Doctoral Thesis

Hybrid energy transmission for multi-energy networks

Author(s):
Favre-Perrod, Patrick

Publication Date:
2008

Permanent Link:
https://doi.org/10.3929/ethz-a-005698158

Rights / License:
In Copyright - Non-Commercial Use Permitted
Hybrid Energy Transmission for Multi-Energy Networks

A dissertation submitted to
ETH ZURICH

for the degree of
Doctor of Sciences

presented by
PATRICK FAVRE-PERROD
Dipl. El.-Ing. ETH
born January 12, 1979
citizen of Château-d’Oex (VD), Switzerland

accepted on the recommendation of
Prof. Dr. Klaus Fröhlich, examiner
Prof. Dr. Goran Strbac, co-examiner

2008
Acknowledgements

I express my gratitude to Prof. Dr. Klaus Fröhlich for his supervision of my thesis work, as well as to his team at the High Voltage Laboratory of ETH Zurich for their support. The Vision of Future Energy Networks project involved many collaborations with colleagues at ETH Zurich, RWTH Aachen, TU Delft and others as well as support from our project sponsors (ABB, AREVA T&D, Siemens and the Swiss federal office of energy). I sincerely thank all of them; the list of the individuals is too long to fit on this page.

I am especially grateful to those who have reviewed my work: Dr. Timm H. Teich who helped translating my English into readable English and Prof. Dr. Goran Strbac who kindly accepted to be the co-examiner of my work. Our discussions permitted to greatly improve this thesis.

The main subject of this thesis, the combined transmission of electricity and chemical power with waste heat reuse, has emerged during a diploma thesis by Ronny Frik and myself under the supervision of Bernd Klöckl. Many thanks to Ronny and Bernd for this very creative collaboration!

This thesis is the result of an effort to present my work in a streamlined way. During the preparation phase of its contents, some more random discussions (not restricted to scientific matters) and collegial support have been necessary. Thank you Andreas, Bernd, Christian, Dominique and Peter (in alphabetic order): you have been great office mates!

Zürich, 4th October 2008, Patrick Favre-Perrod
Summary

The extensive development of renewable, stochastic and distributed energy sources will lead to major changes in the electricity grid. Possible long term trends include a higher level of interaction between different energy carrier systems (electrical, chemical and thermal). This would facilitate storage solutions as well as the inclusion of new participants into public energy networks, e.g. new transportation technologies like hybrid or plug-in cars.

A framework for the description of these upcoming multi-energy networks has been developed in the “Vision of Future Energy Networks” project. It consists of Energy Hubs, interfaces for network participants and Energy Interconnectors, which transmit several forms of energy. Combined infrastructures for multiple energy carriers are an innovative response to future challenges including the integration of renewable sources and novel storage principles. This work aims at proposing a principle scheme for multi-energy transmission, establishing a set of models for this scheme, assessing the achievable performance of such systems under realistic assumptions and determining a suitable application range.

The interconnector principle described in this work is a novel approach to energy transmission, thus it was necessary to determine a promising variant (variant selection), the relevant physical phenomena (model), their implication on the design and operation of an interconnector and the possible application range. The spectrum of the possible energy carriers includes electricity, natural gas, hydrogen, liquid hydrocarbons, compressed air, district heating, district cooling, etc.. A promising solution with respect to the integration into future network concepts is the combination of electric and gaseous chemical energy transmission.

A set of models has been developed for this preferred variant. The specific formulation of the compressible, non-adiabatic gas flow with friction has required an adaptation of existing formulations, which yielded a numerical model. In a second step, analytical approximations have been developed, in order to derive scaling laws for the
interconnector layout.

Based on these models, the relevant operational characteristics of the interconnector system have been identified. The resulting description of the transmissible electric, chemical and thermal power has been used to derive a layout methodology for the interconnector with a given transmission capacity and transmission length.

In a final step, the layout strategy developed has been applied to different scenarios describing various transmission distances and transmissible powers. The comparison of the resulting interconnector dimensioning shows that the most promising application area for further study of the interconnector corresponds to the current medium voltage network level, i.e. the transmission of some tens of MW of electric and chemical power over a distance of some tens of km.

The layout method can now be used in infrastructure scenarios to be developed in the future within the “Vision of Future Energy Networks” project, where interconnectors will form an important part of network development strategies.
Zusammenfassung


Für diese Vorzugsvariante wurden Modelle entwickelt, welche die Beschreibung des kompressiblen, nicht-adiabatischen und rei-
bungsbehaf teten Gasflusses umfassen. In einem weiteren Schritt wurden analytische Näherungen entwickelt, welche die Ableitung einer Layout-Prozedur ermöglichten.

Schließlich konnte diese Layout-Prozedur auf verschiedene Szenarien angewandt werden, welche einen breiten Bereich an Übertragungslängen und -leistungen abdecken. Der Vergleich der resultierenden Interconnector-Auslegungen ergab, dass der meist-versprechende Anwendungsbereich des Interconnector-Prinzips im Bereich einiger zehn MW elektrischer und chemischer Leistung über eine Länge von einigen zehn Kilometern liegt.

Die hier entwickelte Layout-Prozedur kann im Rahmen der in nachfolgenden Projektphasen zu entwickelnden Infrastrukturszenarien angewandt werden.
Contents

Acknowledgements i

Summary ii

Zusammenfassung iv

1 Problem statement 1
   1.1 Challenges in the present grid 1
   1.2 Need for a revolution in energy T&D 2
   1.3 Consequences for energy transmission 3

2 Current approaches 5
   2.1 Future electricity networks 5
   2.2 Multi-Energy networks 6

3 Description of the work scope 9
   3.1 Applicability study 10
   3.2 Relation to other research activities 12

4 Interconnector principle 13
   4.1 The framework 14
      4.1.1 General concept 14
      4.1.2 The Energy Hub 16
      4.1.3 The Energy Interconnector 17
## CONTENTS

7.2 Possible applications ........................................ 102  
  7.2.1 Applications investigated .......................... 102  
  7.2.2 Resulting layout for the selected applications .... 103  
  7.2.3 Discussion ............................................ 113  

8 Conclusions .................................................. 115  
  8.1 Implications for the “Vision of Future Energy Net-works project” ........................................ 115  
  8.2 Application of the interconnector .................. 116  

A Auxiliary equipment model ................................. 119  
  A.1 Compressors .......................................... 119  
  A.2 Heat exchangers and recovery ....................... 121  
    A.2.1 Use of compression waste heat ............... 121  
    A.2.2 Use of warm gas at the bus outlet ........... 125  
  A.3 Overall efficiency .................................. 130  

B Example ...................................................... 133  

C Illustration examples ....................................... 137  
  C.1 Example 1: Distribution ............................ 137  
  C.2 Example 2: Regional distribution .................. 139  
  C.3 Example 3: Bulk transmission ..................... 140  

D Heat exchangers layout ..................................... 143  

Bibliography .................................................. 147  

List of symbols ............................................... 151  

List of figures ............................................... 161  

List of tables ............................................... 166  

Curriculum vitae ............................................. 169
Chapter 1

Problem statement

Energy networks of the future with a rising share of distributed and stochastic energy resources are the general context for this work. This chapter reviews relevant trends, action needed and the potential consequences for energy transmission. Multi-Energy networks, i.e. networks with a strong integration level between different energy carriers represent a particular challenge for energy transmission.

1.1 Challenges in the present grid

After a long period of centralisation of energy generation, the share of installed small scale generators has increased in recent years. The drivers for this evolution include [1, 2]:

- the use of renewable and environmentally friendly energy sources,
- the opportunity to postpone transmission investments,
- the lower risks induced by a smaller generator size,
• as well as competition and energy efficiency policies.

Ensuring supply security and grid stability, understanding and preventing negative effects on power quality, protection and voltage levels as well as adapting the regulatory framework to the changing conditions are some of the challenges resulting therefrom [3 2]. Considering all these factors, a major research effort is needed to determine which network developments will lead to an improved situation overall (in technical, environmental, economical or societal terms).

Besides their contribution to energy generation, distributed generators have the technical potential to provide reactive power, frequency reserve and more. In general it is firmly understood that a further increase in the share of distributed generation should be accompanied by the establishment of an active network [3] (i.e. actively using the services provided by the distributed generators).

1.2 Need for a revolution in energy T&D

Several organisations and governmental bodies have acknowledged the necessity of a radical evolution in the structure and operation of networks. At the European level, the SmartGrids technology platform has identified the main differences between the present and the future grid. New features will include more flexibility in operation (customised power quality, security and maintenance), demand side participation, full integration of distributed resources with centralised ones, more distributed generators close to consumers and a harmonised legal framework.

A similar direction can be found in other strategy plans, e.g. those originating from the U.S. department of energy [4]. The general conclusion is that radically new network schemes are not unlikely to be worked out in the future. Among the discussed solutions, a trend towards integrated systems englobing several energy carriers exists. The drivers for this evolution englobe the rising number of small-
1.3 Consequences for energy transmission

Electricity transmission is also widely affected by these presently implemented or expected changes. The SmartGrids platform identified a research task devoted to new architectures and tools for the transmission networks of the future, which includes the development of intelligent (i.e. controllable) transmission devices as well as new models and methods. The strategic research agenda [5] also acknowledges the potential of multi-energy systems, i.e. the optimisation of several infrastructures for simultaneously utilised different energy carriers.

Enabling technologies or concepts for the evolution of electric energy transmission include composite core conductors, gas insulated lines, evaporative cooling of power cables, conducting polymers and high temperature insulation materials [6]. Despite the trend to more distributed generation, an increase in the installed transmission capacities is expected, especially as a supporting measure for competition [4, 7]. Finally underground transmission is of increasing interest since it lowers the risk of blackouts in extreme weather conditions and the acceptance of new cable lines might be higher than that of new overhead lines and its acceptance in urban areas is anyway likely to be better than for overhead lines. The EU has launched an effort into this direction in a background paper on underground energy transmission [8].

In the context of multi-energy networks, new approaches to energy transmission will be needed as well. In such networks, combined transmission systems may offer benefits in terms of synergies, but they may as well introduce additional constraints into the network layout process. Despite some early approaches to this topic, it remains unclear which combination of carriers, principles and physical dimensions are feasible. All aspects related to the operation
and scalability (feasible power levels, distances, interdependencies between different energy carriers) of a combined transmission will therefore need further clarification.
Chapter 2

Current approaches to future energy networks

Numerous research projects have been or are being devoted to future energy networks. This chapter is a description of the most relevant related research activities which either represent the background or alternative research directions for the topic of this work. Active or smart networks, especially at the distribution level, constitute the mainstream of current research programmes. The modelling and development of integrated networks delivering several energy carriers is addressed in a few of these programmes. In this context, some solutions involving multi-energy transmission (or heat recovery) have been proposed.

2.1 Future electricity networks

The majority of current research activities in the area of future energy networks is related to wider national or international pro-
grammes. The U.S. department of energy has developed the “Grid 2030” vision \[4\]. Its major elements are a national backbone (possibly relying on superconductive cables), regional interconnections as well as local active grids. Based on this the visionary idea of a SuperCity, where hydrogen could play a double role as a coolant for superconductive apparatus and energy carrier (e.g. for electricity storage), has emerged \[9\].

The concept of MicroGrids (small distribution networks with load and sources of comparable size \[10\] are mainly promoted in Europe, e.g. in the (More-)MicroGrids projects. These projects aim at developing controllers and control strategies as well as alternative network designs in order to increase the connected distributed generation share. A variety of further projects at the national and European levels are thematically related to distributed generation, storage and energy management.

Programmes promoting new functions in distribution networks (demand management, power quality selection, more use of IT, etc.) can be found world-wide, e.g. \[11\].

### 2.2 Multi-Energy networks

Some research activities extend their scope into other energy carrier systems. The NEMESS (Network Model of Energy-services Supply System) and DEECO (Dynamic Energy Emission and Cost Optimisation) frameworks e.g. are aimed at supporting the development of “regional energy concepts” \[12\]. Integrated planning has also been applied by SINTEF (Foundation for Scientific and Industrial Research, Norway) for the evaluation of upstream infrastructure needed by decentralised generators (e.g. road transport of biomass) \[13\]. The methodology was developed from a model dedicated to the optimisation of mixed hydro-thermal systems and was extended to natural gas systems including storage and combined heat and power \[14\].

New concepts for energy transmission in the context of several simultaneously utilised energy carriers have been proposed in the
2.2. MULTI-ENERGY NETWORKS

following projects:

- The SuperCable [15]: A conceptual study suggesting the use of superconductive (liquid) hydrogen-cooled cables for “bulk” energy transmission. A share of the hydrogen might be used for energetic purposes (i.e. as an energy carrier). The context of this idea is large-scale generation using nuclear or fossil fuelled plants, thus the resulting transmitted electric power is of the order of one to several GW.

- The ICEFUEL project [16]: The aim of this project is the development of a system for the hybrid transmission of cryogenic fuels (methane or hydrogen), electricity and data.

- Recovering heat from forced-cooled power cables has also been discussed. A study carried out in the Swiss network has shown that the use of this heat is only energetically attractive in a limited number of circumstances [17].

A very specific approach has been chosen in each of these projects: the SuperCable and ICEFUEL projects are defined in order to promote particular technologies (superconductivity and liquid hydrogen transmission), while the study on waste heat recovery was limited to the analysis of existing assets. These studies are not accompanied by a vision for the integration of the new transmission system into a new or improved energy network. This study will be based on a general network development scheme, i.e. multi-energy networks and avoid the consideration of controversial technologies like superconductivity.
CHAPTER 2. CURRENT APPROACHES
Chapter 3

Description of the work scope

This chapter describes the questions to be addressed within this work. As exposed in the previous chapters, multi-energy transmission has not yet been applied in practice. The focus of this work will be on the choice of a suited principle and the investigation of its expected applicability range in terms of transmitted power and transmission distance. This investigation will be based on physical properties and limitations imposed by material properties. As a consequence, studies on detailed designs for transmission devices will not be useful in a first step and shall not be developed.
3.1 Applicability study on the principle of multi-energy transmission

Considering the potential benefits of multi-energy transmission, the necessary tools for the evaluation of infrastructure scenarios involving multi-energy transmission shall be prepared. Within the wide range of available or upcoming energy carriers (e.g. electricity, heat, hydrogen, methane, liquid hydrocarbons, carbon monoxide, compressed air, etc.) a meaningful combination is to be selected for further study. Firstly the selected carriers must cover the requirements arising from future sources and sinks within the network, e.g. biomass gasification or solar hydrogen generation and hybrid vehicles. Secondly, the selection of the carriers will be based on its implication on the design of the transmission system: the use of gaseous or liquid chemical energy carriers may e.g. impact on the achievable performance (transmissible power, efficiency) of a combined transmission system.

The next step is the determination of possible concepts and variants for the selected combination of carriers. Possible overall transmission concepts including the auxiliary equipment shall be compared. Among the questions to be addressed are the placement of compressors, pumps and waste heat recovery equipment (if applicable). The parameters will be identified and their physical and technical limitations will help to determine the applicability of the most promising variant (the “favourite solution”).

Next the specific aspects of combined transmission have to be identified: since auxiliary equipment is shared and several energy carriers are to be transmitted in the same system, a coupling among the permissible transmitted powers is likely. Limits to the scalability of the concept are also to be investigated: the dimensioning of such a system will largely differ for uses ranging from distribution to bulk transmission and for varying ratios among the transmitted powers for each energy carrier.

For the preferred variant, a suitable model must be found, which
permits to describe the “external performance” of a largely unknown system, thus deferring the consideration of physical details whenever possible. The goal of this step is to obtain a model permitting the evaluation of the preferred concept and its description. Thus the resulting model will be abstract and does not address the detailed design, manufacturing, laying, etc. of the system. The determination of the necessary depth of the description is part of this activity. A potentially more complex part of the modelling process is the flow of a gaseous energy carrier with heat absorption. In this context, numerical simulations are likely to be the only precise approach. For the consideration of a large number of different configurations within infrastructure scenarios (in the “Vision of Future Energy Networks” project, see also chapter 4) this is not satisfactory. Where needed, simplified models will thus be developed.

Using the developed model, the operation of a combined transmission system can be described. The prerequisite to that is the identification of the relevant “questions”, i.e. identify the specific features of the hybrid transmission approach as compared to those of decoupled systems. The first goal is to derive a description for the transmission capability of a given system (maximum powers and possibly other limitations). The second goal is to indicate how the transmitted powers can be varied, i.e. which voltages, currents, pressures, etc. must be variable for the operation of a combined transmission system.

The identified constraints on certain parameters (e.g. material parameters) will limit the achievable power level and transmission length. Thus, the concept of the interconnector is to be applied to some general application scenarios in order to determine the rough dimensions, voltage level, etc. required for some relevant potential applications of the interconnector. This will help to determine where the priority efforts for further refinement studies should be applied.

The auxiliary equipment power requirement as well as the potential for waste heat recovery will be discussed with respect to their contribution to the total transmission efficiency.
3.2 Relation to other research activities

The context for this work is the “Vision of Future Energy Networks” project (described in chapter 4). This project will develop scenarios for future energy network infrastructures where multi-energy transmission will be one of the investigated options for interlinking the “Energy Hubs”, which are the interface between the network and the energy producers or consumers.

For the use in these scenarios, a layout procedure for the interconnector system is necessary. This procedure shall help to determine the interconnector dimensions subsequently needed for its simulation (in the scenarios). As a consequence a particular objective of this study is the provision of a suited layout procedure.
Chapter 4

Multi-energy networks and the Energy Interconnector principle

In the first part of this chapter the “Vision of Future Energy Networks” framework is presented: a flexible description for multi-energy networks. Its building blocks are the Energy Hub (interface among the network participants) and the Energy Interconnector (a transmission link for several energy carriers). A wide spectrum of variants for the implementation of the interconnector exists. In order to achieve the goals of this investigation, a primary selection of a preferred variant is done based on a discussion of the relevant design parameters, which could be identified at this early stage.
4.1 The “Vision of Future Energy Networks” framework

4.1.1 General concept

In the “Vision of Future Energy Networks” project a generic scheme for the energy network of the future has been worked out [18, 19, 20]. Figure 4.1 illustrates the basic structure of this modelling framework:

- “Energy” is not restricted to electricity. Each form of energy produced or consumed by the network participants is potentially considered in this multi-energy network approach (e.g. electric, chemical and thermal energy).

- The network participants are connected to customisable interfaces, so-called Energy Hubs.

- Energy Hubs exchange different forms of energy. The interlink between these hubs is called an Energy Interconnector.

- The proposed structure can be seen as a fractal structure: hubs supplying smaller areas can be gathered to larger hubs (supplying e.g. a small city), etc.\footnote{No decision on the adequate scale of a hub can be made now and the framework was expressly defined in order to address this problem.}

The background for these ideas is many-sided. A first motivation for the customised interface is the need to integrate an increasingly diversified population of participants (consumers and producers like distributed generators) having specific requirements (in terms of voltage, frequency, power quality, ...). The hubs have also the potential to make network power flows controllable. Some applications will be more efficient if fuelled by chemical energy (e.g. possibly transportation) and the possibility to flexibly convert energy opens new opportunities for energy management (e.g. energy storage). Finally the multi-energy approach serves to investigate multi-energy transmission, which will be the focus of this work.
4.1. THE FRAMEWORK

Figure 4.1: Illustration of the “Vision of Future Energy Networks” multi-energy network framework.
The definition of the “Vision of Future Energy Networks” framework is motivated by its potential advantages as compared to present solutions. These advantages include:

- **New functionalities**: e.g. energy storage (including sharing storage across different networks), the potential to include new participants (e.g. transportation), customised power (reliability, voltage, frequency).

- **Taking into account any kind of energy production and consumption into the same model allows for a wider optimisation.**

- **Synergies**, i.e. the deployment of technologies involving several carriers (like CHP\(^2\)) or the sharing of auxiliary equipment (control, metering, cooling, etc.) are facilitated in this context.

The use of the “Vision of Future Energy Networks” framework is at least twofold: it permits the development of new network schemes and it provides a context for the evaluation of new ideas and trends, e.g. the Energy Interconnector. The distinctive elements of this approach are: the multi-carrier paradigm, the inclusion of transportation applications and the so-called *greenfield approach* (i.e. the abstraction of pre-existing infrastructures in a first stage - This is consistent with the long-term view of the project).

### 4.1.2 The Energy Hub

The Energy Hub will act as the interface between any kind of producer and consumer of energy and as the connection point for energy transmission equipment. Its tasks will consist of converting, storing, conditioning and possibly managing energy. It therefore consists of conversion and storage devices with the ability to match the consumer needs in a flexible manner like it is suggested in figure 4.2. Within the “Vision of Future Energy Networks” project, the following aspects of the energy hub have been covered to date: modelling

\(^2\)Combined heat and power
of mixed energy carrier flows, reliability aspects of such systems and storage modelling and integration.

4.1.3 The Energy Interconnector

The basic idea of the Energy Interconnector is to combine the transmission of several energy carriers in the described multi-energy context. The expected advantages are a simplification of the laying process (as compared with the individual laying of several separate parallel systems), a possible simplification of the terminal equipment (since it may be shared) as well as the possibility to improve in line storage capacity or efficiency.

Unresolved questions include the choice of the energy carriers, the geometry of the interconnector (and the layout procedure), the concept for waste heat re-use, etc. Smaller possible variations include the choice of materials and the dimensioning of the auxiliary
According to its defined scope (see chapter 3) this work will focus on the development of a layout procedure. The questions will be addressed in the following sequence:

- Figure out a “solution candidate” with some variants that can be covered with a single model, i.e. select the combination of energy forms and carriers to be considered in the further work (section 4.2).
- Identify the missing “model parts” and work out a model. Determine how general this model can be in order to answer relevant network layout questions (chapter 5).
- Characterise the operation of an interconnector system, including auxiliary equipment (chapter 6).
- Elaborate a layout strategy for the interconnector (section 7.1).
- Check the applicability of the concept to generic application scenarios (section 7.2).

It must be stressed that all these questions will only find a definitive answer in the context of the entire system, i.e. within the “Vision of future energy network” framework. The question of the detailed design of the interconnector will only be of crucial interest once an overall network layout has established its advantages over other schemes.

### 4.2 Possible variants and parameters

#### 4.2.1 Preliminary selection of variants

From a general perspective, the spectrum of the potential energy carrier combinations for the interconnector is wide. To develop a model and a layout strategy, a choice has to be made regarding the combination to be considered. Possible forms of energy include
electricity, chemical energy (gaseous or liquid, open or closed cycle), thermal energy (also open or closed cycles) and compressed media. Further possibilities may be water delivery or superconductive or cryogenic electricity transmission.

The choice of this “solution candidate” shall be based on the following criteria:

- A direct use of the transmitted energy carriers is possible.
- There is flexibility in the conversion techniques from the transmitted energy carrier.
- An acceptable conversion efficiency is feasible or can be expected to be achieved.
- Open-cycle cooling of the electrical conductor is potentially feasible.

As a consequence the variant studied in the rest of this work is the combination of electric and (open cycle) gaseous chemical energy transmission. Electric energy transmission is modelled as d.c. Liquid chemical carriers will be considered in the basic model for comparison purposes. The modelled setup is coaxial (as shown in figure 5.1), with a solid insulation material.

4.2.2 Parameters

The “problem definition” will in general include the total length of the interconnector $L_{\text{tot}}$, and its capacity $P_{\text{chMax}}$ and $P_{\text{elMax}}$.

The modelling was done in a way that allows an easy variation of three classes of “parameters” including:

3. i.e. no binding to a unique conversion technology.
4. i.e. the distance between two heat exchangers.
5. Since it does not radically change the discussion, the rated capacity is assumed to be the potential maximum power transferred.
6. All variable names are explained in the list of symbols on page 151 at the end of this thesis.
• Design parameters, which are those dimensions and properties that can be widely varied to achieve the required transmission capacity:

  – The inner radius of the interconnector $R_i$
  – The electrical conductor total cross-sectional area $A_{CTot}$
  – The maximum d.c. voltage at the interconnector terminals $U_{inMax}$

• Design alternatives, which represent possible (discrete) choices of materials or functionalities of parts or subsystems:

  – The choice of the chemical medium: gaseous or liquid, as well as its exact nature.
  – The material of the electrical conductor
  – The presence or absence of waste heat reuse at the terminals
  – The temperature range over which waste heat reuse will operate

• Constrained parameters, which are parameters of the model but can not be freely changed in the design, because they arise from external influences or physical limitations:

  – The specific thermal resistivity of the soil $R_{thE}$
  – The friction factor of the viscous fluid flow $f$
  – Temperature limitations at the interconnector inlet and outlet $T_1$ resp. $T_2$
  – The maximum operating pressure $p_{Max}$
  – The maximum electric current density $J_{Max}$

---

7 including all phases
4.2. VARIANTS AND PARAMETERS

Restricting the parameters to this list allows one to develop a quite general model which ignores implementation details. On the other hand, simple adaptations allow one to approximate slightly different arrangements like e.g. a.c. voltages or several parallel circuits.

This classification of the parameters will be used throughout the next chapters devoted to the layout and application of the interconnector. The design parameters are those parameters which can be adjusted in order to achieve the desired maximum transmittable powers, the design alternatives indicate how different “sub-variants” for the interconnector may be realised (e.g. using different chemical energy carriers) and the constrained parameters will play a role in the determination of the physical limits to the applicability of the interconnector principle.
Chapter 5

Interconnector modelling

This chapter presents the various models of the interconnector which will be used in the upcoming discussion of its operational characteristics and layout procedure. Two main models describe the use of liquid or gaseous energy carriers. They describe the electrical, chemical and thermal parts of the interconnector. These parts are interdependent, which leads to a mathematical description which can only be solved numerically. A simplified set of models permitting the development of analytical scaling laws has thus been developed.

5.1 Modelling approach

The purpose of this study being the assessment of the general idea of the interconnector, terminal powers are the most important information within the model to be developed. Therefore a generic model
Figure 5.1: Illustration of the Energy Interconnector with electric and chemical power transmission as well as waste heat reuse.

according to figure 5.1 has been chosen. It consists of three elements: a hollow electrical conductor (through which a chemical medium can flow), a thermal insulation and the surrounding soil. The electric power $P_{el1}$ and the chemical power $P_{ch}$ are transmitted. A part $P_U$ of the electrical losses $P_V$ is transmitted to the surrounding soil, the rest is transmitted to the flowing medium $P_{CM}$. The heat $P_Q$ absorbed by the medium is the sum of $P_{CM}$ and the internal and wall friction $P_R$.

Several simplifications are made: temperatures in the electrical conductor and the chemical medium depend only on the axial coordinate x (i.e. considering a cross-section of the interconnector, the temperature of the conductor is the same for the whole cross-section). Some construction elements including the electrical insulation are omitted because their respective contributions to the relationships among the terminal powers are not critical (or can be included by other means).

These simplifications obviously limit the achievable accuracy, but they contribute to make the model usable in the context of this study, i.e. the model constitutes a general approach: it does not require knowledge of the layout “details”, applies to several layout variants
and thus permits an insight into basic principles rather than into specific details.

The model includes three parts:

- A model of the fluid flow: This part is specific for gaseous or liquid media. This flow is non-adiabatic, non-isothermal, compressible (except for liquid media) and with friction.

- An electrical model: Ohmic losses are modelled as d.c. losses (with according correction factors for skin and proximity effects).

- A thermal model: Heat transfer between the conductor, the soil and the chemical media are modelled. Since the heat absorbed by the fluid is dependent on the electrical losses, electrical, chemical and thermal powers are coupled.

The models will be presented in the following sections. Since the resulting equations can only be solved numerically, a simplified model leading to partly analytical solutions will also be used, e.g. for the derivation of scaling laws.

5.2 Model of the interconnector with transport of a liquid medium

5.2.1 General overview of the model

The model of the interconnector with a liquid chemical medium is less complex because the only contribution to the pressure drop is friction. The pressure drop per unit length is constant, which leads to the simple expression for the mass flow rate:

$$\dot{m} = \sqrt{\frac{4\pi^2 R_i^5 \rho_m M}{f L_{tot}} (p_1 - p_2)}$$

(5.1)
Figure 5.2: Transmittable chemical vs. electric power for an interconnector with a liquid chemical energy carrier for different outlet temperatures $T_2$ (example, $U_{in}$ is kept constant).
5.2. MODEL WITH A LIQUID MEDIUM

The thermal power $P_U$ transmitted to the surrounding soil can be determined with the thermal model presented in section [5.2.4]. Since the temperature rise of the chemical medium depends on the electrical losses, the transmitted electric and chemical powers are coupled. In this simple case, the relationship is:

$$P_{el} = \sqrt{\frac{A_{cTot} U_{in}^2}{4 L_{tot} \rho}} \left( \frac{c_{mM} (T_2 - T_1) P_{ch}}{w_m} - \frac{f L_{tot} P_{ch}^3}{4 \pi^2 R_i^5 \rho_{mM}^2 w_m^3} + P_U \right)$$

(5.2)

Figure [5.2] illustrates this coupling between $P_{el}$ and $P_{ch}$: for increasing chemical power $P_{ch}$, the increasing medium mass flow rate $\dot{m}$ can evacuate more heat, and thus the transmittable electric power $P_{el1}$ also increases. The same applies to increasing outlet temperature $T_2$. The main difference with gaseous chemical carriers is that for fixed inlet and outlet temperatures a biunique relation between the two kinds of power exists. Gaseous carriers provide more flexibility since the chemical and electric powers can be varied independently of each other within a certain range (the exact nature of this variation range will be specified in chapter [6]).

5.2.2 Chemical model

The models for liquid and gaseous carriers will be based on the same geometry, shown in figure [5.3]: a hollow electrical conductor is separated form the surrounding soil by a thermal insulation layer.

For liquids, the pressure difference between inlet and outlet is the friction pressure drop $^1$

$$p_1 = p_2 + \Delta p_R$$

(5.3)

$^1$In the following description gravity will be ignored.
Figure 5.3: Cross-section and longitudinal view of the basic interconnector model.
The pressure drop rate is constant over the line length since the flow velocity remains constant:

\[ \Delta p_R = f \frac{L_{tot}}{4 R_i} \rho_m \mu M v^2 \]  

(5.4)

where the medium flow velocity \( v \) is:

\[ v = \frac{\dot{m}}{\rho_m \pi R_i^2} \]  

(5.5)

The mass flow rate thus becomes:

\[ \dot{m} = \sqrt{\frac{4 \pi^2 R_i^5 \rho_m \mu M}{f L_{tot}} (p_1 - p_2)} \]  

(5.6)

A pump is only required at the inlet and its compression power is:

\[ P_{Pump1} = \dot{m} \left( \frac{\Delta p_R}{\rho_m \mu M} + \frac{v^2}{2} \right) \]  

(5.7)

Therefore the total electric power equivalent becomes:

\[ P_{F1} = \frac{1}{\eta_1} P_{Pump1} \]  

(5.8)

The Reynold’s number is:

\[ Re = \frac{v d}{\nu} = \frac{2 \dot{m}}{\pi \mu_M R_i} \]  

(5.9)

The viscosity \( \mu_M \) is in the order of magnitude of \( 10^{-3} \text{ Ns m}^{-2} \), the value of \( Re \) will exceed 2000 in most cases. It is thus appropriate to use a constant value for \( f \) in the subsequent steps.

The chemical power transmitted is proportional to the mass flow rate:

\[ P_{ch} = \dot{m} w_m \]  

(5.10)
The heat absorbed by the liquid is proportional to the temperature difference between inlet and outlet and the specific heat capacity of the medium $c_{mM}$:

$$P_Q = \dot{m} c_{mM} (T_2 - T_1) \quad (5.11)$$

The thermal energy available at the line end is a function of the outlet temperature $T_2$ and the cold source temperature $T_{K2}$, ideally:

$$P_{th} = \dot{m} c_{mM} (T_2 - T_{K2}) \quad (5.12)$$

The heat transmitted to the environment is:

$$P_U = \frac{T_1 + T_2}{2} + \Delta T_{LK} - T_U \frac{L_{tot}}{R_{thE'} + R_{thI'} \Delta t} \quad (5.13)$$

Where $\Delta T_{LK}$ is the average temperature difference between the conductor and the medium. This has to be approximated based on experimental data.

The friction losses can be computed based on the work of the friction force per time unit:

$$P_R = \frac{\Delta W}{\Delta t} \quad (5.14)$$

$$= \frac{\Delta p_R \pi R_i^2 L_{tot}}{\Delta t} \quad (5.15)$$

$$= \frac{f L_{tot} \dot{m}}{4\pi^2 R_i^5 \rho_{mM}} \quad (5.16)$$

### 5.2.3 Electrical model

It will be assumed that the electrical conductor in the energy interconnector occupies the geometrical area $A_{geom}$ (for each phase if applicable). If $k_f$ is the fill factor of the conductor then the effective cross-sectional area of each phase conductor is:

$$A_c = k_f A_{geom} \quad (5.17)$$
Thus the total conductor area is \( A_{cTot} = n_{ph} A_c \), where \( n_{ph} \) is the number of the phases (or poles) and \( A_c \) is the conductor cross-section per phase. For d.c. transmission, the transmitted power is:

\[
P_{el} = \frac{1}{2} A_{cTot} U_{in} J \tag{5.18}
\]

If not stated otherwise, all examples and calculations in this work will assume d.c. transmission.

The d.c. resistance of one phase is modelled to be linearly temperature dependent (with \( \alpha_c \) denoting the temperature coefficient of the conductor material):

\[
R_{dc}' = \rho_c A_c = \frac{\rho_c 20}{k_f A_{geom}} (1 + \alpha_c (T_c - 273)) \tag{5.19}
\]

The a.c. resistance of the conductor additionally takes into account losses due to skin and proximity effects:

\[
R_{ac}' = R_{dc}' (1 + y_s + y_p) \tag{5.20}
\]

\( y_s R_{dc} \) and \( y_p R_{dc} \) are the additional resistances due to skin and proximity effects respectively.

According to [21], the contribution of the skin effect can be approximated using the auxiliary variable \( x_s^2 \):

\[
x_s^2 = k_s \frac{2 \pi \mu_0 \mu_{rc} f_e}{R_{dc}} \tag{5.21}
\]

where \( k_s \) depends on the conductor geometry (see the example in subsection [B]) and

\[
\begin{align*}
0 < x_s \leq 2.8 : & \quad y_s = \frac{x_s^4}{192 + 0.8 x_s^4} \\
2.8 < x_s \leq 3.8 : & \quad y_s = -0.136 - 0.177 x_s + 0.0563 x_s^2 \\
3.8 < x_s : & \quad y_s = \frac{x_s}{2 \sqrt{2}} - \frac{11}{15}
\end{align*}
\tag{5.22}
\]

\(^2\)The skin effect and proximity losses will be approximated by making the assumption that these are independent of each other [21].
The proximity effect losses are also geometry dependent. If the energy interconnector is armoured or even shielded, losses in these parts are also to be considered by adding a hypothetical armour and shield resistance ($\lambda_1 R_{ac}'$, resp. $\lambda_2 R_{ac}'$) to the conductor resistance, thus:

$$R_{I'} = R_{ac'} (1 + \lambda_1 + \lambda_2) \quad (5.23)$$

Since the contribution of these losses is minor, d.c. transmission is envisaged and design details are not available, these losses will be neglected in the following steps.

For d.c. transmission, the transmitted electric power $P_{el1}$ and the losses $P_V$ are:

$$P_{el1} = \frac{A_{cTot}}{2} U_{in} J \quad (5.24)$$

$$P_V = R_{I'} L_{tot} I_{tot}^2 = A_{cTot} L_{tot} \rho J^2 \quad (5.25)$$

The specific electrical resistivity will be computed based on the average medium temperature to which a constant temperature $\Delta T_{LK}$ is added (the precision is expected to remain acceptable).

$$\rho = \rho_{c20} \left( 1 + \alpha \left( \frac{T_1 + T_2}{2} + \Delta T_{LK} - 293 \right) \right) \quad (5.26)$$

The following relationship between the losses and the transmitted power comes out:

$$P_V = \frac{4 L_{tot} \rho}{A_{cTot} U_{in}^2} P_{el1}^2 \quad (5.27)$$

The energy balance also remains the same: the powers absorbed by the chemical medium $P_Q$ and the surrounding soil $P_U$ correspond to the sum of the electrical and friction losses $P_V$ and $P_R$

$$P_Q + P_U = P_V + P_R \quad (5.28)$$

Using the equations presented above, an analytical relationship
between the chemical and electric transmitted powers can be derived:

\[
P_{el} = \sqrt{\frac{A_{cTot} U_{in}^2}{4 L_{tot} \rho}} \left( c_{mM} (T_2 - T_1) P_{ch} - \frac{f L_{tot} P_{ch}^3}{4 \pi^2 R_i^5 \rho_{MM}^2 w_m^3} + P_U \right)
\]

(5.29)

Figure 5.2 shows an example of this relationship for various outlet temperatures.

5.2.4 Thermal model

Since the temperature varies along the interconnector, the thermal model is based on the description of a length element \(dx\) of the interconnector and the local specific thermal powers \(P_{R'}, P_{Q'}, P_{CM'}, P_{V'}\) and \(P_{U'}\).

The losses occurring in the electrical conductor and its shielding are transmitted to the surrounding soil and the medium according to the thermal model depicted in figure 5.4: the ohmic and friction losses are heat sources, the soil and flowing medium are heat sinks. The thermal resistances represent: the interface between the medium and the conductor \((R_{thM'})\), the insulation layer \((R_{thI'})\) and the soil \((R_{thE'})\). The losses due to friction \(P_R\) directly occur in the flowing

---

**Figure 5.4:** Thermal model for the energy interconnector.
medium. The electrical conductor is separated from the surrounding soil by a thermal insulation layer with a specific thermal resistance $\lambda_I$. All electrical conductors are modelled as a single heat source $P_V$, which represents the total electrical losses across all phases. The thermal resistivity of the electrical conductor is neglected (because the specific thermal conductivity of metals is several times higher than for insulation materials).

$$R_{thI}' = \frac{1}{2\pi} \frac{\ln \left( \frac{R_a + w_T}{R_a} \right)}{\lambda_I}$$ \hspace{1cm} (5.30)

The soil has the thermal resistance (according to [22] it will be assumed that the heat entirely flows towards the ground surface):

$$R_{thE}' = \frac{1}{2\pi} \frac{\ln \left( \frac{2h}{R_a + w_T} \right)}{\lambda_E}$$ \hspace{1cm} (5.31)

Since the actual thermal conductivity $\lambda_E$ of the soil will highly depend on the considered soil, a constant value of the specific soil thermal resistance $R_{thE}'$ (independent of the outer radius) will be used throughout this work. This is further justified by the fact that within the thermal model, the soil thermal resistance always appears together with the thermal resistance of the outer insulation.

The surface thermal resistance of the interface between the interconnector and the medium depends on the flow velocity and only empirical formulae are available. The approximation proposed in [23] was chosen:

$$R_{thM}' = \frac{1}{2\pi R_i \alpha_{LK}}$$ \hspace{1cm} (5.32)

where:

$$\alpha_{LK} = \alpha_1 + \alpha_2 \sqrt{\frac{v}{1 \text{ m/s}}}$$ \hspace{1cm} (5.33)

with $\alpha_1 = 2$, $\alpha_2 = 12$.

The model of figure 5.4 yields an equation system describing the thermal energy flow. Firstly, the power $P_U'$ transmitted to the surrounding soil is proportional to the temperature difference between
conductor \((T_c)\) and undisturbed soil \((T_U)\). The remainder of the loss power is absorbed by the medium. The following equation system comes out:

\[
P_U' = \frac{T_c - T_U}{R_{thI}' + R_{thE}'} \quad (5.34a)
\]

\[
P_{CM}' = P_V' - P_U' \quad (5.34b)
\]

\[
P_V' = R_{tot}' I_{tot}^2
\]

\[
= \frac{\rho_c 20 J^2 A_{cTot}^2}{k_f A_{geom.tot}} (1 + y_s + y_p) \left(1 + \alpha_c (T_c - 293)\right) \quad (5.34c)
\]

\[
T_c = T + R_{thM}' P_{CM}' \quad (5.34d)
\]

\[
P_Q' = P_R' + P_{CM}' \quad (5.34e)
\]

Solving for \(P_Q\) (the thermal power absorbed by the coolant):

\[
P_Q' = \frac{c_4 (1 + \alpha_c (T - 293))}{1 - c_4 \alpha_c R_{thM}'} + P_R' \quad (5.35)
\]

The friction losses \(P_R\) are discussed in section 5.3.2.

### 5.2.5 Pump model

For liquid media, only one pump at the inlet of the interconnector is necessary. A turbine at the outlet is feasible, but will not be considered here in order to obtain a worst case approximation of the required auxiliary powers. The required pump power corresponds to the work per time unit arising from the friction pressure drop plus a kinetic component:

\[
P_{Pump1} = \dot{m} \left( \frac{\Delta p_R}{\rho Mm} + \frac{v_1^2}{2} \right) \quad (5.36)
\]
where:

\[ v_1 = \frac{\dot{m}}{\rho_m M \pi R_i^2} \]  

(5.37)

The required auxiliary power is thus:

\[ P_{F1} = \frac{P_{\text{Pump}1}}{\eta_{1 \text{Pos}}} \]  

(5.38)

Heat recovery only occurs at the outlet and is modelled identically to the situation with gaseous media, described in the appendix A.2.

5.3 Model of the interconnector with transport of a gaseous medium

5.3.1 General overview of the model

Since the gas flow is compressible and the gas exchanges heat with the surroundings, the temperature rise and pressure drop vary over the interconnector length. Figure 5.5 shows the pressure and temperature profile for a typical situation\(^3\): the mass flow is directed from \( x = 0 \) to \( x = L_{\text{tot}} \), the pressure drops and the temperature increases along the interconnector. Since a rising temperature means more heat transfer to the surroundings, the temperature profiles flattens towards the line end. The electrical and thermal models are the same as for liquid media.

The core of the model is the equation system describing the thermal power flows:\(^4\)

\[ P_V' = P_U' + P_{CM}' \]  

(5.39)

\[ P_Q' = P_R' + P_{CM} \]  

(5.40)

\(^3\)in order to increase the “visibility” of the phenomena, “extreme” parameters (not necessarily realistic ones) have been chosen for the examples.

\(^4\)the apostrophe in \( P' \) denotes specific power per unit length in W/m.
5.3. MODEL WITH A GASEOUS MEDIUM

Figure 5.5: Example for a temperature $T(x)$ and pressure $p(x)$ profile of a gaseous medium along the interconnector.
The first equation describes the conductor, where the ohmic transmission losses $P_V'$ are partly transmitted to the surroundings ($P_U'$) and partly to the flowing chemical medium ($P_{CM}'$). The second equation states that the power absorbed by the medium $P_Q'$ comes from the conductor ($P_{CM}'$) and from internal friction ($P_R'$). These quantities are functions of the mass flow rate, the local temperature and the local pressure. Together with the energy and momentum conservation laws a set of partial differential equations (PDEs) is obtained. The profiles in these examples were obtained with a numerical PDE solver, since no analytical solution exists.

Figure 5.6 shows the heat flows in the electrical conductor: the electrical losses increase with temperature towards the line end. Where the conductor temperature is high, the share of the power transmitted to the surroundings increases. Figure 5.7 shows the heat flows in the flowing medium: the heat $P_Q'$ absorbed by the medium decreases along the interconnector (the heat transmitted from the conductor to the medium $P_{CM}'$ shows a similar behaviour) and internal friction $P_R'$ increases due to the pressure drop, which leads to a higher flow velocity towards the outlet.

The computation of numerical solutions is time consuming and can obviously only be done for fixed dimensions of the interconnector and fixed material properties. In order to derive a layout procedure, a method to calculate the interconnector inlet and outlet power for the entire operational area within reasonable time is needed. Furthermore, the identification of scaling laws is only possible on an analytical basis. An approximate analytical model has therefore been developed and is presented in more details in section 5.3.4. This model can be used for layout tasks, whereas the numerical model may be used in a second refinement step. The analytical model involves only the “overall” power flows, i.e. the integrals of the losses and exchanged heat according to the following definition:

$$P_{\{V,Q,CM,R\}} = \int_{x=0}^{x=L_{tot}} P_{\{V,Q,CM,R\}}' \, dx$$  \hspace{1cm} (5.41)
Figure 5.6: Profiles of the electrical losses in the conductor $P_V'$ and the heat flows at the interface with the soil $P_U'$ and the medium $P_{CM}'$ (example).
Figure 5.7: Profiles of the friction losses $P_R'$, heat transfer from the electrical conductor $P_{CM}'$ and heat absorbed by a gaseous medium (example).
Figure 5.8: Contour of the electric current density $J$ in function of the mass flow rate $\dot{m}$ and the inlet pressure $p_1$ (example).
The analytical model permits calculations of the interconnector state variables over a wide variation range, which will be useful in the determination of its operation area. This can be illustrated by the example shown in figure 5.8 which shows a contour plot of the electric current density $J$ in the conductor as a function of the inlet pressure and the mass flow $\dot{m}$ (this is valid for constant inlet and outlet temperatures $T_1$ and $T_2$, input voltage $U_{in}$ and outlet pressure $p_2$). This representation illustrates how the interconnector can accommodate different combinations of $J$ and $\dot{m}$ by varying the inlet pressure.

Besides the interconnector itself, several other components will be required to implement multi-energy transmission. The most important ones are the compressors and heat exchangers needed to establish the gas flow and to possibly cool it down at the inlet or outlet of the interconnector. Several alternative configurations of
5.3. MODEL WITH A GASEOUS MEDIUM

Compressors and heat exchangers may be imagined. A model for three variants is presented in the appendix \[A\]. The most relevant and general variant (variant B) is illustrated in figure 5.9 at the inlet and outlet a compressor develops the compression powers $P_{\text{Pump}1}$ respectively $P_{\text{Pump}2}$. The thermal power $\dot{Q}_{\text{w}\{1,2\}}$ is extracted in the heat exchangers. Taking into account the respective compression and conversion efficiencies the equivalent electric powers $P_{\text{F}\{1,2\}}$ for the compressors and $P_{\text{w}\{1,2\}}$ from the heat recovery process can be calculated. Put together, the net equivalent electric power requirement of the auxiliary equipment at the inlet and outlet is denoted as $P_{\text{F1tot}}$ and $P_{\text{F2tot}}$ respectively. In general all these powers may be positive or negative, provided that the equipment is designed for bidirectional energy flows.

Since the inlet and outlet pressures depend on $\dot{m}$ and $J$, a similar relationship will also apply to the compressor powers. Figure 5.10 shows this dependence for an example (for constant inlet and outlet temperatures $T_1$ and $T_2$, input voltage $U_{\text{in}}$ and outlet pressure $p_2$ as in figure 5.8). The contour lines of all the auxiliary powers have a sharp bend at their intersections with the horizontal axis because the conversion losses change their sign.

Once the power requirements of the auxiliary equipment are known, transmission efficiencies may be calculated according to section \[A.3\] the following definition of the overall efficiency will be used:

$$\eta_{\text{tot}} = \frac{P_{\text{el1}} - P_{\text{V}} + P_{\text{ch}} - P_{\text{F2}} + P_{\text{w2}}}{P_{\text{el1}} + P_{\text{ch}} + P_{\text{F1}} - P_{\text{w1}}} \quad (5.42)$$

The power flows including the auxiliary power are shown in figure 5.11(b) using the suggested definitions, all power flows at the inlet “enter” the interconnector and all power flows at the outlet “leave” the interconnector. As compared to the actual power flows shown in figure 5.11(a), the auxiliary power flows are summarised into a power flow at the inlet and at the outlet respectively. The power $P_{\text{U}}$ transmitted to the surrounding soil is a loss power and therefore is not part of the system output power.

The fact that the interconnector system is open implies that this
Figure 5.10: Auxiliary power requirements and possible waste heat recovery at the inlet and outlet of an interconnector in dependence upon gas mass flow (example).
5.3. MODEL WITH A GASEOUS MEDIUM

(a) Power flows without combination of the auxiliary powers

(b) Power flows with combination of the auxiliary powers

Figure 5.11: Power flows for the overall interconnector system including auxiliary power.
definition can lead to values greater than unity (e.g. if the gaseous medium is available at a very high pressure $p_0$). Nevertheless $\eta_{tot}$ will be used to analyse variations of the overall efficiency over the operation area. For comparison purposes, electrical and chemical transmission efficiencies will be defined as follows:

$$\eta_{el} = \frac{P_{el1} - P_V}{P_{el1}}$$  \hspace{1cm} (5.43)$$
$$\eta_{ch} = \frac{P_{ch}}{P_{ch} + P_{FTot}}$$  \hspace{1cm} (5.44)$$

A representative example of the efficiencies is given in figure 5.12. The different sharp bends of the contour lines arise from sign changes in the conversion losses of one of the auxiliary powers. The electrical transmission efficiency decreases with $P_{el}$ since the current density increases. The chemical efficiency increases with $P_{el}$ since the friction losses $P_R$ are lower for increasing $P_{el}$. As a result, the overall transmission efficiency $\eta_{tot}$ is maximal for “moderate” values of the electric power.

### 5.3.2 Gas flow

The momentum and energy conservation

The flow of an ideal gas in a pipe with the cross-section $A_i = \pi R_i^2$ is considered. In general, the gas will absorb heat form the pipe wall and receive mechanical energy from the compressor end of the pipe, whereas it will increase its internal energy and give energy to the turbine end of the pipe (see figure 5.3). The analysis will be restricted to steady state operation and interconnectors with a constant cross-sectional area ($A_i = A_o$). For a mass element $\Delta m = \rho_m M A_i \Delta x$ the
Figure 5.12: Contour lines of the electrical, chemical and total transmission efficiency (example).
power balance equation is (see figure 5.13)\(^5\)

\[ P_Q' \Delta x + A_i p_i v_i - A_i p_o v_o + \dot{m} \frac{n_F}{2} \frac{R_g}{M_m} (T_i - T_o) + \frac{\dot{m}}{2} \left( v_i^2 - v_o^2 \right) = 0 \]  
(5.45)

where:

\begin{align*}
P_Q' \Delta x & \quad \text{heat absorbed by } \Delta m \text{ of a length } \Delta x \\
A_i p_i v_i & \quad \text{work of the surrounding gas on } \Delta m \\
A_i p_o v_o & \quad \text{work of } \Delta m \text{ on the surrounding gas} \\
\frac{1}{2} \dot{m} n_F \frac{R_g}{M_m} (T_i - T_o) & \quad \text{variation rate of the internal energy of } \Delta m \\
\frac{1}{2} \dot{m} \left( v_i^2 - v_o^2 \right) & \quad \text{variation rate of the kinetic energy of } \Delta m
\end{align*}

Equation 5.45 can be transformed using:

\[ \rho_{mM} = \frac{M_m p}{R_g T} \]  
(5.46)

\[ v = \frac{\dot{m} R_g}{\pi R_i^2 \rho_{mM}} = \frac{\dot{m} R_g}{M_m \pi R_i^2} \frac{T}{p} \]  
(5.47)

and thus becomes

\[ P_Q' \Delta x - \Delta \left( A_i p v \right) - \dot{m} \frac{n_F R_g}{2 M_m} \Delta T - \frac{\dot{m}}{2} \Delta \left( v^2 \right) = 0 \]
(5.48)

The absorbed heat \( P_Q \) originates from two mechanisms:

- conduction through the pipe wall (\( P_{CM} \))
- and friction in the medium itself (\( P_R \), see also section 5.3.2)\(^6\)

\(^5\)or conservation of energy
\(^6\)\( \dot{m} \) is positive for mass flow from \( x = 0 \) towards \( x = L_{tot} \).
For small $\Delta x$ the Taylor approximations $\Delta T = \Delta x \frac{dT}{dx}$ and
$\Delta \left( \frac{T^2}{p^2} \right) = \Delta x \frac{d}{dx} \left( \frac{T^2}{p^2} \right)$ can be used. A first differential equation for non-isothermal gas flow is obtained:

$$P'_Q = \dot{m} \frac{R_g}{M_m} \left( \frac{n_F}{2} + 1 \right) \frac{dT}{dx} - \frac{1}{2} \frac{\dot{m}^3 R_g^2}{\pi^2 R_i^4 M_m^2} \frac{d}{dx} \left( \frac{T^2}{p^2} \right)$$

(5.49)

An equivalent formulation of the differential equation 5.49 using only first derivatives of $p$ and $T$ is:

$$P'_Q - c_2 \left( \frac{n_F}{2} + 1 \right) \frac{dT}{dx} - c_2 c_3 \frac{T}{p^2} \frac{dT}{dx} + c_2 c_3 \frac{T^2}{p^3} \frac{dp}{dx} = 0$$

(5.50)

Next the momentum conservation law is applied to a mass element $\Delta m$ in the pipeline (see figure 5.13). The forces applied on the mass element are the hydrodynamic forces by the surrounding gas at both ends of the mass element as well as the friction losses at the
interface with the pipe walls and within the medium itself:

\[
\sum F = \frac{\Delta p_{KIN}}{\Delta t} \tag{5.51}
\]

\[
A_i (-\Delta p - \Delta p_R) = \frac{\Delta (m \dot{v})}{\Delta t} \tag{5.52}
\]

\[
A_i (-\Delta p - \Delta p_R) = \dot{m} \frac{\Delta v}{\Delta t} =: A_i \Delta p_M \tag{5.53}
\]

In short:

\[
\Delta p = -\Delta p_R - \Delta p_M \tag{5.54}
\]

Using 5.46 and 5.47

\[
\Delta p_M = \frac{\dot{m}^2 R_g}{A_i M_m \pi R_i^2} \Delta \left( \frac{T}{p} \right) \tag{5.55}
\]

The Taylor approximation of the last term is:

\[
\Delta \left( \frac{T}{p} \right) = \Delta x \frac{d}{dx} \left( \frac{T}{p} \right) \tag{5.56}
\]

\[
= -\frac{\Delta x}{p} \left( \frac{dT}{dx} \frac{1}{p} - \frac{T}{p} \frac{dp}{dx} \right) \tag{5.57}
\]

This yields:

\[
\Delta p_M = c_3 \frac{\Delta x}{p} \left( \frac{dT}{dx} \frac{1}{p} - \frac{T}{p} \frac{dp}{dx} \right) \tag{5.58}
\]

Using the Darcy-Weisbach approximation of the friction pressure drop (see also section 5.3.2)\(^7\) yields:

\[
\Delta p_R = f \frac{\Delta x}{4R_i} \rho_{mM} v^2
\]

\[
= f \frac{R_g}{4\pi^2 R_i^5 M_m} \dot{m}^2 \Delta x \frac{T}{p} \tag{5.59}
\]

\(^7\)Assuming a positive mass flow \(\dot{m}\).
Substituting into 5.54 yields a second differential equation for the gas flow. The resulting equation system is:

\[
\left(1 - c_3 \frac{T}{p^2}\right) \frac{dp}{dx} + \frac{c_3}{p} \frac{dT}{dx} + c_1 \frac{T}{p} = 0 \quad (5.60a)
\]

\[
c_2 c_3 \frac{T^2}{p^3} \frac{dp}{dx} - \left(c_2 \left(\frac{n_F}{2} + 1\right) + c_2 c_3 \frac{T}{p^2}\right) \frac{dT}{dx} + P_Q' = 0 \quad (5.60b)
\]

From equation 5.60b the heat absorbed by the gaseous medium in a pipeline with length \(L_{tot}\) is:

\[
P_Q = \int_0^{L_{tot}} c_2 \left(\frac{n_F}{2} + 1\right) \frac{dT}{dx} + \frac{1}{2} c_2 c_3 \frac{dT}{dx} \left(\frac{T^2}{p^2}\right) dx = c_2 \left(\frac{n_F}{2} + 1\right) (T_2 - T_1) + \frac{1}{2} c_2 c_3 \left(\frac{T_2^2}{p_2^2} - \frac{T_1^2}{p_1^2}\right) \quad (5.61)
\]

In the literature similar equations are used for the simulation of transient phenomena in gas pipelines and networks [24, 25].

**Pipe friction**

The flow equations 5.60a and 5.60b make use of the friction factor \(f\) carried over from equation 5.59. Its determination is based on empirical findings. According to [26] the friction pressure drop can be approximated as:

\[
\Delta p_R = \rho_{mM} f \frac{\Delta x}{4 R_i} v^2 \quad (5.62)
\]

The Reynold’s number is defined by:

\[
Re = \frac{2 \rho_{mM} v R_i}{\mu_M} \quad (5.63a)
\]

\[
= \frac{2 \dot{m}}{\pi R_i \mu_M} \quad (5.63b)
\]
Depending on the value of \( \text{Re} \), a different calculation method for \( f \) has to be used. For laminar flow \((\text{Re} < 2000)\) \( f \) can be computed straightforward:

\[
\text{Re} < 2000 : \quad f = \frac{64}{\text{Re}} \quad (5.64)
\]

For turbulent flow \( f \) is given in an implicit form:

\[
\text{Re} > 2000 : \quad -\frac{1}{\sqrt{f}} = -2 \log_{10} \left( \frac{e/D}{3.7} + \frac{2.51}{\text{Re} \sqrt{f}} \right) \quad (5.65)
\]

In the energy interconnector design strongly turbulent flow in moderately smooth pipes will be assumed, and therefore it will be adequate to assume a constant friction factor \( f \) along the entire pipe \([27]\). This can be checked after the layout is completed.

The work by the medium due to the friction pressure drop is converted into heat either by friction on the pipe walls or by friction in the medium itself according to (using equations \( 5.62 \), \( 5.46 \) and \( 5.47 \)):

\[
\Delta Q_R = \Delta W_R = \Delta p_R A_i \Delta x \quad (5.66)
\]

\[
= f \frac{R_g \Delta x}{4 \pi^2 R_i^5 M_m} \frac{\dot{m}}{p} \frac{T}{\pi R_i^2} \Delta x \quad (5.67)
\]

Thus, along a length \( \Delta x \) of the pipe the following thermal power is developed by friction:

\[
\Delta P_R = \frac{\Delta Q_R}{\Delta t} = f \frac{R_g}{4 \pi R_i^3 M_m} \frac{\dot{m}^2}{p} \frac{T}{\pi R_i^2} \frac{(\Delta x)^2}{\Delta t} \quad (5.68)
\]

Equation \( 5.47 \) can again be used:

\[
\frac{\Delta x}{\Delta t} = v = \frac{\dot{m} R_g}{M_m \pi R_i^2} \frac{T}{p} \quad (5.70)
\]

The specific friction power per unit pipe length unit becomes:

\[
P_{R'} = \frac{P_R}{\Delta x} = f \left( \frac{R_g}{4 \pi^2 R_i^5 M_m^2} \right) \frac{\dot{m}^3}{p^2} T^2 \quad (5.71)
\]
5.3. MODEL WITH A GASEOUS MEDIUM

5.3.3 A model for numerical solutions

The differential equations

Preparing the use of numerical solvers the per unit coordinate \( X \) is introduced as follows:

\[
X = \frac{x}{L_{tot}}
\]  
(5.72)

Thus:

\[
\frac{dp}{dx} = \frac{1}{L_{tot}} \frac{dp}{dX}
\]  
(5.73a)
\[
\frac{dT}{dx} = \frac{1}{L_{tot}} \frac{dT}{dX}
\]  
(5.73b)

Combining the equations from the electrical, thermal and chemical models, yields the following equation system for the pressure and the temperature profiles (see sections 5.3.2 and 5.2.4):

\[
\left(1 - \frac{c_3}{L_{tot}} \frac{T}{p^2}\right) \frac{dp}{dX} + \frac{c_3 L_{tot}}{p} \frac{dT}{dX} + \frac{c_1}{p} T = 0
\]  
(5.74a)
\[
\frac{c_2 c_3}{L_{tot}} \frac{T^2}{p^3} \frac{dp}{dX} - \left( \frac{c_2}{L_{tot}} \left( \frac{n_F}{2} + 1 \right) + \frac{c_2 c_3}{L_{tot}} \frac{T}{p^2} \right) \frac{dT}{dX} + \dot{P}_Q' = 0
\]  
(5.74b)

where

\[
c_1 = f \frac{R_g}{4 \pi^2 R_i^5 M_m} \dot{m}^2
\]  
(5.75a)
\[
c_2 = \dot{m} \frac{R_g}{M_m}
\]  
(5.75b)
\[
c_3 = \frac{\dot{m}^2 R_g}{AM_m \pi R_i^2}
\]  
(5.75c)

\[^8\text{This is useful for numerical simulation since the one-dimensional discretisation is independent of the geometry.}\]
The specific heat absorption of the medium $P'_Q$ is also temperature and pressure dependent and has been treated in section 5.2.4.

A numerical model

These differential equations cannot be solved analytically, but using numerical partial differential equation solvers. The temperature and pressure along the interconnector can be evaluated for a specified geometry (inner radius, length, etc.), material properties and operating point (electrical losses, chemical throughput, inlet or outlet temperature or pressure, etc.). Several software models have been developed for different boundary conditions.

Using numerical PDE solutions to investigate several operating points or geometries is inefficient since the determination of the outlet temperature and pressure requires the computation of the entire temperature and pressure profiles. In addition, these PDEs cannot be solved for the terminal powers. This means that an analytical model would be useful, but that because of the nature of the problem, this analytical model will have to be based on approximations.

5.3.4 Analytical modelling

Gas flow

Although the equation system 5.60b and 5.60a has no analytical solution, analytical expressions for $p(x)$ and $T(x)$ are the prerequisites for a model which can be solved analytically. Therefore the following approximation shall be used: a constant heat transfer $P'_Q$ to the flowing medium is assumed. A further assumption is that the heat absorption of the gaseous medium is similar to the one of non-compressible media. The temperature profile $T(x)$ will therefore be linear:

---

9For all simplifications made in this section, it will be shown that this approximation yields acceptable results in the most common cases.
5.3. MODEL WITH A GASEOUS MEDIUM

\[ T(x) = T_1 + \frac{T_2 - T_1}{L_{\text{tot}}} x \]  

(5.76)

The pressure profile can be calculated using equation (5.49) and taking into account that \(c_2 c_3\) is so small that it can be neglected\(^{10}\):

\[
p(x)^2 - p_1^2 = -\int_0^x 2 c_1 T(x)dx
\]

\[
\Rightarrow p(x) = \sqrt{p_1^2 - c_1 L_{\text{tot}} \left( 2 T_1 \frac{x}{L_{\text{tot}}} + (T_1 + T_2) \left( \frac{x}{L_{\text{tot}}} \right)^2 \right)}
\]

(5.78)

Substituting \(x = L_{\text{tot}}\) gives the outlet pressure of the pipeline:

\[
p_2 = \sqrt{p_1^2 - c_1 L_{\text{tot}} (T_1 + T_2)}
\]

(5.79a)

\[
= \sqrt{p_1^2 - \frac{f R_g L_{\text{tot}} (T_1 + T_2)}{4 \pi^2 R_i^5 M_m}} \frac{\dot{m}^2}{(T_1 + T_2)^2}
\]

(5.79b)

Solving for the mass flow rate \(\dot{m}\) yields\(^{11}\) (the chemical energy flow is assumed to be proportional to \(\dot{m}\) according to \(P_{ch} = w_m \dot{m}\)):

\[
\dot{m} = 2 \pi \sqrt{\frac{M_m (p_1^2 - p_2^2)}{f R_g L_{\text{tot}} (T_1 + T_2)}} R_i^{5/2}
\]

(5.80)

\(^{10}\) \(p(x)\) is a positive quantity.

\(^{11}\) \(\dot{m}\) is still assumed to be positive.
The total stored mass of the gas in the interconnector is:

\[
m_s = \int_0^{L_{tot}} A_i \rho_{mM} \, dx
\]

(5.81)

\[
= \pi R_i^2 \int_0^{L_{tot}} M_m p(x) \frac{R_T(x)}{R_g T(x)} \, dx
\]

(5.82)

\[
= \frac{\pi L_{tot} M_m p_2 R_i^2}{R_g T_2} \left( \frac{p_1}{p_2} - 1 \right) + \ln \left( \Xi \right) \left( \frac{T_1^2 - p_1^2}{T_2^2 - p_2^2} \right) \left( \frac{T_1}{T_2} - 1 \right)^3 \left( 1 + \frac{T_1}{T_2} \right)
\]

(5.83)

where

\[
\Xi = \left( \frac{p_1}{p_2} + \frac{T_1^2}{T_2^2} \right) + \sqrt{\left( \frac{T_1^2}{T_2^2} - 1 \right) \left( \frac{T_1^2}{T_2^2} - p_1^2 \right)} \left( 1 + \frac{T_1}{T_2} \right)
\]

(5.84)

In the detailed calculations, the conditions for the validity of this simplified approach should of course be verified. An example will be discussed in section [5.3.5]

**Approximated thermal model**

As the precise temperature profile \( T(x) \) of the gaseous medium flowing through the energy interconnector is impossible to compute analytically, a simplified approximation of the thermal energy flow will be used (based on the linear profile in equation [5.76]). Therefore equation [5.34a] is integrated along the energy interconnector:

\[
P_Q = P_V - \frac{T_{cAve} - T_U}{R_{thI} + R_{thE}'}
\]

(5.85)

where \( T_U \) is the soil temperature at infinite distance and \( T_{cAve} \) is the mean temperature of the gaseous medium in the energy interconnector:

\[
T_{cAve} = \Delta T_{LK} + \frac{T_2 + T_1}{2}
\]

(5.86)
5.3. MODEL WITH A GASEOUS MEDIUM

A constant temperature difference $\Delta T_{LK}$ between the energy interconnector and the gaseous medium is assumed. Thus the mean specific power transmitted to the surrounding soil becomes:

$$P_U' = \frac{T_{cAve} - T_U}{R_{thI}' + R_{thE}'}$$

(5.87)

And thus the thermal power transmitted to the soil over the entire interconnector length is:

$$P_U = \frac{\Delta T_{LK} + \frac{1}{2} (T_1 + T_2) - T_U}{R_{thI}' + R_{thE}'} L_{tot}$$

(5.88)

The electrical losses in the conductor thus become:

$$P_V = K_V \left( 1 + \alpha_c \left( \Delta T_{LK} + \frac{T_1 + T_2}{2} - 293 \right) \right) J^2$$

(5.89)

where

$$K_V = L_{tot} k_f A_{geomTot} \rho_{c20} (1 + y_s + y_p)$$

(5.90)

An analytical model based on simplified assumptions

Analytical expressions for each power flow can be derived using the approximate pressure and temperature profiles (equations 5.78 and 5.76) previously introduced. For these analytical profiles, it is possible to calculate the chemical, thermal and electric power flows, the overall electrical losses and the heat transmitted to the chemical carrier as well as the surrounding soil. The local specific power is of lower importance in this analysis.

It is suitable (as will be shown later) to express each energy flow in terms of the input and output parameters for the chemical energy carrier $p_1$, $T_1$, $p_2$ and $T_2$.

The temperature profile from equation 5.76 and pressure profile from equation 5.78 apply. Solving for the mass flow and using the
CHAPTER 5. INTERCONNECTOR MODELLING

The definition of chemical power gives:

\[ P_{ch} = w_m \dot{m} \]

\[ = 2 \pi w_m \sqrt{\frac{M_m (p_1^2 - p_2^2)}{f R_g L_{tot} (T_1 + T_2)} R_i^{5/2}} \]  \tag{5.91}

Combining this with previous results, the thermal power absorbed by the gaseous medium becomes:

\[ P_Q = \frac{\pi \sqrt{R_g} \sqrt{p_1^2 - p_2^2} R_i^{5/2}}{f^{3/2} L_{tot}^{3/2} \sqrt{M_m (T_1 + T_2)^{3/2}}} \left( -f L_{tot} \left( 2 + n_F \right) \left( T_1^2 - T_2^2 \right) + \frac{4 \left( p_1^2 - p_2^2 \right) R_i \left( p_1^2 T_2^2 - p_2^2 T_1^2 \right)}{p_1^2 p_2^2} \right) \]  \tag{5.92}

The heat produced by friction losses becomes, if \( p_2^2 T_1^2 - p_1^2 T_2^2 < 0 \):

\[ P_R = \frac{\pi \sqrt{R_g} \sqrt{p_1^2 T_2^2 - p_2^2 T_1^2} R_i^{5/2}}{\sqrt{f L_{tot} M_m (T_1 + T_2)}} \left( 2 \sqrt{p_1^2 - p_2^2} \frac{(T_1 - T_2)}{\sqrt{p_1^2 T_2^2 - p_2^2 T_1^2}} + \ln(\Upsilon) \right) \]  \tag{5.93}

where

\[ \Upsilon = \frac{p_2^2 T_1 + p_1^2 T_2 + \sqrt{(p_1^2 - p_2^2) (p_1^2 T_2^2 - p_2^2 T_1^2)}}{p_2^2 T_1 + p_1^2 T_2 - \sqrt{(p_1^2 - p_2^2) (p_1^2 T_2^2 - p_2^2 T_1^2)}} \]  \tag{5.94}

For \( p_2^2 T_1^2 - p_1^2 T_2^2 > 0 \):

\[ P_R = \frac{2 \pi \sqrt{R_g} \sqrt{p_2^2 T_1^2 - p_1^2 T_2^2} R_i^{5/2}}{\sqrt{f L_{tot} M_m (T_1 + T_2)}} \left( \arctan(\Gamma_2) - \arctan(\Gamma_1) + \frac{\sqrt{p_1^2 - p_2^2} (T_1 - T_2)}{\sqrt{p_2^2 T_1^2 - p_1^2 T_2^2}} \right) \]  \tag{5.95}
5.3. MODEL WITH A GASEOUS MEDIUM

where

\[
\Gamma_1 = \frac{\sqrt{p_1^2 - p_2^2} T_1}{\sqrt{p_2^2 T_1^2 - p_1^2 T_2^2}} \quad (5.96a)
\]

\[
\Gamma_2 = \frac{\sqrt{p_1^2 - p_2^2} T_2}{\sqrt{p_2^2 T_1^2 - p_1^2 T_2^2}} \quad (5.96b)
\]

The permissible electrical losses are (considering the thermal model from figure 5.4):

\[
P_V = P_{CM} + P_U \quad (5.97a)
\]

\[
P_{CM} = P_Q - P_R \quad (5.97b)
\]

The expressions 5.91, 5.92 and 5.97a give the chemical throughput, the absorbed heat and the permissible electrical losses for given boundary conditions \((p_1, T_1, p_2 \text{ and } T_2)\). Considering equation 5.95, it is not possible to solve the flow equations for \(p_1, T_1, p_2 \text{ and } T_2\) analytically\(^{12}\). The determination of \(p_1, T_1, p_2 \text{ and } T_2\) for known electrical losses and chemical power thus involves an iterative numerical procedure but no numerical simulation.

The condition on \(p_2^2 T_1^2 - p_1^2 T_2^2\) can be rewritten as follows (using equations 5.76 and 5.78):

\[
p_2^2 T_1^2 - p_1^2 T_2^2 < 0 \quad (5.98)
\]

\[
\Leftrightarrow \quad p_2^2 \left( \frac{T_1^2}{T_2^2} - 1 \right) \frac{4\pi^2 R_i^5 M_m}{f R_g L_{tot} (T_1 + T_2)} < \bar{m}^2 \quad (5.99)
\]

This condition is fulfilled if \(T_1 < T_2\), which is a design goal of the energy interconnector.

5.3.5 Discussion of the simplified model

The figures 5.14 and 5.15 show comparisons between numerical (simulated) and analytical (calculated) results. The most severe difference shows with the outlet temperature \(T_2\) and with the thermal

\(^{12}\)The solution involves transcendental functions.
Figure 5.14: Comparison between simulated (numerical) and calculated (analytical) temperature and pressure profiles in dependence upon normalised current density (example).
Figure 5.15: Comparison between simulated (numerical) and calculated (analytical) specific power profiles in dependence upon normalised current density (example).
power absorbed by the gas $P_Q$. Fortunately, the discrepancy of the auxiliary power requirement $P_{F_2}$ according to the two procedures is less severe. This could be confirmed in further examples.

Obviously these examples do not constitute a general proof of the adequacy of the simplified model. The purpose of the simplified model is to derive a rough layout rule. The results obtained should subsequently be compared to numerical simulations once the result of the layout procedure is known (an example will be provided in chapter 7).

5.4 Model of the interconnector with transport of a gaseous medium and low temperature energy transmission

The model developed in the previous section can be adapted in order to describe the situation of low temperature energy transmission (variant C). In this case the soil temperature is higher than the temperature of the chemical medium. The model of the auxiliary equipment is discussed in section A.2 while the same interconnector model as for variants A and B can be used.

Figure 5.16 shows the dependence between the mass flow rate and the electric current density for a representative example. The general dependence is the same, with two main differences:

- There is no lower value for the electric current density $J$ because the thermal power flow between the surrounding soil and the interconnector is reversed.

- A minimum value for the mass flow rate $\dot{m}$ exists. This corresponds to the situation where the gas flow is just sufficient to cool down the interconnector to the required temperature (and no additional electrical losses are permissible).

This solution will not be considered in more detail because it
Figure 5.16: Permissible current density vs. mass flow rate for an interconnector with low temperature energy transmission (example with $T_1 = 253\,\text{K}$ and $T_2 = 293\,\text{K}$).
is not as advantageous from a system perspective as the preferred solution selected in section 4.2.
Chapter 6

Operational characteristics of the Energy Interconnector with transmission of a gaseous medium

This chapter describes the limitations which restrict the operation of an interconnector. A maximum for the transmittable electric and chemical powers exists and the transmitted electric and chemical powers are coupled, i.e. they cannot be varied fully independently of each other. The dimensioning of the auxiliary equipment (compressors and heat exchangers) will also influence the operational area (combinations of the transmitted electric and chemical power). The maximum transmittable powers describe a particular design of the interconnector. In order to permit the determination of...
the necessary approximate dimensions of the interconnector for a given maximum power (electric and chemical), scaling laws will be derived.

6.1 Power limitations and dependences

6.1.1 Description of the limitations

In order to develop a layout method for an interconnector system as described above, a description of the maximum transmitted electric and chemical powers is needed. The coupling between the chemical and electric powers (which arises from the fact that the flowing chemical medium removes some of heat form the conductor) has also to be described. In summary, a description for the possible combinations of the electric and chemical power, i.e. the permissible operational area is needed. This will be done using the simplified analytical model presented in the previous sections.

Several classes of limitations can be distinguished:

• Design limitations: These include the maximum permissible operating voltage $U_{inMax}$, the maximum pressure $p_{Max}$ and the maximum outlet temperature $T_{2Max}$.

• Physical limitations: E.g. some combinations of $P_{el}$ and $P_{ch}$ are even not feasible for infinite pressure.

• Limitations given by the auxiliary equipment: Depending on the ratings of the compressors, the operating range of the interconector may be further reduced. Finally the choice of the rating of the waste heat recovery process may similarly restrict the operational area.

Using the analytical model from section 5.3.4, the permissible electrical losses can be expressed as function of $p_2$ (or $p_1$), $\dot{m}$, $U_{in}$ and $T_2$. The detailed equations are given in section 6.1.2 (equations...
6.1. POWER LIMITATIONS AND DEPENDENCES

\[ P_{ch\text{Max}}(P_{V\text{chMax}}), P_{ch\text{APMax}}(P_{V\text{chAPMax}}), P_{ch\text{Min}}(P_{V\text{chMin}}), P_{\text{el\text{Max}}}(P_{V\text{elMax}}), P_{\text{el\text{Min}}}(P_{V\text{elMin}}) \]

Figure 6.1: Nomenclature for the maximum and minimum electric and chemical powers.

6.2 and 6.3. As a result, it can be shown that at constant \( U_{in} \) and \( T_2 \) (see section 6.1.2) two limits of the electric power exist for each value of the chemical power (smaller than its maximum):

- A minimum value of the electrical losses \( P_{VMin} \). This limit corresponds to the situation where the gas takes up no heat from the electrical conductor\(^1\) (thus \( P_{CM} = 0 \)).

- A maximum value of the electrical losses \( P_{el\text{Max}}(\dot{m}) \). This limit depends on the maximum admissible pressure \( p\text{Max} \). For infinite values of the pressure, the electric power remains limited.

For constant \( U_{in} \) and \( T_2 \) the shape of the operational area is as shown in figure 6.1. The operational area is delimited by two curves describing the minimum and maximum electric power as a function

\(^1\)It is physically possible to establish a situation where the friction losses \( P_R \) exceed the heat absorbed by the chemical medium \( P_Q \) and thus contribute to warm up the surrounding soil. This situation is, however, unrealistic with respect to practical applications.
of the chemical power. The represented shape of these limitation curves is characteristic for interconnectors with gaseous chemical media. The figure also introduces a nomenclature for the minimum and maximum transmissible powers. These values will be used to characterise an interconnector in the following sections. With the chosen model, the minimum electrical losses are independent of the mass flow rate, and thus \( P_{el\text{chAMin}} = P_{el\text{chAMax}} \).

In section 6.1.2, the calculation of these maxima and minima is described in more details. The minimum electrical losses can be calculated based on the simplified analytical model as well as the losses at maximum pressure. It is, however, impossible to derive an analytical expression for \( P_{el\text{AMax}} \). This may represent a problem since the aim of the layout strategy is to find out which dimensioning of the interconnector is necessary to achieve a given electric and chemical power transmission capability. In section 7.1.2 scaling laws are presented which provide an alternative to repeated numerical simulations of an interconnector with different geometries.

Obviously a variation of the outlet temperature \( T_2 \) and the input voltage \( U_{in} \) below the maximum values is feasible. Lowering \( T_2 \) means lowering the permissible electrical losses, thus the transmissible electric power is reduced.

Figure 6.2 illustrates the change of the operational area for different values of \( T_2 \). With increasing outlet temperature, the permissible electrical losses increase, which means that the transmittable electric power also increases. This means that operating areas for different values of \( T_2 \) may overlap, which results in a further degree of freedom in the operation of an interconnector system.

The inlet temperature \( T_1 \) may be varied as well. Figure 6.4 shows the resulting change to the operational area: with increasing inlet temperature \( T_1 \), the permissible losses increase and thus the trans-
6.1. POWER LIMITATIONS AND DEPENDENCES

Figure 6.2: Operational area for an interconnector with a gaseous chemical medium for different outlet temperatures $T_2$ (example). Parameter is the outlet temperature $T_2$ [K].

Figure 6.3: Maximum and minimum permissible outlet temperature in function of the operating point (example).
mittable electric power also increases. On the other hand, the share of the ohmic losses which is evacuated by the medium is reduced, which implies a smaller difference between the maximum and minimum electric power.

The practical attractiveness of a variation in $T_1$ and $T_2$ during operation can be expected to be somewhat limited for the following reasons:

- Allowing a higher inlet temperature $T_1$ than the minimum possible increases the electrical losses.

- Operating with a lower outlet temperature $T_2$ will dramatically decrease the conversion efficiency (because of the decreased Carnot efficiency) of the waste heat recovery process (if applicable) and reduce the permissible losses and the available thermal power.
Thus from an operational perspective, $T_1$ and $T_2$ might only be adjusted to allow for operating points which are not feasible for nominal temperatures.

The transmission voltage may also be varied. This affects the relationship between the electric power $P_{el1}$ and the current density $J$. For d.c. transmission, this means:

$$P_{el} = \frac{A_{cTot}}{2} U_{in} J$$

The relation between $\dot{m}$ and $J$ remains unchanged, which implies that for a lower transmission voltage, the operational area is shrunk along the horizontal axis, as illustrated in figure 6.5. The possibility to adapt the transmission voltage thus permits an increase of the theoretical variation range for the electric power from close to zero to its value at maximum voltage.
CHAPTER 6. INTERCONNECTOR OPERATION

Figure 6.6: Optimal transmission voltage (example).

Figure 6.7: Total transmission efficiency with optimal transmission voltage (example).
The transmission voltage has a huge influence on the total transmission efficiency. As suggested in figure 5.12, $\eta_{tot}$ depends on the transmitted electric and chemical power. With variable $U_{in}$ it is thus possible to select the value of the voltage yielding the highest efficiency. This voltage is in general smaller than the highest permissible transmission voltage, as shown in figure 6.6. Even if it is possible to select a transmission voltage with improved overall efficiency, the efficiency gets unacceptably low for small values of the electric power. As shown in figure 6.7, this may set a practical lower limit to the transmissible electric power: the total transmission efficiency has a reasonable value when one of the electric or chemical powers is at least 50% of its maximum. For low transmitted powers, the efficiency becomes unacceptably low.

6.1.2 Limits for the electrical losses at constant temperatures and voltages

In a first step the coupling between the electric and chemical power will be discussed, assuming the temperatures $T_1$ and $T_2$ as well as the voltage $U_{in}$ are fixed. This means that the transmitted electric power $P_{el}$ is proportional to the electric current density $J$.

In similarity to the case of a liquid medium, the sum of the electrical and friction losses $P_V$ and $P_R$ corresponds to the power transmitted to the soil and the chemical medium $P_U$ and $P_Q$.

$$P_V + P_R = P_U + P_Q$$

(6.4)

Using equations 5.92, 5.88, 5.93 and 5.80, these losses can be expressed as a function of the temperatures, mass flow rate and inlet or outlet pressure (equations 6.2 and 6.3 respectively).

For each value of the chemical power, two limits for the permissible losses exist:

- A minimum current density $J_{Min}$: this corresponds to the situation $P_V = P_U$ and $P_R = P_Q$, which means that the temperature rise of the gas is only due to friction. In theory, $P_R > P_Q$
\[(6.9)\]
\[
\frac{\mu_W^{i17}}{\left(\frac{\bar{z}L^{i17}6H^{\bar{z}ui}f + \frac{i}{2}R (\bar{z}L - \bar{z}L) \bar{z}d_{uw}W^{\bar{z}ui}v}{}^{6R}\right)\left(\frac{\bar{z}L^{i17}6H^{\bar{z}ui}f + \frac{i}{2}R (\bar{z}L - \bar{z}L) \bar{z}d_{uw}W^{\bar{z}ui}v}{}^{6R}\right)^{i17}} - \frac{\bar{z}L^{i17}6H^{\bar{z}ui}f + \frac{i}{2}R (\bar{z}L - \bar{z}L) \bar{z}d_{uw}W^{\bar{z}ui}v}{(\bar{z}L - \bar{z}L) (\psi + du)} \frac{\mu_W^{i2}}{6^{i17}6^v} + \frac{i}{2}R \frac{d_{uw}W^{\bar{z}ui}v}{\bar{z}L^{i17}6^{i17}6^v} = \Lambda_d
\]

\[(7.9)\]
\[
\frac{\mu_W^{i17}}{\left(\frac{\bar{z}L^{i17}6H^{\bar{z}ui}f + \frac{i}{2}R (\bar{z}L - \bar{z}L) \bar{z}d_{uw}W^{\bar{z}ui}v}{}^{6R}\right)\left(\frac{\bar{z}L^{i17}6H^{\bar{z}ui}f + \frac{i}{2}R (\bar{z}L - \bar{z}L) \bar{z}d_{uw}W^{\bar{z}ui}v}{}^{6R}\right)^{i17}} - \frac{\bar{z}L^{i17}6H^{\bar{z}ui}f + \frac{i}{2}R (\bar{z}L - \bar{z}L) \bar{z}d_{uw}W^{\bar{z}ui}v}{(\bar{z}L - \bar{z}L) (\psi + du)} \frac{\mu_W^{i2}}{6^{i17}6^v} + \frac{i}{2}R \frac{d_{uw}W^{\bar{z}ui}v}{\bar{z}L^{i17}6^{i17}6^v} = \Lambda_d
\]
6.1. POWER LIMITATIONS AND DEPENDENCES

is also possible, but the considered operational area will be restricted to $P_R < P_Q$ since this is sensible from the point of view of the application (i.e. situations where the soil is heated up by the friction losses in the gaseous medium will not be considered).

- A maximum current density $J_{Max}$, due to the fact that the pressures are limited: $p_1 < p_{1Max}$ and $p_2 < p_{2Max}$. In the following it will be shown that the maximum current density corresponds to the highest values of $p_1$ and $p_2$.

The typical shape of the operational area delimited by the curves corresponding to $P_{VMin}(\dot{m})$ and $P_{VMax}(\dot{m})$, is shown in figure 6.1. This figure also introduces the nomenclature for the maximum and minimum powers at the “edges” of the operational area. Consequently, the minimum electrical losses can be derived from equations 5.88:

$$P_{VMin} = \frac{L_{tot}}{R_{thI} + R_{thE}} \left( \Delta T_{LK} + \frac{T_1 + T_2}{2} - T_U \right)$$  \hspace{1cm} (6.5)

From equation 5.80 it is clear that $p_2 = \text{max} \Leftrightarrow p_1 = \text{max}$ (for constant $\dot{m}$). Thus it is equivalent to show that the electrical losses have their maximum for $p_2 = \text{max}$.

$$\frac{d P_V}{dp_2} \bigg|_{J_{\text{min}}} > 0$$  \hspace{1cm} (6.6)

and

$$\frac{dP_V}{dp_2} > 0 \quad \text{for} \quad p_2 > p_2 \bigg|_{J_{\text{min}}}$$  \hspace{1cm} (6.7)

As discussed in section 6.1.3 it can be shown that the condition stated in equation 6.7 is fulfilled for:

$$f > \frac{6 R_i \left( 5 T_2^2 - T_1^2 \right)}{L_{tot} T_2 \left( T_1 + T_2 \right)}$$  \hspace{1cm} (6.8)

A physical background for this condition can hardly be found.
Since it cannot be established that the conditions [6.6] and [6.8] are universally true, they must be checked each time a maximum electric power is computed using the assumption that the electrical losses are maximum at the highest permissible pressure.

Independently of the permissible maximum operating pressure \( p_{1\text{Max}} \), a physical limit of the electrical losses \( P_V \) can be defined as the permissible losses at infinite inlet pressure:

\[
P_{VMax} = \lim_{p_{(1,2)} \to \infty} P_V = \lim_{p_{(1,2)} \to \infty} P_Q + \lim_{p_{(1,2)} \to \infty} P_U - \lim_{p_{(1,2)} \to \infty} P_R
\]

\[
P_{VMax} = \frac{1}{2 M_m \left( R_{thI} + R_{thE} \right)} \left( \dot{m} R_g \left( 2 + n_F \right) \left( R_{thI} + R_{thE} \right) (T_1 + T_2) \right. \\
+ L_{tot} M_m (T_1 + T_2 - 2 T_U + 2 \Delta T_{LK}) \right)
\]

The upper and lower limits derived for the electrical losses (equations [6.5] and [6.10]) can be transposed into limits for the electric current density.

\[
J_{Max} = \sqrt{ \frac{P_{VMax}}{K_V \left( 1 + \alpha_c \left( \frac{T_1 + T_2}{2} + \Delta T_{LK} - 293 \right) \right) } }
\]

\[
J_{Min} = \sqrt{ \frac{P_{VMin}}{K_V \left( 1 + \alpha_c \left( \frac{T_1 + T_2}{2} + \Delta T_{LK} - 293 \right) \right) } }
\]

### 6.1.3 Justification

As shown in the sign table [6.1] the strategy is to show that the derivative \( \frac{dP_V}{dp_2} \) is positive, which means that the maximum of \( P_V \) is reached when \( p_2 \) is maximum.\(^2\)

\(^2\)The implementation of this check is very simple.

\(^3\)As discussed earlier, this will also correspond to the maximum of \( p_1 \) for fixed \( \dot{m} \).
6.1. POWER LIMITATIONS AND DEPENDENCES

It can be shown that the sign of the derivative changes only once for positive values of the pressure according to table 6.1. The value of $p_dz$ cannot be calculated analytically and thus for each calculation of the maximum losses, it must be checked if the derivative $\frac{dP}{dp_2}$ is positive for the minimum possible pressure (i.e. check if $p_{2Min} > p_dz$).

A detailed calculation shows that the values of the derivatives at $p = 0$, i.e. $f2w_0$ and $f3w_0$ are negative if equation 6.8 is fulfilled.

In summary, the losses are maximum for $P_1 = P_{1Max}$ if equation 6.8 is fulfilled and $\frac{dP}{dp_2}$ is positive for $PV = PV_{Min}$.

### Variable temperatures and voltages

If variable inlet and outlet temperatures or voltages are permissible during operation, the operational area can be computed for each value of these according to section 6.1.2. No general analytical description of the operating area could be derived in either case, which means that the determination of the operation area involves a repeated calculation of the operational area for fixed temperatures and voltages.

Regarding the maximum and minimum powers (as defined in figure 6.1) the following general rules can be drawn with a physical argumentation. The permissible electrical losses increase with the

<table>
<thead>
<tr>
<th></th>
<th>$p_2 = 0$</th>
<th>$p_2 = p_dz$</th>
<th>$p_2 = p_{fp}$</th>
<th>$p_2 \rightarrow \infty$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\frac{dP}{dp_2}$</td>
<td>$-$</td>
<td>$-$</td>
<td>$0$</td>
<td>$+$</td>
</tr>
<tr>
<td>$\frac{d^2P}{dp_2^2}$</td>
<td>$f2w_0$</td>
<td>$+$</td>
<td>$+$</td>
<td>$+$</td>
</tr>
<tr>
<td>$\frac{d^3P}{dp_2^3}$</td>
<td>$f3w_0$</td>
<td>$-$</td>
<td>$-$</td>
<td>$-$</td>
</tr>
</tbody>
</table>

Table 6.1: Sign table for $\frac{dP}{dp_2}$. $p_{dz}$ and $p_{fp}$ are the zeros of $\frac{dP}{dp_2}$ and $\frac{d^2P}{dp_2^2}$ respectively. They have no special meaning in this context.
average temperature of the medium in the interconnector, thus:

- The minimum transmissible electric power (for minimum chemical power) \( P_{elch.AMin} \) will always occur at the lowest permissible values of \( T_1 \) and \( T_2 \).
- The maximum transmissible electric power (for maximum chemical power) \( P_{elAMax} \) will always occur at the highest permissible values of \( T_1 \) and \( T_2 \).

For the operation with variable input voltage it is also true that the maximum electric power will be transmitted at the maximum voltage.

### 6.2 Impact of the auxiliary equipment on system operation and layout

In addition to the transfer capacity limitations introduced in the previous section, the influence of the auxiliary equipment must be discussed. The required turbine power at the inlet e.g. depends on the inlet pressure and the mass flow rate, which are dependent on the electric and chemical power. A similar argumentation applies to the heat exchanger and the auxiliary equipment at the bus outlet. The models for the auxiliary equipment have been presented in section 5.3 and appendix A. Since the power ratings of this equipment set a limit to their input and output mass flow rates, it is possible that the operational area becomes limited further by these ratings.

In general the ratings of the auxiliary equipment can be adapted in order to fit the operational area. This is illustrated in figure 6.8: the limitations arising from the maximum and minimum turbine and heat exchanger powers are shown. The limitations are chosen in order to fit the operational area defined by the minimum and maximum losses: the limitation curves for \( P_{F\{1,2\}\{Min,Max\}} \) are tangent to the operational area defined by the minimum and maximum electric power.
Figure 6.8: Limitation of the operating area by the ratings of the compressors (example). In this example, the ratings are chosen in order not to limit the operation range.
6.3 Scaling laws

Based on the simplified analytical model introduced in section 5.3, some scaling laws can be derived. The scaling laws will be using the following expressions (see also figure 6.1):

\[
    r_1 = \frac{P_{elAMax}}{P_{elchAMin}} \quad (6.13)
\]

\[
    r_2 = \frac{P_{chAMax}}{P_{elAMax}} \quad (6.14)
\]

More details on the calculations and the necessary simplifications are given in section 6.3. It can be shown that for fixed \( r_{\{1,2\}} \), material properties, \( T_1, T_2 \) and \( U_{in} \) the following scaling laws apply (the \( \sim \) sign is used to indicate that two quantities are proportional to each other):

\[
    P_{VAMax} \sim L_{tot} \quad (6.15)
\]

\[
    P_{VchAMin} \sim L_{tot} \quad (6.16)
\]

\[
    P_{elAMax} \sim L_{tot} \quad (6.17)
\]

\[
    P_{elchAMin} \sim L_{tot} \quad (6.18)
\]

\[
    P_{chAMax} \sim L_{tot} \quad (6.19)
\]

\[
    U_{in} \sim L_{tot} \quad (6.20)
\]

\[
    R_i \sim L_{tot}^{3/5} \quad (6.21)
\]

The accuracy of the scaling laws can be assessed in the example shown in figures 6.9 and 6.10. Figure 6.9 shows the maximum and minimum transmittable powers in dependence of the transmission distance. Figure 6.10 shows the transmission voltage in dependence of the transmission distance. As the figures show, these quantities are proportional to \( L_{tot} \). Obviously this is not a formal proof for the accuracy of the laws. Since the use of these laws will only be to obtain a set of initial values in the dimensioning process, this will be acceptable.
6.3. SCALING LAWS

Figure 6.9: Transmissible power for constant $r_1$ and $r_2$ (example).

Figure 6.10: Maximum input voltage for constant $r_1$ and $r_2$ (example).
As discussed in section 6.1, operation with variable $T_2$ and $U_{in}$ is likely to be necessary. The use of the scaling laws can easily be adapted for variable inlet temperature and electric voltage:

- If $T_2$ can be varied within $[T_{2Min}; T_{2Max}]$, $P_{elchAMin}$ will correspond to $T_{2Min}$ and $P_{elAMax}$ to $T_{2Max}$. $P_{elchAMin}$ and $P_{elAMax}$ will be proportional to $L_{tot}$.

- If $U_{in}$ is variable, the lower limit of the electric power may theoretically reach zero independently of the line length.

In conclusion these scaling laws can be used to estimate the achievable maximum powers for any length based on the “one-time” calculation of these powers for a given length and a wide range of $r_1$ and $r_2$.

### 6.4 Derivation of the scaling laws

In order to derive a layout strategy and taking into account the impossibility to solve the relevant equations analytically, a set of scaling laws will be derived. $T_1$, $T_2$, $p_{Max}$ and $J_{Max}$ are set by design and materials limitations and are therefore independent of $L_{tot}$. In this section it will be shown that a scaling law for the interconnector dimensioning (with respect to its length) can be established if the following quantities are kept constant:

$$r_1 = \frac{P_{elAMax}}{P_{elchAMin}}$$  \hspace{1cm} (6.22)

$$r_2 = \frac{P_{chAMax}}{P_{elAMax}}$$  \hspace{1cm} (6.23)

According to section 5.3 (and for d.c. transmission), the electric power and the associated losses are:

$$P_{el1} = U_{in} J \frac{A_{cTot}}{2}$$  \hspace{1cm} (6.24)

$$P_V = J^2 A_{cTot} L_{tot} \rho$$  \hspace{1cm} (6.25)
6.4. DERIVATION OF THE SCALING LAWS

As a consequence:

\[ A_{cTot} = \frac{P_V}{J_{Max}^2 L_{tot} \rho} \] (6.26)

From equations 6.24 and 6.25:

\[ \frac{P_{el1}^2}{P_V} = \frac{U_{in}^2 A_{cTot}^2}{4 A_{cTot} L_{tot} \rho} \] (6.27)

\[ \Rightarrow \frac{P_{elAMax}^2}{P_{elchAMin}^2} = \frac{P_{VAMax}}{P_{VchAMin}} \] (6.28)

\[ \Rightarrow P_{VAMax} = r_1^2 P_{VchAMin} \] (6.29)

From sections 5.3 and 6.1.2:

\[ P_{VchAMin} = L_{tot} P_{U'} \] (6.30)

This means that the electrical losses at minimum transmitted electric and chemical power are proportional to the total length of the interconnector. Substituting in 6.26 yields the required conductor cross-section:

\[ A_{cTot} = \frac{r_1^2 P_{U'}}{J_{Max}^2 \rho} \] (6.31)

Combining equations 6.29 and 6.30 shows that the losses at maximum transmissible electric power are as well proportional to the total length.

\[ P_{VAMax} \sim L_{tot} \] (6.32)

Using 6.24:

\[ \frac{P_{elAMax}}{U_{in}} = \text{const} \] (6.33)

From equation 6.25 it appears that the losses are proportional to the total length for any operating point:

\[ P_V \sim L_{tot} \text{ for each operation point} \] (6.34)
Since $P_V - P_U = P_Q - P_R$ and $P_{\{V,U\}} \sim L_{tot}$:

$$P_Q - P_R \sim L_{tot} \tag{6.35}$$

Using an appropriate approximation, it can be shown that:

$$P_Q - P_R = \frac{R_i^{5/2}}{\sqrt{L_{tot}}} f \left( \text{gas}, T_1, T_2, p_1, p_2 \right) \tag{6.36}$$

Combining this result with equation 6.35, the scaling law for the inner radius can be calculated:

$$R_i \sim L_{tot}^{3/5} \tag{6.37}$$

Approximating the maximum chemical power by setting $p_2 = 0$:

$$P_{\text{chAMax}} = 2\pi \sqrt{\frac{M_m p_{Max}^2}{f R_g L_{tot} (T_1 + T_2)}} R_i^{5/2} \tag{6.38}$$

Combining with 6.37 shows that the maximum chemical power is also proportional to $L_{tot}$.

$$P_{\text{chAMax}} \sim L_{tot}^{-1/2} R_i^{5/2} \tag{6.39}$$

$$\Rightarrow P_{\text{chAMax}} \sim L_{tot} \tag{6.40}$$

With $r_{\{1,2\}} = \text{const}$:

$$P_{\text{elAMax}} \sim L_{tot} \tag{6.41}$$

$$P_{\text{elchAMin}} \sim L_{tot} \tag{6.42}$$

And using 6.33:

$$U_{in} \sim L_{tot} \tag{6.43}$$

\footnote{This approximation leads to an overestimation of $P_{\text{chAMax}}$. The validity of this approximation must be established by checking the result of a any layout based on the scaling laws with a numerical simulation.}
Chapter 7

Dimensioning and application of the Energy Interconnector

This chapter presents a layout procedure for an interconnector system. To circumvent a time consuming iterative procedure using numerical simulations, a procedure based on the previously developed scaling laws is introduced. This procedure is then applied to a set of generic applications and realistic values for all constrained design parameters (e.g. material properties) in order to determine in which power and distance range the interconnector could be used primarily.
7.1 Dimensioning and layout of an interconnector system

7.1.1 Parameters in the layout process

In the model of the interconnector presented in chapter 5, three main types of parameters can be distinguished (as discussed in section 4.2.2): design parameters, design alternatives and constrained parameters.

The goal of the layout procedure will be to determine the combination of the design parameters \( R_i, A_{cTot} \) and \( U_{inMax} \) yielding the required maximum transmission powers over the given line length. This procedure will be presented in section 7.1.2. The effect of variations in design alternatives and constrained parameters will also be briefly discussed in section 7.1.3.

7.1.2 Layout based on scaling laws

The equations presented in the previous sections cannot be solved analytically for the terminal powers. The complexity of the underlying differential equations also prevents a layout based on iterative numerical simulations.

The following layout procedure based on the scaling laws previously presented is thus suggested:

1. Store \( P_{elAMax}/L_{tot}, A_{cTot}, U_{in}/L_{tot} \) and \( R_i/L_{tot}^{3/5} \) as functions of \( r_1 \) and \( r_2 \). This implies solving the simplified equations (section 5.3) iteratively for all combinations of \( r_1 \) and \( r_2 \) in a given range. The results will be valid for a fixed selection of the constrained parameters.

Example: The procedure will be illustrated for an interconnector using hydrogen as the chemical energy carrier and the “standard” values for the constrained and material parameters discussed in sections 4.2.2 and 7.1.3. Figure 7.1 shows an example of data obtained from iterative solving of the analytical
Figure 7.1: Maximum permissible electric power per interconnector length unit in dependence of $r_1$ and $r_2$ (using hydrogen). This data is computed once for a given set of material and constrained parameters and provides the basis for a layout based on scaling laws.
model: the permissible electric power per interconnector length unit in dependence of \( r_1 \) and \( r_2 \) (with hydrogen transmission).

2. The application is defined by \( L_{tot} \), \( P_{chAMax} \) and \( P_{elAMax} \).

\[ r_2 = \frac{P_{chAMax}}{P_{elAMax}} \]

\textit{Example:} In the example:

\[ r_2 = \frac{210 \text{ MW}}{250 \text{ MW}} = 0.84 \]

4. With the stored \( P_{elAMax}(r_1) \) curves, determine \( r_1 \).

\textit{Example:} In the example: \( P_{elAMax}/L_{tot} = 4.032 \text{ MW/km.} \)

The corresponding value of \( r_1 \) is computed as follows: Figure 7.2 is obtained by interpolation of the data shown in figure 7.1 for \( r_2 = 0.84 \). From figure 7.2 the value of \( r_1 \) corresponding to the investigated application can be determined. In this example \( r_1 = 1.506 \).

5. Determine \( A_{cTot} \), \( U_{in} \) and \( R_i \) by interpolation and use of the scaling laws.

\textit{Example:} Figure 7.3 shows the “stored” data for \( R_i/L_{tot}^{3/5} \). The value of \( R_i/L_{tot}^{3/5} \) corresponding to the investigation can be interpolated for \( r_1 = 1.506 \) and \( r_2 = 0.84 \). The same can be done for the transmission voltage \( U_{in} \) and the total conductor cross-sectional area \( A_{cTot} \). The results are:

\[
\frac{R_i}{L_{tot}^{3/5}} = 1.3007 \text{ cm}^2 \text{ km}^{3/5} \\
A_{cTot} = 2869 \text{ mm}^2 \\
\frac{U_{in}}{L_{tot}} = 3.514 \text{ kV km}^{-1}
\]
### Figure 7.2: Maximum permissible electric power per interconnector length unit for \( r_2 = 0.84 \).
Figure 7.3: $R_i/L_{tot}^{3/5}$ in dependence of $r_1$ and $r_2$ (using hydrogen).

For a line length of 64 km:

$$R_i = 15.47 \text{ cm}$$
$$A_{cTot} = 2869 \text{ mm}^2$$
$$U_{in} = 217.8 \text{ kV}$$

6. Check the layout against the analytical model and a numerical simulation (since the scaling laws are approximations).

Example: The analytical model can be solved with the computed values for $R_i$, $A_{cTot}$ and $U_{in}$. The values of the transmissible power obtained in this way are close to the specification of the application:

$$P_{elAMax} = 249.89 \text{ MW}$$
$$P_{chAMax} = 207.78 \text{ MW}$$
7.1. **DIMENSIONING AND LAYOUT**

This means that the scaling laws provide a good approximation of the analytical model. A numerical simulation of the interconnector with $P_{el1} = P_{elAMax}$ and $P_{ch} = P_{chAPMax}$ yields the following result:

$$p_2\big|_{P_{el}=P_{elAMax}} = 23.19 \text{ bar}$$

$$T_2\big|_{P_{el}=P_{elAMax}} = 393.1 \text{ K}$$

The corresponding values obtained with the analytical model are: $p_2 = 23.27 \text{ bar}$ and $T_2 = 393 \text{ K}$. The results of the approximative layout procedure are confirmed by the simulation results.

The essential features of this procedure are the possibility to automate the layout and the relatively low computation time. This is needed in the topological investigations planned in the “Vision of Future Energy Networks” project.

7.1.3 **Influence of constrained and materials parameters**

**Maximum gas temperature**

Two aspects will limit the permissible maximum gas temperature:

- The withstand capability of the materials (especially the electrical insulation). It is not in the scope of this work to discuss new insulation materials. Withstand temperatures can reach 250°C for polytetrafluoroethylene (PTFE) or more commonly 130°C for cross linked polyethylene (XLPE). The choice of the insulation material thus sets a limit to the maximum gas temperature. As a conservative approach, it is assumed that these values will apply for the design of the interconnector.

- The heat recovery process. Table 7.1 gives an overview of possible recovery processes or heat consumers and their required temperature levels.
The surface temperature at the interface with the soil is not considered as a limit, since it may be (arbitrarily) reduced by additional thermal insulation. The space requirements and cost may, however, become prohibitive.

The variation range for the outlet temperature may also be limited by the technology used or the “direct” user of the recovered heat. As a consequence it is reasonable to assume that temperatures slightly above 100 °C will be feasible. In most of the examples used in this work, the maximum outlet temperature $T_{2Max}$ is 120 °C.

### Gas inlet temperature

The inlet temperature is in principle limited by the availability of a cold source after the initial compression phase. An inlet temperature exceeding the ambient temperature corresponds to the transmission of thermal power. Figures 7.4 and 7.5 show the required inner radius and transmission voltage for a prospective application of the interconnector as a function of the inlet temperature. The permissible electrical losses decrease for higher inlet temperatures. In order to achieve the same transmitted power, the inner radius and the transmission voltage have to be increased. The error bars in figures 7.4 and 7.5 show the effect of a 25% variation of the maximum powers and transmission length.

It can be anticipated that the value of thermal energy will de-
Figure 7.4: Inner radius for an interconnector with $P_{elAMax} = 200$ MW, $P_{chAMax} = 240$ MW and $L_{tot} = 50$ km for various inlet temperatures (error bars: effect of a $\pm 25\%$ variation of $P_{elAMax}$, $P_{chAMax}$ and $L_{tot}$).
Figure 7.5: Inlet Voltage for an interconnector with $P_{elAMax} = 200$ MW, $P_{chAMax} = 240$ MW and $L_{tot} = 50$ km for various inlet temperatures (error bars: effect of a ±25% variation of $P_{elAMax}$, $P_{chAMax}$ and $L_{tot}$).
crease in the future. For this reason it is unlikely that the inter-
connector will be used for the transmission of thermal energy at the
expense of higher transmission voltages and increased radii. For all
subsequent calculations and examples, an inlet temperature of $20^\circ$C
has been chosen.

**Electrical conductor**

The material of the electrical conductor does not play a major role
in the layout procedure at this stage, since all aspects related to
the production and laying of the interconnector are excluded from
the investigation. Materials with a higher conductivity will allow
a higher current density, and thus the resulting specific losses are
unlikely to differ significantly. As a consequence this is not discussed
in this work. Copper will be used in all examples.

A better conductor material results in a (slightly) reduced outer
diameter of the interconnector. In the examples, copper will be used.
The outer diameter does not appear directly in the calculation of the
transmissible electric and chemical powers.

**Chemical medium**

Several choices for the chemical energy carrier exist. Gaseous carri-
ers like hydrogen, carbon monoxide, methane and ethane or liquid
carriers like methanol, ethanol and octane have been considered in
this work.

Within the two classes of liquid and gaseous carriers the main
difference among the different carriers is the ratio between the ab-
sorbed thermal power and the chemical energy content. As pointed
out in chapter [5] this relation is only dependent on the temperature
rise for liquid carriers, it is more complex for gaseous carriers (the re-
lation is in fact variable and requires solving the equations presented
in section [5.3]).

As discussed in section [7.1] devoted to the layout procedure, the
coupling between chemical and thermal power does not mean that a
particular application cannot be accommodated by the selection of a suitable $r_1$ factor. A different value of $r_1$ will, however, impact on the operational characteristics of the interconnector system, e.g. a difference arises in the compression and friction losses. These are higher for gases with a smaller molar mass.

Figures 7.6 and 7.7 show the maximum transmittable electric and chemical powers for different gaseous respectively liquid energy carriers (for fixed $r_1 = 2.4$ and $r_2 = 1.5$). Since the permissible electrical losses are nearly independent of the energy carrier used, the transmissible powers vary approximately according to the ratio between the specific thermal capacity and the specific energy content of the carriers.

In a preliminary survey of the possible energy carriers, hydrogen has been identified as the most promising choice with respect to the overall energy system.
Following the argumentation of section 4.2, gaseous carriers are preferred.

More conversion processes from or to hydrogen are known than for the other possible carriers.

Several possibilities for direct use or delivery of hydrogen can be envisaged in the near future (including transportation, biomass gasification and direct solar hydrogen generation).

Hydrogen is part of numerous road maps developed within the research community and governmental bodies.

Gaseous carriers will thus be mainly considered in the discussion of potential applications for the interconnector principle.
Friction factor

The exact determination of the friction factor \( f \) is not possible at this stage, since it is linked to presently unavailable design details and experimental data. However, in the chosen modelling framework, the friction factor is linked to the inner radius of the interconnector, which means that the uncertainty in \( f \) leads to an uncertainty in \( R_i \). Figure 7.8 shows the general dependence: a higher friction factor implies a higher pressure drop and thus requires a larger inner radius to transmit the same chemical power.

Maximum operating pressure

The maximum operating pressure is uncertain at this stage because no construction aspects have been considered at this stage. For the calculations in this work, a maximum pressure of the order of some tens of bars has been assumed.
7.1. **DIMENSIONING AND LAYOUT**

<table>
<thead>
<tr>
<th>Cable</th>
<th>Conductor cross-section mm²</th>
<th>Maximum current A</th>
</tr>
</thead>
<tbody>
<tr>
<td>500/290 kV XLPE Cable</td>
<td>2500</td>
<td>1522…2670</td>
</tr>
<tr>
<td>400/230 kV XLPE Cable</td>
<td>2500</td>
<td>1565…2739</td>
</tr>
<tr>
<td>220/117 kV XLPE Cable</td>
<td>1600</td>
<td>1353…2195</td>
</tr>
<tr>
<td>132/76 kV XLPE Cable</td>
<td>800</td>
<td>949…1467</td>
</tr>
</tbody>
</table>

Table 7.2: Examples of the ampacity of XLPE cables with copper conductor [28]. The maximum current depends on the type of burying.

**Maximum electric current density**

The current density in the electrical conductor influences the local conductor temperature. Because this is not modelled in detail, the layout procedure used in this work is based on an arbitrary maximum current density $J_{Max}$.

Using a solid insulation material (as discussed in section 4.2) means that the achievable current densities will be within the same range as for electrical cables. Examples of the ampacity and conductor cross-section of power cables are given in table 7.2.

Since the expected currents in the interconnector are high, this maximum current density is likely to be below 1 A/mm² (assuming copper as the conductor material). Where nothing else is stated, a conservative value of 0.8 A/mm² will be used.

The impact of a variation of the maximum current density from $J_{Max(1)}$ to $J_{Max(2)}$ can easily be computed for constant transmitted power and losses:

$$P_{el1}' = \text{const} \quad (7.1)$$

$$P_V' = \text{const} \quad (7.2)$$
Using the model presented in section 5.3, $A_{cTot}$ and $U_{in}$ become:

\[
\frac{A_{cTot}(2)}{A_{cTot}(1)} = \left(\frac{J_{Max}(1)}{J_{Max}(2)}\right)^2 \tag{7.3}
\]

\[
\frac{U_{in}(2)}{U_{in}(1)} = \frac{J_{Max}(2)}{J_{Max}(1)} \tag{7.4}
\]

This means that a variation of the maximum current density can be compensated by adapting the conductor cross sectional area $A_{cTot}$ and transmission voltage $U_{in}$.

**Auxiliary equipment**

From the rating of the auxiliary equipment it is possible to estimate the size of the required heat exchanger. The procedure applied for the approximation of the exchanger volume will be described in chapter D of the appendix.

A calculation of the heat exchanger volumes corresponding to a 100 km interconnector according to the examples shown in figure 7.6 shows that exchanger volumes some tens of m$^3$ might be necessary under the assumption that the inlet pressure of the exchanger is maintained above 5 bar$^1$.

Because the space requirement of the heat exchanger may represent a limitation for the applicability of the interconnector, the related questions will need more attention when more detailed layouts are under discussion.

**Soil properties and thermal insulation**

A generic mean value for the soil thermal resistance has been used throughout the examples, since actual soil properties may vary based on its exact nature.

---

$^1$This is likely to be feasible if the interconnector voltage can be adapted.
The choice of the thermal resistance of the outer insulation may be driven by security, performance and cost aspects. Since one motivation for the interconnector is the potential reuse of ohmic losses, a high thermal resistance of the insulation layer was chosen in each example.

The figure 7.9 illustrates that for constant $r_1$ and $r_2$ the maximum transmissible powers decrease with a better insulation, because electrical losses are subject to a lower limit under such conditions. In other terms, to achieve the same transmitted powers with a better insulation, a higher value of $r_1$ must be selected (which impacts on the transmission efficiency).
7.2 Possible applications of the interconnector principle

In this final section the layout procedure developed here is applied to potential generic application scenarios for future energy transmission. This will illustrate which kind of application leads to a reasonable interconnector size and voltage level.

7.2.1 Applications investigated

In order to get a first idea of the size of an interconnector for different types of applications, a set of potential applications has been defined. Two types of descriptions will be used: transmission lines and areas. For these potential applications, the transmitted electric power is within the range of current values, while the chemical power requirement is subject to further discussion. The chosen values correspond to an intermediate scenario where at least part of the mobility sector is supplied with hydrogen or another gaseous chemical energy carrier.

Table 7.3 shows the list of these applications. The applications are specified by the maximum transmitted powers and line length. For areas, the underlying assumptions are also given: a self-sufficiency degree $s$ (in terms of maximum power) as well as a number of connections $n_c$ (it was assumed that these areas are supplied over several connections).

The layout procedure developed can be applied to these general specifications. This will allow for the determination of a range for the three main “dimensions” of an interconnector: its inner radius $R_i$, its maximum transmission voltage $U_{in}$ and the cross-sectional area of the electrical conductor $A_{cTot}$. Based on the resulting layouts

---

2The emphasis of this work is not on determining as realistic as possible applications, but to obtain an insight into the approximate interconnector layout required for differing applications.

3It will be assumed that the maximum load is equally shared among them.
7.2. POSSIBLE APPLICATIONS

<table>
<thead>
<tr>
<th>Application</th>
<th>$P_{elMax}$ [MW]</th>
<th>$P_{chMax}$ [MW]</th>
<th>$L_{tot}$ [km]</th>
<th>$n_c$</th>
<th>$s$</th>
</tr>
</thead>
<tbody>
<tr>
<td>MVDC</td>
<td>200</td>
<td>240</td>
<td>50</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>HVDC</td>
<td>2000</td>
<td>2400</td>
<td>600</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>LV</td>
<td>0.5</td>
<td>0.6</td>
<td>15</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>MV</td>
<td>250</td>
<td>300</td>
<td>50</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>HV</td>
<td>1000</td>
<td>1200</td>
<td>300</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Switzerland</td>
<td>300</td>
<td>400</td>
<td>500</td>
<td>6</td>
<td>80%</td>
</tr>
<tr>
<td>Baden</td>
<td>7</td>
<td>9</td>
<td>15</td>
<td>3</td>
<td>30%</td>
</tr>
<tr>
<td>EPFL</td>
<td>10</td>
<td>12</td>
<td>15</td>
<td>1</td>
<td>0%</td>
</tr>
<tr>
<td>50 households</td>
<td>0.06</td>
<td>0.07</td>
<td>2</td>
<td>1</td>
<td>0%</td>
</tr>
</tbody>
</table>

Table 7.3: List of the investigated “generic” applications ($n_c$: number of connections for the consumer, $s$ degree of self-sufficiency).

the soundness and feasibility of the interconnector principle in these applications can be discussed.

7.2.2 Resulting layout for the selected applications

The figures 7.10, 7.11(a) and 7.12 show the required $R_i$, $U_{in}$ and $A_{cTot}$ for a hydrogen interconnector using the assumptions previously discussed in section 7.1.3 The definition of the applications is subject to discussion: in order to indicate the variation of $R_i$, $U_{in}$ and $A_{cTot}$ in function of the application specifications, the effect of a variation of 25 % of any combination of the application specifications is represented as error bars in the figures 7.10, 7.11(a) and 7.12.

The required inner radius and transmission voltage rise with the transmitted power and distance. The value of the transmission voltages (shown in figure 7.11(a)) seems to be in line with current practice for the “medium voltage” applications while it reaches unrealis-
Figure 7.10: Inner radius for a hydrogen interconnector for various applications and assumptions previously introduced for the material and design parameters (error bars: result of a 25% variation in the specifications of the application).
7.2. POSSIBLE APPLICATIONS

Figure 7.11: Transmission voltage (d.c.) for a hydrogen interconnector for various applications and assumptions previously discussed for the material and design parameters.
Figure 7.12: Conductor cross-sectional area for a hydrogen interconnector for various applications and with the assumptions introduced for the material and design parameters.
As figure 7.11(b) shows, a higher outlet temperature of the gas would allow for lower transmission voltages (but decreased transmission efficiencies). The inner radius required for the transmission of high powers is also impressive (though this issue could possibly be solved by using parallel systems).

The variation of the cross-sectional area $A_{cTot}$ is less pronounced. The layout method implies that the same maximum current density and temperatures were assumed for all cases. This explains the low variations in $A_{cTot}$, since the “required” local thermal power will be of the same order of magnitude for all cases (thus the resulting comparable cross-sectional areas).

Figures 7.13, 7.14 and 7.15 show the interconnector dimensions $R_i$, $U_{in}$ and $A_{cTot}$ for small scale applications. The resulting inner radius and transmission voltage appear to be reasonable. The total cross-sectional area is, however, larger than the “traditional”
Figure 7.14: Transmission voltage for a hydrogen interconnector for “small scale” applications and with the assumptions introduced for the material and design parameters.
7.2. POSSIBLE APPLICATIONS

Figure 7.15: Conductor cross-sectional area for a hydrogen interconnector for “small scale” applications and with the assumptions introduced for the material and design parameters.
solution. The assumption that the inlet and outlet temperatures are similar for each application, which arises from the proposed interconnector concept, implies that the electrical losses need to be comparatively higher for those applications with lower losses. The total efficiency $\eta_{totBMax}$ (see section A.3 in the appendix) for the applications shown in figure 7.13 are 62.4% (LV), 97.7% (Baden), 98.2% (EPFL) and 54.3% (50 households) respectively, as shown in figure 7.16. This is unacceptably low.

Since alternative chemical carriers have different properties, an influence of the carrier choice on the interconnector layout exists. A comparison between different gaseous chemical carriers is shown in figures 7.17, 7.18 and 7.19 where $R_t$, $U_{in}$ and $A_{cTot}$ are shown for the MVDC application. Hydrogen, methane and ethane have similar energy densities $w_m$, while carbon monoxide is a comparatively heavy molecule with a low energy density. This implies that an in-
7.2. POSSIBLE APPLICATIONS

Figure 7.17: Inner radius of an interconnector for various chemical carriers (application: MVDC).

The ratio between the specific energy content and the thermal capacity impacts on the transmission voltage: Methane and ethane “contain” more chemical energy for the same absorbed heat. Therefore lower ohmic losses are permissible, which means that the transmission voltage of an interconnector using methane and ethane is higher for the same transmissible power and maximum current density.

\footnote{In reality the relevant figure is not the thermal capacity but the polytropic coefficient describing the gas flow.}
Figure 7.18: Transmission voltage of an interconnector for various chemical carriers (application: MVDC).

Figure 7.19: Conductor cross-sectional area of an interconnector for various chemical carriers (application: MVDC).
7.2.3 Discussion

The result of the layout procedure applied to the generic applications shows the following:

- Inner radius: pipes corresponding to the calculated sizes are readily available. For the small scale applications (LV, Baden, EPFL, 50 households), the pipe section appear to be rather small.

- Maximum transmission voltage: the layout procedure leads to higher voltages for higher transmitted powers and longer distances. This corresponds to the prevailing practice.

- Conductor cross-sectional area: the low variation in the required cross-sectional area can be explained by the more or less invariant thermal power flow to the surrounding soil.

With respect to the feasibility of the interconnector in the various contexts investigated, the following remarks apply, under the assumptions postulated for these examples:

- Inner radius: Production and laying of pipes with a diameter over 50 cm which incorporate an electrical conductor (and its insulation) is certainly problematic.

- Maximum transmission voltage: besides the high values required for “high voltage” applications, the required transmission voltages in the case of hydrogen are within the feasible range.

- Conductor cross-sectional area: $A_{cTot}$ represents the total required cross section which is (at least) divided into two poles. The calculated cross-sections seem feasible, especially in the context of medium voltage applications.

- Total efficiency: the potential for acceptable values of the total efficiency is restricted to the “large scale applications”.
In appendix C examples corresponding to the three application ranges “low”, “medium” and “high” voltage are presented in more detail. They illustrate the general findings discussed above.

Based on these considerations, the most promising application range for the interconnector concept as presented here appears to be in the power range of present “medium voltage” applications. The choice of hydrogen as a chemical carrier is supported by the results of the comparison, since hydrogen interconnectors require lower voltage levels.
Chapter 8

Conclusions

8.1 Implications for the “Vision of Future Energy Networks project”

This work has clarified the potential role and implications of multi-energy transmission within the “Vision of Future Energy Networks” project. A favoured solution is proposed for inclusion in future infrastructure scenarios.

The integration of different energy carriers into future networks will permit improvements in the network performance as well as improved functionality (e.g. energy management). This trend opens the way for hybrid energy transmission, where the combination of electricity and e.g. hydrogen will play a predominant role. From a “high level” perspective, i.e. without consideration of implementation and design details, this work has provided the following results: a generic modelling framework is available, relevant parameters have been identified and the resulting limitations of the application of the interconnector principle can be discussed on this basis.

The developed model is generic, which means that few indications on the detailed layout of the interconnector are needed. This suits
the “Vision of Future Energy Networks” project needs. Furthermore the proposed layout procedure does not imply a high computational complexity or “manual intervention”, which makes it useful for the topological optimisation activities within the project.

In general, the layout methodology presented in this work shows that increasing the transmissible power is feasible by increasing the transmission voltage and the interconnector inner radius. Based on material properties and physical limitations (like the coupling among the transmitted powers), a promising power range for an interconnector system appears to be the “MVDC” application ($P_{el} = 200\text{ MW}$, $P_{ch} = 240\text{ MW}$ and $L_{tot} = 50\text{ km}$). For “smaller” applications (i.e. less power transmitted over shorter distances), the required conductor cross-section is rather high and the total transmission efficiency drops to unacceptably low values. Larger scale applications would require extreme voltages, which will be very difficult to implement.

From the study of the generic applications, a preferred application (MVDC) has been defined. Longer distances may be achieved with several interconnector sections (and intermediary compressor stations); higher transmitted electric and chemical powers can be achieved with several parallel interconnectors.

8.2 Application of the interconnector principle: Future work

This work permitted to highlight a preferred application for the interconnector. The envisaged next steps will be focussing on this application:

- By sharpening the specification of the application in order to become more precise with respect to the parameters specified in section 7.1.3
- By investigating possible detailed designs, specifically for this particular application.
Finally, the description of a multi-energy system and a combined multi-energy transmission concept can show up interesting development directions for the energy systems of the future even though it is clear that the implementation of the concept as a whole in the exact form as presented here is not likely: the multi-energy framework will be used as a basis for infrastructure scenarios and case studies in subsequent (sub-)projects and the developed tools will certainly find applications in the future optimisation and evolution of present energy networks.
Appendix A

Model of the auxiliary equipment for an interconnector with transport of a gaseous medium

A.1 Compressors

At the inlet of the interconnector, a compressor is necessary to compress the gaseous medium to its inlet pressure \( p_1 \). During the compression, which is assumed to be adiabatic\(^1\) the gas temperature rises to \( T_{1h} \).

\[
T_{1h} = \left( \frac{p_0}{p_1} \right)^{\frac{1-\kappa}{\kappa}} T_0
\]  

\(^1\)This assumption corresponds to a worst case analysis.
where \( \kappa \) is given by the \( n_F \) degrees of freedom of the gas:

\[
\kappa = \frac{n_F}{2} + 1
\]  

(A.2)

The compressor power needed can be subdivided into three terms: the hydrodynamic work (per time unit), the increase of the kinetic energy of the gaseous medium and the increase of the inner energy of the gaseous medium.

\[
P_{Pump1} = p_1 A_1 v_1 - p_0 A_0 v_0 + \frac{\dot{m}}{2} \left( v_1^2 - v_0^2 \right) + \frac{\Delta U}{\Delta t}
\]  

(A.3)

Only ideal gases will be considered, so the rate of change of its inner energy is:

\[
\frac{\Delta U}{\Delta t} = \frac{n_F}{2} \frac{\dot{m}}{M_m} R_g \left( \left( \frac{p_0}{p_1} \right)^{\frac{n_F}{2} + 2} - 1 \right) T_0
\]  

(A.4)

Using equation 5.47:

\[
p A_i v = \frac{\dot{m}}{M_m} R_g T
\]  

(A.5)

Substituting and assuming \( v_0^2 \) is so small that it can be neglected:

\[
P_{Pump1} = \frac{\Delta U}{\Delta t} + A_i (p_1 v_1 h - p_0 v_0) + \frac{\dot{m}}{2} v_1 h^2
\]  

(A.6)

\[
= \left( \frac{n_F}{2} + 1 \right) R_g \dot{m} \left( T_{1h} - T_0 \right) + \frac{\dot{m}}{2} \left( \frac{\dot{m} R_g}{\pi M_m R_i^2} \right)^2 \frac{T_{1h}^2}{p_1^2}
\]  

(A.7)

\[
= \left( \frac{n_F}{2} + 1 \right) R_g \dot{m} \left( \left( \frac{p_0}{p_1} \right)^{\frac{n_F}{2} + 2} - 1 \right) T_0 + \frac{\dot{m}^3 R_g^2 T_{1h}^2}{2 \pi^2 M_m^2 R_i^4 p_1^2}
\]  

(A.8)

\footnote{The hydrostatic work in the compressor can be neglected.}

\footnote{An assumption which holds for hydrogen, methane and natural gas in particular.}

\footnote{This corresponds to a worst case analysis.}
A.2. HEAT EXCHANGERS AND RECOVERY

If necessary, a turbine can be used to expand the gas to its final pressure $p_3$ at the end of the pipeline. The turbine power can also be computed using equation A.8. For the arrangement depicted in figure A.1 (variant A), $T_3$ and $p_3$ are the temperature and pressure at the turbine inlet and $T_4$ and $p_4$ are the temperature and pressure at the turbine outlet. The turbine power is thus:

$$P_{Pump2} = \left( \frac{nF}{2} + 1 \right) \frac{R_g}{M_m} \dot{m} \left( \left( \frac{p_3}{p_4} \right)^{\frac{2}{nF+2}} - 1 \right) T_3 + \frac{\dot{m}^3 R_g^2 T_3^2}{2 \pi^2 M_m^2 R_i^4 p_3^2}$$

(A.9)

$P_{Pump1}$ and $P_{Pump2}$ represent the mechanical work applied to respectively taken from the medium. Positive values indicate that energy is transferred to the fluid. The required electric power $P_{F\{1,2\}}$ or the delivered electric power of the motor/generator connected to the compressor/turbine is given by its efficiency, which can differ for each operation mode:

$$P_{F\{1,2\}} = \begin{cases} \frac{1}{\eta_{\{1,2\}} Pos} P_{Pump\{1,2\}} & \text{for } P_{Pump\{1,2\}} \geq 0 \\ \eta_{\{1,2\}} Neg P_{Pump\{1,2\}} & \text{otherwise} \end{cases}$$

(A.10)

A.2 Heat exchangers and waste heat recovery

A.2.1 Use of compression waste heat

Variants A and B

In a first set of variants (figures A.1 and 5.9), the gas is compressed to the inlet pressure $p_1$ from the pressure $p_0$ (either the pressure of the gas from a production or storage process). During compression (or eventually expansion) the gas temperature will rise (respectively fall). To be used as a coolant in the interconnector, the gas should be cooled down to nearly ambient temperature. This could even yield energy, if an adequate recovery process is available.
The power $P_{Pump1}$ required to compress the gas in the inlet compressor for variant A has been calculated in equation [A.8]. A motor driving this compressor would need the power $P_{F1}$ given in equation [A.10].

The following definition applies:

$$\beta := \frac{\kappa}{\kappa - 1} = \frac{n_F}{2} + 1$$  \hspace{1cm} (A.11)

For simplicity, isobaric cooling of the gas in the heat exchanger is assumed. The extracted heat flow is:

$$\dot{Q}_{w1A} = \left(\frac{n_F}{2} + 1\right) \frac{\dot{m} R_g}{M_m} (T_{1hA} - T_1)$$  \hspace{1cm} (A.12a)

$$= \left(\frac{n_F}{2} + 1\right) \frac{\dot{m} R_g}{M_m} \left(\left(\frac{p_1}{p_0}\right)^{\frac{n_F+2}{2}} - T_0 - T_1\right)$$  \hspace{1cm} (A.12b)

The recovery process uses a cold source with the temperature $T_{K1}$, thus the maximum efficiency of this recovery process corresponds to
the Carnot efficiency:

$$\eta_{c1APos} = 1 - \frac{T_{K1}}{T_{1hA}}$$  \hspace{1cm} (A.13)

The main operation mode of the heat exchanger will be cooling down the gas (i.e. $\dot{Q}_{w1} > 0$) at temperatures exceeding the cold source temperature ($T_{K1}$):

$$P_{w1A} = \begin{cases} \eta_{Rec1APos} \dot{Q}_{w1A} & \text{if } \dot{Q}_{w1A} \geq 0 \text{ and } T_{K1} \leq T_{1} \\ \text{undefined} & \text{otherwise} \end{cases}$$  \hspace{1cm} (A.14)

The total recovery efficiency $\eta_{Rec1APos}$ is the product of the Carnot efficiency $\eta_{c1APos}$ which describes the boundary imposed by the cold source (i.e. independently of a particular recovery process) and the exergy efficiency of a particular recovery process $\eta_{Ex1APos}$, which in turn describes its “intrinsic” performance.

$$\eta_{Rec1APos} = \eta_{c1APos} \eta_{Ex1APos}$$  \hspace{1cm} (A.15)

From this, the total power required at the interconnector entry is the compressor power reduced by the amount of power recuperated from the gas compression.

$$P_{F1ATot} = P_{F1A} - P_{w1A}$$  \hspace{1cm} (A.16)

At the inlet, the situation is the same for both variants A and B.

**Variant C**

The concept of an interconnector system using cryogenic energy transmission is depicted in figure [A.2] At the inlet of the interconnector, the gas is cooled down to the temperature $T_{1}$ by means of a compressor which increases the gas pressure to $p_{1hC}$, a heat exchanger and a valve which lets the gas expand to $p_{1}$, which also causes it to cool down. Assuming adiabatic expansion of the gas, the required pressure at the outlet of the heat exchanger $p_{1kC}$ becomes:

$$p_{1kC} = \left( \frac{T_{1kC}}{T_{1C}} \right)^{\beta} p_{1C}$$  \hspace{1cm} (A.17)
The cooling of the gas in the heat exchanger is assumed to be isobaric, thus the compressor has to compress the gas to the pressure $p_{1hC} = p_{1kC}$. The gas temperature at the inlet of the heat exchanger therefore is:

$$T_{1hC} = \left( \frac{p_{1hC}}{p_0} \right)^{\frac{1}{\beta}} T_0 \quad (A.18)$$

In the heat exchanger, the heat flow $\dot{Q}_{w1C}$ is extracted from the gas:

$$\dot{Q}_{w1C} = \left( \frac{n_F}{2} + 1 \right) \frac{\dot{m} R_g}{M_m} (T_{1hC} - T_{1kC}) \quad (A.19)$$

In an adequate heat recovery system the power $P_{w1C}$ can be recuperated. The normal operation mode of the heat exchanger is to cool down the gas to a temperature superior or equal to the cold source temperature.

$$P_{w1C} = \begin{cases} \eta_{Rec1CP_{Pos}} \dot{Q}_{w1C} & \text{if } \dot{Q}_{w1C} \geq 0 \text{ and } T_{1kC} \geq T_{K1} \\ \text{undefined} & \text{otherwise} \end{cases} \quad (A.20)$$
A.2. HEAT EXCHANGERS AND RECOVERY

where

\[ \eta_{Rec1CP_{Pos}} = \eta_{c1CP_{Pos}} \eta_{Ex1CP_{Pos}} \]  \hspace{1cm} (A.21)

and

\[ \eta_{c1CP_{Pos}} = 1 - \frac{T_{K1}}{T_{1hC}} \]  \hspace{1cm} (A.22)

Finally, the inlet compressor has the mechanical power:

\[ P_{Pump1C} = \frac{\beta R_g}{M_m} \dot{m} \left( \left( \frac{p_0}{p_{1C}} \right)^{-\frac{1}{\beta}} - 1 \right) T_0 + \frac{\dot{m}^3 R_g^2}{2 \pi^2 M_m^2 R_4^4} \frac{T_{1hC}^2}{R_{1C}^2} \]  \hspace{1cm} (A.23)

The motor power \( P_{F1C} \) is again given by equation A.10.

A.2.2 Use of warm gas at the bus outlet

Variants A and B

The two system layouts shown in figures A.1 (variant A) and 5.9 (variant B) will be discussed first. In both cases the gas enters the interconnector at the temperature \( T_1 \) and leaves it at the higher temperature \( T_2 \). The task of the waste heat recovery system is twofold: make use of any temperature difference between the gas and the ambient temperature and bring the gas to the pressure \( p_4 \) required in the distribution system or for its further processing at the receiving end.

The variants A and B only differ in the sequence of the compressor and heat exchanger. Adiabatic compression/expansion of the gas in the compressor/turbine and isobaric change of temperature in the heat exchanger will be assumed in order to compute the recovered power \( P_{F2\{A,B\}Tot} \) in each variant.

Variant A

In variant A the gas passes the heat exchanger directly at the outlet of the interconnector. The process is assumed to be isobaric. The
gas is cooled down to the temperature $T_3$ such that the gas will leave the outlet turbine at the temperature $T_4$.

$$T_{3A} = \left( \frac{p_{3A}}{p_4} \right)^{\frac{1}{\beta}} T_4$$  \hfill (A.24)

Thus the extracted heat flow becomes:

$$\dot{Q}_{w2A} = \left( \frac{n_F}{2} + 1 \right) \frac{\dot{m} R_g}{M_m} (T_2 - T_{3A})$$  \hfill (A.25a)

$$= \left( \frac{n_F}{2} + 1 \right) \frac{\dot{m} R_g}{M_m} \left( T_2 - \left( \frac{p_3}{p_4} \right)^{\frac{2}{n_F+2}} T_4 \right)$$  \hfill (A.25b)

A recovery process working with the cold source temperature $T_{K2}$ (respectively hot source temperature) will have the following Carnot efficiencies:

$$\eta_{c2APos} = 1 - \frac{T_{K2}}{T_2} \text{ if } T_{K2} \text{ is the cold source}$$  \hfill (A.26a)

$$\eta_{c2ANeg} = 1 - \frac{T_2}{T_{K2}} \text{ if } T_{K2} \text{ is the hot source}$$  \hfill (A.26b)

Depending on the temperature difference between the cold source and the gas, several cases must be considered separately:

- The gas is cooled down to a temperature higher or equal to the cold source temperature $T_{K2}$ ($\dot{Q}_{w2A} \geq 0$ and $T_{K2} \leq T_{3A} < T_2$). This corresponds to a waste heat recovery process, which can be utilised.

- The gas is heated up to a temperature lower or equal to the cold source temperature $T_{K2}$ which takes to role of the hot source ($\dot{Q}_{w2A} < 0$ and $T_{3A} \leq T_{K2}$). The gas becomes the cold source of a process, which can also yield energy, provided the recovery process allows for symmetrical operation. Such a scenario, however, is unlikely in the layout of an interconnector.
A.2. HEAT EXCHANGERS AND RECOVERY

- All other cases are assumed to yield an undefined power to the recovery system.

Thus the recovered electric power becomes:

\[
P_{\text{w}2A} = \begin{cases} 
\eta_{\text{Rec}2A\text{Pos}} \hat{Q}_{\text{w}2A} & \text{if } \hat{Q}_{\text{w}2A} \geq 0 \text{ and } T_{K2} \leq T_{3A} < T_2 \\
-\eta_{\text{Rec}2A\text{Neg}} \hat{Q}_{\text{w}2A} & \text{if } \hat{Q}_{\text{w}2A} < 0 \text{ and } T_{3A} \leq T_{K2} \\
\text{undefined} & \text{otherwise}
\end{cases}
\]  
(A.27)

The recovery efficiencies \(\eta_{\text{Rec}2A\{\text{Pos,Neg}\}}\) are the product of the corresponding Carnot efficiency \(\eta_{\text{c2A\{Pos,Neg\}}}\) and the exergy efficiency of the recovery process \(\eta_{\text{Ex2A\{Pos,Neg\}}}\cdot\)

\[
\eta_{\text{Rec}2A\text{Pos}} = \eta_{\text{c2APos}} \eta_{\text{Ex2APos}} \\
\eta_{\text{Rec}2A\text{Neg}} = \eta_{\text{c2ANeg}} \eta_{\text{Ex2ANeg}}
\]  
(A.28a, b)

The power \(P_{\text{Pump}2A}\) of the outlet compressor/turbine has been calculated in equation A.9 and the resulting electric power \(P_{F2A}\) at the motor/generator in equation A.10. The recovered power at the interconnector outlet becomes:

\[
P_{F2ATot} = P_{w2A} - P_{F2A}
\]  
(A.29)

**Variant B**

In variant B, the gas first passes a turbine at the outlet of the interconnector. The turbine is operated such that the desired outlet pressure \(p_{3B} = p_4\) is reached. Thus the mechanical power at the turbine is:

\[
P_{\text{Pump2B}} = \frac{\beta R_g \frac{T_2}{M_m}}{\frac{\hat{m}}{\hat{m}}} \left( \left( \frac{p_{3B}}{p_2} \right)^{\frac{1}{\beta}} - 1 \right) - \frac{\hat{m}^3 R_g^2}{2 \pi^2 M_m^2 R_i^4} \frac{T_2^2}{p_2^2}
\]  
(A.30)

The electric power at the motor/generator can be computed using equation A.10. The gas temperature at the outlet of the turbine is:

\[
T_{3B} = \left( \frac{p_{3B}}{p_2} \right)^{\frac{1}{\beta}} T_2
\]  
(A.31)
The temperature difference to a cold source $T_{K2}$ can be used to extract some heat from the gas ($T_4$ is the temperature the gas is required to have at the end of the interconnector system). The extracted heat flow is:

$$\hat{Q}_{w2B} = \left( \frac{n_F}{2} + 1 \right) \frac{\dot{m} R_g}{M_m} (T_{3B} - T_4) \quad (A.32a)$$

$$= \left( \frac{n_F}{2} + 1 \right) \frac{\dot{m} R_g}{M_m} \left( T_2 - \left( \frac{p_{3B}}{p_2} \right)^{\frac{n_F + 2}{n_F}} T_2 \right) \quad (A.32b)$$

The Carnot efficiency for this process with $T_{K2}$ as a cold, respectively hot source temperature is:

$$\eta_{c2BPos} = 1 - \frac{T_{K2}}{T_{3B}} \quad \text{if } T_{K2} \text{ is the cold source} \quad (A.33a)$$

$$\eta_{c2BNeg} = 1 - \frac{T_{3B}}{T_{K2}} \quad \text{if } T_{K2} \text{ is the hot source} \quad (A.33b)$$

Depending on the temperature difference between the cold source and the gas, several cases must be considered separately:

- The gas is cooled down to a temperature higher or equal to the cold source temperature $T_{K2}$ ($\hat{Q}_{w2B} \geq 0$ and $T_{K2} \leq T_4 < T_{3B}$). This corresponds to a waste heat recovery process yielding energy.

- The gas is heated up to a temperature lower or equal to the cold source temperature (which takes to role of the hot source) ($\hat{Q}_{w2B} < 0$ and $T_4 \leq T_{K2}$). The gas becomes the cold source of a process, which can also yield energy, provided the recovery process allows for symmetrical operation.

- All other cases are assumed to yield an undefined power to the recovery system.

$$P_{w2B} = \begin{cases} 
\eta_{Rec2BPos} \hat{Q}_{w2B} & \text{if } \hat{Q}_{w2B} \geq 0 \text{ and } T_{K2} \leq T_4 < T_{3B} \\
-\eta_{Rec2BNeg} \hat{Q}_{w2B} & \text{if } \hat{Q}_{w2B} < 0 \text{ and } T_4 \leq T_{K2} \\
\text{undefined} & \text{otherwise}
\end{cases} \quad (A.34)$$
A.2. HEAT EXCHANGERS AND RECOVERY

Where:

\[
\eta_{Rec2BPos} = \eta_{c2BPos} \eta_{Ex2BPos} \quad (A.35a)
\]
\[
\eta_{Rec2BNeg} = \eta_{c2BNeg} \eta_{Ex2BNeg} \quad (A.35b)
\]

The overall recovered power at the bus outlet thus becomes:

\[
P_{F2BTot} = P_{w2B} - P_{F2B} \quad (A.36)
\]

Variant C

The waste heat recovery in variant C (cryogenic energy transmission) is similar to variant B and can be modelled as an isobaric cooling of the gas in the heat exchanger \((p_{3C} = p_4)\). The gas pressure and temperature at the bus outlet will, however, be different for both cases. The following quantities are computed in analogy to the computation for variant B:

- Turbine mechanical power:

\[
P_{Pump2C} = \frac{\beta R_g T_{2C}}{M_m} \dot{m} \left( \left( \frac{p_{3C}}{p_{2C}} \right)^{\frac{1}{\beta}} - 1 \right) - \frac{\dot{m}^3 R_g^2}{2 \pi^2 M_m^2 R_i^4} \frac{T_{2C}^2}{p_{2C}} \quad (A.37)
\]

- Turbine outlet gas temperature

\[
T_{3C} = \left( \frac{p_{3C}}{p_{2C}} \right)^{\frac{1}{\beta}} T_{2C} \quad (A.38)
\]

- Extracted thermal power

\[
\dot{Q}_{w2C} = \left( \frac{n_F}{2} + 1 \right) \frac{\dot{m} R_g}{M_m} (T_{3C} - T_4) \quad (A.39)
\]
• Recuperated electric power:

\[
P_{w2C} = \begin{cases} 
\eta_{Rec2CPos} \hat{Q}_{w2C} & \text{if } \hat{Q}_{w2C} \geq 0 \\
-\eta_{Rec2CNeg} \hat{Q}_{w2C} & \text{if } \hat{Q}_{w2C} < 0 \text{ and } T_K2 \leq T_4 < T_3C \\
\text{undefined} & \text{otherwise}
\end{cases}
\]  

(A.40)

where

\[
\eta_{Rec2CPos} = \eta_{c2CPos} \eta_{Ex2CPos} \\
\eta_{Rec2CNeg} = \eta_{c2CNeg} \eta_{Ex2CNeg}
\]  

(A.41a, b)

\[
\eta_{c2CPos} = 1 - \frac{T_K2}{T_3C} \text{ if } T_K2 \text{ is the cold source}
\]  

(A.42a)

\[
\eta_{c2CNeg} = 1 - \frac{T_3C}{T_K2} \text{ if } T_K2 \text{ is the hot source}
\]  

(A.42b)

A.3 Efficiency of the overall interconnector system

The comparison of different interconnector system layouts or operation strategies requires a definition of the efficiency of the overall system. The following definitions are introduced for the efficiencies of the components of this system:

• \( \eta_{send} \) is the efficiency of the inlet compressor / turbine station. The electric power \( P_{el1} \) and the chemical power \( P_{ch} \) pass through the station. Its operation requires the electric power \( P_{F1} \) while the power \( P_{w1} \) can be recovered in the waste heat recovery system.

• \( \eta_{trans} \) is the efficiency of the transmission device itself. The chemical power \( P_{ch} \) is conserved while the ohmic losses \( P_V \) affect the electrical transmission. A fraction \( P_Q \) of these losses is, however, taken over by the chemical medium.
A.3. OVERALL EFFICIENCY

- $\eta_{rec}$ is the efficiency of the receiving end turbine/compressor station. The electric and chemical power are not affected by its operation which enables the recovery of the electric power $P_{w2} - P_{F2}$.

The following definitions for $\eta_{send}$, $\eta_{trans}$ and $\eta_{rec}$ are proposed:

\begin{align*}
\eta_{send} &= \frac{P_{el1} + P_{ch}}{P_{el1} + P_{ch} + P_{F1} - P_{w1}} \quad (A.43a) \\
\eta_{trans} &= \frac{P_{el1} - P_V + P_Q + P_{ch}}{P_{el1} + P_{ch}} \quad (A.43b) \\
\eta_{rec} &= \frac{P_{el1} - P_V + P_{ch} - P_{F2} + P_{w2}}{P_{el1} - P_V + P_Q + P_{ch}} \quad (A.43c)
\end{align*}

These definitions clearly facilitate the introduction of an overall system efficiency $\eta_{tot}$ for the transmission system.

\begin{align*}
\eta_{tot} &= \eta_{send} \eta_{trans} \eta_{rec} \\
&= \frac{P_{el1} - P_V + P_{ch} - P_{F2} + P_{w2}}{P_{el1} + P_{ch} + P_{F1} - P_{w1}} \quad (A.44)
\end{align*}
Appendix B

Example: a coaxial energy interconnector

A coaxial energy interconnector as described in figure [B.1] is considered. Two cylindrical conductors are separated by an electrically insulating layer and thermally insulated from the surroundings.

The cross sectional area of each conductor is:

\[ A_c = \pi k_f \left( R_2^2 - R_1^2 \right) \]  \hspace{1cm} (B.1)

Therefore the following outer radius for the internal conductor becomes:

\[ R_2 = \sqrt{R_1^2 + \frac{A_c}{\pi k_f}} \]  \hspace{1cm} (B.2)

The inner radius of the outer conductor thus is:

\[ R_3 = R_2 + w_i \]  \hspace{1cm} (B.3)

and its outer radius is:

\[ R_4 = \sqrt{R_3^2 + \frac{A_c}{\pi k_f}} \]  \hspace{1cm} (B.4)
APPENDIX B. EXAMPLE

The specific d.c. resistance of this coaxial conductor is:

\[ R'_{dc} = \frac{2\rho_{c20}}{k_f A_c} \left(1 + \alpha_c (T_c - 293)\right) \quad (B.5) \]

The \( k_s \) factor for skin effect losses of a hollow conductor is approximately \[21\]:

\[ k_s = \frac{d'_c - d'_i}{d'_c + d'_i} \left(\frac{d'_c + 2d'_i}{d'_c + d'_i}\right)^2 \quad (B.6) \]

where

\[ d'_c = \sqrt{k_f d_c + (1 - k_f) d_i^2} \quad (B.7) \]

and \( d_i \) and \( d_c \) are the inner, respectively outer diameter of the conductor.

In a coaxial conductor, the value of \( k_s \) is thus different for the inner and the outer conductors. In the following, its mean value will be used:
\[ k_s = \frac{k_{s1} + k_{s2}}{2} \] (B.8)

where

\[ k_{s\{1,2\}} = \frac{d_{c\{1,2\}}' - d_{i\{1,2\}}'}{d_{c\{1,2\}}' + d_{i\{1,2\}}'} \left( \frac{d_{c\{1,2\}}' + 2d_{i\{1,2\}}'}{d_{c\{1,2\}}' + d_{i\{1,2\}}'} \right)^2 \] (B.9a)

\[ d_{c\{1,2\}}' = \sqrt{k_f d_{c\{1,2\}} + (1 - k_f) d_{i\{1,2\}}^2} \] (B.9b)

and

\[ d_{i1} = 2R_1 \] (B.10a)
\[ d_{c1} = 2R_2 \] (B.10b)
\[ d_{i2} = 2R_3 \] (B.10c)
\[ d_{c2} = 2R_4 \] (B.10d)

The proximity effect losses are computed using a formula adapted from [29]:

\[ y_p = \frac{A_c}{\rho_c} \frac{k_p}{2\pi R_a} \sqrt{\frac{1}{2} \frac{\omega \mu_0 \mu_{rc} \rho_c}{}} \] (B.11a)

\[ = \sqrt{\frac{\omega \mu_0 \mu_{rc}}{2 \rho_c} \frac{\pi \left(R_a^2 - R_i^2\right)}{2\pi R_a} \frac{k_f}{\left(1 + \frac{R_{center}}{R_{shield}}\right)}} \] (B.11b)
Appendix C

Illustration examples for the interconnector dimensioning

C.1 Example 1: Dimensioning of an interconnector for energy distribution

In this first example, a scenario for the lowest distribution layer is considered. The situation shown in figure C.1 represents three residential housing estates. Each of those has been defined by its electric and chemical power requirements and the thermal power will result from the layout process.

The system described consists of three interconnectors. The application of the layout procedure presented in section 7.1 yields the inner radius, transmission voltage and conductor overall cross-sectional area summarised in table C.1.

The thermal power available at each hub is given by the interconnector layout and can either be used directly or converted in a
APPENDIX C. ILLUSTRATION EXAMPLES

waste heat recovery process. The calculation of the overall efficiency at maximum electric power \( \eta_{TotBAMax} \) assumes that a share of this energy (50% of the Carnot efficiency) is re-usable.

The following remarks apply to the resulting layout and system performance shown in table C.1:

- The losses are unacceptably high: for the consumers at the end of interconnector i, the combined transmission efficiency is 76% for a transmission length of only 3 km. This is absurdly low because of the underlying assumption that the gas is heated up and cooled down three times, i.e. once in each interconnector i-iii, over this short distance.

- The low transmission voltages and huge conductor cross-sectional areas are unusual for this kind of application and represent an excessive use of material.

This example illustrates that the application of the interconnector principle to end-user distribution under the assumption that waste-heat can be re-used and that hubs are available at both line ends leads to an inefficient layout. In further steps, these assumptions and the layout procedure could be revised for distribution applications.
C.2  Example 2: Dimensioning of an interconnector for regional energy distribution

This second example presents a system of three interconnectors and three hubs, where two hubs are load centres and one hub feeds energy into this system (and can therefore represent the interface to a higher network layer) as shown in figure C.2. The size of the loads and the distance between the hubs suggest that this application can represent a system which corresponds to a part of a current MV network.

As in the first example, the electrical and chemical loads were given whereas the thermal powers are an output of the layout process. The resulting interconnector layouts are shown in table C.2.

The application of the interconnector principle is favourable in this context because:

- The resulting voltage levels are in line with current practice, which indicates that the interconnector solution will lead to a layout which can be compared to current solutions.

- The overall transmission efficiencies (evaluated on the same basis as example 1) are all above 99%, a reasonable value in this context.

<table>
<thead>
<tr>
<th>Line</th>
<th>i</th>
<th>ii</th>
<th>iii</th>
</tr>
</thead>
<tbody>
<tr>
<td>( P_{cl AM max} )</td>
<td>74.8  kW</td>
<td>130  kW</td>
<td>205  kW</td>
</tr>
<tr>
<td>( P_{ch AM max} )</td>
<td>74.6  kW</td>
<td>152  kW</td>
<td>228  kW</td>
</tr>
<tr>
<td>( P_{V AM max} )</td>
<td>16.9  kW</td>
<td>17.4  kW</td>
<td>17.9  kW</td>
</tr>
<tr>
<td>( U_{in} )</td>
<td>143.6 V</td>
<td>242  V</td>
<td>372  V</td>
</tr>
<tr>
<td>( R_i )</td>
<td>2.84  mm</td>
<td>3.76  mm</td>
<td>4.44  mm</td>
</tr>
<tr>
<td>( A_{cTot} )</td>
<td>1300 mm²</td>
<td>1340 mm²</td>
<td>1370 mm²</td>
</tr>
<tr>
<td>( \eta_{Tot BAMax} )</td>
<td>86.5  %</td>
<td>92.5  %</td>
<td>95.0  %</td>
</tr>
</tbody>
</table>

Table C.1: Layout of the interconnectors for example 1.
Within the framework of this work and assuming a reasonable use of the thermal power, the size range of the interconnectors considered in this example is the most promising for further investigation.

C.3 Example 3: Dimensioning of an interconnector for bulk energy transmission

In this final example the application of the interconnector principle to bulk energy transmission is considered: a generator is connected to a load centre via a 300 km line as shown in figure C.3.

The interconnector layout has been performed in the same way as for the two preceding examples and its result is shown in table C.3. The high transmission voltage and the inner diameter exceeding 30 cm represent a challenge for the implementation of such interconnector links. The use of several parallel systems of the size range presented in example 2 may represent a solution to this issue.
### C.3. Example 3: Bulk Transmission

<table>
<thead>
<tr>
<th>Line</th>
<th>i</th>
<th>ii</th>
<th>iii</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_{el AMax}$</td>
<td>100 MW</td>
<td>30 MW</td>
<td>100 MW</td>
</tr>
<tr>
<td>$P_{ch AMax}$</td>
<td>139 MW</td>
<td>49.6 MW</td>
<td>74.4 MW</td>
</tr>
<tr>
<td>$P_{V AMax}$</td>
<td>1.69 MW</td>
<td>0.803 MW</td>
<td>1.45 MW</td>
</tr>
<tr>
<td>$U_{in}$</td>
<td>96.4 kV</td>
<td>36.5 kV</td>
<td>135 kV</td>
</tr>
<tr>
<td>$R_i$</td>
<td>12.6 cm</td>
<td>7.54 cm</td>
<td>10.2 cm</td>
</tr>
<tr>
<td>$A_{c Tot}$</td>
<td>2590 mm$^2$</td>
<td>2060 mm$^2$</td>
<td>1860 mm$^2$</td>
</tr>
<tr>
<td>$\eta_{Tot BAMax}$</td>
<td>99.1 %</td>
<td>98.7 %</td>
<td>99.0 %</td>
</tr>
</tbody>
</table>

Table C.2: Layout of the interconnectors for example 2.

![Interconnector Diagram](image)

Figure C.3: System considered in example 3.

<table>
<thead>
<tr>
<th>Line</th>
<th>i</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_{el AMax}$</td>
<td>750 MW</td>
</tr>
<tr>
<td>$P_{ch AMax}$</td>
<td>496 MW</td>
</tr>
<tr>
<td>$P_{V AMax}$</td>
<td>11.3 MW</td>
</tr>
<tr>
<td>$U_{in}$</td>
<td>1078 kV</td>
</tr>
<tr>
<td>$R_i$</td>
<td>33.2 cm</td>
</tr>
<tr>
<td>$A_{c Tot}$</td>
<td>1740 mm$^2$</td>
</tr>
<tr>
<td>$\eta_{Tot BAMax}$</td>
<td>98.9 %</td>
</tr>
</tbody>
</table>

Table C.3: Layout of the interconnectors for example 3.
Appendix D

Heat exchangers layout

Though it is not the goal of this work to perform an in-depth study of the heat exchanger layout, a simple approximation of the required exchanger volume is useful to assess the feasibility of waste heat recovery. This chapter illustrates how the standard method from \[30\] (VDI) has been adapted. Table \[D.1\] indicates the correspondence in the nomenclature, which depends on the selected waste heat recovery variant.

\(\delta T_K\) and \(\delta T_H\) can be regarded as design values indicating the

<table>
<thead>
<tr>
<th>VDI</th>
<th>Variant A</th>
<th>Variant B</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\vartheta_1)'</td>
<td>(T_2)</td>
<td>(T_{3B})</td>
</tr>
<tr>
<td>(\vartheta_1)''</td>
<td>(T_3)</td>
<td>(T_4)</td>
</tr>
<tr>
<td>(\vartheta_2)'</td>
<td>(T_K + \delta T_K)</td>
<td>(T_K + \delta T_K)</td>
</tr>
<tr>
<td>(\vartheta_2)''</td>
<td>(T_2 - \delta T_H)</td>
<td>(T_2 - \delta T_H)</td>
</tr>
<tr>
<td>(\dot{m}_1)</td>
<td>(\dot{m})</td>
<td>(\dot{m})</td>
</tr>
</tbody>
</table>

Table D.1: Variables used in the VDI heat exchanger layout guideline.
residual temperature difference between the cold respectively hot source and the chemical energy carrier at the outlet of a heat exchanger.

The VDI layout procedure is based on the dimensionless variables $\Theta, \Phi_1, \Phi_2, \Psi_1, \Psi_2$ and $\frac{\dot{W}_1}{\dot{W}_2}$. With two of these quantities known, the remaining four can be computed:

\[ \Phi_1 = \frac{\vartheta_1' - \vartheta_1''}{\vartheta_1' - \vartheta_2'} \]  
\[ \Phi_2 = \frac{\vartheta_2'' - \vartheta_2'}{\vartheta_1' - \vartheta_2'} \]  
\[ \Psi_1 = \vartheta_1'' \]  
\[ \Psi_2 = \vartheta_2'' \]

The mass flow on the secondary side can be computed from the energy balance:

\[ \dot{M}_2 = \frac{c_{p1}}{c_{p2}} \frac{\dot{M}_1}{\dot{M}_2} \frac{\vartheta_1' - \vartheta_1''}{\vartheta_2'' - \vartheta_2'} \]  
\[ \dot{M}_2 = \frac{c_{p1}}{c_{p2}} \frac{\dot{M}_1}{\dot{M}_2} \frac{\vartheta_1' - \vartheta_1''}{\vartheta_2'' - \vartheta_2'} \]  
\[ \dot{M}_2 = \frac{c_{p1}}{c_{p2}} \frac{\dot{M}_1}{\dot{M}_2} \frac{\vartheta_1' - \vartheta_1''}{\vartheta_2'' - \vartheta_2'} \]  
\[ \dot{M}_2 = \frac{c_{p1}}{c_{p2}} \frac{\dot{M}_1}{\dot{M}_2} \frac{\vartheta_1' - \vartheta_1''}{\vartheta_2'' - \vartheta_2'} \]  
\[ \dot{M}_2 = \frac{c_{p1}}{c_{p2}} \frac{\dot{M}_1}{\dot{M}_2} \frac{\vartheta_1' - \vartheta_1''}{\vartheta_2'' - \vartheta_2'} \]

The required heat exchanger surface is given by:

\[ k A_\parallel = \Psi_1 \dot{W}_1 \]  
\[ k A_\parallel = \Psi_1 \dot{W}_1 \]  
\[ k A_\parallel = \Psi_1 \dot{W}_1 \]  
\[ k A_\parallel = \Psi_1 \dot{W}_1 \]  
\[ k A_\parallel = \Psi_1 \dot{W}_1 \]  
\[ k A_\parallel = \Psi_1 \dot{W}_1 \]  
\[ k A_\parallel = \Psi_1 \dot{W}_1 \]  
\[ k A_\parallel = \Psi_1 \dot{W}_1 \]

where $k$ is of empirical nature. Table [D.2] contains values taken from [30], valid for the concentric arrangement shown in figure [D.1] ("field tube heat exchanger").
<table>
<thead>
<tr>
<th>Inner medium</th>
<th>outer medium</th>
<th>k</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gas (1 bar)</td>
<td>Gas (1 bar)</td>
<td>10...35</td>
</tr>
<tr>
<td>Gas (200 bar)</td>
<td>Gas (1 bar)</td>
<td>20...60</td>
</tr>
<tr>
<td>Gas (200 bar)</td>
<td>Gas (200 bar)</td>
<td>150...500</td>
</tr>
<tr>
<td>Gas (200 bar)</td>
<td>Liquid</td>
<td>200...600</td>
</tr>
<tr>
<td>Liquid</td>
<td>Gas Liquid</td>
<td>300...1400</td>
</tr>
</tbody>
</table>

Table D.2: Empirical values for $k$ (from [30])

<table>
<thead>
<tr>
<th>Medium</th>
<th>Typical flow velocity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liquid</td>
<td>0.5...2 [m/s]</td>
</tr>
<tr>
<td>Gas (low pressure)</td>
<td>10...25 [m/s]</td>
</tr>
<tr>
<td>Gas (100 bar)</td>
<td>8...15 [m/s]</td>
</tr>
</tbody>
</table>

Table D.3: Realistic values for flow velocities in a heat exchanger from [31].

In the case of a counterflow heat exchanger:

$$\Theta = \frac{\Phi_1 - \Phi_2}{\ln \left( \frac{1-\Phi_2}{1-\Phi_1} \right)} \quad (D.5)$$

and

$$\Psi_1 = \frac{\Phi_1}{\Theta} \quad (D.6)$$

From this, $A_\parallel$ can be derived.

The size of the heat exchanger will be approximated based on a given flow velocity (as a design parameter). Realistic values have been taken from [31] and are shown in table D.3.

Since the primary and secondary mass flows as well as the flow velocities are known, the radii $R_{TP}$ and $R_{TS}$ and finally the total volume of the exchanger can be calculated ($\epsilon_{FT}$ is a “fill factor” for
the exchanger):

\[ V_{\text{tot}} = \epsilon_{FT} \frac{A_\parallel}{2R_{TP}} (R_{TS} + w_{TS})^2 \]  \hspace{1cm} (D.7)


[10] The microgrids website. [http://microgrids.power.ece.ntua.gr](http://microgrids.power.ece.ntua.gr)


## List of symbols

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Unit</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_0$</td>
<td>m$^2$</td>
<td>Cross sectional area at the pump inlet of gas duct</td>
</tr>
<tr>
<td>$A_1$</td>
<td>m$^2$</td>
<td>Cross sectional area at the pump outlet of gas duct</td>
</tr>
<tr>
<td>$A_c$</td>
<td>m$^2$</td>
<td>Cross sectional area of the electrical conductor of the energy interconnector (per phase or pole)</td>
</tr>
<tr>
<td>$A_{cTot}$</td>
<td>m$^2$</td>
<td>Cross sectional area of the electrical conductor of the energy interconnector (all phases or poles)</td>
</tr>
<tr>
<td>$A_{geom}$</td>
<td>m$^2$</td>
<td>Geometrical cross sectional area of the individual electrical conductor (per phase)</td>
</tr>
<tr>
<td>$A_{geomTot}$</td>
<td>m$^2$</td>
<td>Total geometrical cross sectional area of the electrical conductor (all phases or poles)</td>
</tr>
<tr>
<td>$A_i$</td>
<td>m$^2$</td>
<td>Cross sectional area of the inner conduit of the energy interconnector</td>
</tr>
<tr>
<td>$c_1$</td>
<td>Pa$^2$/mK</td>
<td>Coefficient (1) for gas flow differential equation</td>
</tr>
<tr>
<td>$c_2$</td>
<td>W/K</td>
<td>Coefficient (2) for gas flow differential equation</td>
</tr>
<tr>
<td>$c_3$</td>
<td>Pa$^2$/K</td>
<td>Coefficient (3) for gas flow differential equation</td>
</tr>
<tr>
<td>$c_4$</td>
<td>W/m</td>
<td>Coefficient (4) for gas flow differential equation</td>
</tr>
<tr>
<td>$c_5$</td>
<td></td>
<td>Coefficient (5) for gas flow differential equation</td>
</tr>
<tr>
<td>$c_{mM}$</td>
<td>J/kgK</td>
<td>Specific heat of the chemical medium</td>
</tr>
<tr>
<td>$\epsilon$</td>
<td></td>
<td>Relative roughness of the pipe</td>
</tr>
<tr>
<td>$F$</td>
<td>N</td>
<td>Force</td>
</tr>
<tr>
<td>$f$</td>
<td></td>
<td>Friction factor</td>
</tr>
<tr>
<td>$f_e$</td>
<td>s$^{-1}$</td>
<td>Electrical frequency</td>
</tr>
<tr>
<td>$g$</td>
<td>m/s$^2$</td>
<td>Acceleration due to gravity</td>
</tr>
<tr>
<td>$h$</td>
<td>m</td>
<td>Laying depth</td>
</tr>
<tr>
<td>Symbol</td>
<td>Unit</td>
<td>Description</td>
</tr>
<tr>
<td>--------</td>
<td>-------------</td>
<td>-----------------------------------------------------------------------------</td>
</tr>
<tr>
<td>$I$</td>
<td>A</td>
<td>Electric current intensity (r.m.s.)</td>
</tr>
<tr>
<td>$I_{tot}$</td>
<td>A</td>
<td>Sum of the current intensities of all conductors forming the energy interconnector</td>
</tr>
<tr>
<td>$J$</td>
<td>A/m$^2$</td>
<td>Electric current density in the conductor (r.m.s.)</td>
</tr>
<tr>
<td>$J_{Max}$</td>
<td>A/m$^2$</td>
<td>Maximum admissible electric current density (r.m.s.)</td>
</tr>
<tr>
<td>$J_{Nom}$</td>
<td>A/m$^2$</td>
<td>Electric current density at the nominal point</td>
</tr>
<tr>
<td>$k_f$</td>
<td></td>
<td>Filling factor of the electrical conductor</td>
</tr>
<tr>
<td>$k_s$</td>
<td></td>
<td>Factor for the determination of skin effect losses</td>
</tr>
<tr>
<td>$L_{tot}$</td>
<td>m</td>
<td>Total length of the energy interconnector</td>
</tr>
<tr>
<td>$M_1$, $M_2$</td>
<td>kg/s</td>
<td>Primary (1) and secondary (2) mass flow rate in a heat exchanger</td>
</tr>
<tr>
<td>$M_m$</td>
<td>kg/mol</td>
<td>Molar mass of the chemical medium</td>
</tr>
<tr>
<td>$\dot{m}$</td>
<td>kg/s</td>
<td>Mass flow rate</td>
</tr>
<tr>
<td>$\dot{m}_1$</td>
<td>kg/s</td>
<td>Coolant mass flow rate at the inlet of the energy interconnector</td>
</tr>
<tr>
<td>$\dot{m}_2$</td>
<td>kg/s</td>
<td>Coolant mass flow rate at the end of the energy interconnector</td>
</tr>
<tr>
<td>$m_s$</td>
<td>kg</td>
<td>Coolant mass stored in the energy interconnector</td>
</tr>
<tr>
<td>$n_c$</td>
<td></td>
<td>Number of connections to the main grid of a consumer or area</td>
</tr>
<tr>
<td>$n_F$</td>
<td></td>
<td>Number of degrees of freedom for ideal gases</td>
</tr>
<tr>
<td>$n_{ph}$</td>
<td></td>
<td>Number of phases of the interconnector</td>
</tr>
<tr>
<td>$P_{ch}$</td>
<td>W</td>
<td>Chemical power throughput of the energy interconnector</td>
</tr>
<tr>
<td>$P_{ch,AMax}$</td>
<td>W</td>
<td>Maximum transmissible chemical power (for gaseous carriers)</td>
</tr>
<tr>
<td>$P_{ch,APMax}$</td>
<td>W</td>
<td>Chemical power corresponding to the maximum electric power (for gaseous carriers)</td>
</tr>
<tr>
<td>$P_{ch,Min}$</td>
<td>W</td>
<td>Minimum transmissible chemical power (for gaseous carriers)</td>
</tr>
<tr>
<td>$P_{ch,LMax}$</td>
<td>W</td>
<td>Maximum chemical power of an interconnector with a liquid energy carrier</td>
</tr>
<tr>
<td>$P_{ch,Max}$</td>
<td>W</td>
<td>Maximum chemical power in the context of both liquid and gaseous carriers</td>
</tr>
<tr>
<td>$P_{CM}$</td>
<td>W</td>
<td>Thermal power flow from the electrical conductor to the chemical medium</td>
</tr>
<tr>
<td>$P_{el}$</td>
<td>W</td>
<td>Electric power</td>
</tr>
<tr>
<td>$P_{el1}$</td>
<td>W</td>
<td>Electric input power to the energy interconnector</td>
</tr>
<tr>
<td>$P_{el,AMax}$</td>
<td>W</td>
<td>Maximum transmissible electric power (with gaseous carriers)</td>
</tr>
<tr>
<td>Symbol</td>
<td>Unit</td>
<td>Description</td>
</tr>
<tr>
<td>-----------------</td>
<td>------</td>
<td>-----------------------------------------------------------------------------</td>
</tr>
<tr>
<td>$P_{elchAMax}$</td>
<td>W</td>
<td>Electric power corresponding to the maximum chemical power (for gaseous carriers)</td>
</tr>
<tr>
<td>$P_{elchAMin}$</td>
<td>W</td>
<td>Electric power corresponding to the minimum chemical power (for gaseous carriers)</td>
</tr>
<tr>
<td>$P_{elLMax1}$</td>
<td>W</td>
<td>Maximum electric power of an interconnector with a liquid energy carrier (corresponding to the minimum chemical power)</td>
</tr>
<tr>
<td>$P_{elLMax2}$</td>
<td>W</td>
<td>Maximum electric power of an interconnector with a liquid energy carrier (corresponding to the maximum chemical power)</td>
</tr>
<tr>
<td>$P_{elMax}$</td>
<td>W</td>
<td>Maximum electric power in the context of both liquid and gaseous carriers</td>
</tr>
<tr>
<td>$P_{FTot}$</td>
<td>W</td>
<td>Overall net power needed to transport the chemical medium across the energy interconnector</td>
</tr>
<tr>
<td>$P_{F1A,}$</td>
<td>W</td>
<td>Pump/compressor power at the inlet to transport the chemical medium across the energy interconnector (for recovery variant A, C)</td>
</tr>
<tr>
<td>$P_{F1C}$</td>
<td>W</td>
<td>Pump/compressor power at the inlet to transport the chemical medium across the energy interconnector (for recovery variant A, C)</td>
</tr>
<tr>
<td>$P_{F2}$</td>
<td>W</td>
<td>Pump/compressor power at the outlet to transport the chemical medium across the energy interconnector</td>
</tr>
<tr>
<td>$P_{F2A,}$</td>
<td>W</td>
<td>Pump/compressor power at the outlet to transport the chemical medium across the energy interconnector (for recovery variant A, B, C)</td>
</tr>
<tr>
<td>$P_{F2B,}$</td>
<td>W</td>
<td>Pump/compressor power at the outlet to transport the chemical medium across the energy interconnector (for recovery variant A, B, C)</td>
</tr>
<tr>
<td>$P_{F2C}$</td>
<td>W</td>
<td>Pump/compressor power at the outlet to transport the chemical medium across the energy interconnector (for recovery variant A, B, C)</td>
</tr>
<tr>
<td>$P_{F1Tot}$</td>
<td>W</td>
<td>Power needed at the inlet to transport the chemical medium across the energy interconnector</td>
</tr>
<tr>
<td>$P_{F1ATot}$</td>
<td>W</td>
<td>Power needed at the inlet to transport the chemical medium across the energy interconnector (for recovery variant A)</td>
</tr>
<tr>
<td>$P_{F2Tot}$</td>
<td>W</td>
<td>Power needed at the outlet to transport the chemical medium across the energy interconnector</td>
</tr>
<tr>
<td>$P_{F2ATot}$</td>
<td>W</td>
<td>Power needed at the outlet to transport the chemical medium across the energy interconnector (for recovery variant A, B)</td>
</tr>
<tr>
<td>$P_{F2Btot}$</td>
<td>W</td>
<td>Power needed at the outlet to transport the chemical medium across the energy interconnector (for recovery variant A, B)</td>
</tr>
<tr>
<td>$P_{Pump1}$</td>
<td>W</td>
<td>Inlet pump/compressor mechanical power (for recovery variants A and B)</td>
</tr>
<tr>
<td>$P_{Pump1C}$</td>
<td>W</td>
<td>Inlet pump/compressor mechanical power (for recovery variant C)</td>
</tr>
<tr>
<td>$P_{Pump2A}$</td>
<td>W</td>
<td>Outlet pump/compressor mechanical power (for recovery variant A, B, C)</td>
</tr>
<tr>
<td>$P_{Pump2B}$</td>
<td>W</td>
<td>Outlet pump/compressor mechanical power (for recovery variant A, B, C)</td>
</tr>
<tr>
<td>$P_{Pump2C}$</td>
<td>W</td>
<td>Outlet pump/compressor mechanical power (for recovery variant A, B, C)</td>
</tr>
<tr>
<td>$P_Q$</td>
<td>W</td>
<td>Heat absorption rate by the chemical medium</td>
</tr>
<tr>
<td>$P_R$</td>
<td>W</td>
<td>Heat induced by friction in the chemical medium</td>
</tr>
<tr>
<td>Symbol</td>
<td>Unit</td>
<td>Description</td>
</tr>
<tr>
<td>---------------</td>
<td>---------</td>
<td>------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>$P_{th}$</td>
<td>W</td>
<td>Thermal transmitted power</td>
</tr>
<tr>
<td>$P_U$</td>
<td>W</td>
<td>Thermal power flow from the interconnector to the surrounding soil</td>
</tr>
<tr>
<td>$P_V$</td>
<td>W</td>
<td>Electrical loss power in the interconnector</td>
</tr>
<tr>
<td>$P_{VAMax}$</td>
<td>W</td>
<td>Losses corresponding to the maximum transmissible electric power (for gaseous carriers)</td>
</tr>
<tr>
<td>$P_{VchAMax}$</td>
<td>W</td>
<td>Electrical losses corresponding to the maximum chemical power (for gaseous carriers)</td>
</tr>
<tr>
<td>$P_{VchAMin}$</td>
<td>W</td>
<td>Electrical losses corresponding to the minimum chemical power (for gaseous carriers)</td>
</tr>
<tr>
<td>$P_{w1}$</td>
<td>W</td>
<td>Recovered electric power at the inlet</td>
</tr>
<tr>
<td>$P_{w1A}$, $P_{w1C}$</td>
<td>W</td>
<td>Recovered electric power at the inlet (for recovery variant A, C)</td>
</tr>
<tr>
<td>$P_{w2}$</td>
<td>W</td>
<td>Recovered electric power at the outlet</td>
</tr>
<tr>
<td>$P_{w2A}$, $P_{w2B}$, $P_{w2C}$</td>
<td>W</td>
<td>Recovered electric power at the outlet (for recovery variant A, B, C)</td>
</tr>
<tr>
<td>$P'$</td>
<td>W/m</td>
<td>Specific power</td>
</tr>
<tr>
<td>$p$</td>
<td>Pa</td>
<td>Pressure</td>
</tr>
<tr>
<td>$p_0$</td>
<td>Pa</td>
<td>Pressure of the chemical medium at the inlet of the pump</td>
</tr>
<tr>
<td>$p_1$</td>
<td>Pa</td>
<td>Pressure of the chemical medium at the inlet of the energy interconnector</td>
</tr>
<tr>
<td>$p_{1C}$</td>
<td>Pa</td>
<td>Pressure of the chemical medium at the inlet of the energy interconnector (for variant C)</td>
</tr>
<tr>
<td>$p_{1kC}$</td>
<td>Pa</td>
<td>Pressure of the chemical medium in the inlet waste heat recovery system (for variant C)</td>
</tr>
<tr>
<td>$p_2$</td>
<td>Pa</td>
<td>Pressure of the chemical medium at the outlet of the energy interconnector</td>
</tr>
<tr>
<td>$p_{2C}$</td>
<td>Pa</td>
<td>Pressure of the chemical medium at the outlet of the energy interconnector (for variant C)</td>
</tr>
<tr>
<td>$p_{2Min}$</td>
<td>Pa</td>
<td>Minimum outlet pressure required for the interconnector operation</td>
</tr>
<tr>
<td>$p_3$</td>
<td>Pa</td>
<td>Pressure of the chemical medium in the outlet waste heat recovery system</td>
</tr>
<tr>
<td>$p_4$</td>
<td>Pa</td>
<td>Pressure of the chemical medium after the outlet waste heat recovery system</td>
</tr>
<tr>
<td>$p_i$</td>
<td>Pa</td>
<td>Pressure at the entry of a small mass element</td>
</tr>
<tr>
<td>$p_{Max}$</td>
<td>Pa</td>
<td>Maximum admissible pressure in the interconnector</td>
</tr>
<tr>
<td>$p_{KIN}$</td>
<td>kg/m$^s$</td>
<td>Kinetic momentum</td>
</tr>
<tr>
<td>Symbol</td>
<td>Unit</td>
<td>Description</td>
</tr>
<tr>
<td>------------</td>
<td>---------------</td>
<td>-----------------------------------------------------------------------------</td>
</tr>
<tr>
<td>$p_0$</td>
<td>Pa</td>
<td>Pressure at the end of a small mass element</td>
</tr>
<tr>
<td>$Q$</td>
<td>J</td>
<td>Heat</td>
</tr>
<tr>
<td>$\dot{Q}$</td>
<td>W</td>
<td>Heat flow (thermal power)</td>
</tr>
<tr>
<td>$Q_{w1}$</td>
<td>W</td>
<td>Thermal power extracted from the medium at the inlet</td>
</tr>
<tr>
<td>$\dot{Q}_{w1A}$</td>
<td>W</td>
<td>Thermal power extracted from the medium at the inlet (for variant A, C)</td>
</tr>
<tr>
<td>$\dot{Q}_{w1C}$</td>
<td>W</td>
<td>Thermal power extracted from the medium at the outlet</td>
</tr>
<tr>
<td>$Q_{w2}$</td>
<td>W</td>
<td>Thermal power extracted from the medium at the outlet (for variant A, B, C)</td>
</tr>
<tr>
<td>$R$</td>
<td>Ω</td>
<td>Electrical resistance</td>
</tr>
<tr>
<td>$R'$</td>
<td>$\Omega/m$</td>
<td>Specific electrical resistance</td>
</tr>
<tr>
<td>$Re$</td>
<td>m</td>
<td>Reynolds constant</td>
</tr>
<tr>
<td>$R_a$</td>
<td>m</td>
<td>Outer radius of the electrical conductor of the energy interconnector</td>
</tr>
<tr>
<td>$R_{ac}'$</td>
<td>$\Omega/m$</td>
<td>Alternating current specific electrical resistance per unit length</td>
</tr>
<tr>
<td>$R_{dc}'$</td>
<td>$\Omega/m$</td>
<td>Direct current specific electrical resistance per unit length</td>
</tr>
<tr>
<td>$R_g$</td>
<td>J/mol*K</td>
<td>Gas constant of the chemical medium</td>
</tr>
<tr>
<td>$R_I'$</td>
<td>$\Omega/m$</td>
<td>Alternating current specific electrical resistance per unit length, including proximity effect and shield losses</td>
</tr>
<tr>
<td>$R_i$</td>
<td>m</td>
<td>Inner radius of the electrical conductor of the energy interconnector</td>
</tr>
<tr>
<td>$R_{thE}$</td>
<td>K/W</td>
<td>Thermal resistance of the soil</td>
</tr>
<tr>
<td>$R_{thI}$</td>
<td>K/W</td>
<td>Thermal resistance of the insulator</td>
</tr>
<tr>
<td>$R_{thM}$</td>
<td>K/W</td>
<td>Thermal contact resistance between conductor and chemical medium</td>
</tr>
<tr>
<td>$R_{thE}'$</td>
<td>Km/W</td>
<td>Specific thermal resistivity of the soil</td>
</tr>
<tr>
<td>$R_{thI}'$</td>
<td>Km/W</td>
<td>Specific thermal resistivity of the insulator</td>
</tr>
<tr>
<td>$R_{thM}'$</td>
<td>Km/W</td>
<td>Specific thermal resistivity between conductor and chemical medium</td>
</tr>
<tr>
<td>$r_1$</td>
<td></td>
<td>Ratio of the maximum transmissible electric power $P_{elAMax}$ to the minimum transmissible electric power $P_{elchAMin}$</td>
</tr>
<tr>
<td>Symbol</td>
<td>Unit</td>
<td>Description</td>
</tr>
<tr>
<td>--------</td>
<td>------</td>
<td>-------------</td>
</tr>
<tr>
<td>$r_2$</td>
<td></td>
<td>Ratio of the maximum transmissible chemical power $P_{chAMax}$ to the maximum transmissible electric power $P_{elAMax}$</td>
</tr>
<tr>
<td>$s$</td>
<td></td>
<td>Degree of self-sufficiency of a consumer or an area</td>
</tr>
<tr>
<td>$T(x)$</td>
<td>K</td>
<td>Temperature of the chemical medium along the energy interconnector</td>
</tr>
<tr>
<td>$T_0$</td>
<td>K</td>
<td>Temperature of the chemical medium at the inlet of the chemical medium pump</td>
</tr>
<tr>
<td>$T_1$</td>
<td>K</td>
<td>Temperature of the chemical medium at the inlet of the energy interconnector</td>
</tr>
<tr>
<td>$T_{1c}$</td>
<td>K</td>
<td>Temperature of the chemical medium at the inlet of the energy interconnector (for recovery variant C)</td>
</tr>
<tr>
<td>$T_{1h}$</td>
<td>K</td>
<td>Temperature of the chemical medium in the inlet waste heat recovery system</td>
</tr>
<tr>
<td>$T_{1hC}$</td>
<td>K</td>
<td>Temperature of the chemical medium in the inlet waste heat recovery system (for recovery variant C)</td>
</tr>
<tr>
<td>$T_{1kC}$</td>
<td>K</td>
<td>Temperature of the chemical medium in the outlet waste heat recovery system (for recovery variant C)</td>
</tr>
<tr>
<td>$T_2$</td>
<td>K</td>
<td>Temperature of the chemical medium at the outlet of the energy interconnector</td>
</tr>
<tr>
<td>$T_{2c}$</td>
<td>K</td>
<td>Temperature of the chemical medium at the end of the energy interconnector (for recovery variant C)</td>
</tr>
<tr>
<td>$T_3$</td>
<td>K</td>
<td>Temperature of the chemical medium in the outlet waste heat recovery system</td>
</tr>
<tr>
<td>$T_{3A}$, $T_{3B}$, $T_{3C}$</td>
<td>K</td>
<td>Temperature of the chemical medium in the outlet waste heat recovery system (for recovery variant A, B, C)</td>
</tr>
<tr>
<td>$T_4$</td>
<td>K</td>
<td>Temperature of the chemical medium after the outlet waste heat recovery system</td>
</tr>
<tr>
<td>$T_c$</td>
<td>K</td>
<td>Temperature of the electrical conductor</td>
</tr>
<tr>
<td>$T_{cAve}$</td>
<td>K</td>
<td>Average temperature of the electrical conductor</td>
</tr>
<tr>
<td>$T_K$</td>
<td>K</td>
<td>Cold source temperature</td>
</tr>
<tr>
<td>$T_{K1}$</td>
<td>K</td>
<td>Cold source temperature at the interconnector inlet</td>
</tr>
<tr>
<td>$T_{K2}$</td>
<td>K</td>
<td>Cold source temperature at the interconnector outlet</td>
</tr>
<tr>
<td>$T_U$</td>
<td>K</td>
<td>Temperature of the soil</td>
</tr>
<tr>
<td>$T_i$</td>
<td>K</td>
<td>Temperature at the entry of a small mass element</td>
</tr>
<tr>
<td>Symbol</td>
<td>Unit</td>
<td>Description</td>
</tr>
<tr>
<td>--------</td>
<td>------</td>
<td>-------------</td>
</tr>
<tr>
<td>$T_o$</td>
<td>K</td>
<td>Temperature at the end of a small mass element</td>
</tr>
<tr>
<td>$t$</td>
<td>s</td>
<td>Time</td>
</tr>
<tr>
<td>$\Delta U$</td>
<td>J</td>
<td>Internal energy difference</td>
</tr>
<tr>
<td>$U_{in}$</td>
<td>V</td>
<td>d.c. input voltage of the energy interconnector</td>
</tr>
<tr>
<td>$U_{in,Max}$</td>
<td>V</td>
<td>Maximum d.c. input voltage of the energy interconnector</td>
</tr>
<tr>
<td>$V$</td>
<td>m$^3$</td>
<td>Volume</td>
</tr>
<tr>
<td>$v$</td>
<td>m/s</td>
<td>Flow velocity of the chemical medium</td>
</tr>
<tr>
<td>$v_0$</td>
<td>m/s</td>
<td>Flow velocity of the chemical medium before the pump (at the interconnector entry)</td>
</tr>
<tr>
<td>$v_1$</td>
<td>m/s</td>
<td>Flow velocity of the chemical medium at the inlet of the energy interconnector</td>
</tr>
<tr>
<td>$v_{1h}$</td>
<td>m/s</td>
<td>Flow velocity of the chemical medium in the inlet waste heat recovery system</td>
</tr>
<tr>
<td>$v_2$</td>
<td>m/s</td>
<td>Flow velocity of the chemical medium at the outlet of the energy interconnector</td>
</tr>
<tr>
<td>$v_3$</td>
<td>m/s</td>
<td>Flow velocity of the chemical medium in the outlet waste heat recovery system</td>
</tr>
<tr>
<td>$v_i$</td>
<td>m/s</td>
<td>Flow velocity at the entry of a small mass element</td>
</tr>
<tr>
<td>$v_o$</td>
<td>m/s</td>
<td>Flow velocity at the end of a small mass element</td>
</tr>
<tr>
<td>$W$</td>
<td>J</td>
<td>Work</td>
</tr>
<tr>
<td>$\dot{W}_1, \dot{W}_2$</td>
<td>W/K</td>
<td>Primary and secondary specific heat capacity flow</td>
</tr>
<tr>
<td>$W_R$</td>
<td>J</td>
<td>Work of the friction force in the medium</td>
</tr>
<tr>
<td>$w_i$</td>
<td>m</td>
<td>Thickness of electrical insulation layer</td>
</tr>
<tr>
<td>$w_m$</td>
<td>J/kg</td>
<td>Specific energy of the chemical medium</td>
</tr>
<tr>
<td>$w_T$</td>
<td>m</td>
<td>Thickness of thermal insulation layer</td>
</tr>
<tr>
<td>$x$</td>
<td>m</td>
<td>Position on the energy interconnector</td>
</tr>
<tr>
<td>$x_s$</td>
<td>m</td>
<td>Constant for the determination of the skin effect losses</td>
</tr>
<tr>
<td>$X$</td>
<td></td>
<td>Normalised position on the energy interconnector</td>
</tr>
<tr>
<td>$y_p$</td>
<td></td>
<td>Loss factor for skin effect losses</td>
</tr>
<tr>
<td>$y_s$</td>
<td></td>
<td>Loss factor for proximity effect losses</td>
</tr>
<tr>
<td>$\alpha_1$</td>
<td></td>
<td>Coefficient for the determination of $\alpha_{LK}$</td>
</tr>
<tr>
<td>$\alpha_2$</td>
<td></td>
<td>Coefficient for the determination of $\alpha_{LK}$</td>
</tr>
<tr>
<td>$\alpha_c$</td>
<td>K$^{-1}$</td>
<td>Temperature coefficient of the electrical conductor</td>
</tr>
<tr>
<td>$\alpha_{LK}$</td>
<td>$\frac{W}{m^2 K}$</td>
<td>Heat transfer coefficient between conductor and chemical medium</td>
</tr>
<tr>
<td>$\beta$</td>
<td></td>
<td>Intermediary result ($\beta := \frac{\kappa}{\kappa-1}$)</td>
</tr>
<tr>
<td>$\Delta p$</td>
<td>Pa</td>
<td>Pressure difference</td>
</tr>
<tr>
<td>$\Delta p_M$</td>
<td>Pa</td>
<td>Intermediary result</td>
</tr>
<tr>
<td>Symbol</td>
<td>Unit</td>
<td>Description</td>
</tr>
<tr>
<td>--------</td>
<td>-------</td>
<td>------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>$\Delta p_R$</td>
<td>Pa</td>
<td>Pressure drop due to friction</td>
</tr>
<tr>
<td>$\Delta Q$</td>
<td>J</td>
<td>Heat difference</td>
</tr>
<tr>
<td>$\Delta Q_R$</td>
<td>J</td>
<td>Heat produced by friction in the medium</td>
</tr>
<tr>
<td>$\Delta t$</td>
<td>s</td>
<td>Time interval</td>
</tr>
<tr>
<td>$\Delta T_{LK}$</td>
<td>K</td>
<td>Temperature difference between the conductor and the chemical medium in the energy interconector</td>
</tr>
<tr>
<td>$\Delta W_R$</td>
<td>J</td>
<td>Work by the medium due to the friction pressure drop</td>
</tr>
<tr>
<td>$\delta T_H$</td>
<td>K</td>
<td>Temperature difference between the hot source and the working fluid temperature at the outlet of the heat exchanger.</td>
</tr>
<tr>
<td>$\delta T_K$</td>
<td>K</td>
<td>Temperature difference between the cold source and the medium temperature at the outlet of the heat exchanger.</td>
</tr>
<tr>
<td>$\eta_1$</td>
<td></td>
<td>Efficiency of the inlet pump/compressor</td>
</tr>
<tr>
<td>$\eta_{1\text{Neg}}$</td>
<td></td>
<td>Efficiency of the inlet pump/compressor for negative $P_{Pump1}$</td>
</tr>
<tr>
<td>$\eta_{1\text{ANeg}}$, $\eta_{1\text{CNeg}}$</td>
<td></td>
<td>Efficiency of the inlet pump/compressor for negative $P_{Pump1{A,C}}$ (for recovery variant A, C)</td>
</tr>
<tr>
<td>$\eta_{1\text{Pos}}$</td>
<td></td>
<td>Efficiency of the inlet pump/compressor for positive $P_{Pump1}$</td>
</tr>
<tr>
<td>$\eta_{1\text{APos}}$, $\eta_{1\text{CPos}}$</td>
<td></td>
<td>Efficiency of the inlet pump/compressor for positive $P_{Pump1{A,C}}$ (for recovery variant A, C)</td>
</tr>
<tr>
<td>$\eta_{2\text{Neg}}$</td>
<td></td>
<td>Efficiency of the outlet pump/compressor for negative $P_{Pump2}$</td>
</tr>
<tr>
<td>$\eta_{2\text{ANeg}}$, $\eta_{2\text{BNeg}}$, $\eta_{2\text{CNeg}}$</td>
<td></td>
<td>Efficiency of the outlet pump/compressor for negative $P_{Pump2{A,B,C}}$ (for recovery variant A, B, C)</td>
</tr>
<tr>
<td>$\eta_{2\text{Pos}}$</td>
<td></td>
<td>Efficiency of the outlet pump/compressor for positive $P_{Pump2}$</td>
</tr>
<tr>
<td>$\eta_{2\text{APos}}$, $\eta_{2\text{BPos}}$, $\eta_{2\text{CPos}}$</td>
<td></td>
<td>Efficiency of the outlet pump/compressor for positive $P_{Pump2{A,B,C}}$ (for recovery variant A, B, C)</td>
</tr>
<tr>
<td>$\eta_c$</td>
<td></td>
<td>Carnot efficiency</td>
</tr>
<tr>
<td>$\eta_{c1\text{Neg}}$</td>
<td></td>
<td>Carnot efficiency of inlet waste heat recovery system for negative $Q_{w1}$</td>
</tr>
<tr>
<td>$\eta_{c1\text{ANeg}}$, $\eta_{c1\text{CNeg}}$</td>
<td></td>
<td>Carnot efficiency of inlet waste heat recovery system for negative $Q_{w1{A,C}}$ (for recovery variant A, C)</td>
</tr>
<tr>
<td>$\eta_{c1\text{Pos}}$</td>
<td></td>
<td>Carnot efficiency of inlet waste heat recovery system for positive $Q_{w1}$</td>
</tr>
</tbody>
</table>
Symbol | Unit | Description
--- | --- | ---
η<sub>c1APos</sub>, η<sub>c1CPos</sub> |  | Carnot efficiency of inlet waste heat recovery system for positive $Q_{w1\{A,C\}}$ (for recovery variant A, C)
η<sub>c2Neg</sub> |  | Carnot efficiency of outlet waste heat recovery system for negative $Q_{w2}$
η<sub>c2ANeg</sub>, η<sub>c2BNeg</sub>, η<sub>c2CNeg</sub>, η<sub>c2Pos</sub> |  | Carnot efficiency of outlet waste heat recovery system for negative $Q_{w2\{A,B,C\}}$ (for recovery variant A, B, C)
η<sub>c2APos</sub>, η<sub>c2BPos</sub>, η<sub>c2CPos</sub> |  | Carnot efficiency of outlet waste heat recovery system for positive $Q_{w2\{A,B,C\}}$ (for recovery variant A, B, C)
η<sub>el</sub> |  | Electrical efficiency
η<sub>pump</sub> |  | Pump efficiency
η<sub>Rec1Neg</sub> |  | Efficiency of inlet waste heat recovery system for negative $Q_{w1}$
η<sub>Rec1ANeg</sub>, η<sub>Rec1BNeg</sub>, η<sub>Rec1CNeg</sub>, η<sub>Rec1Pos</sub> |  | Efficiency of inlet waste heat recovery system for positive $Q_{w1}$
η<sub>Rec2Neg</sub> |  | Efficiency of outlet waste heat recovery system for negative $Q_{w2}$
η<sub>Rec2ANeg</sub>, η<sub>Rec2BNeg</sub>, η<sub>Rec2CNeg</sub>, η<sub>Rec2Pos</sub> |  | Efficiency of outlet waste heat recovery system for positive $Q_{w2\{A,B,C\}}$ (for recovery variant A, C)
η<sub>Rec2APos</sub>, η<sub>Rec2CPos</sub> |  | Efficiency of outlet waste heat recovery system for positive $Q_{w2A}$ (for recovery variant A, C)
$\vartheta_1'$, $\vartheta_1''$, $\vartheta_2'$, $\vartheta_2''$ | K | Primary (1) and secondary (2) inlet ($'$) and outlet ($''$) temperatures used in the heat exchanger layout
$\kappa$ |  | Isentropic heat exponent (ratio of specific heats)
$\lambda$ | W m K<sup>-1</sup> | Heat conductivity
$\lambda_1$ |  | Factor for armour losses
$\lambda_2$ |  | Factor for shield losses
$\lambda_c$ | W m K<sup>-1</sup> | Thermal conductivity of the electrical conductor
### LIST OF SYMBOLS

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Unit</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\lambda_E$</td>
<td>$\frac{W}{mK}$</td>
<td>Thermal conductivity of the soil</td>
</tr>
<tr>
<td>$\lambda_I$</td>
<td>$\frac{W}{mK}$</td>
<td>Thermal conductivity of the insulator material</td>
</tr>
<tr>
<td>$\mu_0$</td>
<td>$\frac{Vs}{Am}$</td>
<td>Permeability of vacuum</td>
</tr>
<tr>
<td>$\mu_M$</td>
<td>Ns/m$^2$</td>
<td>Viscosity of the chemical medium</td>
</tr>
<tr>
<td>$\mu_{rc}$</td>
<td>$\frac{Ns}{m^2}$</td>
<td>Relative permeability of the electrical conductor</td>
</tr>
<tr>
<td>$\rho$</td>
<td>$\Omega m$</td>
<td>Electrical resistivity of the electrical conductor</td>
</tr>
<tr>
<td>$\rho_{e20}$</td>
<td>$\Omega m$</td>
<td>Electrical resistivity of the electrical conductor at 20 degrees Celsius</td>
</tr>
<tr>
<td>$\rho_{mm}$</td>
<td>kg/m$^3$</td>
<td>Mass density of the chemical medium</td>
</tr>
<tr>
<td>$\Gamma, \Gamma_1, \Gamma_2$</td>
<td></td>
<td>Intermediate result</td>
</tr>
<tr>
<td>$\Theta$</td>
<td></td>
<td>Intermediate result</td>
</tr>
<tr>
<td>$\Upsilon$</td>
<td></td>
<td>Intermediate result</td>
</tr>
<tr>
<td>$\Xi$</td>
<td></td>
<td>Intermediate result</td>
</tr>
<tr>
<td>$\Phi_1, \Phi_2$</td>
<td></td>
<td>Intermediate results used in the heat exchanger dimensioning</td>
</tr>
<tr>
<td>$\Psi_1, \Psi_2$</td>
<td></td>
<td>Intermediate results used in the heat exchanger dimensioning</td>
</tr>
</tbody>
</table>

### Abbreviations

- **a.c.** Alternating current
- **CHP** Combined heat and power
- **ch** Chemical
- **d.c.** Direct current
- **el** Electric
- **HVAC** High voltage a.c.
- **HVDC** High voltage d.c.
- **max** Maximal
- **min** Minimal
- **MV** Medium voltage
- **PDE** Partial differential equation
- **r.m.s.** Root mean square
- **sim.** Result of a numerical simulation
- **th** Thermal
- **T&D** Transmission and distribution
# List of Figures

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.1</td>
<td>Illustration of the “Vision of Future Energy Networks” multi-energy network framework.</td>
<td>15</td>
</tr>
<tr>
<td>4.2</td>
<td>Illustration of the Energy Hub concept.</td>
<td>17</td>
</tr>
<tr>
<td>5.1</td>
<td>Illustration of the Energy Interconnector with electric and chemical power transmission as well as waste heat reuse.</td>
<td>24</td>
</tr>
<tr>
<td>5.2</td>
<td>Transmittable chemical vs. electric power for an interconnector with a liquid chemical energy carrier for different outlet temperatures $T_2$ (example, $U_{in}$ is kept constant).</td>
<td>26</td>
</tr>
<tr>
<td>5.3</td>
<td>Cross-section and longitudinal view of the basic interconnector model.</td>
<td>28</td>
</tr>
<tr>
<td>5.4</td>
<td>Thermal model for the energy interconnector.</td>
<td>33</td>
</tr>
<tr>
<td>5.5</td>
<td>Example for a temperature $T(x)$ and pressure $p(x)$ profile of a gaseous medium along the interconnector.</td>
<td>37</td>
</tr>
<tr>
<td>5.6</td>
<td>Profiles of the electrical losses in the conductor $P_V'$ and the heat flows at the interface with the soil $P_U'$ and the medium $P_{CM}'$ (example).</td>
<td>39</td>
</tr>
<tr>
<td>5.7</td>
<td>Profiles of the friction losses $P_R'$, heat transfer from the electrical conductor $P_{CM}'$ and heat absorbed by a gaseous medium (example).</td>
<td>40</td>
</tr>
<tr>
<td>Figure</td>
<td>Description</td>
<td></td>
</tr>
<tr>
<td>--------</td>
<td>-------------</td>
<td></td>
</tr>
<tr>
<td>5.8</td>
<td>Contour of the electric current density $J$ in function of the mass flow rate $\dot{m}$ and the inlet pressure $p_1$ (example).</td>
<td></td>
</tr>
<tr>
<td>5.9</td>
<td>Interconnector system layout and power flow for waste heat recovery variant B. The figure also illustrates the naming convention used for temperatures and pressures at the inlet and outlet of the interconnector.</td>
<td></td>
</tr>
<tr>
<td>5.10</td>
<td>Auxiliary power requirements and possible waste heat recovery at the inlet and outlet of an interconnector in dependence upon gas mass flow (example).</td>
<td></td>
</tr>
<tr>
<td>5.11</td>
<td>Power flows for the overall interconnector system including auxiliary power.</td>
<td></td>
</tr>
<tr>
<td>5.12</td>
<td>Contour lines of the electrical, chemical and total transmission efficiency (example).</td>
<td></td>
</tr>
<tr>
<td>5.13</td>
<td>Mass element in the pipe.</td>
<td></td>
</tr>
<tr>
<td>5.14</td>
<td>Comparison between simulated (numerical) and calculated (analytical) temperature and pressure profiles in dependance upon normalised current density (example).</td>
<td></td>
</tr>
<tr>
<td>5.15</td>
<td>Comparison between simulated (numerical) and calculated (analytical) specific power profiles in dependance upon normalised current density (example).</td>
<td></td>
</tr>
<tr>
<td>5.16</td>
<td>Permissible current density vs. mass flow rate for an interconnector with low temperature energy transmission (example with $T_1 = 253$ K and $T_2 = 293$ K).</td>
<td></td>
</tr>
<tr>
<td>6.1</td>
<td>Nomenclature for the maximum and minimum electric and chemical powers.</td>
<td></td>
</tr>
<tr>
<td>6.2</td>
<td>Operational area for an interconnector with a gaseous chemical medium for different outlet temperatures $T_2$ (example). Parameter is the outlet temperature $T_2$ [K].</td>
<td></td>
</tr>
<tr>
<td>6.3</td>
<td>Maximum and minimum permissible outlet temperature in function of the operating point (example).</td>
<td></td>
</tr>
<tr>
<td>6.4</td>
<td>Operational area for an interconnector with a gaseous chemical medium for different inlet temperatures $T_1$ (example).</td>
<td></td>
</tr>
<tr>
<td>6.5</td>
<td>Operational area at different input voltages (example).</td>
<td></td>
</tr>
<tr>
<td>FIGURE</td>
<td>TITLE</td>
<td>PAGE</td>
</tr>
<tr>
<td>----------</td>
<td>-----------------------------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>6.6</td>
<td>Optimal transmission voltage (example)</td>
<td>72</td>
</tr>
<tr>
<td>6.7</td>
<td>Total transmission efficiency with optimal transmission voltage (example)</td>
<td>72</td>
</tr>
<tr>
<td>6.8</td>
<td>Limitation of the operating area by the ratings of the compressors (example). In this example, the ratings are chosen in order not to limit the operation range.</td>
<td>79</td>
</tr>
<tr>
<td>6.9</td>
<td>Transmissible power for constant ( r_1 ) and ( r_2 ) (example)</td>
<td>81</td>
</tr>
<tr>
<td>6.10</td>
<td>Maximum input voltage for constant ( r_1 ) and ( r_2 ) (example)</td>
<td>81</td>
</tr>
<tr>
<td>7.1</td>
<td>Maximum permissible electric power per interconnector length unit in dependence of ( r_1 ) and ( r_2 ) (using hydrogen). This data is computed once for a given set of material and constrained parameters and provides the basis for a layout based on scaling laws.</td>
<td>87</td>
</tr>
<tr>
<td>7.2</td>
<td>Maximum permissible electric power per interconnector length unit for ( r_2 = 0.84 ).</td>
<td>89</td>
</tr>
<tr>
<td>7.3</td>
<td>( R_i/L_{tot}^{3/5} ) in dependence of ( r_1 ) and ( r_2 ) (using hydrogen).</td>
<td>90</td>
</tr>
<tr>
<td>7.4</td>
<td>Inner radius for an interconnector with ( P_{elAMax} ) = 200 MW, ( P_{chAMax} ) = 240 MW and ( L_{tot} ) = 50 km for various inlet temperatures (error bars: effect of a ( \pm 25% ) variation of ( P_{elAMax} ), ( P_{chAMax} ) and ( L_{tot} )).</td>
<td>93</td>
</tr>
<tr>
<td>7.5</td>
<td>Inlet Voltage for an interconnector with ( P_{elAMax} ) = 200 MW, ( P_{chAMax} ) = 240 MW and ( L_{tot} ) = 50 km for various inlet temperatures (error bars: effect of a ( \pm 25% ) variation of ( P_{elAMax} ), ( P_{chAMax} ) and ( L_{tot} )).</td>
<td>94</td>
</tr>
<tr>
<td>7.6</td>
<td>Minimum and maximum transmissible powers for an interconnector with different gaseous chemical carriers (example).</td>
<td>96</td>
</tr>
<tr>
<td>7.7</td>
<td>Minimum and maximum transmissible powers for an interconnector with different liquid chemical carriers (example).</td>
<td>97</td>
</tr>
<tr>
<td>7.8</td>
<td>Inner radius of an interconnector in function of the friction factor for constant maximum chemical power (example).</td>
<td>98</td>
</tr>
</tbody>
</table>
7.9 Maximum chemical and electric power at constant 
r_1,r_2 for various thermal resistances of the outer in-
sulation (example) ........................................... 101

7.10 Inner radius for a hydrogen interconnector for various 
applications and assumptions previously introduced 
for the material and design parameters (error bars: 
result of a 25% variation in the specifications of the 
application) ..................................................... 104

7.11 Transmission voltage (d.c.) for a hydrogen intercon-
connector for various applications and assumptions previ-
ously discussed for the material and design parameters. 105

7.12 Conductor cross-sectional area for a hydrogen inter-
connector for various applications and with the as-
sumptions introduced for the material and design pa-
rameters. ..................................................... 106

7.13 Inner radius for a hydrogen interconnector for “small 
scale” applications and with the assumptions intro-
duced for the material and design parameters .... 107

7.14 Transmission voltage for a hydrogen interconnector for 
“small scale” applications and with the assumptions 
introduced for the material and design parameters. ... 108

7.15 Conductor cross-sectional area for a hydrogen inter-
connector for “small scale” applications and with the 
assumptions introduced for the material and design 
parameters ..................................................... 109

7.16 Efficiency $\eta_{TotBAMax}$ for a hydrogen interconnector 
for “small scale” applications and with the assump-
tions introduced for the material and design parameters. 110

7.17 Inner radius of an interconnector for various chemical 
carriers (application: MVDC) .......................... 111

7.18 Transmission voltage of an interconnector for various 
chemical carriers (application: MVDC) ................. 112

7.19 Conductor cross-sectional area of an interconnector 
for various chemical carriers (application: MVDC) ... 112
LIST OF FIGURES
## List of Tables

<table>
<thead>
<tr>
<th>Table</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.1</td>
<td>Sign table for ( \frac{dP_V}{dp_2} ). ( pdz ) and ( pfp ) are the zeros of ( \frac{dP_V}{dp_2} ) and ( \frac{d^2P_V}{dp_2^2} ) respectively. They have no special meaning in this context.</td>
</tr>
<tr>
<td>7.1</td>
<td>Temperature range for waste heat recovery equipment or &quot;direct&quot; heat consumers</td>
</tr>
<tr>
<td>7.2</td>
<td>Examples of the ampacity of XLPE cables with copper conductor [28]. The maximum current depends on the type of burying.</td>
</tr>
<tr>
<td>7.3</td>
<td>List of the investigated &quot;generic&quot; applications (( n_c ): number of connections for the consumer, ( s ) degree of self-sufficiency)</td>
</tr>
<tr>
<td>C.1</td>
<td>Layout of the interconnectors for example 1</td>
</tr>
<tr>
<td>C.2</td>
<td>Layout of the interconnectors for example 2</td>
</tr>
<tr>
<td>C.3</td>
<td>Layout of the interconnectors for example 3</td>
</tr>
<tr>
<td>D.1</td>
<td>Variables used in the VDI heat exchanger layout guideline</td>
</tr>
<tr>
<td>D.2</td>
<td>Empirical values for ( k ) (from [30])</td>
</tr>
<tr>
<td>D.3</td>
<td>Realistic values for flow velocities in a heat exchanger from [31]</td>
</tr>
</tbody>
</table>
Curriculum vitae

1979  Born in Vevey, Switzerland
1985-1989  Primary school in Rougemont, Switzerland
1989-1994  Secondary school in Château-d’Oex, Switzerland
1994-1998  College in Bulle, Switzerland
1998-2003  Studies in electrical engineering and information technology, ETH Zurich
2003-2008  Research assistant at the Power Systems and High Voltage Laboratories, ETH Zurich
Since 2008  Technology consultant at the AREVA T&D Technology Centre in Stafford, United Kingdom