model.w[model.I[e][0], e, t] * fuel_util[e,t] /1.1534914168
        for obj in block.objs:
            in_max = obj.in_max[0] + add_out[obj.uid]
            Ri[obj.uid] = 1.1534914168*I * (OCV-alfa*0.95)/(0.95*2*in_max)
        out = (OCV - alfa*fuel_util[e,t] - Ri[e])*I *0.96*0.9 * block.y[e,t]
        return(model.w[e, model.O[e][0], t] == out)
    def power_in_rule(block, e, t):
        alfa = 0.08725; OCV = 0.11564; R = 0.45; Uf = 0.8; Ri = {}
        I = model.w[model.I[e][0], e, t] * fuel_util[e,t] /1.1534914168
        for obj in block.objs:
            Imax = (obj.in_max[0] + add_out[obj.uid]) * fuel_util[e,t]
    /1.1534914168
            Ri[obj.uid] = R*I* 1.5 / Imax
        ele_in = -(OCV -alfa*fuel_util[e,t] -Ri[e])*I /(0.9*0.96) * (1-block.y[e,t
    ])
        return(model.w[model.I[e][1], e, t] == ele_in)
    def hydrogen_out_rule(block, e, t):
        I = model.w[model.I[e][0], e, t] * fuel_util[e,t] /1.1534914168
        out = I*block.y[e,t]*1.199821776 * (1/fuel_util[e,t] - 1)
        out += I*(1-block.y[e,t])*1.4812614519
        return(model.w[e, model.O[e][1], t] == out)
    def heat_out_rule(block, e, t):
        # Energy balance: in - out = heat
        heat = model.w[model.I[e][0], e, t] + model.w[model.I[e][1], e, t]
        heat -= model.w[e, model.O[e][0], t] + model.w[e, model.O[e][1], t]
        model.w[e, model.O[e][2], t].setlb(0)
        return(model.w[e, model.O[e][2], t] == 0.95 * heat)

    block.power_out = po.Constraint(block.indexset, rule=power_out_rule,
                                 doc="Ele_out = i*(0.119 + (1.14-0.143)*U_f
    -0.2*i)")
    block.power_in = po.Constraint(block.indexset, rule=power_in_rule,
                                 doc="Ele_in = i*(0.03922 -0.143*0.8 -0.45*i)"
    )
    block.hydrogen_out = po.Constraint(block.indexset, rule=hydrogen_out_rule,
                                 doc="H_2,out = i*1.199*(1/U_f -1)")
    block.heat_out = po.Constraint(block.indexset, rule=heat_out_rule,
                                 doc="Heat_out = 0.95*(CH4_in - H2_out -
    Ele_out)")
```