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MEASURING THE IMPACT OF RENEWABLE ENERGY TECHNOLOGIES ON ENERGY SECURITY

A Multi-level Assessment of the German Heating Sector

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"Was alle angeht, können nur alle lösen. Jeder Versuch eines Einzelnen, für sich zu lösen, was alle angeht, muß scheitern."

("What concerns everyone can only be resolved by everyone. Each attempt of an individual to resolve for himself what is the concern of everyone is doomed to fail.")

Friedrich Reinhold Dürrenmatt, Die Physiker.

Acknowledgements

Writing these words, I realise that a long journey soon reaches its end. And though I usually have my steps properly planned, this time, life catches me pretty unprepared. With handing in this thesis, my academic education and – more importantly – my student life have come to an end. With this thesis, I close a chapter of eighteen years full of friendships, laughter, moving, seminar papers, night shifts, and ongoing change from primary school to university. I don't know what the next chapter will look like. But like in any good book, the upcoming pages should save some surprises.

I may never again have the chance to dedicate a piece of work to someone, so I dedicate this to my greatest teachers in life – grandma and grandpa. I know that someday we'll sit together on that garden bench in the shade again and have all the time in the world to talk or just be quiet. There might be a piece of cake involved as well, who knows. Be that as it may, I think the May bug is ready to fly now. But he would still appreciate a little guidance on the way.

I'm very grateful for my parents. Thank you for all your support and for never questioning any of the choices I made on my way.

Thank you, Tanja, for being my source of endless love, care, and calmness and for going the distance with me. It is an honour to travel with you and I'm glad that our journey has just begun.

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Thank you, B18, MESPOM 7, and everyone at the Tute, for making the place to what it is. With all its ups and downs it has certainly become a second home for me – a place to remember, to miss, and to return to.

Among all these extraordinary people, I especially like to thank Tess for increasing my Kiwi vocabulary, for an open ear, some gossip, and for not being too bossy in Poland; Sæmi for saving a seat for me, for being a grumpy bearded friend, and for the amazing time and hospitality of you and Kristín in the land of ice and fire; Gabi for being an awesome roommate, occupying the kitchen table, preparing the best breakfast, and for bringing so many decoration elements into Lomma house and my life; Henrik for all your wisdom, the cigars, the mojitos, and a perfect foot massage; Sara for coffee breaks and burgers; Eduardo for revealing all the joy in life and for your BBQ skills; Kes and Emma for putting us up in your lovely house and for making the time in Sweden incredibly cosy and luxury; Philip and Peter for your understanding and support in a time of bitter fate; Luis for truly caring about students and education; Birgitta for being heart and soul of our tiny mansion in the middle of Lund and for your helping words and actions.

I like to thank the few interviewees for accepting the unenviable task to fill out complicated questionnaires in the main holiday season. And I like to thank everyone at ISI, especially Jan, who didn't turn away my cryptic questions but helped me out with valuable data instead.

And not least, I like to thank my supervisors, especially Barbara, for your time and support to make this thesis a piece of work I am actually (finally) proud of.

This is also for everyone else who accompanied me through all these years and the time in Sweden and whose name I won't explicitly mention here. Be sure that you are ever present in my heart and memories and I truly hope the future will give us many more moments to share. Luckily, this world is a tiny place after all.

Abstract

This thesis has been written as input for a publicly funded research project on the economic evaluation of the implications of renewable energy expansion in the German electricity and heating sector. So far, the project has only qualitatively assessed the impact of renewable energy deployment on energy security. This thesis presents the first approach of its kind to quantitatively assess the influence of renewable energy deployment on energy security. The German heating sector is taken as a case-study to carry out this assessment.

The political, societal, and academic discourse on energy security in Germany is focussing on supply-based price and quantity risks and discusses *energy security* mainly as *security of supply*. Based on this narrow definition, the overall impact of renewable energy deployment is assumed to be beneficial to energy security. This thesis scrutinises this hypothesis in developing a methodological approach aiming at appropriately assessing the complexity and heterogeneity of energy security and at broadening the currently narrow discourse on energy security in Germany.

This thesis highlights that the complexity and heterogeneity of energy security can be delineated with the help of dimensions (i.e. different stakeholders' views on and perceptions of energy security) and characteristics (i.e. more or less pronounced requirements of energy systems and their subcomponents necessary to meet energy security). Within these dimensions and characteristics, indicators allow to measure the impact of the deployment of renewable energy technologies to energy security.

This thesis further reveals that the deployment of renewable energy technologies in the German heating sector could be beneficial, harmful, or neutral to energy security depending on the deployed technology and the regarded subsector or end-use of thermal energy.

Keywords: energy security, heat security, renewable energy, German heating sector

Executive Summary

Background

The growing deployment of renewable energy technologies in Germany has been accompanied by a discussion on its impact on businesses, industries, households, and the economy as a whole. This discussion has been mainly cost-driven and has focussed almost entirely on the electricity sector. The benefit effects of renewable energy deployment however stayed on the side-line of this discussion. A holistic scientific assessment accounting for the multiplicity and complexity of these effects in the form of a cost-benefit-analysis is missing.

Against this background, in 2008, the German Federal Ministry for the Environment, Nature Conservation, and Nuclear Safety (BMU) initiated and funded a multi-year research project on the economic evaluation of costs and benefit effects of renewable energy expansion in the German electricity and heating sector. The study shall develop integrated methodological approaches to assess the costs and benefits of renewable energy deployment preferably on an economic basis. It shall further expand the focus on the electricity sector by the heating sector. The study has been conducted since by four research institutions[1] under the direction of the Fraunhofer Institute for Systems and Innovation Research in Karlsruhe, Germany (Fraunhofer ISI). The study is referred to as ImpRES – short for impacts of renewable energy sources.

Justification

ImpRES is funded to carry out an economic evaluation of costs and benefit effects of renewable energy expansion in the German electricity and heating sector. So far, the project has only qualitatively assessed the implications of renewable energy deployment for energy security. For an economic evaluation in the form of a cost benefit analysis however, a quantitative analysis of the implications of renewable energy deployment for energy security is indispensable.

The political, societal, and academic discourse on energy security in Germany is focussing on supply-based price and quantity risks. *Energy security* is commonly understood and discussed as *security of supply*. Scholars argue that this current perspective on energy security is too narrow to appropriately account for the complexity and heterogeneity of energy security. The reviewed literature recognises a need for a more integrated conception of energy security.

So far, ImpRES and similar studies assume the overall impact of renewable energy deployment to be beneficial to energy security. This assumption implicitly includes two unproven hypotheses: (1) There is an unambiguous overall impact of renewable energy deployment on energy security; (2) This overall impact is beneficial to energy security.

Research Aim, Research Questions, and Relevance

I write this thesis in collaboration with the Fraunhofer ISI in the context of ImpRES. With this thesis, I intend to contribute to closing these existing research gaps. In other words, I intend to quantitatively measure the impact of renewable energy deployment to energy security in the context of ImpRES. I try to approach the complexity and multiplicity of the contemporary energy security understanding in developing and applying a methodological approach to assess energy security. To that end, the German heating sector is taken as a case-study to carry out the

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[1] The four research institutions comprise the Fraunhofer Institute for Systems and Innovation Research in Karlsruhe, the German Institute for Economic Research in Berlin, the Institute of Economic Structures Research in Osnabrück, and the Institut für Zukunftsenergiesysteme in Saarbrücken.

assessment. Despite this sector having the biggest share in Germany's end energy consumption, the public discussion is still focussing on the electricity sector and hence neglects the heating sector. My thesis shall help to bring the heating sector into the spotlight of discussion as well.

The guiding research question of my thesis is derived from the hypothesis of ImpRES that the overall impact of renewable energy deployment on energy security is beneficial. To scrutinise this hypothesis, two objectives have been formulated. The first objective is to assess how energy security could generally be delineated and quantified. The second is to assess the implications of renewable energy deployment for energy security in the German heating and power sector. Based on these objectives, the guiding research question is formulated as:

> What are the implications of the end-use of renewable energy fuels and technologies for energy security in the German heating sector and how could these implications be quantified?

To achieve the outlined objectives and the research aim of my thesis, I break this overarching question down into two sub-questions:

1. What are relevant attributes of energy security in the German heating sector and how could they be measured?

2. How does the end-use of renewable energy fuels and technologies as opposed to fossil-based energy provision in the German heating sector influence energy security measured by its previously defined attributes?

Research Methods

My research comprises elements of quantitative and qualitative methods. From a literature analysis, I develop a methodological approach for assessing energy security in a given established energy system. This approach consists of eight main steps:

In a first step, I depict the status quo in the German heating sector, its subsectors, its end-uses of energy, and the technologies for heat generation it comprises. In a second step, I create two scenarios of the German heating sector based on the objectives of ImpRES. The first scenario is a simplified depiction of the status quo in the German heating sector, including fossil-based and renewable energy technologies. The second scenario comprises fossil-based energy technologies only. Both scenarios have the same total end-use energy volume. In a third step, I disaggregate the German heating sector according to disaggregation rules found in the literature into decomposition levels where renewable energies play a significant role. In a fourth step, I delineate the contemporary energy security understanding with the help of relevant energy security attributes found in literature on energy security. In a fifth step, I select metrics from the reviewed literature and expert surveys to quantitatively assess the identified attributes. In a sixth step, I collect data from expert interviews, a literature analysis, and from different data bases to calculate indicator values for each heat generation technology. With the help of these indicator values, I assess energy security in a seventh step on a decomposition level and in an eight step for the whole heating sector. In a comparative analysis, the difference between the indicator values of the two scenarios allows me to draw conclusions on the energy security impact of renewable energy technologies on a sector and on a decomposition level.

The analysis of my thesis can be divided into two categories: a technology-based and an indicator-based analysis. The disaggregation in decomposition levels allowed me to compare, analyse, and interpret energy security metrics of relevant technologies for heat in a technology-based analysis. Indicator values for the same technology could differ significantly depending on the decomposition level. This observation would have been neglected otherwise. The aggregation of energy security indicators on a sector level allowed me to compare, analyse, and interpret energy security metrics of the two scenarios in an indicator-based analysis. This indicator-based comparative analysis served as a prerequisite for measuring the impact of renewable energy deployment on energy security in the whole heating sector.

Key Findings and Conclusions

In my thesis, I present a comprehensible approach for a systematic assessment of energy security that goes beyond the assessment of price and quantity risks. Being the first energy security assessment of its kind for the German heating sector, the thesis reveals that:

- A rigid definition of energy security can hardly be obtained due to the complexity and heterogeneity of the subject. My thesis showed that with the help of energy security attributes the contemporary energy security understanding can be delineated without rigidly defining energy security. Attributes help to broaden the current narrow discourse of energy security in Germany to better assess the complexity and heterogeneity of the subject.

- Attributes of energy security can be divided into dimensions (i.e. different stakeholders' views on and perceptions of energy security) and characteristics (i.e. more or less pronounced requirements of energy systems and their subcomponents necessary for the existence of energy security).

- Within these dimensions and characteristics, energy security can be measured with the help of indicators borrowed from other disciplines or specifically designed for the purpose of the assessment.

- The indicator selection process is far from trivial. The indicators assessed in my thesis are to be seen as exemplary and non-exclusive.

- The deployment of renewable energy technologies in the German heating sector could be beneficial, harmful, or neutral to (attributes of) energy security depending on the deployed technology and the regarded subsector or end-use of thermal energy. A direct conclusion whether renewable energy deployment is beneficial or harmful to energy security in the German heating sector can hence not be drawn.

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Abbreviations

BMU	German Federal Ministry for the Environment, Nature Conservation, and Nuclear Safety
°C	Degree Celsius
COP	Coefficient of performance
e.g.	Exempli gratia (for example)
Fraunhofer ISI	Fraunhofer Institute for Systems and Innovation Research, Karlsruhe, Germany
GDP	Gross domestic product
H-HW	Hot water in households
H-SH	Space heating in households
i.e.	Id est (that is)
ImpRES	Study on the impacts of renewable energy sources
I-PH	Process heat in the industry
I-SH	Space heating in the industry
km	Kilometre
m	Metre
m^3	Cubic metre
PJ	Petajoule
RE	Renewable energy / renewable energies
S-SH	Space heating in the service sector
t	Tonne

1 Introduction

1.1 Background

The growing deployment of renewable energy technologies in Germany has been accompanied by a discussion on its impact on businesses, industries, households, and the economy as a whole. This discussion has been mainly cost-driven and has focussed almost entirely on the electricity sector. The benefit effects of renewable energy deployment however stayed on the side-line of this discussion. A holistic scientific assessment accounting for the multiplicity and complexity of these effects in the form of a cost-benefit-analysis is missing. (Breitschopf et al., 2010; van Mark, 2010)

Against this background, in 2008, the German Federal Ministry for the Environment, Nature Conservation, and Nuclear Safety (BMU) initiated and funded a multi-year research project on the economic evaluation of costs and benefit effects of renewable energy expansion in the German electricity and heating sector. The study shall develop integrated methodological approaches to assess the costs and benefits of renewable energy deployment preferably on an economic basis. It shall further expand the focus on the electricity sector by the heating sector. The study has been conducted since by four research institutions[2] under the direction of the Fraunhofer Institute for Systems and Innovation Research in Karlsruhe, Germany (Fraunhofer ISI). The study is commonly referred to as ImpRES – short for impacts of renewable energy sources. (ISI, n.d.; van Mark, 2010)

ImpRES classifies the identified impacts of renewable energy deployment according to a conceptualised framework that shall avoid gaps and double-counting of effects and that currently consists of three categories: system-analytical aspects, distributional aspects, and macro-economic aspects. System-analytical aspects comprise direct and indirect system costs and benefit effects of the renewable energy deployment. Distributional aspects show which stakeholders are burdened and which are disburdened by the promotion of renewable energies. Macro-economic aspects map national or sectoral impacts such as impacts on the GDP and the employment on a macro-economic level. If possible, impacts are converted into monetary terms. (Breitschopf et al., 2010) Figure 1-1 gives an overview on the impacts that have been quantified so far.

1.2 Problem Definition and Research Aim

The impacts mentioned in Figure 1-1 have been quantified and discussed and are updated on an annual basis in the context of ImpRES. Besides the indicators listed above, the study has identified other important impacts that have not yet been captured or have only been discussed qualitatively but not quantitatively. The influence of renewable energies on energy security constitutes one of the impacts requiring further exploration. Despite this research gap, ImpRES generally assumes renewable energies to have a beneficial impact on energy security. (Breitschopf et al., 2010 & 2012; van Mark, 2010)

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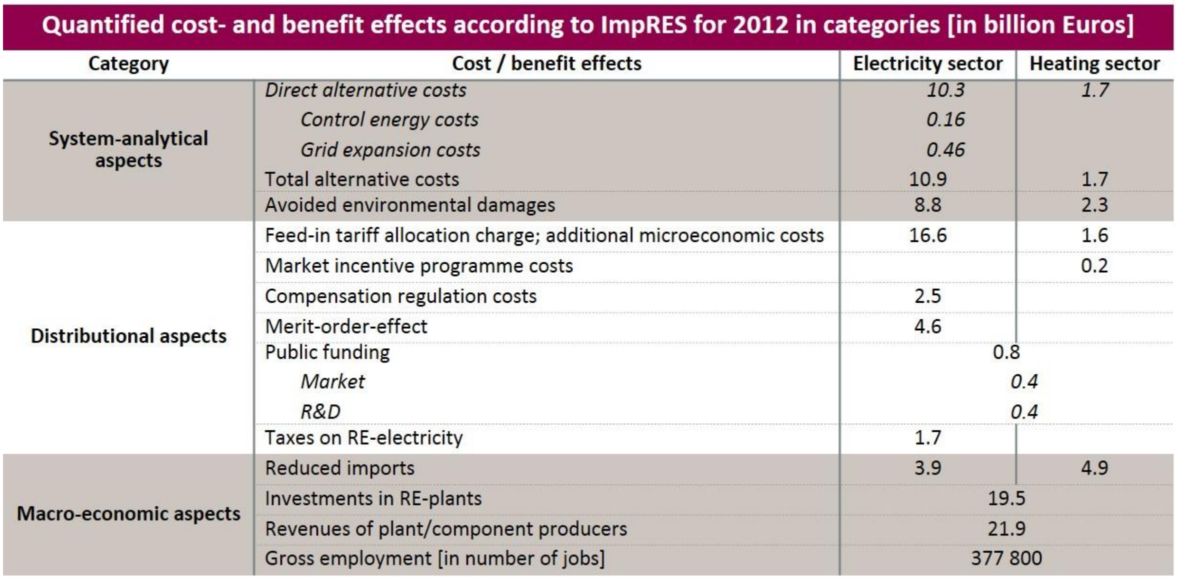
[2] The four research institutions comprise the Fraunhofer Institute for Systems and Innovation Research in Karlsruhe, the German Institute for Economic Research in Berlin, the Institute of Economic Structures Research in Osnabrück, and the Institut für Zukunftsenergiesysteme in Saarbrücken.



Quantified cost- and benefit effects according to ImpRES for 2012 in categories [in billion Euros]

Category	Cost / benefit effects	Electricity sector	Heating sector
System-analytical aspects	*Direct alternative costs*	*10.3*	*1.7*
	Control energy costs	*0.16*	
	Grid expansion costs	*0.46*	
	Total alternative costs	10.9	1.7
	Avoided environmental damages	8.8	2.3
Distributional aspects	Feed-in tariff allocation charge; additional microeconomic costs	16.6	1.6
	Market incentive programme costs		0.2
	Compensation regulation costs	2.5	
	Merit-order-effect	4.6	
	Public funding	0.8	
	Market	*0.4*	
	R&D	*0.4*	
	Taxes on RE-electricity	1.7	
Macro-economic aspects	Reduced imports	3.9	4.9
	Investments in RE-plants	19.5	
	Revenues of plant/component producers	21.9	
	Gross employment [in number of jobs]	377 800	

Figure 1-1: Quantified cost- and benefit effects according to ImpRES for 2012 in categories [in billion Euros]

Source: Breitschopf et al., 2012 & 2013; Discrepancies in sums might occur through rounding differences.

Following the major discourse on energy security in Germany and the European Union, ImpRES currently puts energy security on one level with price and quantity risks resulting from high import dependency and low diversification of energy portfolios. Hence, *energy security* in Germany is generally discussed and understood as *security of supply*. (Breitschopf et al., 2012; EC, 2001; Ranau, 2008) Although the influence of renewable energies to energy security is regarded significant and despite import dependency and diversification have been identified as relevant aspects of energy security, a quantitative assessment on the impact of renewable energy deployment on energy security has not yet been carried out. (Breitschopf et al., 2012)

Contemporary literature on energy security agrees on import dependency and diversification being necessary aspects of energy security. Yet, scholars argue that these aspects cannot be sufficient for describing the complexity and multiplicity of energy security. There is a need for a more integrated conception accounting for dimensions like societal, environmental, and technical concerns as well as for energy efficiency. This will allow policy and decision makers to ground their course of action on a more holistic understanding of energy security. (Cherp & Jewell, 2011a & 2011b; Sovacool, 2011 & 2012; Sovacool & Mukherjee, 2011; Vivoda 2010, Yergin, 2006)

I[3] write this thesis in collaboration with the Fraunhofer ISI in the context of ImpRES. With this thesis, I intend to contribute to closing these existing research gaps. In other words, I intend to quantitatively measure the impact of renewable energy deployment to energy security in the

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[3] Throughout this thesis, I will use first person narrative. This may break with the reader's conception of how a scientific text should be written and therefore might require a short explanation: The first person narrative in my thesis ought not to be confused with the first person narrative in novels or short stories where the author presents personal thoughts, opinions, and feelings. My thesis is still to be seen as a scientific piece of work. I use the first person narrative exclusively to avoid creating an artificial barrier or distance between myself and my thesis. From personal experience, such artificial distance is likely to bore the reader. The first person narrative, as a personal element of style, should keep the reader interested and ease the process of reading and understanding this thesis.

context of ImpRES. I try to approach the complexity and multiplicity of the contemporary energy security understanding in developing and applying a methodological approach to assess energy security. To that end, the German heating sector is taken as a case-study to carry out the assessment. Despite this sector having the biggest share in Germany's end energy consumption, the public discussion is still focussing on the electricity sector and hence neglects the heating sector. I hope that my thesis will help to bring the heating sector into the spotlight of discussion as well. An assessment of energy security in the German heating sector seems also feasible for the scope of this thesis.

1.3 Research Questions

The guiding research questions of my thesis are derived from two objectives of ImpRES. The first objective is to assess how energy security could generally be delineated and quantified. The second is to assess the implications of renewable energy deployment for energy security in the German heating and power sector. So far, ImpRES assumes the impact of renewable energy deployment to be beneficial to energy security. (Breitschopf et al., 2010 & 2012; van Mark, 2010) Since a holistic methodological approach for quantifying the impact of renewable energies on energy security does not yet exist, this assumption remains a hypothesis. For the purpose of my thesis, I will hence take one step back in posing the research question:

> What are the implications of the end-use of renewable energy fuels and technologies for energy security[4] in the German heating sector and how could these implications be quantified?

To achieve the outlined objectives of my thesis, I break this overarching question down into two sub-questions:

1. What are relevant attributes of energy security in the German heating sector and how could they be measured?

2. How does the end-use of renewable energy fuels and technologies as opposed to fossil-based energy provision in the German heating sector influence energy security measured by its previously defined attributes?

1.4 Research Process and Methodology

The research process of my thesis can be broken down into seven main steps: (1) research idea, (2) literature analysis, (3) research design, (4) data collection, (5) analysis, (6) reflection, and (7) conclusions and recommendations. During this process, I received regular feedback from my supervisors.

The **research idea** for my thesis was initiated by the Fraunhofer ISI in the context of ImpRES. The intention was to quantify the net benefit of renewable energy deployment to energy security in Germany. For this purpose an integrated methodological approach accounting for the complexity of the contemporary energy security understanding had to be developed. Already in the early phase of my research process, I decided to focus on the German heating sector and to conduct an indicator-based comparative analysis of energy security between two sector scenarios of equal energy volume. The difference in indicator values between the two scenarios would allow me to measure the impact of renewable energy technologies on energy security.

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[4] The concept of energy security as employed in this thesis will be explained in Chapter 2.

I started this work with a quick search on energy security within online databases. In parallel, I conducted a rough literature review on the German heating sector in order to get a good overview on this system and its subcomponents and technologies.

To get a deeper understanding, this initial review was followed by a more thorough **literature analysis** that can be broken down into three categories: (a) energy security, its components, and assessment approaches; (b) the German heating sector, its subsectors, and end-uses for energy; and (c) renewable and non-renewable technologies for heat generation.

(a) The energy security category comprises:

- Academic journal articles and books on energy security, its definitions, its components, and the historic development of its understanding; among them especially articles in Johansson et al. (2012), *Global Energy Assessment,* Sovacool (2011), *The Routledge Handbook of Energy Security,* and journal articles in *Energy Policy,*
- Documents from political bodies and agencies related to energy policy and energy security; among them especially documents by the European Commission, the Energy Research Centre of the Netherlands, the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety, the German Federal Ministry of Economics and Technology, the German Federal Environment Agency, and the International Energy Agency,
- Studies and documents from universities and other research institutions concerning energy security, and
- Documents from non-governmental organisations.

The relevant results of this review are outlined in Chapter 2.

(b) The heating sector category comprises:

- Studies and documents from universities and other research institutions concerning the German heating sector; among them especially publications by the AG Energiebilanzen e.V., the Technical University Munich, the Fraunhofer Institute for Systems and Innovation Research, and the Rheinisch-Westfälisches Institut für Wirtschaftsforschung,
- Documents from political bodies and agencies related to politics regarding the German heating sector; among them especially documents by the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety, the German Federal Ministry of Economics and Technology, the German Federal Environment Agency, and
- Reports from industry associations.

The relevant results of this review are outlined in Chapter 3.

(c) The technology category comprises:

- Academic journal articles and books; among them especially IEA (2007), *Renewables for Heating and Cooling,* and Recknagel et al. (2012), *Taschenbuch für Heizung + Klimatechnik,*
- Studies and documents from universities and other research institutions concerning technologies for heat generation; among them especially publications by the AG

Energiebilanzen e.V., the Technical University Munich, the Fraunhofer Institute for Systems and Innovation Research, and the Rheinisch-Westfälisches Institut für Wirtschaftsforschung, and

- Reports from industry associations.

The relevant results of this review are outlined in Chapter 3.

This literature analysis served as the basis of my **research design**. My research comprises elements of quantitative and qualitative methods. From the literature, I derived an integrated methodological approach for assessing energy security in a given established energy system. This approach consists of eight main steps:

In a first step, it was vital to understand the system under analysis. I therefore depicted the status quo in the German heating sector, its subsectors, its end-uses of energy, and the technologies for heat generation it comprises.

In a second step, it was important to describe the actual subject that is going to be assessed. For the purpose of my thesis, I therefore created two scenarios of the German heating sector. The first scenario is a simplified depiction of the status quo in the German heating sector, including fossil-based and renewable energy technologies. The second scenario is comprised of fossil-based energy technologies only. Both scenarios have the same total energy volume. In an indicator-based comparative analysis, the difference between the indicator values of the two scenarios would allow me to draw conclusions on the energy security impact of renewable energy technologies.

In a third step, it was important to account for the complexity of the system under analysis in disintegrating it into relevant decomposition levels. To allow for a detailed analysis and to account for its complexity, I broke down the German heating sector into two levels, i.e. subsectors (industry, service sector, and households) and end-uses of energy (space heating, process heat, and hot water). Some of these levels were further broken down into sublevel combinations (referred to as decomposition levels) where renewable energies played a significant role. One sublevel combination was for instance process heat in the industry; another was space heating in households. This disaggregation would later allow me to analyse energy security (with the help of indicators defined in step five) in relevant sublevel combinations and then to aggregate the levels again to draw conclusions on energy security in the whole heating sector.

In a fourth step, my approach required a delineation of the energy security understanding in the given system with the help of characteristics and dimensions of energy security. Characteristics constitute necessary attributes of energy security, while dimensions shall account for different stakeholders' views on these attributes. The reviewed literature helped me to define a final set of relevant characteristics and dimensions for energy security in the German heating sector. Expert talks and consultation with my supervisors helped me to revise this final set and adapt it where necessary.

In a fifth step, relevant indicators to measure energy security had to be defined. The set of indicators has to account for technology specific energy security aspects while being valid for all technologies. Further, the set of indicators has to account for all characteristics and dimensions while being valid for all decomposition levels. The reviewed literature helped me to create a pre-selection of relevant indicators. Expert surveys and consultation with my supervisors helped me to select indicators from the final set for the analysis in my thesis. Sometimes the lack of data could place restrictions on indicators as well.

In a sixth step, data had to be collected and indicator values had to be calculated on the different decomposition levels. This means that for each heat generation technology (e.g. coal firing) at each decomposition level (e.g. space heating in industry) an indicator value is calculated. This allowed me to analyse and interpret energy security on a technology-basis within different decomposition levels. In a seventh step, indicator values had to be aggregated according to the shares of different technologies in the decomposition level. This allowed me to analyse and interpret energy security on an indicator-basis within the different decomposition levels. In an eighth step, decomposition levels of both scenarios were aggregated to a sector level according to the decomposition levels' share in the heating sector. A scenario comparison then allowed me to draw conclusions on the overall impact of renewable energies in the German heating sector. Steps six to eight are depicted in Figure 1-2.

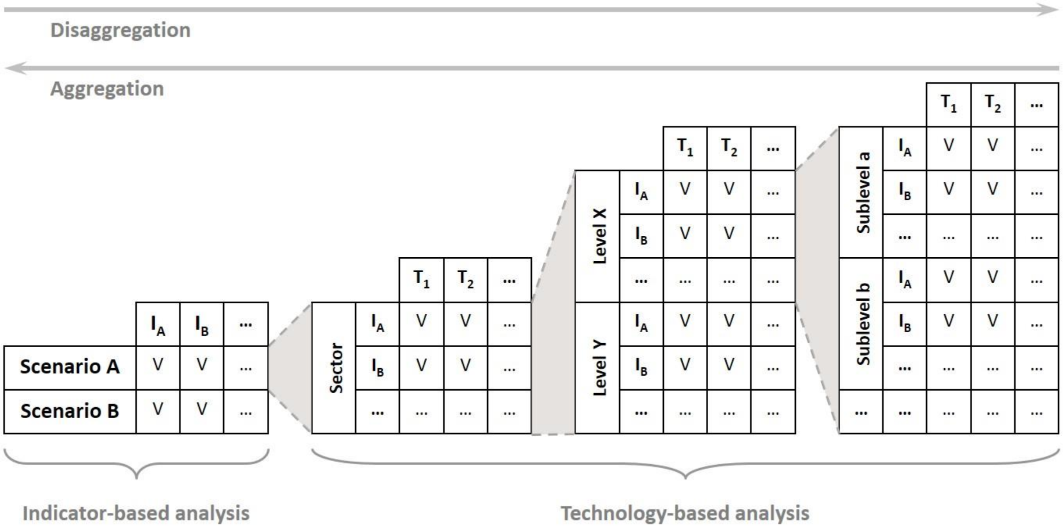


Figure 1-2: Disaggregation of the German heating sector into levels and sublevels

I = indicator, T = technology, V = indicator value

The **data collection** included primary and secondary data collection. Primary data collection was carried out through anonymous expert surveys and interviews. The interviewees were chosen due to their experience in the field of (renewable) energy (security). Each of the interviewees also has experience in at least one of the dimensions identified to be relevant for energy security. To guarantee their anonymity, each interviewee has been assigned a random number. Figure 1-3 gives an overview of the people interviewed for this thesis.

Secondary data was used to calculate indicator values. This data was collected from three groups of sources: (a) statistical databases, (b) scientific studies, and (c) reports.

(a) Statistical databases comprise especially:

- Databases at the German Federal Office of Economics and Export Control,
- Databases at the German Federal Institute for Geosciences and Natural Resources,
- Databases at the German Federal Bureau of Statistics,
- Databases at the Economist Intelligence Unit,
- Databases at the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety,

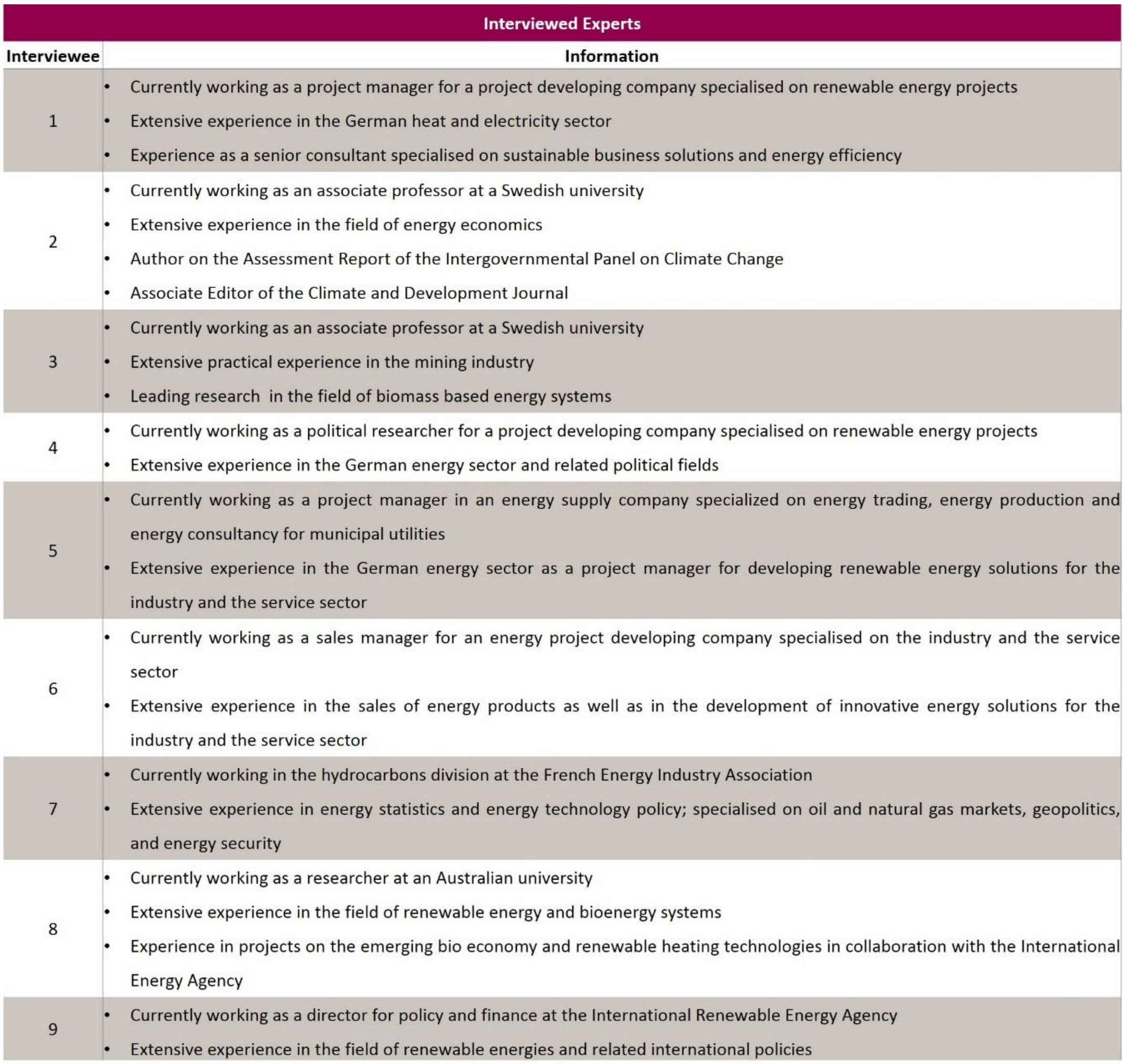
- Databases at the German Federal Ministry of Economics and Technology, and
- Databases at the German Federal Environment Agency.

(b) Scientific studies comprise especially:

- Publications by the AG Energiebilanzen e.V.,
- Publications by the Technical University Munich,
- Publications by the Fraunhofer Institute for Systems and Innovation Research, and
- Publications by the Rheinisch-Westfälisches Institut für Wirtschaftsforschung

(c) Reports comprise especially:

- Company reports from heat technology producers, and
- Market reports from industry associations; among them especially publications by the Association of German Engineers and the Verein der Kohlenimporteure e.V..



Interviewed Experts

Interviewee	Information
1	• Currently working as a project manager for a project developing company specialised on renewable energy projects • Extensive experience in the German heat and electricity sector • Experience as a senior consultant specialised on sustainable business solutions and energy efficiency
2	• Currently working as an associate professor at a Swedish university • Extensive experience in the field of energy economics • Author on the Assessment Report of the Intergovernmental Panel on Climate Change • Associate Editor of the Climate and Development Journal
3	• Currently working as an associate professor at a Swedish university • Extensive practical experience in the mining industry • Leading research in the field of biomass based energy systems
4	• Currently working as a political researcher for a project developing company specialised on renewable energy projects • Extensive experience in the German energy sector and related political fields
5	• Currently working as a project manager in an energy supply company specialized on energy trading, energy production and energy consultancy for municipal utilities • Extensive experience in the German energy sector as a project manager for developing renewable energy solutions for the industry and the service sector
6	• Currently working as a sales manager for an energy project developing company specialised on the industry and the service sector • Extensive experience in the sales of energy products as well as in the development of innovative energy solutions for the industry and the service sector
7	• Currently working in the hydrocarbons division at the French Energy Industry Association • Extensive experience in energy statistics and energy technology policy; specialised on oil and natural gas markets, geopolitics, and energy security
8	• Currently working as a researcher at an Australian university • Extensive experience in the field of renewable energy and bioenergy systems • Experience in projects on the emerging bio economy and renewable heating technologies in collaboration with the International Energy Agency
9	• Currently working as a director for policy and finance at the International Renewable Energy Agency • Extensive experience in the field of renewable energies and related international policies

Figure 1-3: Interviewed Experts

The **analysis** of my thesis can be divided into two categories: a technology-based and an indicator-based analysis (see Figure 1-2). The disaggregation in levels and sublevels allowed me to compare, analyse, and interpret energy security metrics of relevant technologies for heat generation on different decomposition levels in a technology-based analysis. Indicator values for the same technology could differ significantly depending on the decomposition level. This observation would have been neglected otherwise. The aggregation of energy security indicators on a sector level allowed me to compare, analyse, and interpret energy security metrics of the two scenarios in an indicator-based analysis. This indicator-based comparative analysis served as a prerequisite for measuring the impact of renewable energy technologies on energy security.

In a **reflection**, I stepped back from the immediate topic of my thesis and discussed my methodological, theoretical, and analytical choices. I also discussed the legitimacy of my research questions and whether I could answer them fully. In addition, I reflected on the generalizability of my results and whether they could be relevant in a different context.

Finally, I presented the main findings of my research and drew **conclusions** regarding the research questions. Based on these conclusions I gave **recommendations** to the audience and suggestions for further research.

1.5 Limitations and Scope

Two types of limitations are placed upon this thesis: limitations of choice and limitations due to circumstances. Limitations that might influence the assessment and its result are particularly discussed in Chapter 5.

I decided to conduct this energy security assessment within the following **limitations of choice**:

Firstly, my thesis focuses on Germany and assesses the German heating sector only. This sets the geographical and sector boundaries to the conducted energy security assessment. The introduced hybrid approach could generally be applied to other energy sectors and other countries or regions. However, energy security in sub-Saharan Africa's electricity sector has other implications than energy security in the Dutch transport sector. Hence, if applied in another context, the dimensions, characteristics, and indicators would have to be reassessed and adapted to the respective context.

Secondly, I limited the set of existing characteristics of energy security to six characteristics relevant for assessing the German heating sector. This does not mean the excluded characteristics are generally unimportant for assessing the German heating sector. Especially in an assessment including a broader time horizon, new heat generation technologies, or future scenarios, the selection of characteristics would have to be different. Yet, in the comparative analysis of my thesis focusing on an existing market with established technologies, many characteristics are regarded as inherent and therefore less relevant for the purpose of this assessment. The exclusion of characteristics is further explained in Chapter 3.

Thirdly, my thesis assesses a limited set of energy security indicators. At this point, I explicitly want to point out that the presented list of relevant indicators as well as the finally assessed indicators are to be regarded as non-exclusive. The set could and should be broadened in future assessments to derive a more holistic picture of the assessed dimensions and characteristics. The choice and exclusion of indicators is further explained in Chapter 3.

Fourthly, the calculation method of indicators is not always unambiguously defined. For many indicators, several calculation methods exist resulting in different numerical results. Even if the calculation method is rigidly defined, the input data for this calculation might be obtained from different sources resulting in significant numerical discrepancies. Hence, for the calculation of some indicator values subjective choices have to be made that might influence the assessment's results. To not further increase the degree of subjectivity in my analysis, I refrain from aggregating indicators according to mainly subjective aggregation criteria but to assess each indicator individually. I will discuss ambiguous indicators and the choice not to aggregate indicators in Chapter 5.

This limitation also implies that the numerical results presented in Chapter 4 are not to be seen as absolute values for assessing energy security in the German heating sector. The mere numbers are only a reflection of the way the scenarios are composed and of the way the indicators are calculated. The absolute values presented are the mere product of the technology share and the respective indicator value and are in themselves not particularly meaningful for assessing energy security. What should be seen as more important is the (relative) change in indicator values for the decomposition levels through renewable energy deployment. In these figures, the direction and severity of impact of renewable energy deployment on energy security can be measured. However, neither the direction nor the severity of impact can be scaled to scenarios with a higher or lower share or a different composition of renewable energies in the German heating sector. It is valid only for the comparative analysis of the two scenarios as composed in this thesis. The relative change allows hence to draw conclusions on how energy security in the status quo of the German heating sector is influenced by the current share and composition of renewable energy technologies as opposed to a scenario of the status quo in which this current share and composition of renewable energy technologies would be replaced by fossil-based heat generation technologies. The scalability of results is further discussed in Chapter 5.

Fifthly, my thesis is based on a comparative scenario analysis comparing a simplified scenario of the status quo in the German heating sector with a mere fossil-based energy technology scenario that is derived from status quo data. My assessment hence compares two distinct scenarios of the German heating sector at the same point in time which lies in the past. In this regard, my assessment differentiates from other energy security assessments that try to assess future scenarios, new generation technologies, or energy security in an energy system over a period of time. This decision has been made to account for the requirements of ImpRES which is measuring the status quo in an energy system on an annual basis over several years to derive conclusions on real past developments in the energy sector. This limitation is excluding the important dimension of time to a certain degree. To compensate for this exclusion, the time dimension is included in the indicator calculation by taking into account developments of indicator components over a period of time.

Finally, writing this thesis on the subject of energy security, I will not explicitly define the concept of energy security itself in a rigid definition but indirectly delineate the concept of energy security through inherent characteristics and important dimensions. I consider this a strong limitation since it breaks with the methodology of classical reasoning in scientific work where a concept is first explicitly defined and then applied. I argue for this decision since the concept of a rigid energy security definition is much more contested than the attributes (i.e. characteristics and dimensions) of energy security understanding. In explicitly defining and selecting these attributes, I try to guide the reader through my thesis despite the initial breach with scientific methodology.

Some limitations have been placed upon this work due to **circumstances**:

Firstly, this thesis is restricted to a very limited set of primary data. All in all over 30 experts in the field of (renewable) energy (security) were asked to respond to a survey or were asked for a personal interview. The first interview and survey requests were sent out on June 25 with a first reminder on July 14 and a second reminder on August 3. The initial deadline for collecting survey and interview answers was set to August 2 and postponed to August 16. By this time, only nine complete survey responses have been received and only three short e-mail conversations took place. This limited set of responses places strong restrictions to the degree to which expert opinions and primary data could be included in the assessment of my thesis.

Secondly, the availability of data restricted the delineation and disaggregation of the German heating sector. In my thesis, the German heating sector is disaggregated into three subsectors (industry, service sector, and households) and three end-uses of thermal energy (space heating, process heat, and hot water). This disaggregation is commonly used in assessments of the German heating sector (e.g. in AGEB, 2013) and hence allowed me to use a broader database than other disaggregation methods. Similarly, different energy carriers are aggregated in my thesis to one technology according to established aggregation rules for assessing the German heating sector (e.g. AGEB, 2013 and BMU, 2013) due to broader data availability. In Chapter 5, I will discuss how the sector delineation might influence the assessment of my thesis.

Secondly, not all databases could be accessed as planned due to legal restrictions, secrecy obligations, or too costly access fees. Where this was the case, the closest proxy data was used and the replacement was indicated in the assessment. Further, due to the high degree of decentralisation in the German heating sector, it is very difficult to obtain specific data for each heat generation plant. Therefore, often only average or estimated data are used for indicator calculations. The use of such abstracted data sets is indicated in the assessment. Sometimes, the lack of data lead to the total exclusion of indicators from the assessment of my thesis. Such exclusions are explained in Chapter 3.

1.6 Audience

Firstly, I write this thesis for scholars in the field of (renewable) energy (security) research, mainly, but not exclusively, in the context of ImpRES and comparable studies. In my thesis, I derive an integrated methodological approach for mapping the complexity and multiplicity of the contemporary understanding of energy security. This approach shall help any scholar to analyse and measure energy security of a given system. It shall help to move away from the narrow focus of most energy security research on import dependency and diversification to a more holistic conception. While the derived approach focuses on the German heating sector, it is generally applicable to other established energy systems and sectors. The set of characteristics, dimensions, and indicators might however change according to the respective context.

Secondly, I also write this thesis for policy- and decision makers in the field of (renewable) energy (security) policy, mainly, but not exclusively, for the German heating sector. In my thesis I measure relevant characteristics and dimensions of energy security with the help of indicators and indices. The results can serve as a decision support for any cost-benefit-analysis concerned with (renewable) energy security. While the results are limited on the German heating sector, the developed assessment approach can generally be applied in cost-benefit-analyses for other energy systems and sectors.

Finally, I write this thesis for any third party interested in (renewable) energy security and related fields. With my thesis, I hope to broaden the view in the currently narrowed discourse on the topic.

1.7 Disposition

In Chapter 1, I present the nature of the problem addressed in my thesis. I describe the methodology I used to collect data to address my research questions. In this chapter, I identify research limitations, describe the audience for which this research may be useful, and provide a thesis outline.

In Chapter 2, a more thorough analysis of approaches to quantify energy security is presented. In this chapter, I provide relevant definitions for the field of study, outline the evolution of the energy security understanding through time, and present the main components of a contemporary energy security assessment. Based on these components, I derive an energy security assessment framework for the purpose of my thesis.

Chapter 3 presents the main findings of applying the derived framework on scenarios of the German heating sector. In this chapter, I describe the heating sector and its relevant technologies, its subsectors and end-uses of energy. Then, I create two sector scenarios serving as a basis for comparative analysis. I further identify and explain relevant decomposition levels of the heating sector, relevant energy security characteristics and dimensions, and relevant indicators and indices for the purpose of my assessment.

Chapter 4 presents a comparative analysis of the two sector scenarios. In this chapter, I calculate indicator values and aggregate them for different decomposition levels of the sector on a technology-basis. Finally, I measure energy security on an indicator-basis in comparing the two sector scenarios.

In Chapter 5, I reflect about the methodological and analytical choices of my research. I discuss whether my research questions have been legitimate and whether they have been answered fully. I will further discuss whether my findings could be relevant in a different context.

In Chapter 6, I summarise the main findings and lessons learned in the course of my research. I highlight main research contributions and provide suggestions for further research.

2 Approaches to Energy Security Quantification

2.1 Relevant Definitions

Several reoccurring terms in my thesis require an adequate definition since they are used inconsistently in the literature and might have different denotations in the use of language in everyday life. To facilitate the reader's understanding of the terminology used in my thesis, I take the purchase of a basket filled with fruits as a metaphor for energy security.

The understanding of energy security has changed throughout time – just like the purchase of a basket of exotic fruits was regarded as a luxury in war times and is almost taken for granted today. By **perspective** I refer to the differing focus in discourses on energy security throughout history. Perspectives should not be confused with **dimensions,** a term with which I refer to different stakeholders' views on and perceptions of energy security. Dimensions could be seen as different shoppers' interests in the same basket of fruits. One might try to maximise the overall Vitamin D content of the basket while another might try to minimise its overall costs.

Any system can be broken down into subsystems depending on what part of the system shall be observed. In my thesis, I break down the German heating sector into several subsectors and end-uses of energy. I refer to the resulting disintegration stages as **decomposition** or **sublevels**. In the fruit basket, these levels could resemble fruits suitable to produce jelly from or nuts digestible by small children. Resulting subsystems can be aggregated to systems again.

By **sector** I refer to the German heating sector as a whole. The end-use energy volume of the German heating sector is assumed to be firmly fixed for the purpose of this thesis. Hence the basket of fruit has to be filled either or the other way. The fuel composition of the sector varies however depending on the underlying **scenario** – just like the composition of fruits in the same basket might vary depending on the season or on the shopper's current preferences while the basket's volume remains the same. I will use two sector scenarios for the purpose of this thesis.

By **characteristics** I refer to requirements of energy systems and their subcomponents necessary for the existence of energy security. Necessary requirements for buying a basket of fruits are for example the availability of sufficient fruits to fill the basket or the affordability of the filled basket to the shopper's budget. Requirements can be met to a higher or lower degree. There might not be enough bananas to fill the basket but combined with apples and pears the whole basket could be filled with fruits. There might be cheaper and more expensive options of filling the basket but as long as the overall costs remain within the shopper's budget the basket can be bought. Characteristics hence constitute necessary attributes of energy security that could be more or less pronounced.

By **indicator** I refer to a simple quantitative metric allowing to measure the same characteristics on different levels. The production costs of the fruits or the pesticide use per kilo are examples for indicators. Several indicators can be aggregated to what I refer to as **index**. To allow for a holistic assessment of energy security, the set of indicators has to account for all characteristics and dimensions. The resulting set of indicators also has to be valid for each and every technology in the heating sector.

By **technology** I refer to the technique of producing heat such as geothermal heating or coal firing. Technologies resemble fruit categories like drupes, nuts, and berries. One technology can consist of many sub-technologies or fuels – just like drupes consist of peaches and cherries.

2.2 Evolution of the Energy Security Understanding

In the early twentieth century, energy security started to become a practical concern on the policy agenda of most nation states. For several decades now, energy security has also become a distinct research area for scholars. The understanding of energy security however has developed significantly ever since. (Cherp, 2012; Cherp & Jewell, 2011b) An overview on the evolution of energy security understanding will help to comprehend its contemporary nature. Cherp and Jewell (2011b) argue that there are at least three different perspectives on energy security that have evolved from distinct and independent policy challenges for energy security: a sovereignty, a robustness, and a resilience perspective. (Cherp & Jewell, 2011b)

Through the war times of the early twentieth century, securing the fuel supplies for the military was regarded the main energy security concern. Many armies switched from domestic fuels to imported oil. Especially during World War II, battles over oil fields, transportation routes, and refineries were of high strategic importance. In post-war times, most industrialised states became increasingly dependent on foreign oil and gas supplies for transportation, food production, health care, manufacturing, heating, and electricity generation. During these times, the most important policy challenge for energy security was to protect long-term fuel supplies from intentional hostile actions by malevolent agents within or outside military conflicts. The resulting discourse has been shaped by a sovereignty perspective focussing on geopolitical theories and strategic security studies. (Cherp & Jewell, 2011b; Klare, 2008; Müller-Kraenner, 2008; Yergin, 2006)

During the last decades of the twentieth century, knowledge from natural and technical science combined with computer modelling and system analysis gave insight into the behaviour of complex systems. The increasing complexity of energy systems increased the sensitivity of societies to short-term supply disruptions because of extreme natural events or technical failures. Protection against these short-term disruptions became the most important policy challenge for energy security. The resulting discourse broadened the energy security understanding by a robustness perspective focussing on scientific and engineering thinking. (Cherp & Jewell, 2011b; Farrell et al., 2004)

The deregulation of energy supply that mainly took place in the 1980s and 1990s changed the view on energy from being a public good into being a market commodity. Not the physical availability of energy but its price became the most important policy challenge for energy security. The resulting discourse further broadened the energy security understanding by a resilience perspective focussing on economic theory, especially on investment theory and the diversification of risk. (Awerbuch, 1995; Bar-Lev & Katz, 1976; Cherp & Jewell, 2011b, Stirling, 1994)

Cherp and Jewell (2011b) argue that so far, these three identified perspectives on energy security have only been discussed and analysed isolated from each other. The complexity of the contemporary energy security challenge, however, requires an integration of these formerly isolated perspectives. (Cherp & Jewell, 2011b) According to Goldthau and Sovacool (2012), energy security is characterised by a strong vertical complexity involving multiple technological systems, a strong horizontal complexity involving multiple stakeholders, high entailed costs of energy production and consumption, and strong system inertia due to the centralised nature of many energy systems. A holistic energy assessment methodology has to account for these features. (Goldthau & Sovacool, 2012) Energy security challenges between and within energy systems are highly heterogenic depending on the context, scale, and time-frame of assessment. Developing a methodology that accounts for the complex nature of energy security in a holistic way is far from trivial and there are still many points of contention between scholars in the field. (Sovacool & Lim, 2011)

2.3 Components of a Contemporary Energy Security Assessment

Despite many points of contention, scholars in the field agree that an integrated energy security assessment approach consists of three main components. First it needs to define the concept of energy security and its characteristics and to account for different perspectives and stakeholder views on the topic. Then, indicators and indices can help to measure the identified characteristics within different dimensions. Last, system dynamics and interdependencies of different aspects of energy security should be accounted for. (Cherp & Jewell, 2011b & 2012; Sovacool, 2011; Sovacool & Lim, 2011)

2.3.1 Definitions, Characteristics, and Dimensions of Energy Security

The list of **definitions** of energy security is nearly inexhaustible. Almost any assessment or discussion of energy security contains a highly contextualised definition for the purpose of the given assessment. Sovacool (2011) provides an introduction to energy security comprising 45 different definitions of the concept. (Sovacool, 2011) Winzer (2012) lists 36 definitions of scholars focussing on the security of supply while Martchamadol and Kumar (2012) provide eleven definitions of energy security from international organisations and nation states. (Martchamadol & Kumar, 2012; Winzer, 2012) Some of these definitions focus on primary energy supply while others focus on final energy consumption. One definition might refer to short-term supply while another is concerned with long-term energy security. Some definitions define what energy security is or ought to be while others define what energy security is not or should not be. Definitions might vary between and even within different geographical scales. Energy security in Eritrea is not considered the same as energy security in the United States – just as energy security for the car producing industry in Munich is not the same as energy security for a flat owner in Berlin. In addition, the energy world is volatile and ever changing. Hence, technologies and fuels that are considered secure today might not be considered secure tomorrow. (Pasqualetti, 2011)

Reviewing these extensive lists of definitions, it becomes clear that a single definition of the concept will be hard to find. Yet, despite the high contextualisation, many of the reviewed definitions mention similar **characteristics** of an energy system or its energy technologies that are important for energy security. (Martchamadol & Kumar, 2012; Sovacool, 2011; Winzer, 2012) Figure 2-1 comprises the fifteen most commonly mentioned characteristics. The size of the words indicates how frequently they appear in the literature. This shall give an indication of the perceived importance of these characteristics in the contemporary discourse on energy security.

Figure 2-1: Commonly mentioned characteristics important for energy security

Source: Among others: Martchamadol & Kumar, 2012; Sovacool, 2011; Winzer, 2012

Many of these characteristics require their own definition which in turn is highly contextualised depending on the stakeholders involved in the energy security assessment. Pasqualetti and Sovacool (2012) outline the importance of scale to energy security and how different stakeholders have different views on the same characteristics. **Dimensions** can help to map perspectives on energy security and the views of different stakeholders on the topic and hence help to show how these stakeholders interpret the respective characteristics. (Pasqualetti & Sovacool, 2012) The range of dimensions is almost as broad as the range of definitions depending on the context of the assessment and the level of aggregation of different stakeholder groups.

Mükusch (2012) identifies three dimensions of energy security: state, economy, and society. (Mükusch, 2012) Martchamadol and Kumar (2012 & 2013) follow a similar approach and discuss four dimensions: an institutional, a social, an environmental, and an economic dimension. (Martchamadol & Kumar, 2012 & 2013)

Cherp (2012) discusses different perspectives as well as different stakeholder views on energy security in great detail. (Cherp, 2012) In a related framework however, Cherp and Jewell (2011a) limit the discussion to five dimensions: a natural, an economic, a technical, a political, and a diversity perspective. (Cherp & Jewell, 2011a)

Von Hippel et al. (2011) define six dimensions of energy security: an economic, a technological, an environmental, a socio-cultural, a military, and an energy supply dimension. Vivoda (2010) adds five additional dimensions to von Hippel et al. (2011). (Vivoda, 2010; von Hippel et al., 2011) Closely related are the dimensions identified by Augutis et al. (2012) incorporating technological, natural, economical, socio-political, terrorism, and war threats to energy security. (Augutis et al., 2012) Similarly, Winzer (2012) does not explicitly address perspectives or stakeholder views in his assessment. He rather identifies different sources of risk (human, technical, and natural) and different scopes of impact (technical, societal, and economic) that could account for dimensions. (Winzer, 2012)

Indriyanto et al. (2011) argue that the new energy security paradigm relates very closely with the sustainable development paradigm and its three dimensions: social, economical, and environmental. (Indriyanto et al., 2011)

The different dimensions, perspectives and stakeholder views I found in the reviewed literature revolve around six main dimensions of energy security mapped in Figure 2-2. The size of the words indicates how frequently they are mentioned in the literature. This shall give an indication of the perceived importance of these dimensions in the contemporary discourse on energy security.

Figure 2-2: Main dimensions of energy security in the literature

2.3.2 Indicators and Indices for Energy Security

Indicators are measures that help to assess energy security. Indicators can be quantitative or qualitative. Several simple indicators can be combined to complex indicators or **indices**.

Many indicators in energy security assessments are borrowed from other disciplines. Indicators for price volatilities and energy portfolio variances for example are borrowed from economic theory. Indicators for disruption and failure probabilities are borrowed from infrastructure analysis while indicators mapping actor dependencies are generally borrowed from political science. Some scholars also specifically create energy security indicators. Gupta (2008) for example designs an index to measure the relative vulnerability of oil importing nation states.

(Gupta, 2008) Lefèvre (2010) creates two indices for measuring energy security implications of fossil fuel-based resource concentrations. (Lefèvre, 2010)

The majority of indicators focuses on the short- or long-term fuel supply. Import dependencies or resource to production ratios of certain fuels are typical examples for such supply focused indicators. (among others: Indriyanto et al., 2011; Kruyt et al., 2009; Jewell, 2011) Only few indicators address the energy demand in measuring energy efficiency or the need for specific properties of energy services. (among others: Jansen & Seebregts, 2010; Jansen & van der Welle, 2011; Sovacool & Mukherjee, 2011)

Overall, two indices have played a dominant role in energy security assessments: the supply/demand-index and the Shannon-Wiener-diversity-index. (IEA, 2007a) The supply/demand index allows to measure availability and scarcity of energy resources. The Shannon-Wiener-diversity-index allows to measure the degree of diversification in a given energy portfolio. Jansen and Seebregts (2010) as well as Kessels (2011) discuss these two indices in great detail. (Jansen & Seebregts, 2010; Kessels, 2011) The European Union also uses these indices to assess the energy security status of its nation states. (Scheepers et al., 2007)

Most scholars identify and select indicators specifically for the purpose of their assessment. Hence, the number and nature of indicators can differ significantly depending on the objective of the respective energy security assessment. (among others: Prambudia & Nakano, 2012; Selvakkumaran & Limmeechokchai, 2012; Winzer, 2012)

When general sets of indicators are introduced, they are likely to be impractical for the energy security evaluation of a specific energy system. Sovacool and Mukherjee (2011) for instance conducted an extensive literature research combined with expert interviews to compile a list of 320 simple and 52 complex indicators for policymakers and scholars to generally analyse, track, measure, and compare national performance on energy security. The indicators are grouped into five dimensions and twenty components. Sovacool has been criticised for this list being too long and generic and later also prioritised indicators for the use in specific assessments. (Sovacool, 2012 & 2013; Sovacool & Brown 2011; Sovacool & Mukherjee, 2011)

In the reviewed literature, all scholars compile indicators in a way that the resulting set of indicators can be applied to every technology or fuel in the assessed energy system. Moreover, all scholars use dimensions and/or characteristics to structure their indicators. The choice of indicators is hence often also limited to and predefined by this choice of dimensions and characteristics. (among others: Cherp 2012; Cherp & Jewell, 2011a; Martchamadol & Kumar, 2012 & 2013; von Hippel et al., 2011; Vivoda, 2010)

Reviewing the literature, it becomes clear that in order to be practical for assessing energy security of a specific system, the set of indicators to measure energy security should be compiled according to the context and the objective of the underlying assessment. The set can be compiled from similar assessments, extensive indicator listings, or specifically designed. It seems valuable to structure the indicators according to predefined dimensions and characteristics. These place a top-down requirement on the set of indicators, i.e. every indicator in the resulting set has to account for at least one of the relevant dimensions and characteristics. Moreover, the set has to fulfil a bottom-up requirement, i.e. every indicator has to account for technology specific energy security aspects while being valid for all technologies and fuels in the assessed system.

2.3.3 Indicator Aggregation and System Dynamics

Decision makers supposedly benefit from the aggregation of complex evaluation criteria into few decision criteria. Similarly, energy security assessments often use aggregation models to weigh and rank indicators in order to ease decision making.

Energy systems, regardless of their composition, are complex buildings. Like any system, they are composed of flows and stocks and are subject to positive and negative feedback loops and information delays. The more centralised an energy system is the more vulnerable it is to system inertia. In addition, energy systems can be volatile and might change rapidly. (Goldthau & Sovacool, 2012; Meadows, 2008; Pasqualetti, 2011)

Although many aggregation models can be found, the interconnectedness, the interdependencies, and the dynamics within energy systems are often neglected and only discussed by few scholars in the field of energy security. However, these topics become relevant when different indicators and dimensions are aggregated into a common metric for energy security. (Von Hippel et al., 2011) Mükusch (2012) recognises that different dimensions can influence each other and can be influenced by external forces. (Mükusch, 2012) Similarly, Winzer (2012) acknowledges that there might be interdependencies between different dimensions. Although several potential interdependencies are addressed, an explanation remains very generic. Winzer (2012) decides not to aggregate indicators. (Winzer, 2012) Lefèvre (2010) maps causal relations between different components of energy security, i.e. in elaborating how system element A might influence system element B. The identified relations remain however unilateral. Mutual relationships, i.e. the reverse influence of element B on element A, are not addressed. (Lefèvre, 2010)

Three approaches of indicator aggregation have become popular among scholars in the field of energy security: optimisation models, multi-attribute analyses with factor weighing or ranking, and path comparisons (sometimes referred to as matrix approaches). (Von Hippel et al., 2011)

Optimisation models are mathematical models that intend to determine an optimal solution from a range of option combinations according to certain predefined criteria. Optimisation models have the advantage of providing a single optimal solution to decision makers. This solution is however heavily dependent on the subjectively chosen variables and optimisation criteria. (Von Hippel et al., 2011) Ranking models apply ranking or weighing algorithms to different indicators and dimensions to arrive at a numerical score that allows decision makers to compare different options. Ranking models have the advantage of providing a single metric that allows an easy comparison of different options. The weighing of different indicators or dimensions however is likely to be derived from subjective choices. (Von Hippel et al., 2011) Path comparisons compare different options leading (roughly) to the same results. Path comparisons have the advantage of allowing for a direct comparison between different options. However, it is still up to subjective choices which features in the comparison are more and which are less important. (Von Hippel et al., 2011) The reviewed literature contains a few variations of these three approaches:

Markandya and Pemberton (2010) introduce an economic optimisation model to analyse energy security of a system where there is a risk of disruption of imported energy. The model outlines the importance of an energy tax to maximise the expected utility of a system and how the level of this tax depends on four key parameters, i.e. risk aversion, probability of disruption, demand elasticity, and cost of disruption. The model shows how internal pricing can reduce the uncertainty of impacts of foreign energy supply. (Markandya & Pemberton, 2010)

Augutis et al. (2012) present a technique to measure the level of energy security on one scale. The introduced technique assigns a numeric value to different indicators of energy security according to a threshold scale. The technique is applied on the case of Lithuania. Indicators are grouped into different categories. Weights can (subjectively) be assigned to individual indicators as well as to indicator groups. (Augutis et al., 2012) Similarly, Selvakkumaran and Limmeechokchai (2012) aggregate their set of indicators in (subjectively) assigning them weights according to the importance of the respective indicator on the policy agenda. The resulting equations can be used in an optimisation model for creating an optimal energy security scenario according to a set policy agenda. (Selvakkumaran & Limmeechokchai, 2012)

Gupta (2008) uses the principal component analysis to mathematically structure a large set of individual indicators into fewer linear combinations of indicators. (Gupta, 2008) Martchamadol and Kumar (2013) propose an indicator aggregation method to assess a nation state's energy security status. Similar to Gupta (2008), principal component analysis is used to combine single indicators into groups. These groups can (subjectively) be weighed for instance according to expert opinions. The resulting combined indicator can range from zero to ten, with ten indicating highest energy security. The scale makes it easy to rank different countries according to their energy security status in a comprehensive manner. (Martchamadol & Kumar, 2013) A similar approach is used by Gnansounou (2011). (Gnansounou, 2011)

Jewell (2011) introduces a category scale aggregating different indicators for each technology. For the resulting categories, the range of indicator values observed is arbitrarily divided into low, medium, and high. This allows a "grading" of resulting indicator values. The method is explained in great detail allowing the reader to follow the arbitrary classification. However, the division and grading remains subjective in the end. (Jewell, 2011) An alternative ranking approach is presented by Sovacool and Brown (2011) who developed a method of ranking the energy security state of different countries without aggregating or weighing different indicators. For each indicator, the mean indicator value of all assessed countries is calculated. The countries are then ranked according to how many standard deviations they are above or below that mean. This method has the benefit of allowing for a relatively objective separate indicator-based comparison of different energy systems. However, it is not able to account for the interdependencies of different elements within the energy system. Interrelations between indicators are not addressed. (Sovacool & Brown, 2011)

Badea et al. (2011) develop an aggregation rule for different energy security indicators. Instead of using weights for different indicators, the aggregation rule is derived from the group decision theory and uses (subjective) risk-aversion levels of the decision makers to group indicators into risk-prone, risk neutral, and risk-averse. (Badea et al., 2011)

Hughes and Shupe (2011) present a generic framework to measure energy security of any given energy system. Derived from decision analysis, a decision matrix is developed mapping energy security choices and subjectively assigned weights. An algorithm helps to rank the choices and to arrive at a final decision on energy security. (Hughes & Shupe, 2011)

Only two approaches seem to limit the exposure to subjectivity in trying to objectively account for the dynamics and the interdependencies within energy systems and hence for the interdependencies and dynamics among energy security indicators and dimensions: Hughes (2012) uses structured system analysis techniques to assess the security of energy systems. Environmental and behavioural models of the system help him to depict relations between different system components. In other words he maps the components of the energy system and their relations with the help of stock and flow diagrams. (Hughes, 2012) Prambudia and Nakano (2012) take this technique one step further. With the help of a simulation model the authors try to simulate interdependencies of different indicators and dimension with the help of stock-and-flow diagrams and causal-loop diagrams. The influential direction of a relation between two indicators could however not always be defined by the authors. It is further questionable if the chosen modelling is a realistic depiction of the complex energy system. (Prambudia & Nakano, 2012) In illustrating the latter model, Figure 2-3 gives an idea of the complexity of system dynamics approaches.

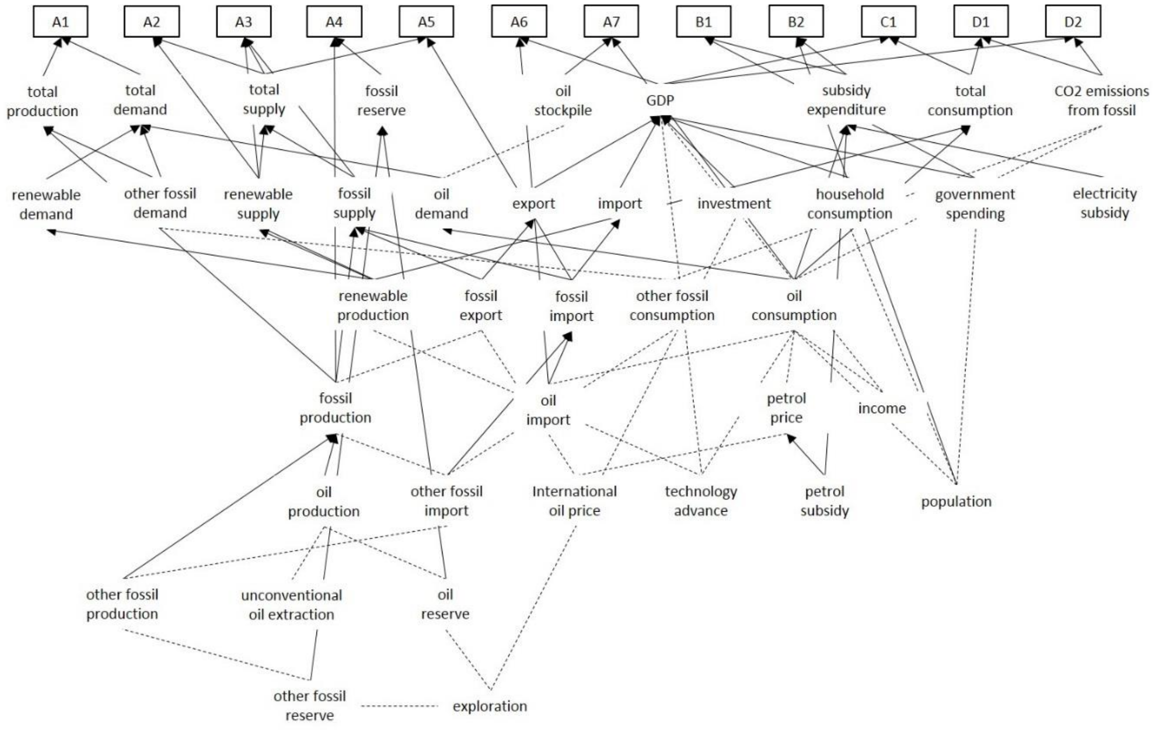
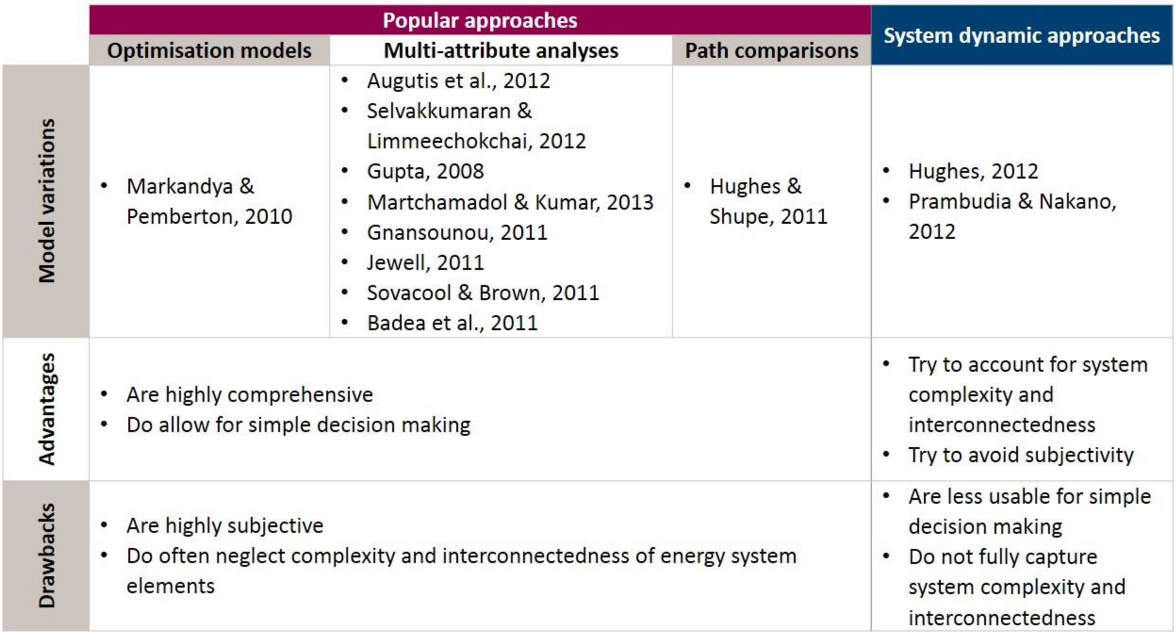


Figure 2-3: Part of the energy system model by Prambudia & Nakano (2012)

Arrows represent relationships between indicators and metrics, dotted lines represent interrelations with unclear influential direction; Boxes refer to indicators; Different capital letters indicate different dimensions

Source: Prambudia & Nakano, 2012

Figure 2-4 gives an overview on indicator aggregation approaches found in the reviewed literature. Generally only few scholars discuss system dynamics and interdependencies before aggregating dimensions and indicators in their approaches. Reviewing these approaches, it becomes clear that any scholar assessing energy security will face a trade-off between the comprehensiveness, the transparency, and the subjectivity of any indicator aggregation model. The more detailed relevant dimensions and indicators are assessed, the less straightforward the resulting outcome is. Similarly, the higher the degree of aggregation to ease decision making, the bigger the chances of concealing important aspects or misleading the decision maker through making subjective pre-choices. (Kruyt et al., 2009; le Coq & Paltseva, 2009; von Hippel et al., 2011) According to Sovacool (2012), it is crucial to find the right balance between usability and perfectibility when assessing energy security. (Sovacool, 2012)



	Popular approaches			System dynamic approaches
	Optimisation models	**Multi-attribute analyses**	**Path comparisons**	
Model variations	• Markandya & Pemberton, 2010	• Augutis et al., 2012 • Selvakkumaran & Limmeechokchai, 2012 • Gupta, 2008 • Martchamadol & Kumar, 2013 • Gnansounou, 2011 • Jewell, 2011 • Sovacool & Brown, 2011 • Badea et al., 2011	• Hughes & Shupe, 2011	• Hughes, 2012 • Prambudia & Nakano, 2012
Advantages	• Are highly comprehensive • Do allow for simple decision making			• Try to account for system complexity and interconnectedness • Try to avoid subjectivity
Drawbacks	• Are highly subjective • Do often neglect complexity and interconnectedness of energy system elements			• Are less usable for simple decision making • Do not fully capture system complexity and interconnectedness

Figure 2-4: Overview of different indicator aggregation approaches in the literature

Following the argumentation of Kruyt et al. (2009), I refrain to aggregate indicators for the purpose of my thesis[5]. I will instead analyse each indicator separately. I do this not because I think indicators are isolated in reality. Meadows (2008) convincingly argues that no part of any system can act in isolation. Consequently, system elements measured by one indicator interact with other parts of the system measured by other indicators. (Kruyt et al., 2009; Meadows, 2008) I refrain to aggregate indicators because an adequate depiction of the interrelations and dynamics within the assessed energy system would likely go beyond the scope of my thesis and any attempt to simplify these interrelations and dynamics would expose the analysis to the dangers of subjective choices and evaluations.

Analysing each indicator separately will not conceal the complexity of energy systems and energy security for the end of facilitating decision making but will address the system's complexity and shed lights on elements that should be accounted for in the decision making process. This will consequently lead to a longer and more complex decision making process. Decision making processes on complex subjects such as energy security ought not to be primarily quick and simple. They ought to deliver an optimal decision result. In order to do so, the decision maker should have unconcealed information about the single components. It is hence not the researcher's duty to predetermine a decision in aggregating indicators and in that way risking to mislead the decision maker. It is the researcher's duty to supply the decision maker with complete information necessary for the decision making process in order to achieve an optimal result adequate to the respective circumstances in which the decision takes place.

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[5] This does not mean that I refrain to aggregate *indicator values*. The indicator values for import dependency for instance are calculated on a decomposition level and then aggregated (according to the levels' shares) to a sector level. Similarly, indicator calculations might weigh and aggregate *indicator subcomponents*. Variety, balance, and disparity, for instance, are equally weighted and aggregated through multiplication to one diversity indicator. The relinquishment to aggregate or weigh indicators refers to the aggregation of indicators to draw a conclusion on energy security, e.g. to value import dependency twice as high as diversity of availability.

2.4 Deriving an Energy Security Assessment Approach

2.4.1 Approaches and Frameworks in the Literature

Based on the identified relevant components (energy security definitions, characteristics and dimensions; energy security indicators and indices; and indicator aggregation methods), some scholars have developed approaches and frameworks for an integrated energy security assessment.

Cherp and Jewell (2012) suggest a generic energy security assessment framework consisting of six main steps. First, methodological choices have to define what constitutes an energy security concern and what the appropriate level of detail for the assessment will be. Second, energy security has to be defined for the purpose of the assessment. Third, the assessed energy system has to be delineated. Fourth, vulnerabilities, i.e. threats to energy security, in the assessed energy system have to be identified. This step would allow an integration of vulnerabilities from different perspectives. Fifth, indicators for the defined vulnerabilities have to be identified and measured. Sixth, the indicator values have to be interpreted regarding the question posed by the assessment. The resulting framework is systematic enough to ensure scientific accuracy but flexible enough to account for particular circumstances and perspectives. (Cherp & Jewell, 2012) The framework hence presents a stepwise methodology to assess energy security in any given energy system. However, the framework requires a strict definition of energy security which is isolated from the system under analysis. The framework allows for a comparison of different energy systems or different energy security statuses of regions or nation states against the background of the same strict energy security definition. The framework might however fail to account for specific system features if only one energy system or different scenarios of one system are assessed. Implementations of the framework can be found in Cherp (2012) and Jewell (2011).

Cherp and Jewell (2011a) propose an approach that closely resembles this framework. Here the authors cluster system vulnerabilities according to storylines. These storylines resemble dimensions of energy security. Each storyline can be divided into three distinct mindsets resembling different perspectives on energy security. The resulting matrix should allow for a comprehensive structuring of energy security indicators. (Cherp & Jewell, 2011a)

Kruyt et al. (2009) present an energy security spectrum consisting of four classifications (availability, affordability, acceptability, and accessibility) derived from different definitions of energy security. Classifications are assumed to represent bigger global orientations such as globalisation or economic efficiency. Each classification that is regarded partially overlaps with two other classifications because the related global orientation overlaps with other global orientations as well. The remaining fourth classification is however assumed to be strictly antipodal to the regarded classification because the related global orientations are strictly antipodal to each other as well. (Figure 2-5). Energy security indicators can be structured according to the four classifications. Generally, the spectrum allows for an integration of different perspectives and dimensions of energy security in one assessment. Although the energy security spectrum is designed to assess long-term security of supply, it could also be applied for a broader assessment of energy security. (Kruyt et al., 2009) The acknowledgement of the overlapping of different energy security classifications seems valuable. As elaborated before, no system element can act in isolation. This makes it hard to draw rigid boundaries between classifications, dimensions, characteristics, or indicators. Because of the mentioned interconnectedness in any system, it is questionable whether two system elements can be regarded strictly opposed to each other as depicted in the spectrum by Kruyt et al. (2009). (Environmental) acceptability for instance does not necessarily contradict (economic) affordability. Especially if external costs are included in the examination, the influential relation could as well be positive. (among others: HEAL, 2013)

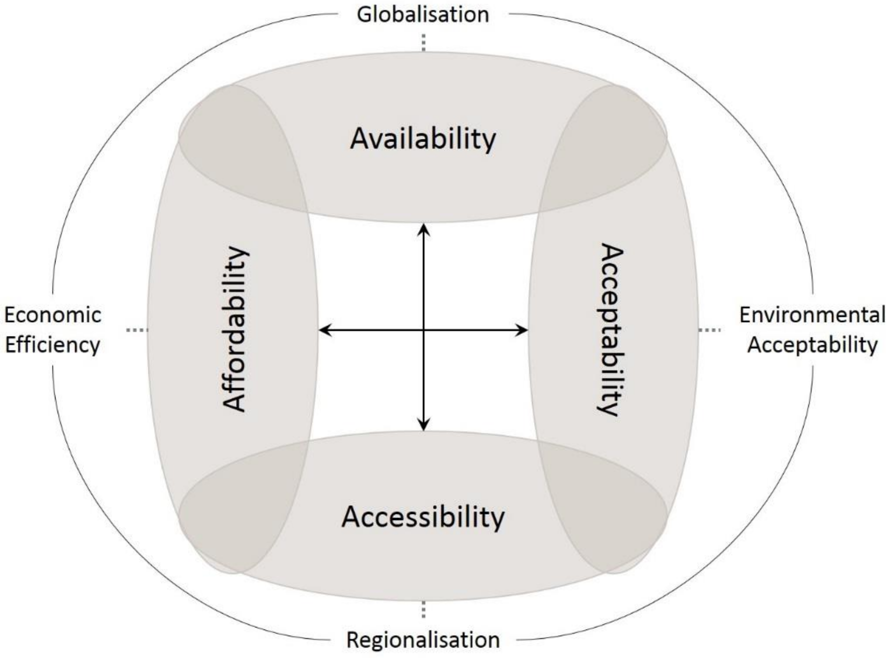


Figure 2-5: Energy security spectrum by Kruyt et al. (2009)

Grey ellipses depict energy security classifications; Text next to the ellipses represents global orientations related to the classifications

Souce: Kruyt et al., 2009

Jansen and van der Welle (2011) consider the demand for energy services the most important component to energy security. Different stakeholders have different requirements for useful energy services. Only if these requirements are met, energy security is given. The authors assess the whole value chain of providing an energy service with a set of indicators. (Jansen & van der Welle, 2011) Meeting the energy demand is crucial for any energy system, yet there might be relevant energy security aspects on the supply side of energy that do not appear when regarding the value chain of energy provision only. Winzer (2012) on the other hand presents a framework that assesses threats to supply security within three fields: source of risk, scope of impact, and severity of impact. Although different perspectives and dimensions are not explicitly addressed within the framework, they could be integrated into the sources of risks and the scope of the impacts. Indicators help to measure different risks, the scope, and severity of their impacts. This framework however neglects aspects related to the demand for energy services. (Winzer, 2012)

Reviewing the literature and existing frameworks and approaches in the field, it becomes clear that any general framework for assessing energy security has its drawbacks when being applied within a specific context or for a specific purpose. Approaches to assess energy security are therefore likely to be specifically designed according to the assessed system and the underlying objective of the assessment. For the purpose of my thesis, I therefore combine the advantages of the discussed general frameworks with elements accounting for the peculiarities of assessing energy security of a functioning energy system in Germany for the purpose of ImpRES in a hybrid approach. I apply this approach to the German heating sector, but it could generally also be applied to other energy systems in comparable countries to assess the impact of renewable energy technologies on energy security in these systems. At this stage, I want to point out that this hybrid approach has its drawbacks itself. I will discuss these in Chapter 5.

2.4.2 Creating a Hybrid Approach

No single approach found in the literature seems fully applicable to the assessment I like to carry out in this thesis. Yet, all of the discussed approaches contain elements I consider valuable for the purpose of my thesis.

The framework of Cherp and Jewell (2012) provides a clear structure for the methodological steps necessary to carry out an energy security assessment. (Cherp & Jewell, 2012) Yet, a strict definition of energy security seems inadequate due to the complexity of stakeholder requirements for different characteristics. It seems hence valuable to indirectly define energy security in mapping relevant characteristics and relevant dimensions of the concept. Identifying the relevant characteristics and dimensions requires a preceding delineation of the assessed energy system. The system under assessment has hence to be defined first before an energy security understanding can be derived.

Clustering indicators like in Cherp and Jewell (2011b) provides structure both for the researcher to carry out and for the reader to comprehend the assessment. Yet, contrary to Cherp and Jewell (2011b), it seems valuable to cluster the indicators according to dimensions and characteristics instead of clustering them according to dimensions and perspectives since many perspectives can be inherent in either characteristics or dimensions of energy security. The resilience perspective on energy security for example could be incorporated in the characteristic of diversity while the sovereignty perspective could be incorporated in the political dimension.

I agree with the partial overlapping of dimensions and characteristics as seen in Kruyt et al. (2009), for it can be difficult to specifically assign indicators to one characteristic and one dimension only. It also seems valuable to incorporate both the supply and demand side of energy (services) and associated risks into an energy security analysis.

Based on these prerequisites and the reviewed literature, I developed the following hybrid energy security assessment approach for the purpose of my thesis (Figure 2-6):

1. Depicting the status quo in the German heating sector, its subsectors, its end-uses for energy, and the applied technologies for heat generation to understand the system under analysis.

2. Creating two sector scenarios of the German heating sector with the same end-use energy volume; one scenario being comprised of fossil-based technologies only; the other being a simplified depiction of the status quo that comprises fossil-based and renewable energy technologies. In a comparative analysis, the difference in energy security between the two scenarios can be attributed to the deployed renewable energy technologies.

3. Breaking down the German heating sector into different decomposition levels to reduce its complexity and to allow for an energy security analysis of each level.

4. With the help of literature review and expert interviews identifying relevant characteristics and dimensions of energy security in the German heating sector to derive an energy security understanding for the purpose of my assessment.

5. Based on literature review and expert interviews, select relevant indicators according to the requirements defined by the identified dimensions, characteristics, and relevant technologies in the German heating sector.

6. Collecting data and calculating indicator values for each decomposition level to allow for a level analysis and interpret energy security on a technology-basis.

7. Adding indicator values according to the shares of different technologies on a sector level to allow for a scenario analysis on an indicator-basis without aggregating different indicators.

8. Comparing and analysing the different scenarios by measuring the differences in indicator values to draw conclusions on the impact of renewable energies in the German heating sector.

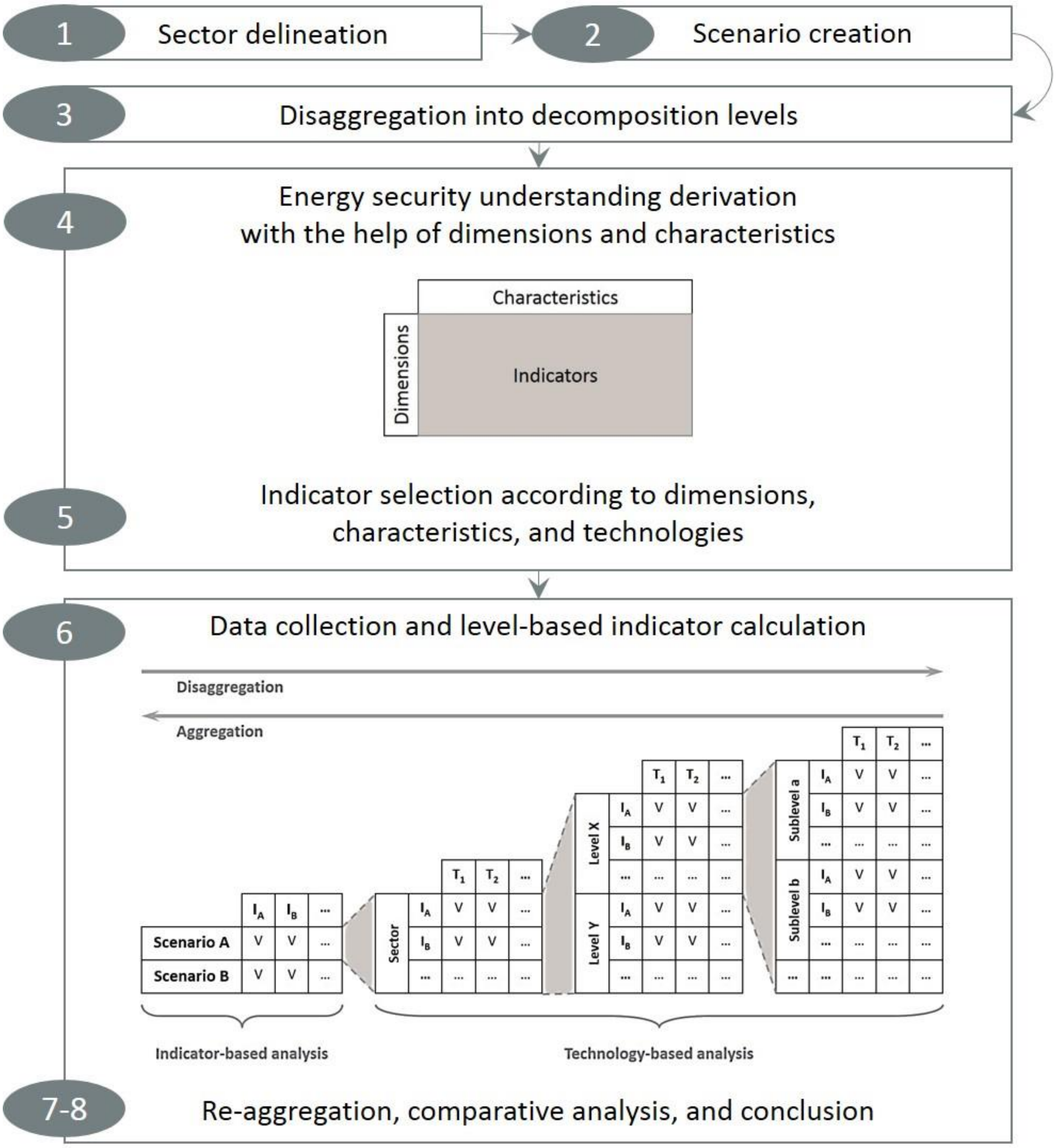


Figure 2-6: Hybrid energy security assessment approach for the purpose of this thesis

I = indicator, T = technology, V = indicator value

3 An Energy Security Assessment Framework for the German Heating Sector

3.1 Sector Delineation and Status Quo

The German heating sector is highly decentralised. Over 90% of the final energy demand for thermal energy is provided by building integrated generating technologies. The remaining 9.43% of the thermal energy is produced in centralised generation plants and fed into local or regional district heating networks. (AGEB, 2013; Steinbach et al., 2013)

The heating sector is commonly divided into three main subsectors: industry, service sector, and households. The composition of these sectors is outlined in Figure 3-1. Since the vast majority of available data sets are based on this division, I will stick to the same subsector differentiation within my thesis. Traffic, a fourth sector that is sometimes mentioned in the literature, is neglected in this thesis due to its insignificantly small end-use of thermal energy. (AGEB, 2013)

Industry	**Service Sector**	**Households**
- mining - food and tobacco industry - paper mills - chemical industry - rubber and plastic industry - glass and ceramic industry - metal industry - plant construction and engineering - vehicle construction - other industries	- building sector - office businesses - manufacturing business - trade - hospitals, schools, bathhouses - hotels, hostels, and restaurants - bakeries and butcheries, other food shops - laundry shops - agriculture and horticulture - airports - textile and leather shops - hauliers - other services	- all private households

Figure 3-1: Compositions of the main subsectors in the German heating sector

Source: AGEB, 2013; ISI, 2012; LfE, 2012; RWI, 2012

The final energy consumption in the German heating sector consists of five main end-uses: space heating, space cooling, process heat, process cooling, and hot water. Figure 3-2 shows how these end-uses are distributed among the different subsectors. Renewable energies account for only 0.1 PJ in cooling technologies. Due to the insignificantly small share of renewable energy technologies for these end-uses, I will neglect space cooling and process cooling for the scope of my thesis. Space heating, process heat and hot water accounted for an end-use of thermal energy of 4 614.6 PJ in 2011. (AGEB, 2013)

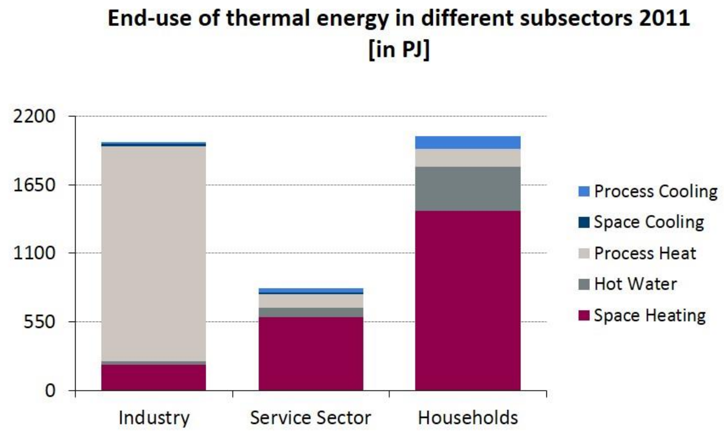


Figure 3-2: End-use of thermal energy in different subsectors 2011

Source: AGEB, 2013

For the remaining end-uses, eight technologies are relevant: electricity, natural gas, oil, and coal firing, and four renewable energy technologies (biomass (9.09%) and biogas (0.98%) firing, geothermal (0.71%) and solar thermal (0.44%) heating. (AGEB, 2013; BMU, 2013) The distribution of these technologies is shown in Figure 3-3. Detailed data for the energy mix in the German heating sector for 2011 can be found in Appendix I.

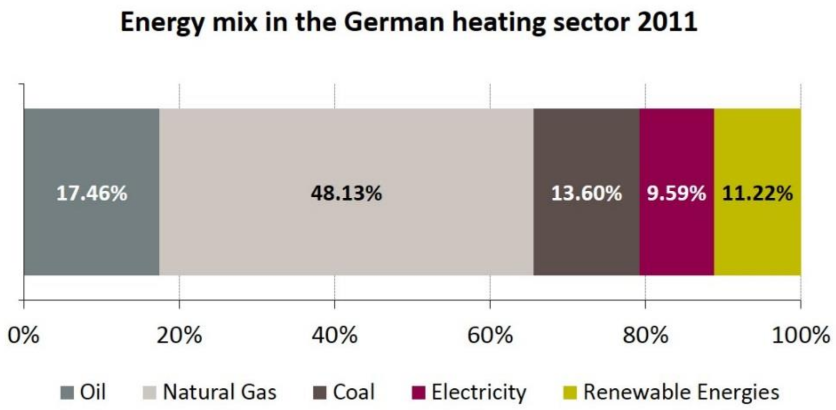


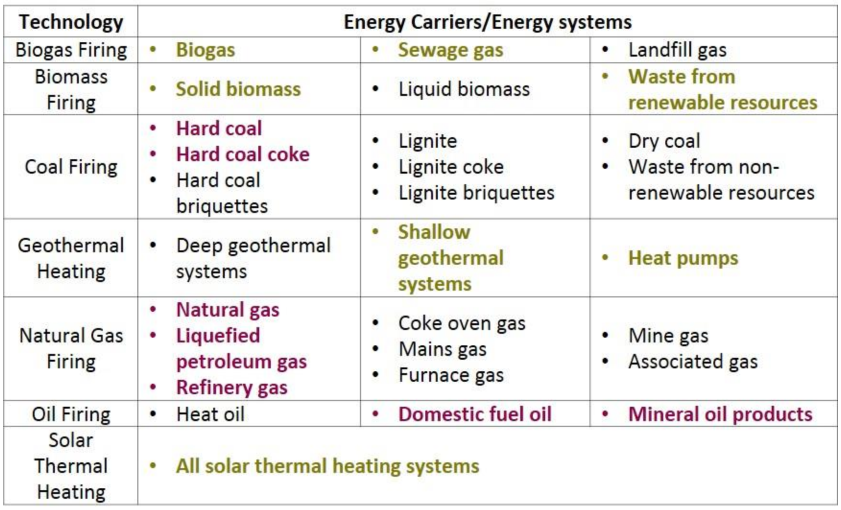
Figure 3-3: Energy mix in the German heating sector

Source: AGEB, 2013; BMU, 2013; ISI, 2012; LfE, 2012; RWI, 2012; Steinbach et al., 2013

Although thermal energy directly generated by electricity constitutes almost ten per cent of the energy mix in the sector, I will not further discuss or analyse heat directly generated from electricity in my thesis. I do this to maintain simplicity. Electricity generation can be based on similar technologies to heat generation such as coal or gas firing. But it might also be based on specific technologies such as wind power, photovoltaic, or nuclear energy. (AGEB, 2013; BMWi, 2013) Such specific technologies also embody specific characteristics different from those of heat generation technologies. Combining an analysis of heat and electricity generating technologies would require a set of characteristics, dimensions, and indicators specific enough to appropriately account for the peculiarities of inherently different generation technologies and flexible enough to be valid for each of these technologies. (Cherp & Jewell, 2012) The resulting analysis is not likely to be meaningful to assess energy security in the German heating sector.

The analyses of the power and the heating sector in Germany should therefore be strictly separated even if the hybrid energy security assessment approach presented in my thesis could generally be applied to the power sector as well. However, electricity does play a significant role in powering heat pumps. (Recknagel et al., 2012)Therefore price and efficiency data for electricity is included when assessing heat pumps.

In this thesis, I follow the aggregation rules of AGEB (2013) and BMU (2013), according to which one technology can comprise several energy carriers. Figure 3-4 maps the aggregation of different energy carriers in the sector as applied in my thesis. The main energy carriers in every technology have been highlighted green for renewable technologies and red for conventional technologies. (AGEB, 2013; BMU, 2013)



Technology	Energy Carriers/Energy systems		
Biogas Firing	• **Biogas**	• **Sewage gas**	• Landfill gas
Biomass Firing	• **Solid biomass**	• Liquid biomass	• **Waste from renewable resources**
Coal Firing	• **Hard coal** • **Hard coal coke** • Hard coal briquettes	• Lignite • Lignite coke • Lignite briquettes	• Dry coal • Waste from non-renewable resources
Geothermal Heating	• Deep geothermal systems	• **Shallow geothermal systems**	• **Heat pumps**
Natural Gas Firing	• **Natural gas** • **Liquefied petroleum gas** • **Refinery gas**	• Coke oven gas • Mains gas • Furnace gas	• Mine gas • Associated gas
Oil Firing	• Heat oil	• **Domestic fuel oil**	• **Mineral oil products**
Solar Thermal Heating	• **All solar thermal heating systems**		

Figure 3-4: Technologies and corresponding energy carriers and systems in the German heating sector

Source: AGEB, 2013; BMU, 2013

Gas firing can be based on **natural gas** or **biogas** that is burned in gas-condensing boilers to heat a heat transfer medium like air or water in a closed heating system. The most common heat transfer medium in Germany is water. Some households, mainly in old buildings, use gas-fired furnaces to directly heat the inside air. (Recknagel et al., 2012) **Oil** firing systems work similar to gas heating systems. Heating oil is burned in condensing boilers to heat a heat transfer medium in a closed system. (Recknagel et al., 2012)

Coal and **biomass** firing follow the same principle. Coal or biomass is used in boilers to heat a heat transfer medium which is usually water or air in a closed system. The most common biomass used in Germany is wood in the form of firewood, wood chips, and wood pellets. Some households, mainly in old buildings, use wood- and coal-fired furnaces to directly heat the inside air. (Recknagel et al., 2012)

In **solar thermal** heating systems, solar thermal collectors, usually mounted on a roof or on special racks, collect thermal energy from sunlight. The absorbed sunlight heats a heat transfer medium which most commonly is water or air. (Miller & Spoolman, 2009; Recknagel et al., 2012)

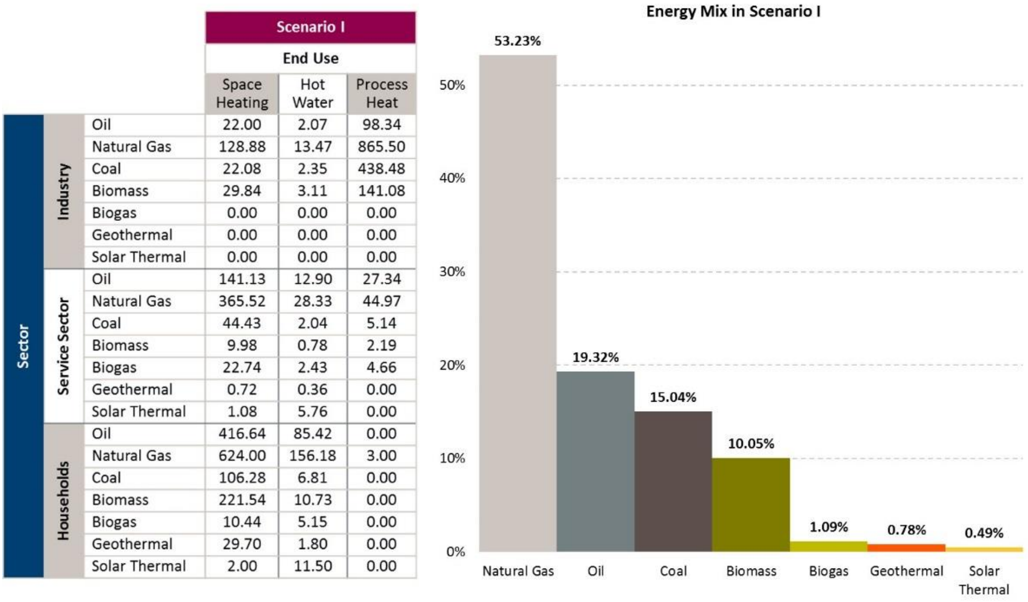
We distinguish two major **geothermal** technologies: deep geothermal systems and shallow geothermal systems or heat pumps. Deep geothermal systems operate in depths of 500 to 5 000 m. Heat energy is in a constant flow from the Earth's interior (~ 6 000 °C) to the surface.

Close to active tectonic plates water can enter deep into the fracture rock zones and form high temperature systems of hot water or pressurised steam. Deep drillings allow extracting this energy source where geological conditions are favourable. (IEA, 2007b; Miller & Spoolman, 2009) In Germany, deep geothermal systems generally directly supply district heating networks, thermal baths or directly heat buildings. (Hofmann et al., 2013) Shallow geothermal systems extract ambient heat from depths of about three to six metres. Heat pumps allow exploiting the temperature differences between the Earth's surface and the underground. Low temperature heat from soil, rock, and underground water can be transported to the surface level where it can be used for space or water heating. In summer, when surface temperatures are high and ground temperatures are lower, shallow geothermal system circulate a heat carrier fluid through the heat pump transporting the surface heat into the ground to be stored for extraction in winter when surface temperatures are low and ground temperatures are higher. (IEA, 2007b; Miller & Spoolman, 2009; Recknagel et al., 2012)

3.2 Two Sector Scenarios for 2011

To measure the impact of renewable energy technologies on energy security in the German heating sector, I created two sector scenarios. Scenario I contains both, conventional and renewable energy technologies for heat generation. Scenario II is based on conventional energy technologies for heat generation only. To maintain simplicity, I assume there are no energy losses from the generation to the end-use of thermal energy. This assumption for the scenario creation has no impact on the assessment. When assessing single technologies within each scenario, the respective conversion efficiency and hence the energy losses are accounted for.

Scenario I is a simplification of the status quo in German heating sector. I subtracted the share of electricity from the energy mix for space heating, hot water, and process heat of 2011. Besides, I also itemised the shares of district heating and renewable energies into their respective technologies. The resulting end-use of thermal energy in Scenario I is roughly 4 170 PJ. Since I assume no energy losses, the energy input in Scenario I equals 4 170 PJ as well. Figure 3-5 maps the resulting energy mix for Scenario I in detail.

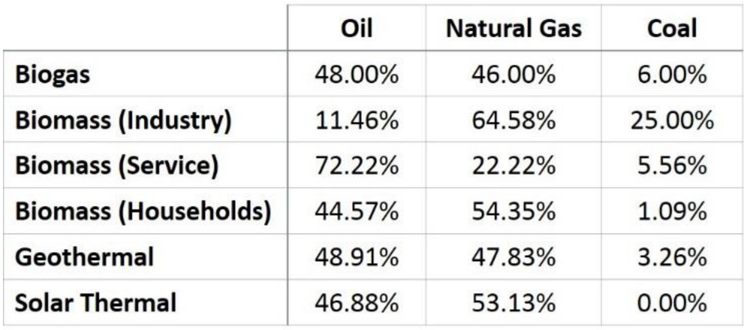


			Scenario I		
			End Use		
			Space Heating	Hot Water	Process Heat
Sector	Industry	Oil	22.00	2.07	98.34
		Natural Gas	128.88	13.47	865.50
		Coal	22.08	2.35	438.48
		Biomass	29.84	3.11	141.08
		Biogas	0.00	0.00	0.00
		Geothermal	0.00	0.00	0.00
		Solar Thermal	0.00	0.00	0.00
	Service Sector	Oil	141.13	12.90	27.34
		Natural Gas	365.52	28.33	44.97
		Coal	44.43	2.04	5.14
		Biomass	9.98	0.78	2.19
		Biogas	22.74	2.43	4.66
		Geothermal	0.72	0.36	0.00
		Solar Thermal	1.08	5.76	0.00
	Households	Oil	416.64	85.42	0.00
		Natural Gas	624.00	156.18	3.00
		Coal	106.28	6.81	0.00
		Biomass	221.54	10.73	0.00
		Biogas	10.44	5.15	0.00
		Geothermal	29.70	1.80	0.00
		Solar Thermal	2.00	11.50	0.00

Figure 3-5: Energy mix for Scenario I [in PJ]

Source: Based on AGEB, 2013; ISI, 2012; LfE, 2012; RWI, 2012, Steinbach, 2013; Rounding errors might occur due to different data bases.

Conventional technologies for heat generation can generally be substituted with renewable energy technologies and vice versa. Memmler et al. (2009) analysed the German heating sector to empirically determine which renewable energy technology is most likely to substitute conventional technologies in the short-term and vice versa. Operators of thermal energy generation technologies in the industry, the service, and the household sector were asked with which readily available technology they would replace their current technology. The substitution likelihood mainly depended on economic and technical feasibility as well as on the energy efficiency of available options. Based on the operators' answers and the technological feasibility of replacement, the authors developed a substitution factor matrix for technologies in the heating sector. Figure 3-6 maps the resulting substitution factors for renewable energy technologies. Solar thermal energy would for instance substitute 46.88% oil and 53.13% natural gas. (Memmler et al., 2009)



	Oil	**Natural Gas**	**Coal**
Biogas	48.00%	46.00%	6.00%
Biomass (Industry)	11.46%	64.58%	25.00%
Biomass (Service)	72.22%	22.22%	5.56%
Biomass (Households)	44.57%	54.35%	1.09%
Geothermal	48.91%	47.83%	3.26%
Solar Thermal	46.88%	53.13%	0.00%

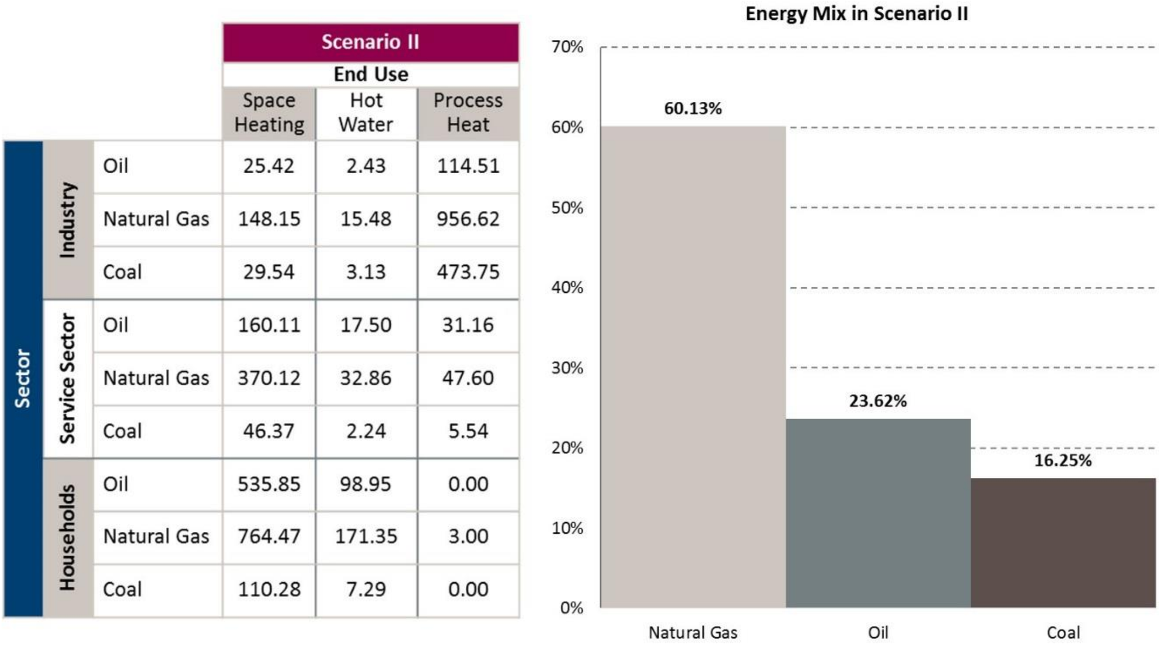
Figure 3-6: Substitution factors for renewable energy technologies

District heating and electricity have been neglected as substitution options; the exceeding of 100% might occur through rounding errors; where differences between sectors are insignificant, average values have been used without further sector differentiation.

Source: Memmler et al., 2009

Based on the end-use of thermal energy from Scenario I, Scenario II is created in substituting each renewable energy technology with the respective shares of conventional energy technologies according to these substitution factor. For example, one PJ of biogas is substituted with 0.48 PJ of oil, 0.46 PJ of natural gas, and 0.06 PJ of coal. Biomass is substituted according to its shares in the three subsectors. The resulting energy mix is depicted in detail in Figure 3-7. The resulting end-use and hence also the input of thermal energy in Scenario II is, similar to Scenario I, roughly 4 170 PJ.

Since both scenarios are based on the same end-use energy volume, I am able to derive the energy security impact of renewable energy technologies through an indicator-based comparative analysis of the two scenarios.



			Scenario II		
			End Use		
			Space Heating	Hot Water	Process Heat
Sector	Industry	Oil	25.42	2.43	114.51
		Natural Gas	148.15	15.48	956.62
		Coal	29.54	3.13	473.75
	Service Sector	Oil	160.11	17.50	31.16
		Natural Gas	370.12	32.86	47.60
		Coal	46.37	2.24	5.54
	Households	Oil	535.85	98.95	0.00
		Natural Gas	764.47	171.35	3.00
		Coal	110.28	7.29	0.00

Figure 3-7: Energy mix for Scenario II [in PJ]

Source: Based on AGEB, 2013; ISI, 2012 & 2013; LfE, 2012; RWI, 2012, Steinbach, 2013; Rounding errors might occur due to different data bases.

3.3 Relevant Decomposition Levels

In the previous sections, I broke down the German heating sector and the two scenarios derived from it into three subsector levels (industry, service sector, and households) and into three end-use levels (space heating, hot water, and process heat).

For the purpose of my thesis, it seems valuable to specifically analyse subsector-end-use-combinations, i.e. decomposition levels, in which renewable energies play a significant role. Figure 3-8 maps the absolute and relative contribution of renewable energies to end-uses in different subsectors. Decomposition levels in which renewable energies contribute less than 10.00 PJ will not be analysed in detail even if their relative contribution in the sublevel is bigger than 10.00%. This decision has mainly been made to maintain simplicity in the assessment. It does not affect the final sector and scenario-level assessment since at these higher levels, the neglected sublevels are included in the assessment. In Figure 3-8, sublevels which will not be analysed in detail are shaded in grey. These sublevels are however accounted for in the aggregated analysis on a sector- and scenario-level.

	Space Heating	**Hot Water**	**Process Heat**
Industry	29.84 PJ (14.72%)	3.11 PJ (14.79%)	141.08 PJ (9.14%)
Service Sector	34.52 PJ (5.99%)	9.33 PJ (17.75%)	6.85 PJ (8.12%)
Households	263.68 PJ (18.69%)	29.18 PJ (10.51%)	0.00 PJ (0.00%)

Figure 3-8: Absolute and relative contribution of renewable energies to end-uses in different subsectors

Source: AGEB, 2013; ISI, 2012; LfE, 2012; RWI, 2012

The relevant decomposition levels for my thesis are hence space heating in industry, service sector, and households, hot water in households, and process heat in industry. Each technology will first be assessed for each indicator. Following this analysis, each decomposition level will be analysed on a technology and an indicator-basis. Finally, a comparative analysis will compare both scenarios on an indicator-basis.

3.4 Relevant Energy Security Characteristics and Dimensions

The reviewed literature adduces good reasons for rejecting a strict definition of energy security in favour of defining the concept of energy security through characteristics and dimensions.

3.4.1 Characteristics

Fifteen commonly used characteristics have been identified from the literature: acceptability, accessibility, adequacy, affordability, availability, controllability, diversity, efficiency, feasibility, indigenous, reliability, sustainability, timeliness, quality, and utility.

With the German heating sector, I assess an energy system based on established technologies. Even the creation of two scenarios for the purpose of this assessment does not change the nature of technology components and does not significantly alter their share in the system. These technologies have hence proven feasible to reliably deliver useful and controllable energy of adequate quality in a timely manner. Thus, the characteristics **adequacy, controllability, feasibility, reliability, timeliness, quality, and utility** can assumed to be given and are not relevant for the purpose of this assessment. However, these characteristics could become valuable when assessing future scenarios comprising new technologies or significantly changing the share of certain technologies.

At this stage, I want to point out that the fact that these characteristics are given does not mean the heating sector is optimised regarding them. The degree to which the requirements inherent in these characteristics are met, depends on past decisions. The way a system and its components are designed and structured can result in a strong path dependency on this underlying structure. The resulting system might be far from an optimal solution. (Meadows, 2008) My thesis does generally not refer to an optimal solution but to ordinal scales when assessing characteristics, dimensions, and indicators to analyse energy security.

Although the concept of **sustainability** itself has a broad range of definitions, Indriyanto et al. (2011) show that it can be integrated into different dimensions such as a social, an economic, and an environmental dimension. (Indriyanto et al., 2011) Keeping the term in perspective, it mainly describes the ability of a system to endure. Blum and Legey (2012) describe three co-constituting properties necessary for the ability of a system to endure: resilience, adaptability, and transformability. Resilience is the capability of the system to absorb disturbances, adaptability is the capability of actors in the system to influence resilience, and transformability is the capability of creating a fundamentally new system if external circumstances require this. (Blum & Legey, 2012) According to Meadows (2008), any system might be limited in its survival capacities. (Meadows, 2008) Taking a broader time perspective, it might therefore be debatable whether the German heating sector as a whole is resilient enough to endure. In my assessment however, I compare two scenarios of a functioning system with established technologies at the same point in time which lies in the past. For this specific point in time, I assume this energy system to be designed to survive and thus I consider the characteristic of sustainability as given. What colloquially is referred to as sustainability, highly correlates with acceptability and can hence be regarded inherent in that characteristic.

From a geopolitical perspective and a political dimension, it might make sense to consider **indigenous** energy carriers and technology components as securer, since the probability for hostile actions through malevolent agents to occur is significantly smaller if a resource does not have to be sourced from abroad. (Cherp, 2012; Cherp & Jewell, 2011b) This does not make domestic energy carriers securer per se. Solar thermal energy for example can domestically be sourced but bears insecurities due to its intermittent natural availability. Indigenous alone can hence not be regarded as a necessary energy security characteristic. (Pasuqaletti, 2011) What colloquially is referred to as indigenous security, highly correlates with political accessibility and natural availability. For the purpose of my thesis, I will therefore include the indigenous element of energy security in the political and the natural dimension as well as in the characteristics of accessibility and availability, but not as a separate characteristic.

Six of the fifteen identified characteristics remain relevant for assessing the German heating sector: acceptability, accessibility, affordability, availability, diversity, and efficiency.

According to APERC (2007), **acceptability** refers to negative environmental impacts of an energy system's components. (APERC, 2007) As defined in my thesis, acceptability also concerns negative impacts of different heat generation technologies on other systems such as the environment, the society, or the economy. The bigger the harm of one system element is to the environment, the society or other systems the higher is the threat to energy security.

According to APERC (2007), **accessibility** refers to barriers to accessing energy resources. (APERC, 2007) These barriers are commonly referred to as geopolitical barriers but may include technical barriers as well. (Hughes & Shupe, 2011) The less accessible relevant resources for energy generation are the higher is the threat to energy security. The more accessible these resources are on the other hand the higher is the energy security status of the system.

Affordability incorporates economic attributes such as fluctuations in fuel prices or production costs. (Kruyt et al., 2009) The less affordable relevant resources for energy generation are, i.e. the more their prices fluctuate, the higher is the threat to energy security. The more affordable these resources are however the higher the energy security status of the system.

The characteristic of **availability** was initially defined by APERC (2007) with a focus on oil and other fossil fuels. (APERC, 2007) For Kruyt et al. (2009), the term comprises all elements relating to geological existence. (Kruyt et al., 2009) For this thesis, I stick to the latter definition and define availability as concerning the geological or natural existence of relevant resources for different heat generation technologies. An energy source or important technology components have to be geologically existent in order to generate energy. If the geological or natural existence of a resource relevant for energy generation is threatened, energy security is consequently threatened as well.

Increasing **diversity** is a strategy rooted in economic theory to deal with incomplete knowledge about the probability or the outcome of a (decision related) event. (Brealey et al., 2007; Mankiw & Taylor, 2011) The literature distinguishes four aspects of incomplete knowledge: risk, uncertainty, ambiguity, and ignorance. We face risk, when both, probability and outcome of the event are known. With uncertainty, we know the outcome of the event but we do not know its probability. We talk about ambiguity, when we know the probability of the event but we cannot be sure about its outcome. And ignorance is referred to a state in which we neither know about the probability nor about the outcome of an event. Increasing the diversity of a system will make it more resistant regardless of which aspect of incomplete knowledge the system has to face. Any increase in diversity within an energy system will hence immediately increase energy security. This does not mean that any additional option does per se increase energy security.

Important is a significant increase in diversity. (Stirling, 2011) Stirling (1994 & 2011) identifies three co-constituting properties of diversity (Figure 3-9): variety, balance, and disparity. Variety refers to the number of diverse options. Balance refers to the evenness in contribution of these options. And disparity refers to the degree of difference between these options. (Stirling, 1994 & 2011) For the purpose of my thesis, I will stick to Stirling's definition of diversity.

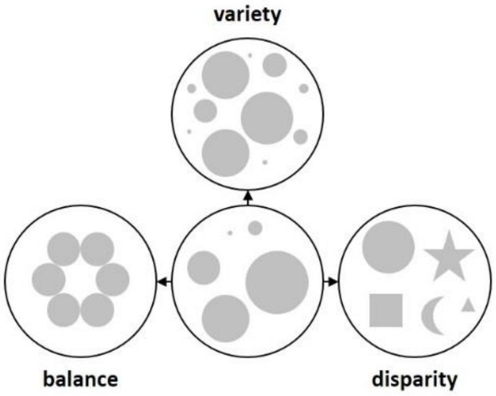


Figure 3-9: Schematic depiction of three co-constituting properties of diversity

Source: Stirling, 2011

Increasing **efficiency** is a classical economic strategy to hedge against resource and technology related risks. Efficiency can be understood in many ways. For the purpose of my thesis, I stick to a technological understanding of efficiency: (1) achieving the same outcome with less input, i.e. reducing the overall need for energy; or (2) achieving a higher outcome with the same input, i.e. making better use of the resource and the technology. (Mankiw & Taylor, 2011) For any given point in time, the more efficiently single system components work and, respectively, the more efficiently the whole energy system is, the lower is the threat to energy security. For a period of time however, this does not necessarily have to hold true. Over time, any increase in energy efficiency can be outweighed by an increase in the energy consumption of the actors within the system. (Meadows, 2008)

Figure 3-10 shows the importance interviewees assign to the chosen six characteristics. The quadrangle depicts the mean importance assigned by the group of interviewees, the grey line depicts the highest and lowest importance value assigned to the respective characteristic. The importance interviewees assign to the single characteristics highly correlates with the frequency these characteristics appear in the reviewed literature (see Chapter 2). Affordability and acceptability are rated to be the most important characteristic with the smallest variance in interviewee answers. Accessibility, and availability are regarded as almost equally important by the group of interviewees. The two least important characteristics according to the group of interviewees are diversity and efficiency. However, the variances show that the importance of diversity was more contested among the interviewees and could be rated from *unimportant for* to *critical to* energy security. All of the six chosen characteristics are on average rated *important for*, *very important for,* or *critical to* energy security. I will hence include all six characteristics in my assessment.

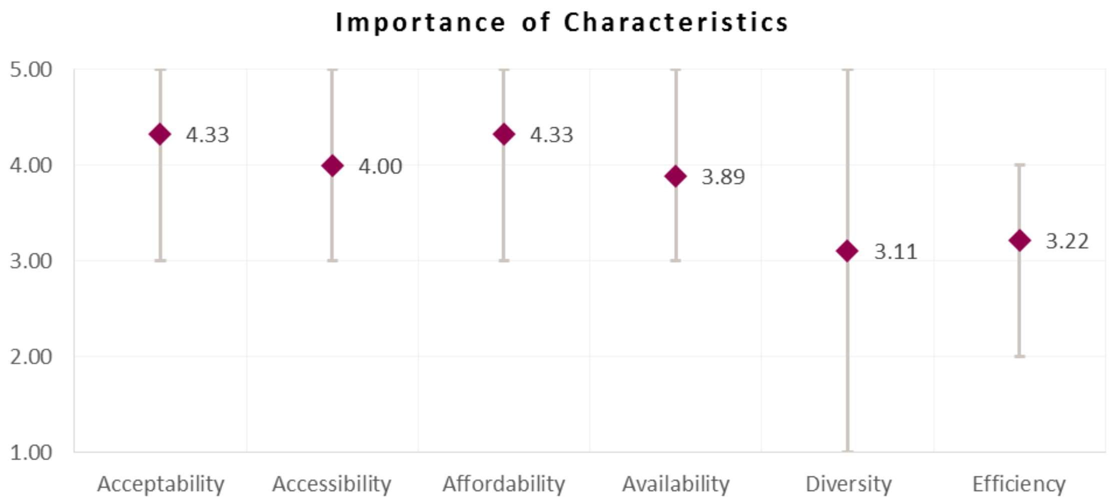


Figure 3-10: Mean, highest, and lowest importance of characteristics according to interviewees

1 = unimportant, 2 = slightly important; 3 = important; 4 = very important; 5 = critical

3.4.2 Dimensions

Besides the characteristics, the literature review has identified six main dimensions of energy security. Depending on the purpose and the audience of the assessment, some scholars only discuss a limited part of the set of dimensions while others further break down the whole set or parts of it into more dimensions. For the purpose of this assessment, I will stick to the complete set of dimensions: a natural, an environmental, an economic, a technical, a societal, and a political dimension. Following Kruyt et al. (2009), the assessment of my thesis does not draw rigid boundaries for each dimension. An overlapping of two or more dimensions is generally possible. (Kruyt et al., 2009) Recalling the way I defined dimension in Chapter 2, this has naturally to be the case since the same stakeholder might be part of two or more stakeholder groups represented in the dimensions. Each member of a society, for instance, is likely to be a member of the economy in either or the other way, just as she is standing in a relationship with her environment. Yet, for the purpose of depiction, I define the dimensions separately.

The **natural** dimension comprises elements related to the natural and geological occurrence of relevant resources required for different heat generation technologies. The **environmental** dimension comprises elements that affect the environment such as water and land use for different heat generation technologies or their emissions to air and water. The **societal** dimension takes into account elements that affect the society such as health impacts or employment effects from different heat generation technologies. The **political** dimension mainly deals with elements that affect the political system such as important relations to third parties for the supply and deployment of different heat generation technologies while the **technical** dimension is primarily concerned about elements related to the (functioning of the) system infrastructure of different heat generation technologies. The **economic** dimension cares mainly about economic elements of different heat generation technologies such as fuel prices and their volatility or component and production cost fluctuations. (among others: Brown & Dworkin, 2011; Cherp & Jewell, 2011a; Indriyanto et al., 2011; von Hippel et al., 2011; Winzer, 2012)

Figure 3-11 shows that the interviewees confirm the choice to include all six dimensions in the assessment. All dimensions are on average rated to be *important* or *very important for* energy security. Again, the importance interviewees assign to the single dimensions highly correlates with the frequency these dimensions appear in the reviewed literature (see Chapter 2).

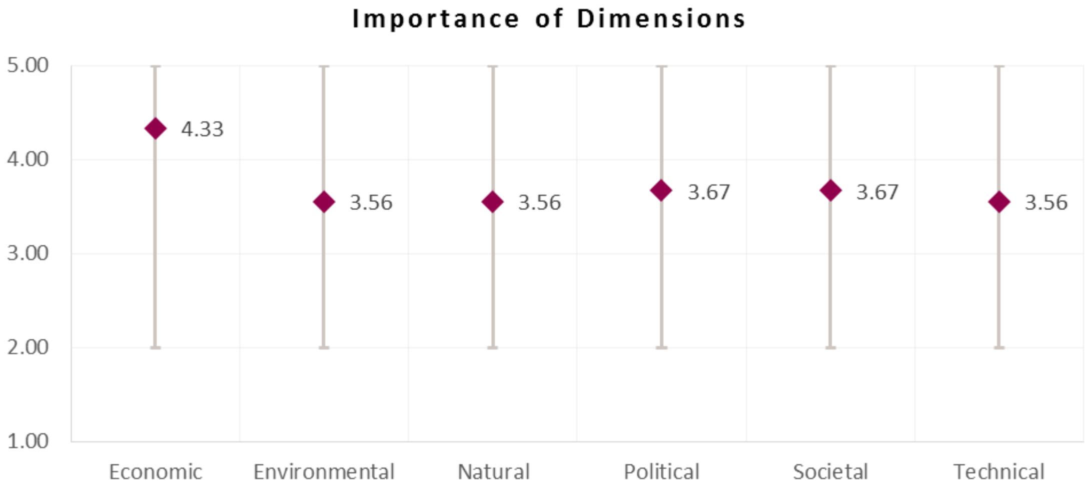


Figure 3-11: Mean, highest, and lowest importance of dimensions according to interviewees

1 = unimportant, 2 = slightly important; 3 = important; 4 = very important; 5 = critical

Including all relevant characteristics and dimensions of energy security in the assessment, the resulting matrix for an energy security assessment of the German heating sector is comprised as depicted in Figure 3-12.

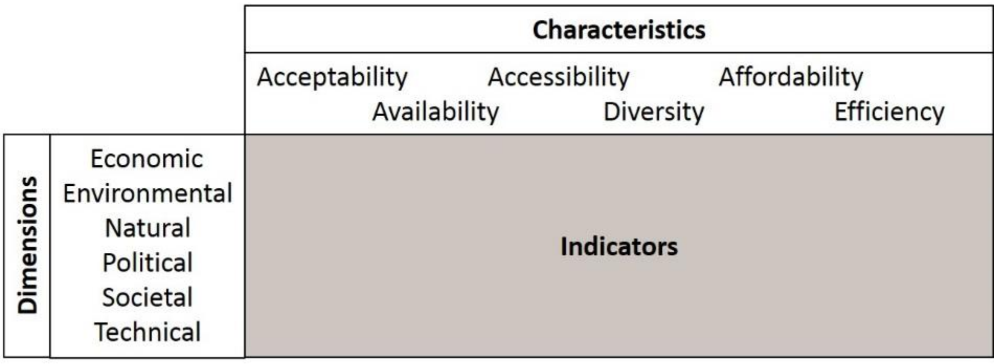


Figure 3-12: Matrix of relevant characteristics and dimensions of energy security in the German heating sector

3.5 Relevant Energy Security Indicators and Indices

3.5.1 Relations of Indicators, Dimensions, and Characteristics

The way this energy security assessment approach is structured, the set of relevant indicators[6] has to fulfil a top-down and a bottom-up selection requirement. The matrix of relevant dimensions and characteristics constitutes the top-down requirement. The resulting complete set of relevant indicators has to account for each of the dimensions and characteristics defined by the hierarchy of the assessment approach. This means that for each dimension and for each characteristic, there needs to be at least one indicator in the matrix. The technologies in the German heating sector constitute the bottom-up requirement. This means that the resulting complete set of indicators has to account for specific technology characteristics relevant to energy security but at the same time the set has to be valid for all technologies. This means that

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[6] I do not further differentiate between indicators and indices. The two terms are used interchangeably.

each indicator has to be valid for every technology. Both requirements are indispensable. To allow for a comparative analysis, the resulting set of indicators has to be applied on each decomposition level and for both scenarios.

From reviewing the literature, I identified the indicators mapped in Figure 3-13 and Figure 3-14 as relevant to assessing energy security in the German heating sector and to fulfilling all selection requirements. (among others: Cherp & Jewell, 2011a; Jewell, 2011; Kruyt et al., 2009; Martchamadol & Kumar, 2012 & 2013; Sovacool, 2013; Sovacool & Mukherjee, 2011) The list should be regarded as non-exclusive and could be broadened in future assessments. Figure 3-13 depicts to which dimensions the single indicators can be assigned. The dimensions – even if depicted separately – often overlap and are interrelated like any other system element. (Meadows, 2008) This interrelation is depicted by grey connection lines. Some indicators can be assigned to several dimensions. I only address the main relations between indicators and dimensions. Since dimensions are interrelated and sometimes overlap, an indicator could possibly be assigned to more dimensions than addressed in this thesis. Figure 3-13 shows that the first part of the top-down requirement is fulfilled: for each dimension there is at least one indicator in the indicator set. In the next section, the indicators are explained in detail.

Additionally, Figure 3-13 maps the indicators' correlation with energy security. Red text indicates a negative correlation between the indicator and energy security, i.e. the higher the indicator value, the lower the energy security stage and vice versa. Green text indicates a positive correlation between the indicator and energy security, i.e. the higher the indicator value, the higher the energy security stage and vice versa.

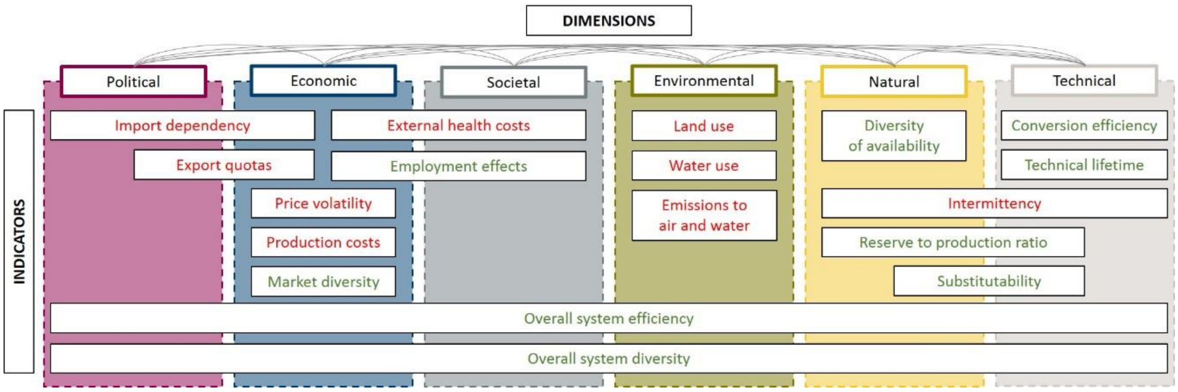

Figure 3-13: Relevant indicators and their main relation to dimensions; correlations with energy security

Red text indicates a negative correlation between the indicator and energy security; green text indicates a positive correlation between the indicator and energy security

Figure 3-14 maps the relevant energy security indicators and their corresponding characteristics. Again, one indicator might incorporate multiple characteristics. I only discuss the main relations between indicators and characteristics. Since all system elements – and hence also energy security characteristics – are interrelated, one indicator might however be related to more than the discussed characteristics. (Meadows, 2008) Figure 3-14 shows that also the second part of the top-down requirement is fulfilled: for each characteristic, there is at least one indicator in the indicator set. In the next section, the indicators are explained in detail.

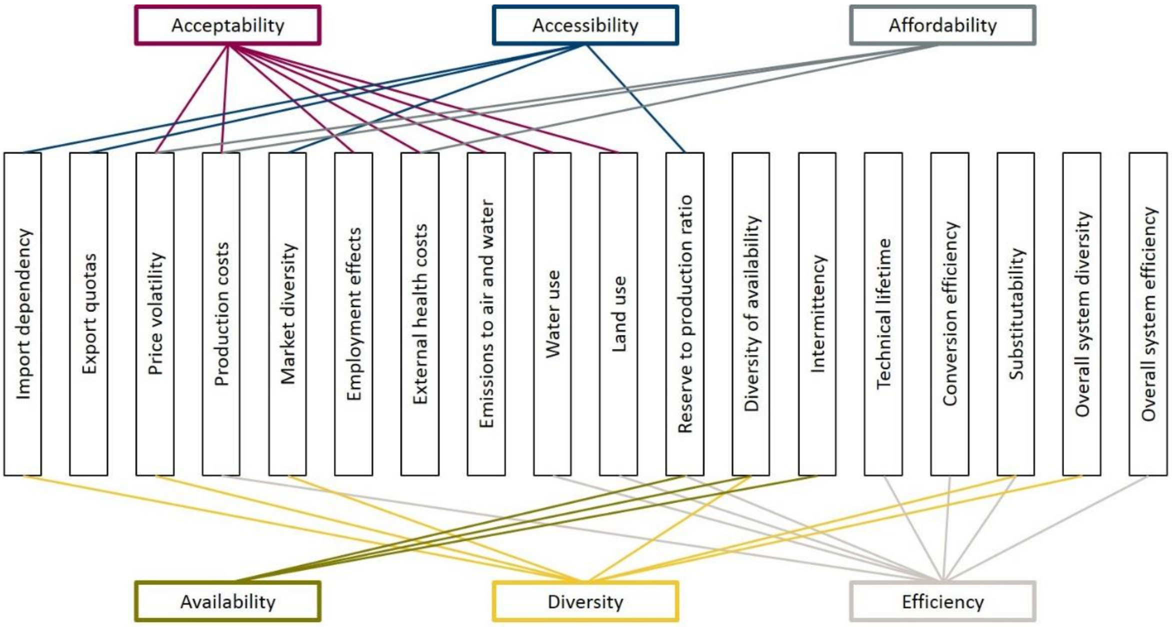

Figure 3-14: Relevant indicators and their main relation to characteristics

3.5.2 Indicator Explanation

In the following, each relevant indicator as applied in this assessment is explained in brief. This section shall give a general explanation on the nature of each indicator. Single calculation steps for the indicator values, the single indicator components, and the underlying data for indicator calculations will be explained in Chapter 4.

Import dependency measures the import dependency of relevant resources[7] for each heat generation technology by using the net import quota for these resources from different sourcing countries. Although import quotas are generally indicators of economic nature they shall mainly account for the political dimension in my thesis. (Interviewee 2, July 5, 2013) For the purpose of this assessment, import dependency is regarded as a proxy to the political accessibility and the political risk diversity of resources. Therefore, the import quotas have to be weighted with factors accounting for the threat of hostile actions by malevolent agents. (Cherp, 2012; Cherp & Jewell, 2011b) Such risks are highest outside the German sovereign territory, i.e. within the sourcing countries and on the transport routes. (Cherp, 2012; Liss, 2011) Since a detailed country and transport route risk assessment is beyond the scope of this thesis, two proxies have been used to account for these threats. The first is the Economist Intelligence Unit's Political Instability Index comprising fifteen political risk indicators measuring the stability of governance infrastructure, societal resilience and the risk of drastic societal changes, the threat of political violence and critical actions by sub-state or politically motivated groups, and business and macroeconomic risks in different countries. (EIU, 2009 & 2013) This Index is used as a country risk proxy. The second is the transport distance from the sourcing country to Germany. I assume that there is a simple positive correlation between the transport distance and the transport risk, i.e. the longer distance a relevant resource has to travel, the higher the threat of an accident or a hostile action. Both proxies can be exchanged with similar proxies or preferably with specific risk assessments. The indicator can be applied to all technologies even if for some

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[7] For the German heating sector, import dependent relevant resources are exclusively fuels. (Miller & Spoolman, 2009; Recknagel et al., 2012) Assessing other energy sectors like the power sector, this picture might change since then also technology components such as rare earth metals have to be imported.

technologies the import dependency and hence the indicator value might be zero. The indicator is negatively correlated with energy security. (Cherp & Jewell, 2011a; Jewell, 2011; Kruyt et al., 2009; Martchamadol & Kumar, 2012 & 2013; Sovacool, 2013; Sovacool & Mukherjee, 2011)

Export quotas is an indicator accounting for the accessibility in both the economic and the political dimension. Export quotas can be introduced by sourcing countries to limit the exported amounts of relevant resources. Depending on the imposed quota, export quotas can artificially reduce the accessibility of certain resources in reducing the supplied amount. If the quota sets the exported amount lower than the amount demanded, the price for the respective resource will increase. Due to their potentially negative impact on the accessibility and affordability, export quotas are assumed to have a negative impact on energy security. Markets for relevant resources do generally not supply one heat generation technology only. Oil for example is used for heat generation, electricity generation, in the transport sector and in the chemical industry. Moreover, export quotas are assumed to affect all subsectors and end-uses in the heating market to the same degree. Hence, the indicator value of one technology is the same for all regarded subsectors and end-uses. (Mankiw & Taylor, 2011; Sovacool & Mukherjee, 2011)

Price volatility and production costs are two indicators accounting for the economic dimension, economic affordability and economic acceptability. **Price volatility** measures the relative volatility in the purchasing price of fuels and relevant technology components over the last years with a monthly resolution. This indicator can be applied for all technologies, even if some fuels like solar energy are generally freely available. **Production costs** measures the production costs of generating one unit of thermal energy for different technologies. According to VDI (2007), production costs include capital-related costs (e.g. depreciation and interest), operation related costs (e.g. maintenance costs), and demand-related costs (e.g. fuel and lubricant costs). (Seefeldt et al., 2011; VDI, 2007) Both indicators are negatively correlated with energy security. (Cherp & Jewell, 2011a; Kruyt et al., 2009; Martchamadol & Kumar, 2012 & 2013; Sovacool & Mukherjee, 2011)

Market diversity is a mainly economic diversity and accessibility indicator. It measures the degree of competition in the production, transport, and retail markets relevant for different technologies by the actor diversity in these markets. Following Stirling (2011), the indicator assesses the number of actors in the respective market (variety), the market share of these actors (balance), and the degree of difference between these actors (disparity). (Stirling, 2011) The indicator is positively correlated with energy security. (Cherp & Jewell, 2011a; Jewell, 2011; Kruyt et al., 2009; Martchamadol & Kumar, 2012 & 2013; Sovacool, 2013; Sovacool & Mukherjee, 2011)

Conversion efficiency and technical lifetime are indicators accounting mainly for efficiency in the technical dimension. **Conversion efficiency** calculates the average energy conversion efficiency for different technologies at regular conditions. **Technical lifetime** calculates the average technical lifetime for (main system components of) different heat generation technologies. Both indicators are positively correlated with energy security. (Jewell, 2011; Sovacool & Mukherjee, 2011)

Intermittency is an indicator accounting for availability in the natural and the technical dimension. It measures the annual time in which a technology cannot be used to its full capacity due to natural fuel intermittencies, maintenance and repair times, and other technical interruptions. Due to the combination of technical and natural elements, this indicator can be applied to all technologies even if many technologies do not face problems with the intermittency of fuels. The indicator is negatively correlated with energy security. (Sovacool & Mukherjee, 2011; Winzer, 2012) At this stage, I explicitly want to stress that intermittency, as understood in my thesis, does not only refer to intermittent renewable energy sources, i.e. to natural availability, but also to technical intermittencies and disruptions.

Diversity of availability is an indicator accounting for diversity and availability in the natural dimension. It measures the diversity of natural occurrence of relevant resources. Following Stirling (2011), the indicator assesses the number of resource deposits (variety), the size of these deposits (balance), and the degree of difference between these deposits (disparity). (Stirling, 2011) Since a detailed risk assessment of every existing deposit is beyond the scope of this thesis, all extractable deposits have been summed up at a country level and are then weighted with the Economist Intelligence Unit's Political Instability Index of the respective country and the transport distance from this country to Germany. These indices serve as proxies for the deposit- and transport specific risks and help to assess the disparity between deposits. Both proxies could be exchanged with similar proxies or preferably with specific risk assessments. The indicator is positively correlated with energy security. (Cherp & Jewell, 2011a; Jewell, 2011; Kruyt et al., 2009; Martchamadol & Kumar, 2012 & 2013; Sovacool, 2013; Sovacool & Mukherjee, 2011)

Reserve to production ratio is an indicator accounting for accessibility, availability, and resource efficiency in the technical and natural dimension. The indicator measures the remaining lifespan of relevant resources by dividing the amount of known reserves of a relevant resource by the annual usage amount of this resource. The indicator is positively correlated with energy security. (Cherp & Jewell, 2011a; Kruyt et al., 2009; Martchamadol & Kumar, 2012 & 2013; Sovacool, 2013; Sovacool & Mukherjee, 2011)

Substitutability is an indicator accounting for the general natural substitutability measuring the specific energy content, i.e. the calorific value, of different fuels or transfer media, respectively. The indicator is positively correlated with energy security. (Sovacool & Mukherjee, 2011)

Three indicators mainly account for the environmental dimension: land use, water use, and emissions to air and water. These indicators are strongly connected to environmental acceptability but also to the efficient use of resources. **Land use** calculates the average area needed in the whole value chain from resource extraction to heat generation for producing one unit of thermal energy. **Water use** calculates the average amount of water needed in the whole value chain from resource extraction to heat generation for producing one unit of thermal energy. **Emissions to air and water** assesses the most climate damaging types of emissions to air and water and calculates their average amounts caused in the whole value chain from resource extraction to heat generation for producing one unit of thermal energy. All three environmental indicators are negatively correlated with energy security. (Brown & Dworkin, 2011; Kruyt et al., 2009; Martchamadol & Kumar, 2012 & 2013; Sovacool, 2013; Sovacool & Mukherjee, 2011)

Two indicators – although economic in nature (Interviewee 2, July 5, 2013) – shall mainly account for the societal dimension and the societal acceptability in my thesis: external health costs and employment effects. **External health costs** calculates the annual health costs (e.g. costs related to the treatment of respiratory, cardiovascular, and nervous diseases or premature deaths) caused by impacts attributable to the whole value chain from resource extraction to heat generation for generating one unit of thermal energy. (HEAL, 2013) This indicator is negatively correlated with energy security. **Employment effects** calculates the annual gross job creation attributable to the whole value chain from resource extraction to heat generation for generating one unit of thermal energy. From this figure, the net job creation in the heating sector can be derived. This indicator is positively correlated with energy security. (Sovacool & Mukherjee, 2011)

Overall system efficiency compares the total energy use in the two scenarios on a decomposition and sector level. The system with highest energy use is regarded to have an efficiency level of zero. The total energy use differences in per cent can be used as a proxy for efficiency in the other systems. The indicator is hence positively correlated with energy security. (Cherp & Jewell, 2011a; Kruyt et al., 2009; Martchamadol & Kumar, 2012 & 2013; Sovacool, 2013; Sovacool & Mukherjee, 2011)

Overall system diversity compares the diversity of technologies in the two scenarios on a decomposition and sector level. Following Stirling (2011), the indicator assesses the number of different heat generation technologies (variety), their share in the decomposition level (balance), and the degree of difference between these technologies (disparity). The indicator is positively correlated with energy security. (Cherp & Jewell, 2011a; Jewell, 2011; Kruyt et al., 2009; Martchamadol & Kumar, 2012 & 2013; Sovacool, 2013; Sovacool & Mukherjee, 2011)

3.5.3 Assessed Indicators

Figure 3-15 shows the importance interviewees assign to the relevant indicators. The quadrangle depicts the mean importance assigned by the group of interviewees, the grey line depicts the highest and lowest importance value assigned to the respective characteristic. The big variances in many of the indicator ratings reveal how contested the importance of different indicators is considered among energy experts in distinct fields. Only two indicators were on average not rated as at least being *important for* energy security: technical lifetime and water use. Since the indicator rating is contested, I will not rely on the interviewees' answers only to exclude or select indicators. A few indicators have however been excluded for other reasons. These exclusions do not influence the assessment's result. However, a discussion of the exclusion is given in Chapter 5.

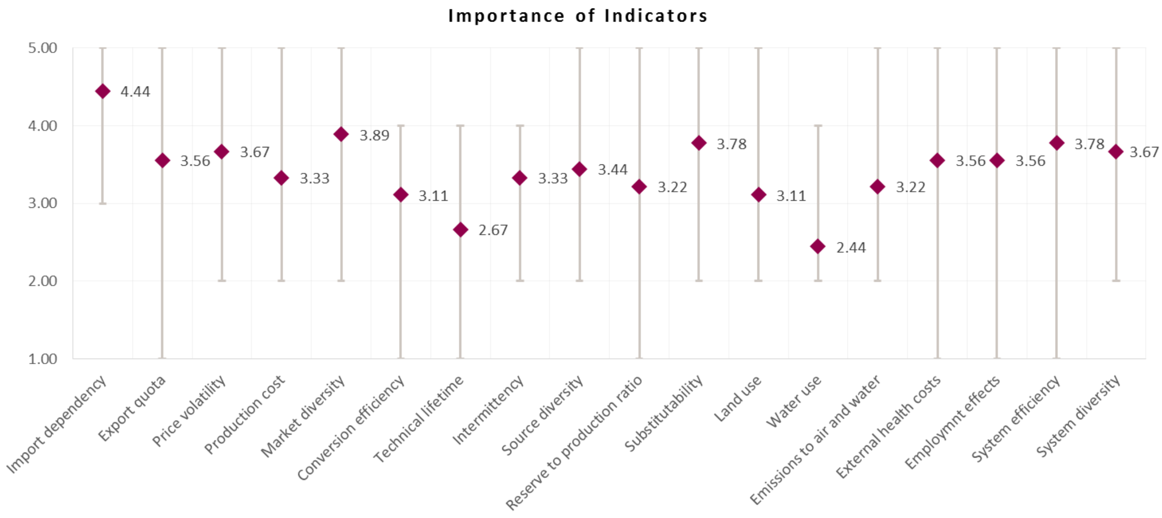

Figure 3-15: Mean, highest, and lowest importance of indicators according to interviewees

1 = unimportant, 2 = slightly important; 3 = important; 4 = very important; 5 = critical

According to BAFA (2012 & 2013) and DERA (2012 & 2013), the impact of **export quotas** on the German heating sector is insignificant. In recent years, no sourcing country relevant to the German heating sector has imposed export quotas on relevant resources. (BAFA, 2012 & 2013; DERA, 2012 & 2013) Therefore, this indicator will not be included in the assessment of my thesis.

Market diversity for conventional energy technologies can best be based on data about market participants (in the production, transport, and retail markets) liable for energy taxation in Germany. According to Seefeldt et al. (2011), the German oil market comprises approximately 100 distinct taxable subjects, the gas market approximately 800. Data on the coal market and particularly on the market for renewable energy technologies and fuels is hard to obtain and reliable data bases do not exist. (BBT, 2007; Seefeldt et al., 2011) Due to the lack of available data, especially for markets of renewable energy carriers, this indicator will not further be assessed in my thesis.

According to VDI (2007), the **technical lifetime** of (main system components of) different heat generation technologies does not differ significantly and is generally estimated to be twenty years regardless of the type of heat generation technology. (VDI, 2007) Due to the insignificant differences in the technical lifetime values for (main system components of) different heat generation technologies, a further assessment of this indicator does not seem useful for the purpose of this thesis.

According to DERA (2013) reserve estimates for different resources differ significantly from year to year and the annual resource usage can fluctuate considerably. These circumstances might undermine the meaningfulness of the **reserve to production ratio**. (DERA, 2013; Interviewee 3, July 7, 2013) This indicator will therefore not further be assessed in my thesis.

Although rated with the third highest importance, **substitutability** will not further be assessed in this thesis. Memmler et al. (2009) shows that each heat generation technology can be generally substituted by other technologies (see Figure 3-6). Technological substitutability is hence given for each heat generation technology. However, this method can only assign substitution factors to exchange relations of different generation technologies, but not to the technologies themselves. (Memmler et al., 2009) Therefore, a comparison based on fuels would be required for instance. The usefulness of a substitutability comparison based on the specific energy content of fuels and transfer media used in different heat generating technologies is questionable since it would have to take place at different stages within the technologies. While classical fuels can easily be compared based on their higher or lower heating value, the assessment of the energy content of the transfer media used in geothermal or solar thermal heat generation technologies would have to take place after energy conversion steps have already occured. For instance, measuring the energy content of water in solar thermal plants would not measure the energy content of the initial fuel, i.e. the sunlight, and would hence not be directly comparable to the calorific value of classical initial fuels like biogas. (IEA, 2007b) Due to the lacking direct comparability, this indicator will not further be assessed within my thesis.

Environmental and societal indicators (**land use, water use, emissions to air and water, external health costs, and employment effects**) have already been quantified in ImpRES and will hence not further be assessed in this thesis. (Breitschopf et al., 2010, 2012 & 2013)

Although the **overall system efficiency** is a relevant indicator for the German heating sector, the way the sector scenarios in this thesis are designed, the total energy use and hence the overall system efficiency of both scenarios does not differ. This indicator will therefore not further be assessed in my thesis.

I explicitly want to point out that the vast indicator exclusion I carry out at this point of my thesis will not affect the requirements placed upon my assessment. Figure 3-16 maps the remaining indicators selected for the assessment of my thesis and their relations to characteristics and dimensions. It is important to point out that the selected indicators still fulfil the top-down requirement and account as a complete set for each of the relevant characteristics and dimensions, except the societal and the environmental dimension. The respective indicators for these two dimensions have already been quantified by ImpRES and will hence not be regarded here but could be used to complement the assessment carried out within my thesis. The remaining set of indicators does hence still fulfil all top-down, bottom-up, and technology specific requirements of my assessment.

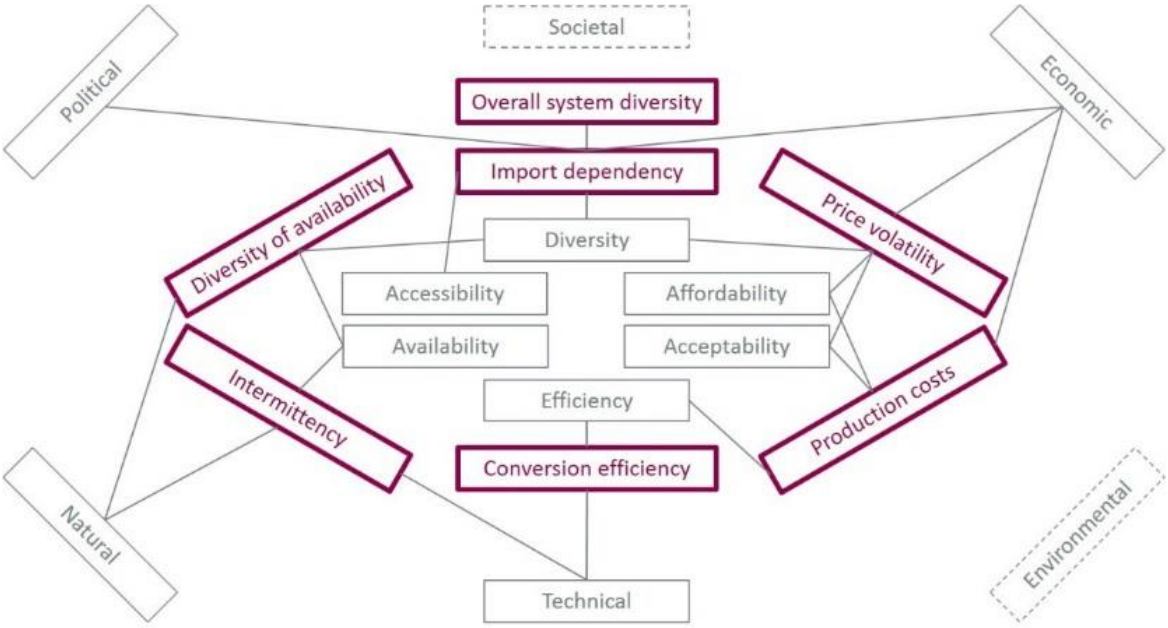

Figure 3-16: Selected indicators (red) assessed in this thesis and their relations to characteristics and dimensions

4 Analysing Energy Security in the German Heating Sector

4.1 Indicator Value Calculation and Technology Analyses

This section will briefly explain the calculation of the selected relevant indicators and map the resulting indicator values for each heat generation technology. In my thesis, I generally provide the latest available indicator data. Where indicator values are likely to fluctuate, I provide trends or use the average value for the data sets of the eight[8] latest available years.

I explicitly want to point out that the calculation methods of indicators are not always unambiguously defined. For many indicators, several calculation methods exist and would hence produce different numerical results. The calculation methods presented here are therefore to be seen as subjectively chosen examples for the respective indicators. Since the calculation method of indicators might influence the assessment's result, ambiguous indicators are further discussed in Chapter 5. Even if the calculation method is rigidly defined, the input data for this calculation might be obtained from different sources resulting in significant numerical discrepancies. Where this is the case, I used the arithmetic mean of the available data sources.

The technology-based analysis as carried out in my thesis reveals that depending on the assessed indicator – and also depending on the assessed subsector and end-use – the deployment of renewable energy technologies can both be more beneficial or more harmful to energy security compared to the deployment of conventional technologies.

4.1.1 Import Dependency

To calculate the indicator values for **import dependency**, the sourcing countries and imported amounts of relevant resources for different heat generation technologies are mapped. The data is based on BAFA (2012 & 2013), VDKI (2012), and DERA (2012 & 2013). From these data, import shares for each relevant resource can be calculated. In addition, the political instability factor and the straight line distance to Germany for each of these sourcing countries is listed. This information is based on EIU (2013) and DFT (n.d.). Further, the net import quota for each relevant resource is obtained according to Umweltbundesamt (2011). The indicator value for the import dependency of relevant resources for each heat generation technology is calculated as:

$$\left(\frac{\sum_{i=1}^{n}(import\ share\ country_i * instability\ factor_i\ * distance_i\ )}{1\ 000}\right) * net\ import\ quota$$

With:

$$n = total\ amount\ of\ sourcing\ countries$$

For better legibility, the indicator value is divided by 1 000. Figure 4-1 maps the indicator values for the import dependency for relevant resources of different heat generation technologies. The complete data set for import dependency can be found in Appendix IV.

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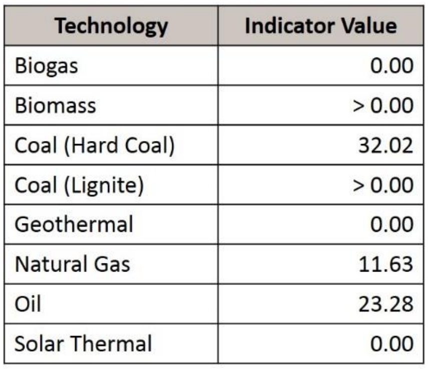
[8] Eight years is the time frame commonly used by the German Federal Bureau of Statistics to norm energy indices. (Destatis, 2013)

Only three relevant resources are imported to a significant degree: hard coal, natural gas, and oil. Comparing the indicator values for imported relevant resources, natural gas registers the lowest import dependency and hence in this respect the least harmful influence on energy security. The import dependency of oil is more than twice as high, import dependency for hard coal is 2.75 times as high. Renewable energy technologies and lignite do not – or only to an insignificant degree – affect import dependency. In this respect, their use is hence most beneficial to energy security.



Technology	Indicator Value
Biogas	0.00
Biomass	> 0.00
Coal (Hard Coal)	32.02
Coal (Lignite)	> 0.00
Geothermal	0.00
Natural Gas	11.63
Oil	23.28
Solar Thermal	0.00

Figure 4-1: Indicator values for import dependency

Source: BAFA, 2012 & 2013; DERA, 2012 & 2013; EIU, 2013; DFT, (n.d.); Umweltbundesamt (2011); VDKI, 2012

4.1.2 Price Volatility

The **price volatility** for relevant resources of different heat generation technologies is calculated on a monthly basis according to Brealey et al. (2007) with the formula for assessing price fluctuations:

$$\sigma_{m=2}^{M}\left(\ln\left(\frac{p_m}{p_{m-1}}\right)\right) * \sqrt{12}$$

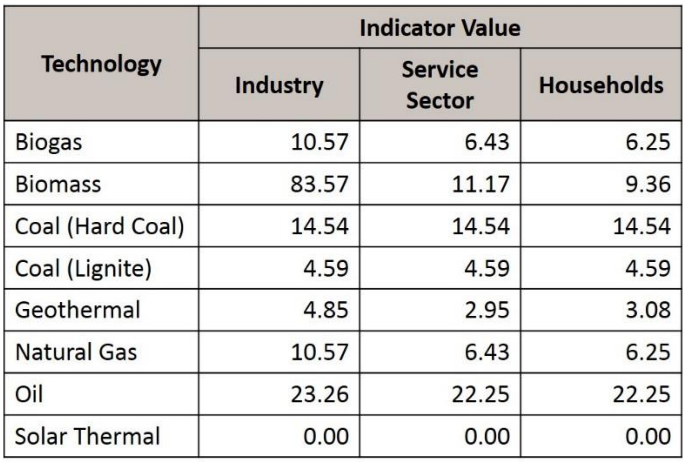
With:

$$\sigma = standard\ deviation;\ p_m = price\ index\ value\ in\ month\ m;\ M = total\ number\ of\ months$$

The formula calculates the standard deviation of price changes for all regarded months from month m to month M. The single price changes are calculated in dividing each month's price index value with the price index value of the preceding month. The natural logarithm helps to lessen the influence of statistical outliers. The resulting standard deviation is multiplied by the radical of twelve to calculate the volatility on a monthly basis.

The price data is based on Destatis (2013). Geothermal heat generation systems are assumed to run on electricity, hence electricity price data is used for calculating the geothermal indicator values. Figure 4-2 maps the indicator values for price volatility of different heat generation technologies. The complete data set for this indicator can be found in Appendix V.

Generally, the price volatility for relevant resources of each heat generation technology is higher – and hence, in this respect, the harmful impact on energy security is bigger – in industry prices than in household or service sector prices. This difference is especially significant in biomass, biogas, and natural gas. Fluctuations in biomass prices are almost nine times higher for industry prices than for prices on the household level. For biogas and natural gas prices fluctuations are almost twice as high. Solar thermal and geothermal heat generation technologies have the lowest price volatility – and hence the least harmful impact on energy security – for all sectors.



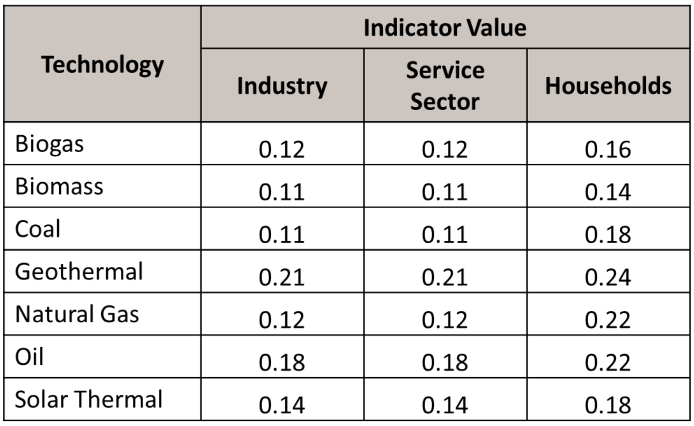
Technology	Indicator Value		
	Industry	Service Sector	Households
Biogas	10.57	6.43	6.25
Biomass	83.57	11.17	9.36
Coal (Hard Coal)	14.54	14.54	14.54
Coal (Lignite)	4.59	4.59	4.59
Geothermal	4.85	2.95	3.08
Natural Gas	10.57	6.43	6.25
Oil	23.26	22.25	22.25
Solar Thermal	0.00	0.00	0.00

Figure 4-2: Indicator values for price volatility

Source: Brealey et al., 2007; Destatis, 2013

4.1.3 Production Costs

Data for **production costs** are based on Seefeldt et al. (2011). Specific production cost data for the industry sector could not be obtained. Therefore service sector costs have been used to assess the industry sector. Generally, production costs in the industry can be assumed to be lower than production costs in the service sector. (Seefeldt et al., 2011) Figure 4-3 maps the average production costs of different heat generation technologies.



Technology	Indicator Value		
	Industry	Service Sector	Households
Biogas	0.12	0.12	0.16
Biomass	0.11	0.11	0.14
Coal	0.11	0.11	0.18
Geothermal	0.21	0.21	0.24
Natural Gas	0.12	0.12	0.22
Oil	0.18	0.18	0.22
Solar Thermal	0.14	0.14	0.18

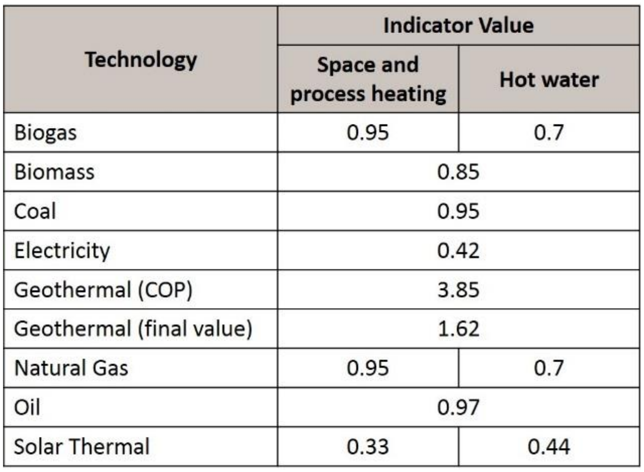
Figure 4-3: Indicator values for production costs

Source: Seefeldt et al., 2011

Indicator values for production costs for most heat generation technologies in the service (and the industry) sector do not differentiate significantly and range between 0.11 and 0.14. Only oil and geothermal technologies register significantly higher production costs and hence, in this respect, a more harmful impact on energy security. Production costs in households are generally on a higher level but have a smaller variance between the distinct technologies.

4.1.4 Conversion Efficiency

The indicator values for **conversion efficiency** are based on Dengler et al. (2012). The average conversion efficiency values for households and the service sector do not differ significantly. Hence, I do not differentiate between the efficiency values of the same technology in these two sectors. Specific data for industry applications could not be obtained, so I used service sector data for industry applications. According to Dengler et al. (2012), industry applications are likely to have a slightly higher conversion efficiency due to commonly installed waste heat recovery systems. (Dengler et al., 2012) While the differences between sectors are hence insignificant, differences between space or process heat and water heating do exist in some technologies. For geothermal heat generation technologies, the coefficient of performance (which is generally higher than 100%) is multiplied with the average conversion efficiency of electricity generation based on Umweltbundesamt (2013) since it is assumed that the majority of geothermal heating systems run on electricity. (Dengler et al., 2012; Umweltbundesamt, 2013) Figure 4-4 maps the indicator values for conversion efficiency of different heat generation technologies.



Technology	Indicator Value	
	Space and process heating	Hot water
Biogas	0.95	0.7
Biomass	0.85	
Coal	0.95	
Electricity	0.42	
Geothermal (COP)	3.85	
Geothermal (final value)	1.62	
Natural Gas	0.95	0.7
Oil	0.97	
Solar Thermal	0.33	0.44

Figure 4-4: Indicator values for conversion efficiency

Source: Dengler et al., 2012; Umweltbundesamt (2013)

Especially for gas firing technologies, conversion efficiencies are lower for hot water generation than for space or process heat while for solar thermal technologies conversion efficiency is higher for hot water generation than for space and process heat. Conventional heat generation technologies register relatively high conversion efficiency values of 95% or more and are hence most beneficial to energy security in this respect. Solar thermal technologies and electricity production register relatively small conversion efficiencies.

4.1.5 Intermittency

To calculate the indicator values for **intermittency**, data on maintenance and repair efforts as well as data on the natural intermittency in the availability of relevant resources have to be mapped. This data is based on VDI (2007) and SoDa (2013). For each heat generation technology, the indicator value is then calculated as:

$$\left(\frac{maintenance\ and\ repair\ costs}{investment}\right) * \left(\frac{t_m}{t_n}\right) * \left(\frac{1}{\bar{x}(degree\ of\ natural\ availability)}\right) * 10\ 000$$

With:

$$t_m = repair\ and\ maintenance\ hours;\ t_n = hours\ of\ natural\ availability;\ \bar{x} = arithmetic\ mean$$

For better legibility, the indicator is multiplied by 10 000. The formula shows that intermittency, as understood in my thesis, does not only refer to intermittent renewable energy sources, i.e. to natural availability, but also to technical intermittencies and disruptions. Figure 4-5 maps the indicator values for intermittency of different heat generation technologies. The complete data set for this indicator can be found in Appendix VI.

Technology	Indicator Value
Biogas	0.57
Biomass	0.51
Coal	0.51
Geothermal	0.91
Natural Gas	0.57
Oil	0.80
Solar Thermal	0.49

Figure 4-5: Indicator values for intermittency

Source: SoDa, 2013; VDI, 2007

Intermittency indicator values generally do not differ significantly and range from 0.49 to 0.57. The solar thermal technology scores highest in the natural availability component of intermittency but has relatively low maintenance expenditures and short repair times leading to the lowest intermittency value. Geothermal and oil firing technologies however register significantly higher intermittency indicator values – and hence have in this respect more harmful impact on energy security – with 0.91 and 0.80, respectively, due to high maintenance expenditures.

4.1.6 Diversity of Availability

To calculate the indicator values for **diversity of availability**, the countries with natural occurrences of relevant resources and respective extractable amounts of these resources for different heat generation technologies are mapped. The data is based on BMWi (2013) and DBFZ (2009). From these data, extractable shares for each relevant resource can be calculated. In addition, the political instability factor and the straight line distance to Germany for each of these sourcing countries is listed. This information is based on EIU (2013) and DFT (n.d.). Derived from Stirling (2011), the indicator value for diversity of availability of relevant resources for each heat generation technology is calculated as:

$$variety * balance * disparity * 100$$

With:

$$variety = \frac{n}{100}$$

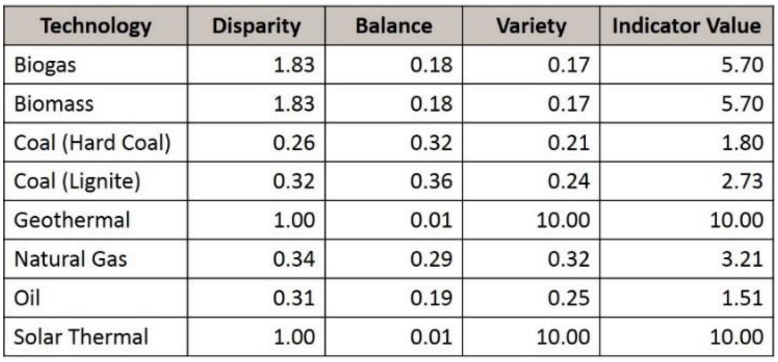
$$balance = \frac{1}{\sigma^2{}_i^n(extractable\ resource\ share\ country_i)} * 1\,000$$

$$disparity = \frac{1}{\sum_{i=1}^{n}(extractable\ resource\ share\ country_i * instability\ factor_i\ * distance_i\ )} * 10\,000$$

$$n = total\ amount\ of\ sourcing\ countries;\ \sigma^2 = variance$$

Variety refers to the number of diverse potential sourcing countries. Balance refers to the evenness of the countries' shares in the total amount of extractable relevant resources. Disparity refers to the degree of difference between the potential sourcing countries. (Stirling, 1994 & 2011) For better legibility of the single steps, variety is divided by 100, balance is multiplied by 1 000, disparity is multiplied by 10 000, and the resulting indicator value is multiplied by 100. Relevant resources for geothermal and solar thermal technologies (i.e. solar radiation and geothermal heat) are basically infinitely available at no transport distances (i.e. within Germany). The formulas listed above can hence hardly be applied without resulting in discordant values. For this reason, the disparity value of the geothermal and the solar thermal technology is set to one since plants set up in Germany are assumed to have a similar degree of disparity. Other countries have not been assessed for these technologies since geothermal and solar thermal energy are not likely to be imported to a significant degree. The balance value is set to ten since the variance $\sigma^2{}_i^n$ is assumed to be close to zero, hence the potential balance is assumed to be high. Figure 4-6 maps the indicator values for the import dependency for relevant resources of different heat generation technologies. The complete data set for diversity of availability can be found in Appendix VII.

Oil and hard coal register the lowest diversity of availability indicator values. Natural gas registers an even higher diversity of availability value than the domestically available lignite. All in all, fossil-based heat generation technologies register significantly lower diversity of availability values – and have in this respect hence a less beneficial impact on energy security – than renewable energy technologies for heat generation.



Technology	Disparity	Balance	Variety	Indicator Value
Biogas	1.83	0.18	0.17	5.70
Biomass	1.83	0.18	0.17	5.70
Coal (Hard Coal)	0.26	0.32	0.21	1.80
Coal (Lignite)	0.32	0.36	0.24	2.73
Geothermal	1.00	0.01	10.00	10.00
Natural Gas	0.34	0.29	0.32	3.21
Oil	0.31	0.19	0.25	1.51
Solar Thermal	1.00	0.01	10.00	10.00

Figure 4-6: Indicator values for diversity of availability

Source: BMWi, 2013; DBFZ, 2009; DFT, (n.d.); EIU, 2013; VDKI, 2012

4.1.7 Overall System Diversity

Derived from Stirling (2011), for each regarded (sub)sector, the indicator value for the **overall system diversity** is calculated as:

$$variety * balance * disparity$$

With:

$$variety = \frac{n}{7}$$

$$balance = \frac{1}{\sigma^2{}_i^n(share\ of\ technology_i)}$$

$$disparity = \frac{d}{2}$$

$$n = number\ of\ technologies; \sigma^2 = variance;\ d = number\ of\ disparate\ technology\ groups$$

Variety refers to the number of diverse heat generation technologies taken from the total pool of seven distinct generation technologies discussed in my thesis. Balance refers to the evenness of the technologies' shares in the regarded (sub)sector. Disparity refers to the degree of difference between the technologies. For the purpose of this assessment, I only differentiate between two disparate technology groups, i.e. renewable and non-renewable heat generation technologies. (Stirling, 1994 & 2011) Since this indicator does not assess single technologies but the technology mix within different (sub)sectors, indicator values for single technologies are not given here.

4.2 Decomposition Level Analyses

As outlined in Chapter 3, five sublevels are analysed with the help of the indicator values calculated above: space heating in the industry (I-SH), process heat in the industry (I-PH), space heating in the service sector (S-SH), space heating in households (H-SH), and hot water in households (H-HW). The sublevel analysis takes place on a technology-basis. Therefore, the indicator values have been multiplied with the respective technology shares in the sublevels of both scenarios (Figure 3-5 & Figure 3-7). For better legibility and due to the high degree of complete data, the figures presented in this chapter focus on the household sector. Figures for the complete decomposition level analyses can be found in Appendix VIII-XIII.

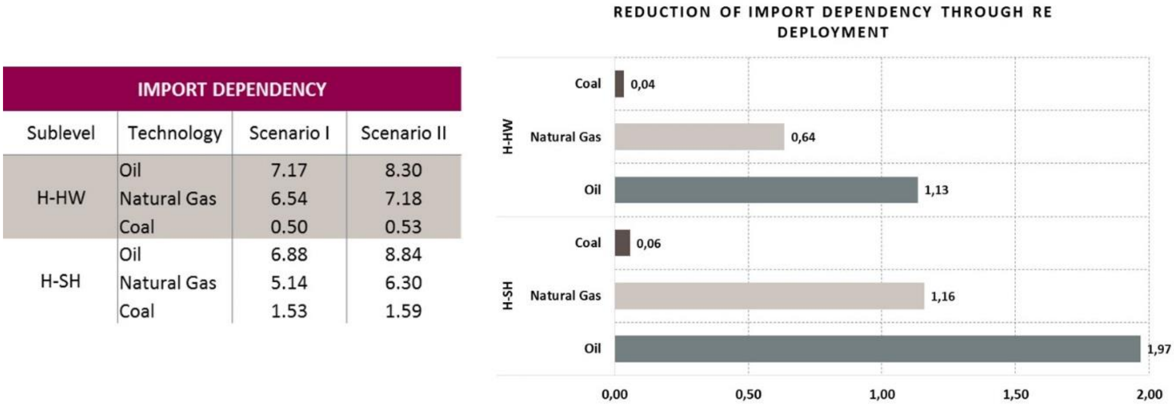
I explicitly want to point out that the numerical results presented here are not to be seen as absolute values for assessing energy security in the German heating sector. The mere numbers are only a reflection of the way the scenarios are composed and of the way the indicators are calculated. The absolute values presented here are the mere product of the technology share and the respective indicator value and are in themselves not particularly meaningful for assessing energy security. What should be seen as more important is the (relative) difference in indicator values for the two scenarios. In these figures, the direction and severity of impact of renewable energy deployment on energy security can be measured. In this context, it is important to mention that neither the direction nor the severity of impact can be scaled to scenarios with a higher or lower share or a different composition of renewable energies in the German heating sector. It is valid only for the comparative analysis of the two scenarios as composed in this thesis. The relative change allows hence to draw conclusions on how energy security in the status quo of the German heating sector is influenced by the current share and composition of renewable energy technologies as opposed to a scenario of the status quo in which this current share and composition of renewable energy technologies would be replaced by fossil-based heat generation technologies. The scalability of results will be further discussed in Chapter 5.

Similar to the technology-based analysis, the decomposition-level analysis as carried out in my thesis reveals that depending on the assessed indicator – and also depending on the assessed decomposition levels – the deployment of renewable energy technologies can both be more beneficial or more harmful to energy security compared to the deployment of conventional technologies.

4.2.1 Import Dependency

Figure 4-7 maps the absolute import dependency values for each technology in the assessed household levels. The complete analysis of all assessed deposition levels is depicted in Appendix VIII. Despite its lowest import dependency value, natural gas registers the most significant impact on import dependency due to its high share in all decomposition levels. Coal on the other hand has despite its high specific import dependency value no significant impact on import dependency due to its small share in many of the decomposition levels. Only in process heat in the industry (I-PH), the use of coal significantly influences the import dependency impact. Oil has the highest influence on import dependency in applications the service sector and in households.

Through the deployment of renewable energy technologies for heat generation, import dependency is reduced in all of the assessed decomposition levels. This reduction is most significant in space heating in households (H-SH) with a reduction of 19.02%, followed by space heating in the industry sector (I-SH) with a reduction of 16.12%, and hot water generation in households (H-HW) with a reduction of 11.28%. In process heat in the industry (I-PH) import dependency is reduced by 8.89% and in space heating in the service sector (S-SH) it is reduced by 6.96%.



IMPORT DEPENDENCY

Sublevel	Technology	Scenario I	Scenario II
H-HW	Oil	7.17	8.30
	Natural Gas	6.54	7.18
	Coal	0.50	0.53
H-SH	Oil	6.88	8.84
	Natural Gas	5.14	6.30
	Coal	1.53	1.59

Figure 4-7: Technology-based import dependency values (absolute) for the assessed household levels

The direction of impact for this assessment is hence clear: deployment of renewable energies decreases import dependency. It hence increases energy security especially with regard to political accessibility and diversity. The severity of impact in the assessed scenarios ranges from seven per cent to nineteen per cent with a variance of 0.20%.

4.2.2 Price Volatility

Figure 4-8 maps the absolute price volatility values for each technology in the assessed household levels. The complete analysis of all assessed deposition levels is depicted in Appendix IX. Natural gas and biomass have the most significant price volatility impact for the industry sector while the service sector and households are more affected by the price volatility of oil. Biogas, geothermal, and solar thermal energy do not significantly influence price volatility values in the assessed decomposition levels. This is mainly due to the low share of biogas in the assessed decomposition levels and to the low price volatility values for geothermal and solar thermal heat generation technologies.

Through the deployment of renewable energy technologies for heat generation, price volatility impact increases especially for the industry sector. Space heating in the industry sector (I-SH) registers an increase of 114.16%, process heat in the industry sector (I-PH) an increase of 52.84%. Space heating in the service sector (S-SH) registers a slight decrease in price volatility impact of 1.59%. The biggest decreases in price volatility impact is found in the households with a decrease of 7.24% for space heating and 13.53% for hot water.

Price Volatility			
Sublevel	**Technology**	**Scenario I**	**Scenario II**
H-SH	Oil	6.57	8.45
	Natural Gas	2.76	3.38
	Coal	1.10	1.14
	Biomass	1.47	0.00
	Biogas	0.07	0.00
	Geothermal	0.06	0.00
H-HW	Oil	6.85	7.93
	Natural Gas	2.76	3.86
	Coal	0.36	0.38
	Biomass	0.36	0.00
	Biogas	0.17	0.00
	Geothermal	0.02	0.00

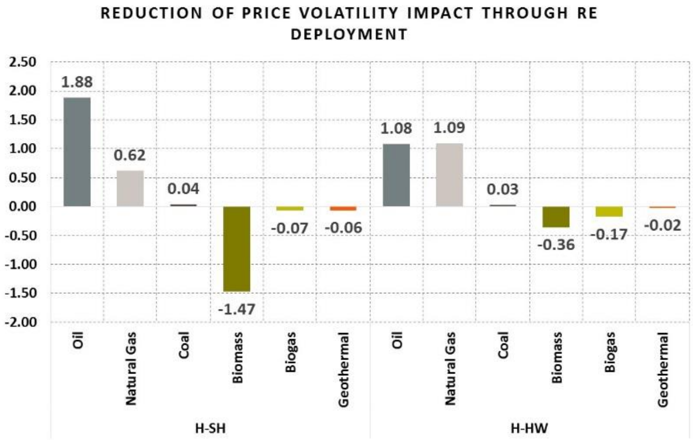


Figure 4-8: Technology-based price volatility values (absolute) for the assessed household levels

The direction of impact for this assessment is hence dependent on the regarded subsector: deployment of renewable energies decreases price volatility impacts for households and the service sector. For these sectors, energy security is increased especially with regard to the economic affordability and acceptability. Price volatility impacts for the industry sector are increased by renewable energy deployment and hence energy security is decreased in this respect. The severity of impact ranges from - 114% to + 14% with a variance of 23.76%.

4.2.3 Production Costs

Figure 4-9 maps the absolute production cost values for each technology in the assessed household levels. The complete analysis of all assessed deposition levels is depicted in Appendix X. Since production costs generally do not differ very much for distinct technologies within the same subsector, natural gas has the most significant influence on production cost values due to its high shares in all decomposition levels. Renewable energies and coal have a relatively low influence on production costs in all decomposition levels.

Production Costs			
Sublevel	**Technology**	**Scenario I**	**Scenario II**
H-SH	Oil	3.64	4.69
	Natural Gas	4.92	6.02
	Coal	0.80	0.83
	Biomass	1.89	0.00
	Biogas	0.16	0.00
	Geothermal	0.37	0.00
	Solar Thermal	0.02	0.00
H-HW	Oil	3.80	4.40
	Natural Gas	6.25	6.86
	Coal	0.26	0.28
	Biomass	0.46	0.00
	Biogas	0.39	0.00
	Geothermal	0.11	0.00
	Solar Thermal	0.56	0.00

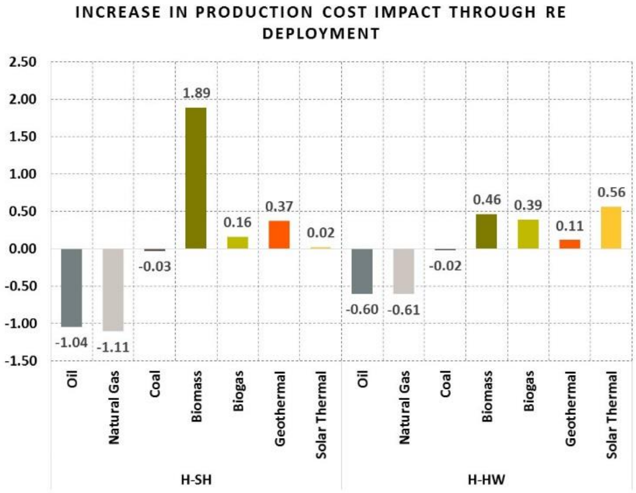


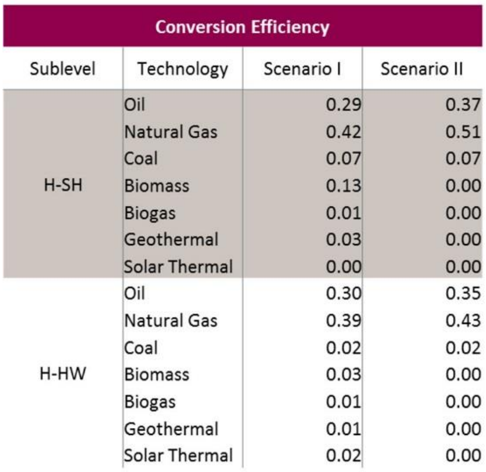
Figure 4-9: Technology-based production cost values (absolute) for the assessed household levels

For better legibility, the absolute values have been multiplied by 100.

Through the deployment of renewable energy technologies for heat generation, the production cost impact decreases for all assessed decomposition levels. Energy security is hence increased especially with regard to economic acceptability, affordability and efficiency. Impacts in the assessed scenarios are relatively small and range from 0.72% to 3.36% with a variance of 0.01%.

4.2.4 Conversion Efficiency

Figure 4-10 maps the absolute conversion efficiency values for each technology in the assessed household levels. The complete analysis of all assessed deposition levels is depicted in Appendix XI. Due to their small shares of these technologies in the respective decomposition levels, the significantly lower conversion efficiencies of solar thermal heat generation and gas fired water heating do not significantly influence conversion efficiency values. Generally, natural gas firing has the highest influence on conversion efficiency values due to its high share in all assessed decomposition levels.



Conversion Efficiency			
Sublevel	Technology	Scenario I	Scenario II
H-SH	Oil	0.29	0.37
	Natural Gas	0.42	0.51
	Coal	0.07	0.07
	Biomass	0.13	0.00
	Biogas	0.01	0.00
	Geothermal	0.03	0.00
	Solar Thermal	0.00	0.00
H-HW	Oil	0.30	0.35
	Natural Gas	0.39	0.43
	Coal	0.02	0.02
	Biomass	0.03	0.00
	Biogas	0.01	0.00
	Geothermal	0.01	0.00
	Solar Thermal	0.02	0.00

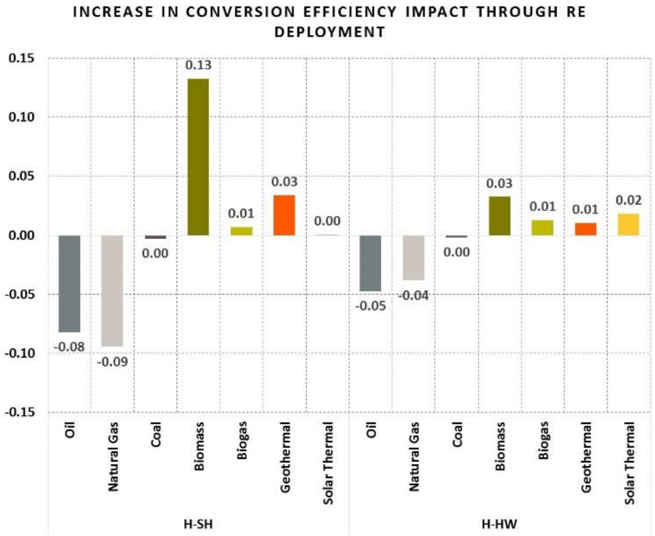


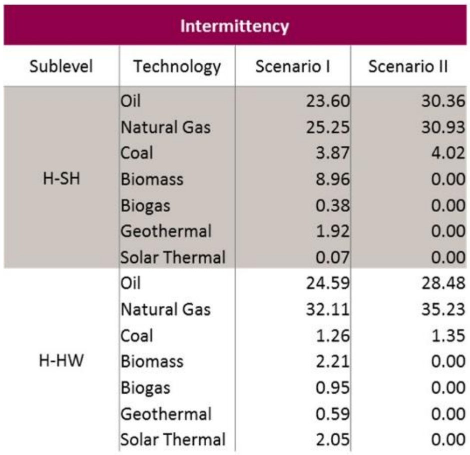
Figure 4-10: Technology-based conversion efficiency values (absolute) for the assessed household levels

Through the deployment of renewable energy technologies for heat generation, the conversion efficiency decreases for all assessed decomposition levels. Energy security hence decreases especially with regard to technical efficiency. Impacts in the assessed scenarios are however relatively small and range from 0.29% to 1.66% with a variance of 0.003%.

4.2.5 Intermittency

Figure 4-11 maps the absolute intermittency values for each technology in the assessed household levels. The complete analysis of all assessed deposition levels is depicted in Appendix XII. Since intermittency values generally do not differ very much for distinct technologies, natural gas has the most significant influence on intermittency values due to its high shares in all decomposition levels. Apart from the industry sector, the second most influential generation technology is oil due to its high specific intermittency value and medium-sized share in the service sector and the households.

Through the deployment of renewable energy technologies for heat generation, the intermittency impact decreases for all assessed decomposition levels. Energy security hence increases especially with regard to natural and technical availability. Impacts in the assessed scenarios are however relatively small and range from 0.19% to 2.00% with a variance of 0.01%.



Intermittency			
Sublevel	Technology	Scenario I	Scenario II
H-SH	Oil	23.60	30.36
	Natural Gas	25.25	30.93
	Coal	3.87	4.02
	Biomass	8.96	0.00
	Biogas	0.38	0.00
	Geothermal	1.92	0.00
	Solar Thermal	0.07	0.00
H-HW	Oil	24.59	28.48
	Natural Gas	32.11	35.23
	Coal	1.26	1.35
	Biomass	2.21	0.00
	Biogas	0.95	0.00
	Geothermal	0.59	0.00
	Solar Thermal	2.05	0.00

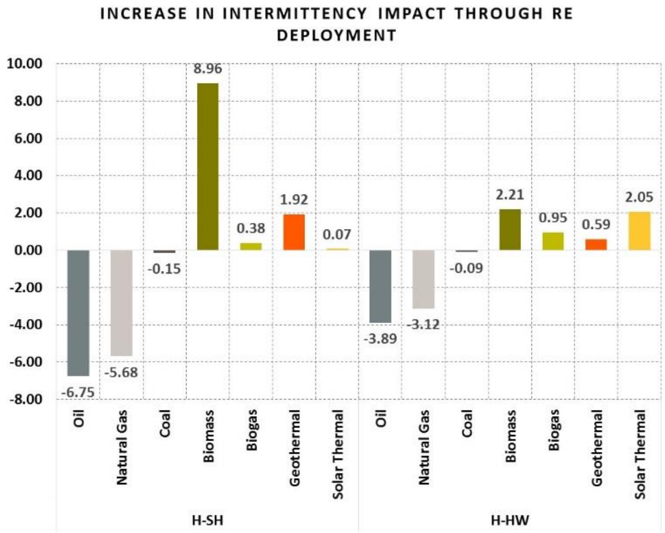
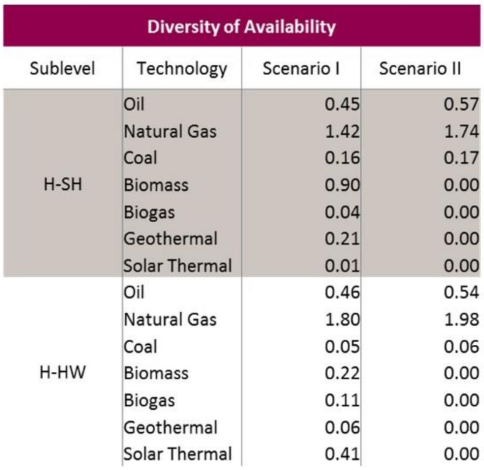


Figure 4-11: Technology-based intermittency values (absolute) for the assessed household levels

For better legibility, the absolute values have been multiplied by 100.

4.2.6 Diversity of Availability

Figure 4-12 maps the absolute diversity of availability values for each technology in the assessed household levels. The complete analysis of all assessed deposition levels is depicted in Appendix XIII. Despite the relatively low indicator value, natural gas has the most significant influence on the diversity of availability values due to its high share in all of the assessed decomposition levels.



Diversity of Availability			
Sublevel	Technology	Scenario I	Scenario II
H-SH	Oil	0.45	0.57
	Natural Gas	1.42	1.74
	Coal	0.16	0.17
	Biomass	0.90	0.00
	Biogas	0.04	0.00
	Geothermal	0.21	0.00
	Solar Thermal	0.01	0.00
H-HW	Oil	0.46	0.54
	Natural Gas	1.80	1.98
	Coal	0.05	0.06
	Biomass	0.22	0.00
	Biogas	0.11	0.00
	Geothermal	0.06	0.00
	Solar Thermal	0.41	0.00

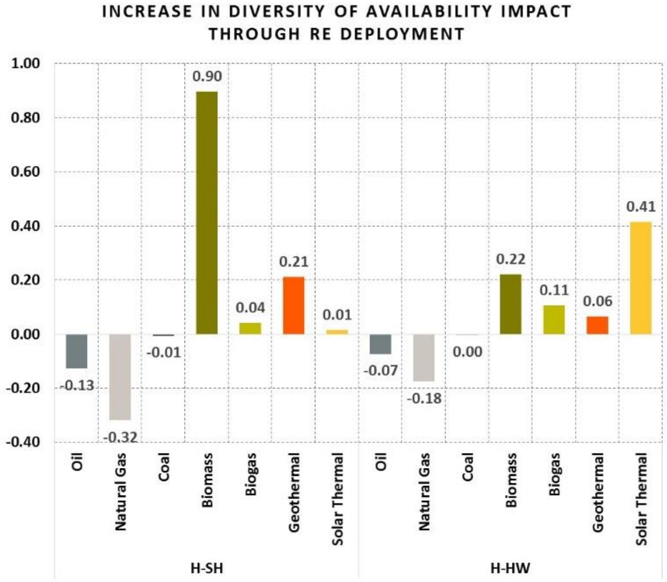


Figure 4-12: Technology-based diversity of availability values (absolute) for the assessed household levels

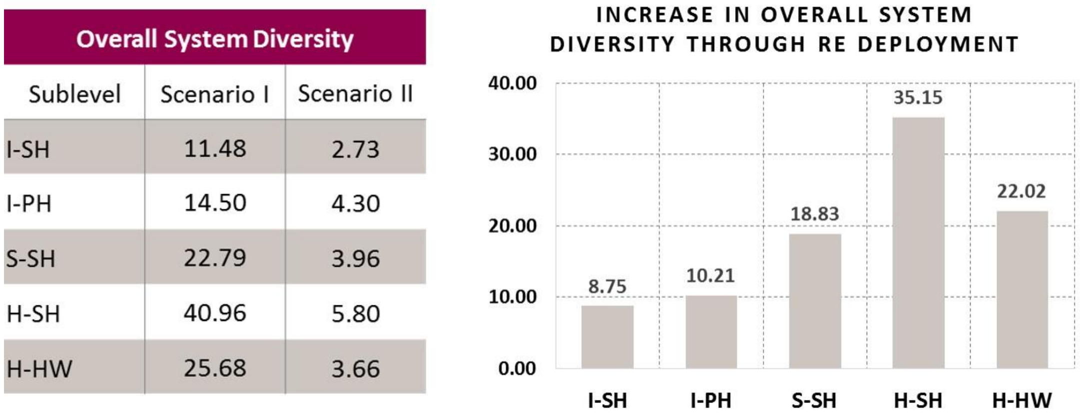
Through the deployment of renewable energy technologies for heat generation, diversity of availability (and hence energy security in this respect) is increased in all of the assessed decomposition levels. This increase in diversity of availability impact is most significant in households with an increase of 28.66% in space heating and an increase of 21.50% in hot water generation, followed by space heating in the industry (I-SH) with an increase of 15.75%. In process heat in the industry (I-PH) diversity of availability is increased by 5.28% and in space heating in the service sector (S-SH) it is increased by 8.53%.

The direction of impact for this assessment is hence clear: deployment of renewable energies increases diversity of availability. It hence increases energy security especially with regard to natural availability and diversity. The severity of impact in the assessed scenarios ranges from five per cent to 29 per cent with a variance of 0.72%.

4.2.7 Overall System Diversity

Figure 4-13 maps the absolute overall system diversity values for each assessed decomposition level. Through the deployment of renewable energy technologies for heat generation, overall system diversity is increased in all of the assessed decomposition levels. This increase in overall system diversity is most significant in households with an increase of 605.84% in space heating, an increase of 600.83% in hot water generation, followed by space heating in the service sector (S-SH) with an increase of 475.24%. In process heat in the industry (I-PH) overall system diversity is increased by 237.59% and in space heating in the industry (I-SH) it is increased by 320.56%.

The direction of impact for this assessment is hence clear: deployment of renewable energies increases overall system diversity and hence increases energy security with regard to diversity in all dimensions. The severity of impact in the assessed scenarios ranges from a doubling to a sixfold increase with a variance of 219.06%.



Overall System Diversity		
Sublevel	Scenario I	Scenario II
I-SH	11.48	2.73
I-PH	14.50	4.30
S-SH	22.79	3.96
H-SH	40.96	5.80
H-HW	25.68	3.66

Figure 4-13: Sublevel-based overall system diversity values (absolute)

4.3 Comparative Scenario Level Analysis

Figure 4-14 maps the absolute indicator values weighted according to the shares of the decomposition levels (and hence according to the shares of each technology) for the two scenarios assessed in my thesis. The scenarios include all decomposition levels, i.e. also the levels that have not been assessed separately in this thesis. In addition, the relative increase in indicator values is mapped graphically. Red colour represents indicators that are negatively correlated with energy security, green colour represents indicators that are positively correlated with energy security.

The scenario-level analysis as carried out in my thesis reveals that depending on the assessed indicator – and also depending on the assessed decomposition levels – the deployment of renewable energy technologies can both be more beneficial or more harmful to energy security compared to the deployment of conventional technologies.

On a scenario-level, the deployment of renewable energy technologies for heat generation decreases the overall **import dependency** impact by 23.21%. Hence, for the assessed scenarios, the deployment of renewable energy technologies increases overall energy security in the German heating sector especially with regard to political accessibility and diversity.

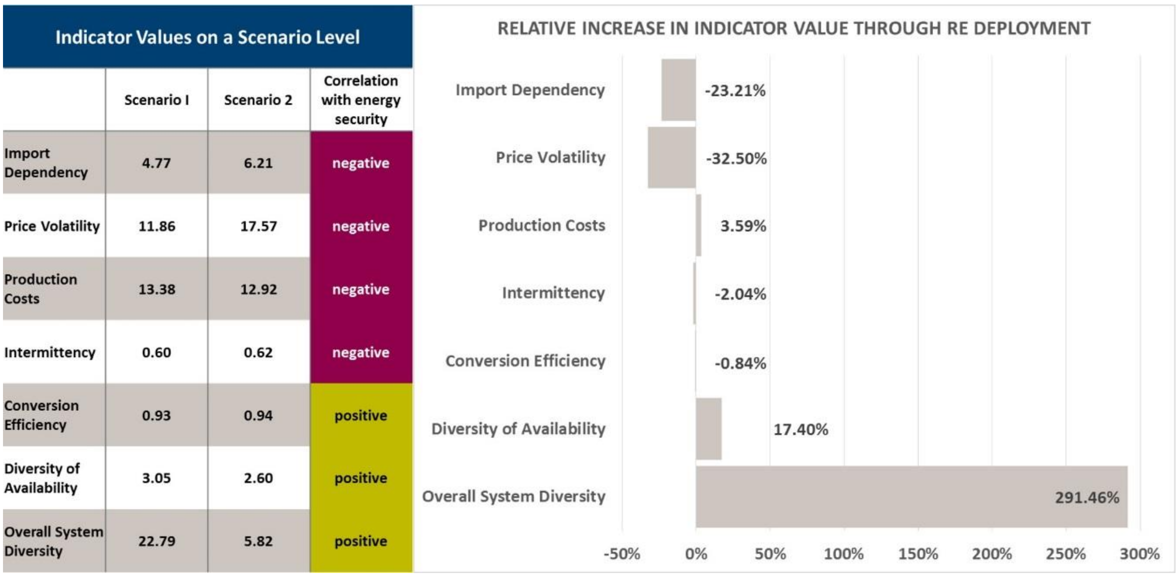
Despite the negative impacts of renewable energy technology deployment on **price volatility** in the industry sector, the overall price volatility impact on a scenario-level decreases through the deployment of renewable energy technologies by 32.50% and hence also increases energy security with regard to economic affordability and acceptability.

Although the deployment of renewable energy technologies decreases **production costs** in all assessed decomposition levels, the overall production cost impact on a scenario-level slightly increases through the deployment of renewable energy technologies by 3.59%. Hence, for the assessed scenarios, the deployment of renewable energy technologies decreases overall energy security with regard to economic acceptability, affordability and efficiency in the German heating sector.

On a scenario-level, the deployment of renewable energy technologies for heat generation slightly decreases the overall **intermittency** impact by 0.84%. Hence, for the assessed scenarios, the deployment of renewable energy technologies slightly increases overall energy security with regard to natural and technical availability in the German heating sector.

Although the deployment of renewable energy technologies slightly increases **conversion efficiency** in all assessed decomposition levels, the overall conversion efficiency impact on a scenario-level slightly decreases through the deployment of renewable energy technologies by 0.84%. For the assessed scenarios, the deployment of renewable energy technologies decreases overall energy security with regard to technical efficiency in the German heating sector.

Just like on the assessed decomposition levels, the deployment of renewable energy technologies increases the **diversity of availability** and the **overall system diversity** impact also on a scenario-level by 17.40% and 291.46%, respectively. Hence, overall energy security in the German heating sector increases with regard to natural availability and diversity in all dimensions through the deployment of renewable energy technologies.



Indicator Values on a Scenario Level

	Scenario I	Scenario 2	Correlation with energy security
Import Dependency	4.77	6.21	negative
Price Volatility	11.86	17.57	negative
Production Costs	13.38	12.92	negative
Intermittency	0.60	0.62	negative
Conversion Efficiency	0.93	0.94	positive
Diversity of Availability	3.05	2.60	positive
Overall System Diversity	22.79	5.82	positive

Figure 4-14: Indicator-based scenario comparison

5 Discussion

5.1 Research Aim, Formulation and Legitimacy of Research Questions

In the context of ImpRES, the research aim of my thesis is to approach the complexity and multiplicity of the contemporary energy security understanding in developing and applying a methodological approach to assess energy security. My thesis further aims at quantitatively assessing the implications of the end-use of renewable energy fuels and technologies for energy security in Germany. To that end, the German heating sector is taken as a case-study to carry out the assessment. Despite this sector having the biggest share in Germany's end energy consumption, the public discussion on energy issues is still focussing on the electricity sector and hence neglects the heating sector. My thesis aims at bringing the heating sector into the spotlight of discussion as well.

The research project ImpRES is funded to carry out an economic evaluation of costs and benefit effects of renewable energy expansion in the German electricity and heating sector. So far, the project has only qualitatively assessed the implications of renewable energy deployment for energy security. For an economic evaluation in the form of a cost-benefit analysis however, a quantitative analysis of the implications of renewable energy deployment for energy security is indispensable. Moreover, the political, societal, and academic discourse on energy security in Germany focuses on supply-based price and quantity risks. *Energy security* is commonly understood and discussed as *security of supply*. Scholars argue that this current perspective on energy security is too narrow to appropriately account for the complexity and multiplicity of energy security. The reviewed literature recognises a need for a more integrated conception of energy security.

The first research question directly addresses the revealed research gaps. Firstly, in asking for the constituting attributes of energy security, the energy security understanding is revised and the focus on price and quantity risks is altered and broadened. With the help of attributes, i.e. dimensions and characteristics, my thesis delineates the concept of energy security in a comprehensive way. Secondly, to be able to quantify the impact of renewable energy deployment on energy security, a method and metrics to measure the identified characteristics and dimensions is required. Hence, the research question *"What are relevant attributes of energy security in the German heating sector and how could they be measured?"* has full legitimacy with regard to the underlying research aim.

However, the way the first research question is formulated might impact the assessment approach. To obtain an unambiguous answer when asking for the constituting attributes of energy security, a strict and unique definition of energy security would be required. Such a definition is not given in my thesis. Instead, the energy security understanding and hence the identified attributes are derived from reviewing a broad body of existing energy security definitions and assessments, involving different actors, different geographical contexts, and different time frames. I consider this missing definition a strong limitation since it breaks with the methodology of classical reasoning in scientific work where a concept is first explicitly defined and then applied. I argue for this decision regardless, since the concept of a rigid energy security definition is much more contested than the attributes (i.e. characteristics and dimensions) of energy security understanding. In identifying, explicitly defining, and selecting these attributes, I am able to develop a delineation of the width and depth of the contemporary energy security understanding without rigidly defining energy security itself.

So far, ImpRES and similar studies assume the overall impact of renewable energy deployment to be beneficial to energy security. This assumption implicitly includes two hypotheses: (1) There is an unambiguous overall impact of renewable energy deployment on energy security; (2) This overall impact is beneficial to energy security.

The second research question directly scrutinises these hypotheses. To account for the complexity and multiplicity of the contemporary energy security understanding, the implications of renewable energy deployment for the different attributes of energy security have to be assessed. Only then, a conclusion on the overall impact of renewable energy deployment on energy security could be drawn. Hence, the research question *"How does the end-use of renewable energy fuels and technologies as opposed to fossil-based energy provision in the German heating sector influence energy security measured by its previously defined attributes?"* has full legitimacy with regard to the underlying research problem and allows to assess both beneficial and harmful implications for different attributes of energy security.

5.2 Methodological, Theoretical, and Analytical Choices

5.2.1 Isolated Analysis of the Heating Sector

In my assessment, I tried to analyse the German heating sector in separation of the German electricity sector in excluding thermal energy that is directly generated from electricity. I only included electricity price and efficiency data for the calculation of indicator values for heat pumps. Separating the heating from the electricity sector allowed me to carry out a more technology specific analysis. Electricity generation can be based on similar technologies to heat generation such as coal or gas firing. But it might also be based on specific technologies such as wind power, photovoltaic, or nuclear energy. Such specific technologies also embody specific characteristics different from those of heat generation technologies. Combining an analysis of heat and electricity generating technologies would have required a set of characteristics, dimensions, and indicators specific enough to appropriately account for the peculiarities of inherently different generation technologies and flexible enough to be valid for each of these technologies. The resulting analysis would not have been likely to be meaningful to assess energy security in the German heating sector. Based on this reasoning, I still argue for a strict separation of the energy security analyses of the two sectors.

At this point however, I explicitly want to point out that these systems do not operate isolated from each other in reality. Electricity is powering the control and feedback control systems of nearly all heat generation technologies – regardless if renewable or conventional – particularly, but not exclusively, in the industry sector. Any threat to electricity security hence immediately creates a threat to heat security. Similarly, some technologies included in this analysis generate combined heat and power. Any threat to heat security for these technologies is hence likely to be a threat to electricity security as well. Despite the separate analyses of the two sectors, these interdependencies should be accounted for when making decisions on either of the sectors or their elements. The mere energy security assessment of the German heating sector is only part of the actual energy security state in the sector – it has to be combined with the results from assessing the German electricity sector.

5.2.2 Heating Sector Delineation and Disaggregation

In my thesis, the German heating sector is disaggregated into three subsectors (industry, service sector, and households) and three end-uses of thermal energy (space heating, process heat, and hot water). This disaggregation is commonly used in assessments of the German heating sector (e.g. in AGEB, 2013) and hence allowed me to use a broader database than other disaggregation methods. Similarly, different energy carriers are aggregated in my thesis to one technology according to established aggregation rules for assessing the German heating sector (e.g. AGEB, 2013 and BMU, 2013) due to broader data availability. Biomass for instance comprises different types of wood, wood pellets, and woodchips – but also different types of food waste.

Especially the aggregation of energy carriers to technologies could influence the results since the technology-based indicator values are directly depending on the technology composition. The remaining decomposition- and sector-level analysis is based on these indicator values. It would be desirable to obtain detailed data on an energy carrier-basis to get a more accurate picture of the German heating sector. This is likely to require a significant primary data collection effort that would go beyond the scope of this thesis.

5.2.3 Comparative Analysis and Scenario Development

The development of the two scenarios assessed in my thesis is based on ImpRES and the decision to conduct a comparative analysis of two scenarios of the German heating sector. Scenario I is a simplification of the German heating sector in 2011 comprising both renewable and conventional energy technologies for heat generation. Scenario II is created in substituting each renewable energy technology with conventional energy technologies for heat generation. The substitution factors are based on a study by the German Federal Environment Agency.

My thesis hence assesses (scenarios of) the status quo in the German heating sector, i.e. it assesses a functioning system composed of established technologies. Following the methods applied in ImpRES, the indicator values are calculated based on past data dependent on the types and shares of technologies in the assessed system. Consequently, one of the major drawbacks of this approach is that the results I obtain in my thesis are valid for the comparison of these specific scenarios only. Production costs or conversion efficiencies for renewable energy technologies, for instance, might change significantly if these technologies were deployed to a bigger extent or replaced by new heat generation technologies. Neither the severity nor the direction of renewable energy deployment impact can therefore be scaled to other (present or future) scenarios since the technology-based indicator values are directly dependent on the scenario composition.

5.2.4 Expert Survey and Interviews

My thesis is restricted to a very limited set of primary data. All in all over 30 experts in the field of (renewable) energy (security) were asked to respond to a survey or were asked for a personal interview. After nine weeks, only nine complete and four incomplete survey responses have been received and only three short e-mail conversations took place. This limited set of responses places strong restrictions to the degree to which expert opinions and primary data could be included in the assessment of my thesis.

In order not to falsify the survey results, only completely answered surveys are included in my thesis. Although the expert survey has been tested and approved by ten people whereof six had experience in the energy sector, feedback on the survey often demanded a further clarification of survey questions. This clarification often altered the experts' answers on the respective questions. This is a strong indication that the survey might have not been fully understandable without further guidance. It is hence questionable whether those experts not asking for such guidance understood the survey questions in the way they were intended to be understood. Similarly, the answers are likely to be influenced by the professional background of the respondents and interviewees. Depending on the interviewee's background and occupation the energy security understanding is likely to differ significantly. Technicians have a different understanding of what energy security is or ought to be than politicians do. I tried to eliminate this bias in questioning a balanced group of experts from different backgrounds. The low number of respondents however cannot fully eliminate this professional bias.

Therefore, the survey is to be seen as an expert check on the selections made during my research process but not as guiding primary data. Further research could place stronger emphasis on the collection and inclusion of expert opinions and other primary data for assessing energy security.

5.2.5 Indicator Selection and Exclusion Requirements

The approach presented in my thesis places a relatively weak top-down requirement on the selection of indicators. Each dimension and each characteristic has to be reflected in at least one indicator in the resulting indicator set. This requirement can lead to a one-sided indicator analysis. For example, the substitutability indicator can be assessed from a technical dimension and an availability characteristic, i.e. it can be assessed whether it is technically possible to substitute one technology with another available technology. Similarly, this indicator could be assessed from an economic dimension and an affordability characteristic, i.e. it can be assessed which substitution possibility is the most economically feasible. Then, the indicator could also be assessed from a technical dimension and an efficiency characteristic, i.e. it can be assessed which substitution technology is the most energy efficient. Although the resulting set in my thesis aims at assessing energy security in a balanced way, the threat of a one-sided indicator analysis should be limited through a stricter top-down requirement.

Another drawback of the weak indicator requirements is the double-counting of some energy security attributes. Since one indicator can generally account for one or more energy security attributes, some of these attributes are double- or triple-counted in the energy security assessment. Economic acceptability for instance is reflected in both, the price volatility and the production costs indicator. The double-assignment of indicators to energy security attributes might even lead to conflicting results. The deployment of renewable energies is beneficial for economic acceptability in the industry sector according to the production costs indicator but harmful according to the price volatility indicator.

In my thesis, I excluded a few indicators due to the lack of available data for the respective indicator calculation. This indicator exclusion does not influence the general nature of my assessment and its results since the remaining set of indicators fulfils all top-down and bottom-up requirements. Yet, some of the indicators considered to be most important for an energy security assessment could not be included in my assessment. One example is the substitutability indicator.

Depending on the dimension and characteristic within which substitutability is assessed, it can be an essential element of energy security. This thesis excluded the substitutability indicator partially for the reason that general technical substitutability for each technology is given and hence less important for energy security. Assessing the same indicator from an economic affordability or a technical availability perspective, the picture changes significantly. Especially technologies for process heat in the industry, are designed so that oil can be substituted with natural gas or other fuels within a few minutes to react to price fluctuations or fuel scarcity. Similarly, many old stoves for space heating in households can be fired with different kinds of biomass and coal to react to availability fluctuations. Again, a stricter top-down requirement for the indicator selection would reduce the threat of missing significantly important indicators in the energy security assessment.

A stricter top-down requirement avoiding a one-sided analysis and double-counting could be for instance the requirement that there should be one indicator only for each dimension-characteristic combination in the resulting set of metrics. Such a requirement is however likely to place high barriers to important indicators. The scholar would hence have to decide whether price volatility or production costs are more adequate to assess economic acceptability. This trade-off explicitly reveals that the indicator selection process is far from trivial. The selection process and the resulting set of indicators is hence to be seen as exemplary and non-exclusive.

5.2.6 Indicator Calculation and Aggregation

The indicator calculation is not always unambiguously defined in the literature. For many indicators, several calculation methods exist and hence produce different numerical results. The calculations presented in my thesis are therefore to be seen as subjectively chosen examples for the respective indicators. This thesis should by no means be seen as a statistical analysis of energy security. The calculated absolute values in my assessment should be given less attention than the general statement on the context specific trade-off between beneficial and harmful impact of renewable energy deployment.

Similarly, even if the indicator calculation is rigidly defined, the input data for this calculation might be obtained from different sources resulting in significant numerical discrepancies. Where this is the case, I use the arithmetic mean of the available data sources. For some indicator components, specific data could not be obtained and proxy or aggregated data is used. Similarly, where indicator calculation methods create discordant values for some technologies, fixed values are used and explained. Although any alteration of data was indicated, the numerical results might have been falsified. More effort needs to be put in the compilation of complete data sets and in assessing the statistical significance of necessary data alteration.

In my thesis, I refrain to aggregate and weigh indicators. This does not mean that I refrain to aggregate indicator values. The indicator values for import dependency for instance are calculated on a decomposition level and then aggregated (according to the levels' shares) to a sector level. Similarly, indicator calculations might weigh and aggregate indicator subcomponents. Variety, balance, and disparity, for instance, are equally weighted and aggregated through multiplication to one diversity indicator. The relinquishment to aggregate or weigh indicators refers to the aggregation of indicators to draw a conclusion on energy security, e.g. to value import dependency twice as high as diversity of availability.

In my thesis, indicators are not aggregated but analysed separately because an adequate depiction of the interrelations and dynamics within the assessed energy system is likely to go beyond the scope of my thesis. Any attempt to simplify these interrelations and dynamics would expose the analysis to dangers of subjective choices and evaluations. I argue that the decision maker should have unconcealed information about the assessed system elements and that it is not the researcher's duty to predetermine a decision in aggregating indicators and in that way risking to mislead the decision maker.

This argumentation holds true especially with regards to the broad audience I address. I write this thesis for policy- and decision makers in the field of (renewable) energy (security) policy. Depending on the context of the (policy) decision, the implications for energy security and the importance of single attributes of energy security for the underlying decision can differ significantly. From an economic perspective, a two minute interruption of space heating in households is unproblematic while a two minute interruption of process heat in the industry sector can lead to high economic losses. Every decision maker pursues different objectives. Despite the exposure to subjectivity, any indicator aggregation could only serve as a decision making support for a certain group of policy- and decision makers and would be of less use to the remaining audience.

5.3 Relevance and Generalizability of Results

The first research question (*"What are relevant attributes of energy security in the German heating sector and how could they be measured?")* can fully be answered in my thesis. With the help of a literature review and expert interviews, characteristics and dimensions were identified as main attributes of energy security and indicators are identified as metrics to measure energy security regarding these attributes. My thesis presents a comprehensible approach to identify attributes and indicators. As discussed above however, this approach has its drawbacks and the identified attributes and indicators are therefore to be seen as exemplary and non-exclusive.

Also the second research question *("How does the end-use of renewable energy fuels and technologies as opposed to fossil-based energy provision in the German heating sector influence energy security measured by its previously defined attributes?")* can be answered. My thesis shows that the impact of renewable energy deployment on (attributes of) energy security in the German heating sector could be beneficial, harmful, or neutral depending on the regarded technology, the regarded subsector, and the regarded end-use of thermal energy.

The absolute numerical results obtained in my thesis should be given less attention. Firstly, because the ambiguous indicator calculation leads to ambiguous numerical results. The mere absolute indicator values are hence not meaningful for assessing energy security. A comparison of indicator values within one indicator (e.g. comparing the intermittency values for coal firing and solar thermal technologies) is however legitimate. This allows for a technology ranking according to the regarded indicator. Secondly, because indicator calculation is in many cases based on incomplete data bases, proxy values, and data alterations. Thirdly, because indicator values directly depend on the technology composition and technology maturity within the assessed scenarios. These scenarios represent a functioning system composed of established technologies. The indicator values are calculated based on past data dependent on the types and shares of technologies in the assessed system. Production costs or conversion efficiencies for renewable energy technologies, for instance, might change significantly if these technologies were deployed to a bigger extent or replaced by different technologies. Neither the severity nor the direction of renewable energy deployment impact can therefore be scaled to other scenarios since the technology-based indicator values are directly dependent on the scenario composition and are hence not generalizable.

In my thesis, I present a comprehensible approach for a systematic assessment of energy security that goes beyond the assessment of price and quantity risks. The approach is applied to the German heating sector. The general nature of the approach, i.e. the indicator based comparative energy security analysis of energy sector scenarios within characteristics and dimensions, can be applied to every energy system and in every geographical context. Since the characteristics, dimensions, and indicators are derived from the purpose of the assessment and the nature of the underlying scenarios, it is however important to adapt the attributes and metrics of energy security according to the underlying context and the purpose of the assessment. Assessments with a broader time horizon and a change in technology compositions, for instance, cannot take characteristics such as reliability or feasibility as inherent. In a different geographical or cultural context, other attributes and indicators might become more relevant. The approach is hence only generalizable in a contextualised manner.

6 Conclusions and Recommendations

6.1 Main Findings and Conclusions Delivered in the Analysis

Since 2008 the German Federal Ministry for the Environment, Nature Conservation, and Nuclear Safety is funding a multi-year research project on the economic assessment of costs and benefit effects of renewable energy expansion in the German electricity and heating sector. The study, referred to as ImpRES – short for impacts of renewable energy sources –, identifies the impact of renewable energy deployment on energy security as a significant aspect that has not yet been quantitatively assessed.

The major discourse on energy security in Germany and the European Union currently puts energy security on one level with price and quantity risks resulting from high import dependency and low diversification of energy carrier portfolios. In the public, academic, and political discourse in Germany, e*nergy security* is commonly understood and discussed as *security of supply*. The impact of renewable energy deployment on energy security is commonly regarded as beneficial. Scholars however argue that the current understanding of energy security is too narrow to account for the complexity and multiplicity of energy security. There is a need for a more integrated conception of the subject that will allow policy and decision makers to ground their course of action on a holistic understanding of energy security.

Against this background and in the context of ImpRES, my thesis aimed at approaching the complexity and multiplicity of the contemporary energy security understanding in developing and applying a methodological approach to assess energy security. My thesis further aimed at quantitatively assessing the implications of the end-use of renewable energy fuels and technologies for energy security in Germany. To that end, the German heating sector is taken as a case-study to carry out the assessment. Despite this sector having the biggest share in Germany's end energy consumption, the public discussion on energy issues is still focussing on the electricity sector and hence neglects the heating sector. My thesis aimed at bringing the heating sector into the spotlight of discussion as well.

The guiding research question has been formulated as:

> What are the implications of the end-use of renewable energy fuels and technologies for energy security in the German heating sector and how could these implications be quantified?

To achieve the outlined objectives of my thesis, I break this overarching question down into two sub-questions:

1. What are relevant attributes of energy security in the German heating sector and how could they be measured?

2. How does the end-use of renewable energy fuels and technologies as opposed to fossil-based energy provision in the German heating sector influence energy security measured by its previously defined attributes?

For the purpose of my assessment, I created two scenarios of the German heating sector. The first scenario was a simplified depiction of the status quo in the German heating sector, including fossil-based and renewable energy technologies. The second scenario was comprised of fossil-based energy technologies only. Both scenarios had the same total energy volume. In an indicator-based comparative analysis, the difference between the indicator values of the two scenarios allowed me to draw conclusions on the energy security impact of renewable energy technologies. To allow for a detailed analysis and to account for its complexity, I broke down the German heating sector into two levels, i.e. subsectors and end-uses of energy. Some of these levels were further broken down into sublevel combinations (referred to as decomposition levels) where renewable energies played a significant role. One sublevel combination was for instance process heat in the industry; another was space heating in households. This disaggregation later allowed me to analyse energy security on these decomposition levels and then to aggregate the levels again to draw conclusions on energy security in the whole heating sector.

The literature review in Chapter 2 revealed that there are at least three different perspectives on energy security that have evolved from distinct and independent policy challenges for energy security. The first and oldest is a sovereignty perspective focussing on geopolitical theories and strategic security studies. During the last decades of the twentieth century, the discourse on energy security understanding was broadened by a robustness perspective focussing on scientific and engineering thinking. In the last 30 years, the discourse on energy security understanding was further broadened by a resilience perspective focussing on economic theory, especially on investment theory and the diversification of risk. Since these three perspectives are co-constituting for the contemporary energy security understanding but have so far mainly been analysed separate from each other, I tried to develop a methodological approach for assessing energy security that accounts for all three perspectives.

The literature review in Chapter 2 further revealed that the amount of strict definitions on energy security is almost inexhaustible, highly contextualised, and therefore too contested to have general validity. Against this background I decided not to finitely define energy security but to look for (less contested) attributes of energy security to delineate the contemporary understanding of the subject. From reviewing the literature, I identified these attributes as dimensions and characteristics of energy security. Dimensions refer to the contemporary views of different stakeholders on energy security while characteristics refer to requirements of energy systems and their subcomponents necessary for the existence of energy security. Although separately defined in my thesis, both, dimensions and characteristics, might overlap in reality and cannot always be strictly separated.

Since my assessment analysed two scenarios of the same functioning energy system composed of established technologies, some attributes were assumed to be inherent in the system and have therefore been excluded from the assessment. The remaining attributes constituted a matrix of six dimensions (an economic, an environmental, a natural, a political, a societal, and a technical dimension) and six characteristics (acceptability, accessibility, affordability, availability, diversity, and efficiency) relevant for my assessment.

This matrix constituted a top-down requirement for the metrics to measure energy security in my assessment. The complete set of metrics had to account for each dimension and characteristics in the matrix. This means that for each dimension and for each characteristic, there needed to be at least one metric in the matrix. The technologies in the German heating sector on the other hand constituted a bottom-up requirement. This means that the resulting complete set of metrics had to account for specific technology characteristics relevant to energy security. At the same time the set had to be valid for all technologies. This means that each metric had to be valid for every technology. Both requirements, the top-down and the bottom-up requirement, were indispensable. To allow for a comparative analysis, the resulting set of metrics had to be applied on each decomposition level and for both scenarios.

From the literature review, consultation with my supervisors, and expert surveys and interviews, I identified a set of indicators suitable for metrics to measure energy security. Indicators in energy security assessments can be borrowed from other disciplines such as economic theory or political science or specifically designed for assessing energy security. The set of indicators is usually contextualised for the purpose of the respective assessment. The chosen set of indicators in my assessment is to be seen as a non-exclusive example selected for the purpose of my thesis. This set could be revised and broadened in future assessments. The lack of available data forced me to reduce the preliminary set of indicators to a set of seven indicators that were assessed in my thesis: import dependency, price volatility, production costs, conversion efficiency, intermittency, diversity of availability, overall system diversity. This reduced set still fulfilled both assessment requirements.

At this point, I was able to fully answer my first research question *"What are relevant attributes of energy security in the German heating sector and how could they be measured?"*:

- Attributes of energy security can be divided into dimensions (i.e. different stakeholders' views on and perceptions of energy security) and characteristics (i.e. more or less pronounced requirements of energy systems and their subcomponents necessary for the existence of energy security).

- A rigid definition of energy security can hardly be obtained due to the complexity and heterogeneity of the subject. My thesis showed that with the help of both, dimensions and characteristics, the contemporary energy security understanding can be delineated without finitely defining energy security.

- The relevant dimensions of energy security in the German heating sector were identified as an economic, an environmental, a natural, a political, a societal, and a technical dimension. The relevant characteristics were identified as acceptability, accessibility, affordability, availability, diversity, and efficiency. These attributes help to broaden the current discourse of energy security in Germany to appropriately assess energy security.

- Within these dimensions and characteristics, energy security can be measured with the help of indicators borrowed from other disciplines or specifically designed for the purpose of the assessment. For each dimension and for each characteristic, there has to be at least one indicator in the resulting set of metrics. Similarly, the resulting set of metrics has to account for the peculiarities of each assessed technology while being valid for every technology in the assessed system.

- The indicator selection process is far from trivial. The indicators assessed in my thesis (import dependency, price volatility, production costs, conversion efficiency, intermittency, diversity of availability, overall system diversity) are to be seen as exemplary and non-exclusive.

Many energy security assessments aggregate indicators according to subjectively defined optimisation, rating, or weighing criteria without appropriately accounting for the underlying dynamics and interdependencies of system elements in the assessed energy system. This is usually done for the end of simplifying decision making on energy security. My thesis reveals that it is hardly possible to appropriately account for the system dynamics and interdependencies of system elements in an energy system in an understandable way. The perception of what is optimal for energy security varies depending on the decision or policy maker's perspective and the context in which the (policy) decision takes place. An economist in a recession would optimise different variables under different constraints than a politician prior to elections. To reduce the exposure to subjectivity and to provide the audience of my thesis with an assessment on which individual decisions can be grounded, I chose to refrain from the aggregation of indicators and analysed each indicator separately instead.

To answer my second research question, I applied the selected set of seven indicators to calculate indicator values for each heat generation technology to assess energy security on a technology-basis. These indicator values were then multiplied with the respective technology shares in the decomposition levels and in the overall scenarios. In this way, I was able to assess energy security on a technology- and indicator-basis on a decomposition level and to assess energy security on an indicator-basis on a scenario level. The differences in indicator values between the two scenarios allowed me to draw conclusions on the impact of renewable energy deployment in the German heating sector.

Many of the indicators I used in my assessment are based on ambiguous calculation methods. This means that for many indicators, several calculations exist and hence produce different numerical results. The calculations presented in my thesis are therefore to be seen as subjectively chosen examples for the respective indicators. Since these subjective choices influence the numerical results of my assessment, the mere calculated absolute indicator values should be given less attention.

Similarly, the severity and the direction of relative indicator value changes (i.e. the impact of renewable energy technology deployment) is to be seen as valid for the assessment of my thesis only. Since the technology-based indicator values are directly dependent on the scenario composition, neither the severity nor the direction of renewable energy deployment impact can be scaled to other scenarios.

The general statement of my assessment is however not affected by the choice of the indicator calculation methods or the scenario composition: The technology-based analysis as carried out in my thesis revealed that depending on the assessed indicator – and also depending on the assessed subsector and end-uses of thermal energy – the deployment of renewable energy technologies could be beneficial, harmful, or neutral to (attributes of) energy security compared to the deployment of conventional technologies. Similarly, the decomposition-level and the scenario-level analyses as carried out in my thesis revealed that depending on the assessed indicator – and also depending on the assessed decomposition levels – the deployment of renewable energy technologies could be beneficial, harmful, or neutral to (attributes of) energy security compared to the deployment of conventional technologies.

At this point, I was able to answer my second research question *"How does the end-use of renewable energy fuels and technologies as opposed to fossil-based energy provision in the German heating sector influence energy security measured by its previously defined attributes?"*:

- ➢ The deployment of renewable energy technologies in the German heating sector could be beneficial, harmful, or neutral to (attributes of) energy security depending on the deployed technology and the regarded subsector or end-use of thermal energy.
- ➢ Since I refrain to weigh or aggregate indicators, the overall impact of renewable energy deployment on energy security in the German heating sector as assessed in my thesis cannot be determined. The perception of what is optimal for energy security varies depending on the decision or policy maker's perspective and the context in which the (policy) decision takes place.

6.2 Contribution to the Body of Literature

In my thesis, I present a comprehensible approach for a systematic assessment of energy security in the German heating sector that goes beyond the assessment of price and quantity risks resulting from high import dependency and low diversification of energy carrier portfolios. If contextualised to the specific circumstances and requirements of the underlying assessments, the presented approach can generally be applied to other energy systems in other countries or regions. Since this thesis is the first attempt to analyse energy security in the German heating sector, the obtained results should be revised and further investigated and the presented approach should be further refined.

The assessment sets the very basic foundation of an indicator-based energy security assessment, particularly – but not exclusively – for the annual retrospective impact assessment of renewable energy deployment in the German heating and electricity sector according to the objectives of ImpRES. This foundation can be used to develop a set of indicators for the quantification of annual energy security changes to be included in ImpRES.

My thesis starts to bring the heating sector and the way it is influenced by the deployment of renewable energy technologies into the spotlight of discussion. It shows that it is worthwhile to assess more complex energy systems particularly – but not exclusively – in terms of energy security. Although my short thesis cannot account for the total complexity of the highly decentralised heating sector, this step is an inalienable prerequisite to contribute to a mature discussion on the growing deployment of renewable energies in Germany, on the complexity of energy systems, their current state, and their past and future developments.

Contradicting the hypothesis of ImpRES, my thesis shows that the impact of renewable energy deployment on energy security is not necessarily beneficial but can be harmful or neutral as well.

6.3 Recommendations to the Audience

Scholars in the field of (renewable) energy (security) research should take this thesis to broaden their perspective on energy security. The contemporary understanding of energy security goes beyond price and quantity risks, import dependency and diversification and should hence be assessed as such. Such a broad assessment will reveal that renewable energies are likely to have both, beneficial and harmful impact on energy security, depending on the regarded subsector or end-use. If contextualised, the presented approach can be applied and adapted to other energy systems in other countries or regions. The approach sets a basic foundation to develop a set of indicators for the retrospective quantification of annual energy security changes and should be included and further developed as such in ImpRES and comparable studies.

I further want to engage scholars in the field not to aggregate assessment results to ease the decision making of third parties. In doing so, the researcher exposes the assessment results to threats of subjectivity risking a biased decision.

Policy- and decision makers in the field of (renewable) energy (security) policy should broaden their view on energy security beyond price and quantity risks, import dependency and diversification before taking course of action. They should refrain from basing decisions on pre-selected decision criteria for the end of easing their decision making process. Energy (security) policy is far from trivial and hence can and ought not to be simplified too much. Any decision maker should take the time and effort to regard the single components and results of energy security assessments. Preferably, the decision maker should also acquire knowledge about the interdependencies and dynamics of single system elements and against this background arrive at a decision taking into account the circumstances specific to this decision, affected stakeholders, and involved system elements.

6.4 Suggestions for Future Research

Further research – if applying the same hybrid approach – should place stricter top-down requirements on indicator selection. The indicator selection process should be revised and refined. Against this background further indicators for assessing energy security should be investigated to allow for a balanced analysis of energy security without double-counting certain attributes.

Future work on energy security should investigate ways of depicting the assessed energy system in more detail and obtain respective detailed data sets. Future research should improve data selection methods, e.g. in establishing standards for the collection and compilation of data. In this context, further research should analyse the significance of indicators and how the indicator calculation impacts the obtained results.

Upcoming research could place stronger emphasis on the collection and inclusion of expert opinions and other primary data for assessing energy security. Primary data collection should investigate ways to eliminate the respondents' subjective pre-definition of energy security and other biases stemming from the professional background of the respondents or the circumstances in which the data collection takes place.

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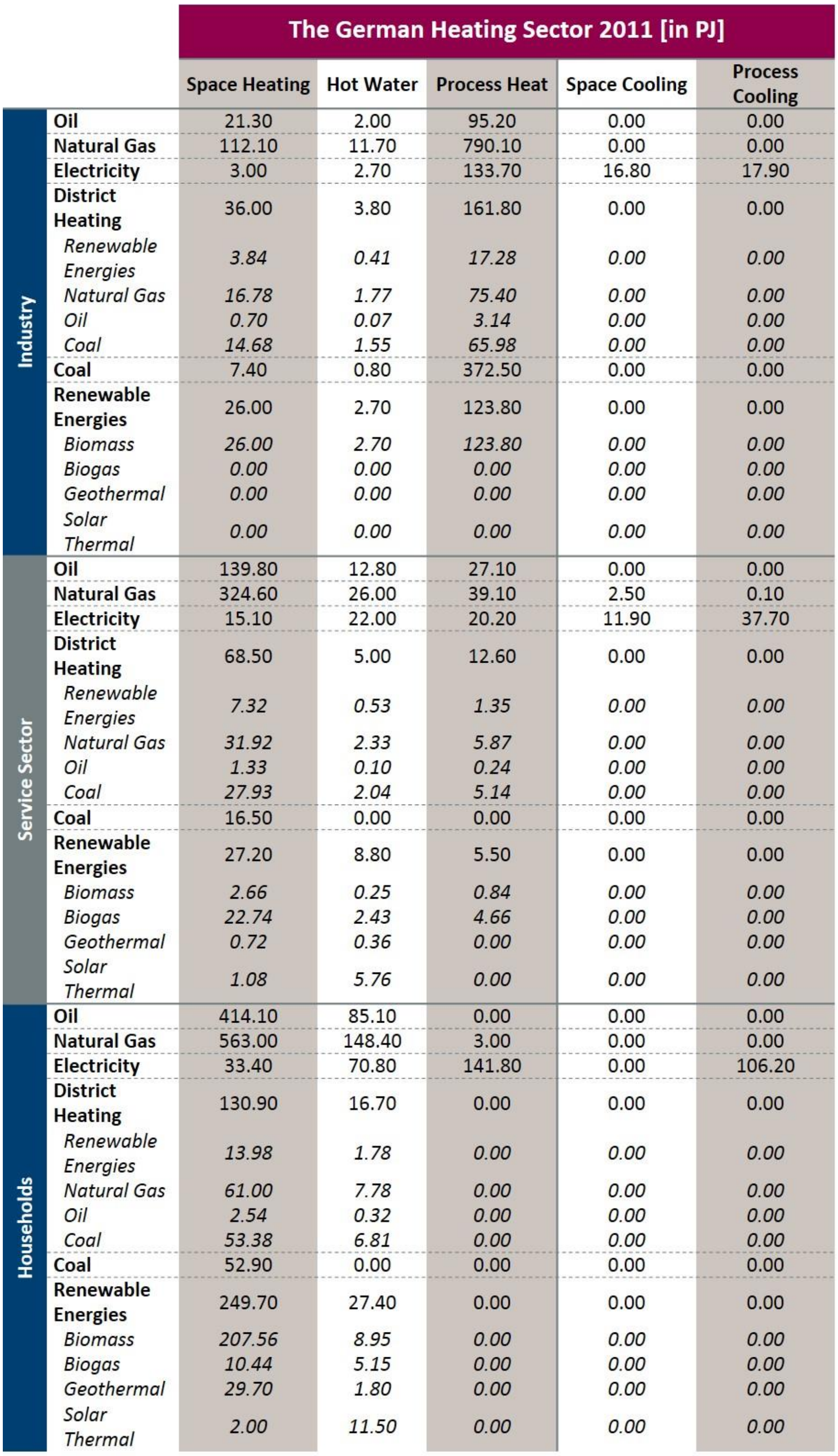
Appendix I: The German Heating Sector 2011

The table contains detailed data on the energy mix in the German heating sector in 2011[in PJ]. Small discrepancies in the numbers might stem from rounding differences. Where different data bases provided different figures, the arithmetic mean has been used.



The German Heating Sector 2011 [in PJ]

		Space Heating	Hot Water	Process Heat	Space Cooling	Process Cooling
Industry	**Oil**	21.30	2.00	95.20	0.00	0.00
	Natural Gas	112.10	11.70	790.10	0.00	0.00
	Electricity	3.00	2.70	133.70	16.80	17.90
	District Heating	36.00	3.80	161.80	0.00	0.00
	Renewable Energies	*3.84*	*0.41*	*17.28*	*0.00*	*0.00*
	Natural Gas	*16.78*	*1.77*	*75.40*	*0.00*	*0.00*
	Oil	*0.70*	*0.07*	*3.14*	*0.00*	*0.00*
	Coal	*14.68*	*1.55*	*65.98*	*0.00*	*0.00*
	Coal	7.40	0.80	372.50	0.00	0.00
	Renewable Energies	26.00	2.70	123.80	0.00	0.00
	Biomass	*26.00*	*2.70*	*123.80*	*0.00*	*0.00*
	Biogas	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*
	Geothermal	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*
	Solar Thermal	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*
Service Sector	**Oil**	139.80	12.80	27.10	0.00	0.00
	Natural Gas	324.60	26.00	39.10	2.50	0.10
	Electricity	15.10	22.00	20.20	11.90	37.70
	District Heating	68.50	5.00	12.60	0.00	0.00
	Renewable Energies	*7.32*	*0.53*	*1.35*	*0.00*	*0.00*
	Natural Gas	*31.92*	*2.33*	*5.87*	*0.00*	*0.00*
	Oil	*1.33*	*0.10*	*0.24*	*0.00*	*0.00*
	Coal	*27.93*	*2.04*	*5.14*	*0.00*	*0.00*
	Coal	16.50	0.00	0.00	0.00	0.00
	Renewable Energies	27.20	8.80	5.50	0.00	0.00
	Biomass	*2.66*	*0.25*	*0.84*	*0.00*	*0.00*
	Biogas	*22.74*	*2.43*	*4.66*	*0.00*	*0.00*
	Geothermal	*0.72*	*0.36*	*0.00*	*0.00*	*0.00*
	Solar Thermal	*1.08*	*5.76*	*0.00*	*0.00*	*0.00*
Households	**Oil**	414.10	85.10	0.00	0.00	0.00
	Natural Gas	563.00	148.40	3.00	0.00	0.00
	Electricity	33.40	70.80	141.80	0.00	106.20
	District Heating	130.90	16.70	0.00	0.00	0.00
	Renewable Energies	*13.98*	*1.78*	*0.00*	*0.00*	*0.00*
	Natural Gas	*61.00*	*7.78*	*0.00*	*0.00*	*0.00*
	Oil	*2.54*	*0.32*	*0.00*	*0.00*	*0.00*
	Coal	*53.38*	*6.81*	*0.00*	*0.00*	*0.00*
	Coal	52.90	0.00	0.00	0.00	0.00
	Renewable Energies	249.70	27.40	0.00	0.00	0.00
	Biomass	*207.56*	*8.95*	*0.00*	*0.00*	*0.00*
	Biogas	*10.44*	*5.15*	*0.00*	*0.00*	*0.00*
	Geothermal	*29.70*	*1.80*	*0.00*	*0.00*	*0.00*
	Solar Thermal	*2.00*	*11.50*	*0.00*	*0.00*	*0.00*

Source: AGEB, 2013; ISI, 2012; LfE, 2012; RWI, 2012, Steinbach, 2013

Appendix II: Expert Survey

The following pages contain the expert survey as sent out to my interviewees. It consists of an introduction page and three questions.

Objective

The purpose of this survey is twofold. It aims to:

1) **establish an integrated definition of energy security for the German heating sector,** and then based on the derived definition,

2) **develop a set of indicators to assess energy security in the German heating sector.**

The research is carried out on behalf of the International Institute for Industrial Environmental Economics at Lund University, Sweden (http://www.iiiee.lu.se/), in cooperation with the Fraunhofer Institute for Systems and Innovation Research, Germany (http://www.isi.fraunhofer.de).

The following definitions and key assumptions are central to this survey and questions are designed to reflect these:

Characteristic:
Characteristics are requirements of energy systems and their subcomponents that are necessary for the existence of energy security in the system. Requirements can generally be met to a higher or a lower degree. The resulting set of characteristics however has to account for all necessary attributes of energy security in the German heating sector.

Dimension:
Any stakeholder to the German heating sector pursues her own objective and has his own view regarding energy security. Dimensions shall help to group these objectives and views. It is important that the resulting set of dimensions accounts for all possible objectives and views on energy security.

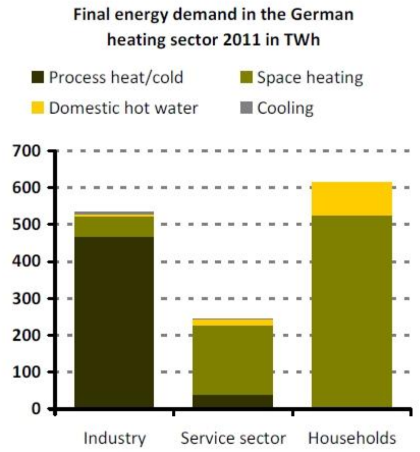
Indicator:
Indicators are quantitative metrics that support the measurement of energy security. The resulting set of indicators has to account for the characteristics and the dimensions of energy security but it also has to account for the special properties of the German heating sector and its subcomponents.

This survey will pose you three central questions. These are to support the derivation of a definition for energy security, and to delineate indicators that can account for key dimensions and characteristics of the German heating sector.

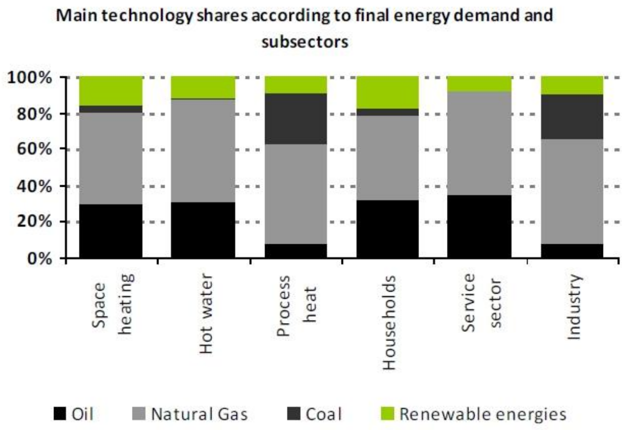
However, in order to ensure that all informants to this survey share common baseline information on the German heat sector, please examine the brief description of the German heat sector in the following box prior to addressing survey questions.

The German Heating Sector – A quick overview

- Provision of heat: decentralized, 90% by building integrated heat generating technologies
- Consumer sectors: households, industry and service sector
- End-use: space heating and cooling, process heating and cooling, hot water
- Technologies: oil, natural gas and coal firing, renewable energies (83% solid biomass, 8% biogas, 5% geothermal, and 4% solar thermal energy)



Final energy demand in the German heating sector 2011 in TWh



Main technology shares according to final energy demand and subsectors

Question 1

Please allocate the level of importance for energy security you associate with the following dimensions according to the following scale: 1: unimportant, 2: slightly important; 3: important; 4: very important; 5: critical. If you believe that a dimension of importance is absent, please add it.

Level of Importance (Points)	Dimension	Observation
	Economic	Comprises economic elements of different heat generation technologies such as fuel prices and their volatility or component and production costs.
	Environmental	Comprises elements that affect the environment such as carbon emissions, waste, water and land use for different heat generation technologies.
	Natural	Comprises elements related to the natural and geological occurrence of relevant resources required for different heat generation technologies.
	Political	Comprises elements that affect the political system such as important relations to third parties for the supply and deployment of different heat generation technologies.
	Societal	Comprises elements that affect the society such as job creation and health impacts from different heat generation technologies and related fuels.
	Technical	Comprises elements related to the (functioning of the) system infrastructure of different heat generation technologies.

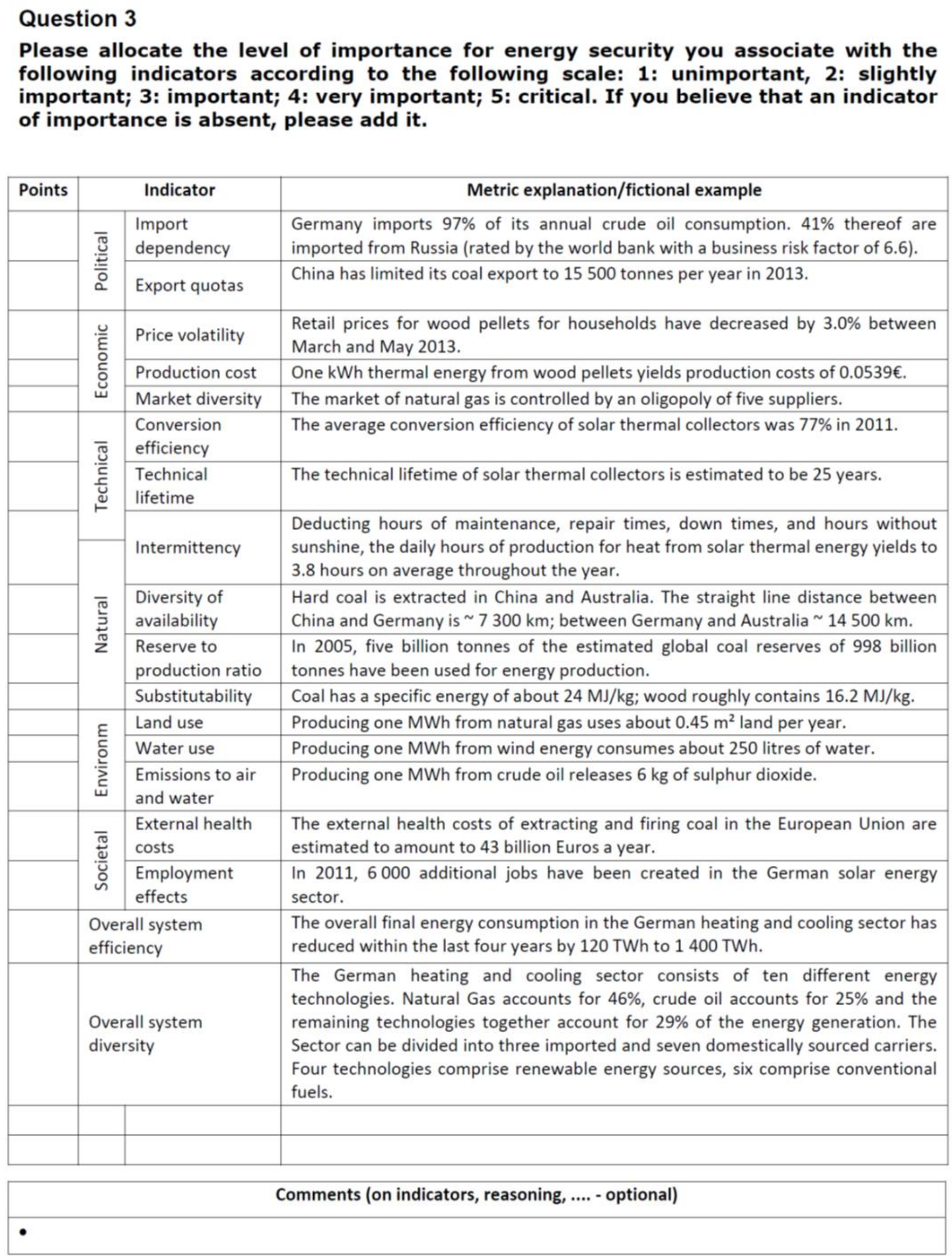
Comments (optional)
•

Question 2

Please allocate the level of importance for energy security you associate with the following characteristics according to the following scale: 1: unimportant, 2: slightly important; 3: important; 4: very important; 5: critical. If you believe that a characteristic of importance is absent, please add it.

Level of importance (Points)	Characteristic	Observation
	Acceptability	Concerns negative impacts of different heat generation technologies on other systems such as the environment, the society, or the economy.
	Accessibility	Concerns barriers such as technical or geopolitical obstacles to accessing resources relevant for different heat generation technologies.
	Affordability	Concerns economic attributes such as fuel prices or production costs for different heat generation technologies.
	Availability	Concerns the geological or natural existence of relevant resources for different heat generation technologies.
	Diversity	Concerns the degree of diversification of different system components and the system itself.
	Efficiency	Concerns the degree of efficiency of different system components and the system itself.

Comments (optional)
•



Question 3

Please allocate the level of importance for energy security you associate with the following indicators according to the following scale: 1: unimportant, 2: slightly important; 3: important; 4: very important; 5: critical. If you believe that an indicator of importance is absent, please add it.

Points	Indicator		Metric explanation/fictional example
	Political	Import dependency	Germany imports 97% of its annual crude oil consumption. 41% thereof are imported from Russia (rated by the world bank with a business risk factor of 6.6).
		Export quotas	China has limited its coal export to 15 500 tonnes per year in 2013.
	Economic	Price volatility	Retail prices for wood pellets for households have decreased by 3.0% between March and May 2013.
		Production cost	One kWh thermal energy from wood pellets yields production costs of 0.0539€.
		Market diversity	The market of natural gas is controlled by an oligopoly of five suppliers.
	Technical	Conversion efficiency	The average conversion efficiency of solar thermal collectors was 77% in 2011.
		Technical lifetime	The technical lifetime of solar thermal collectors is estimated to be 25 years.
	Natural	Intermittency	Deducting hours of maintenance, repair times, down times, and hours without sunshine, the daily hours of production for heat from solar thermal energy yields to 3.8 hours on average throughout the year.
		Diversity of availability	Hard coal is extracted in China and Australia. The straight line distance between China and Germany is ~ 7 300 km; between Germany and Australia ~ 14 500 km.
		Reserve to production ratio	In 2005, five billion tonnes of the estimated global coal reserves of 998 billion tonnes have been used for energy production.
		Substitutability	Coal has a specific energy of about 24 MJ/kg; wood roughly contains 16.2 MJ/kg.
	Environm	Land use	Producing one MWh from natural gas uses about 0.45 m² land per year.
		Water use	Producing one MWh from wind energy consumes about 250 litres of water.
		Emissions to air and water	Producing one MWh from crude oil releases 6 kg of sulphur dioxide.
	Societal	External health costs	The external health costs of extracting and firing coal in the European Union are estimated to amount to 43 billion Euros a year.
		Employment effects	In 2011, 6 000 additional jobs have been created in the German solar energy sector.
	Overall system efficiency		The overall final energy consumption in the German heating and cooling sector has reduced within the last four years by 120 TWh to 1 400 TWh.
	Overall system diversity		The German heating and cooling sector consists of ten different energy technologies. Natural Gas accounts for 46%, crude oil accounts for 25% and the remaining technologies together account for 29% of the energy generation. The Sector can be divided into three imported and seven domestically sourced carriers. Four technologies comprise renewable energy sources, six comprise conventional fuels.

Comments (on indicators, reasoning, ... - optional)
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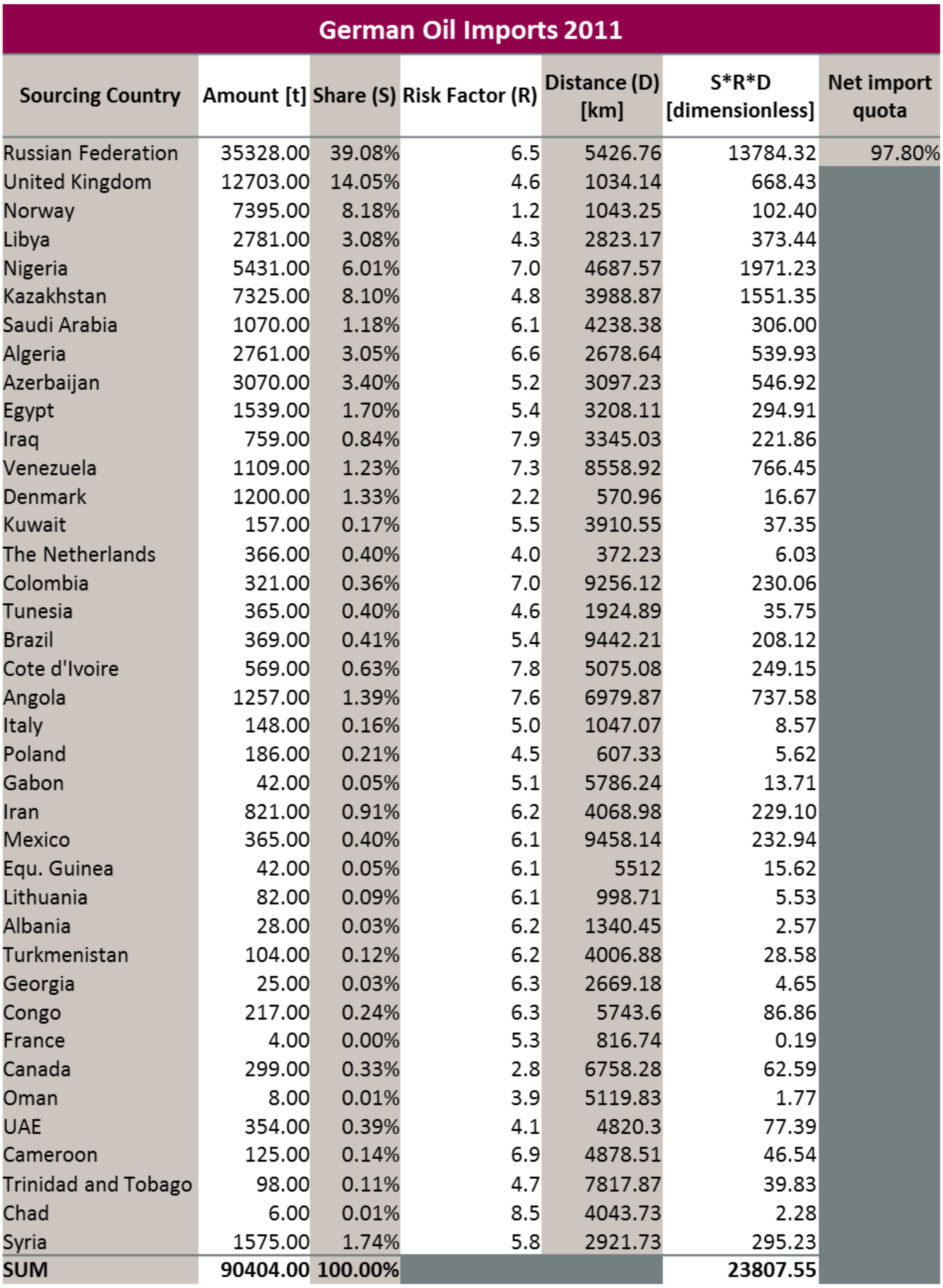
Appendix III: Survey Results

The following table shows the results of the expert survey.

		Expert Ratings											
		Interviewee 1	Interviewee 2	Interviewee 3	Interviewee 4	Interviewee 5	Interviewee 6	Interviewee 7	Interviewee 8	Interviewee 9	Mean	Min	Max
Dimensions	Economic	5	5	4	5	2	5	4	4	5	4.33	2.00	5.00
	Environmental	4	5	3	4	5	2	3	4	2	3.56	2.00	5.00
	Natural	4	5	4	4	5	3	2	2	3	3.56	2.00	5.00
	Political	4	5	4	4	4	4	3	2	3	3.67	2.00	5.00
	Societal	4	5	3	2	4	4	4	2	5	3.67	2.00	5.00
	Technical	2	5	5	5	4	3	2	2	4	3.56	2.00	5.00
Characteristics	Acceptability	4	5	3	5	5	4	5	4	4	4.33	3.00	5.00
	Accessibility	4	5	4	4	4	5	3	3	4	4.00	3.00	5.00
	Affordability	5	5	4	5	4	5	4	4	3	4.33	3.00	5.00
	Availability	4	4	4	4	4	5	3	3	4	3.89	3.00	5.00
	Diversity	4	4	4	2	2	3	3	5	1	3.11	1.00	5.00
	Efficiency	4	4	3	4	2	3	3	3	3	3.22	2.00	4.00
Indicators	Import dependency	5	5	4	4	5	5	3	5	4	4.44	3.00	5.00
	Export quota	4	5	3	2	5	1	3	4	5	3.56	1.00	5.00
	Price volatility	4	5	5	4	2	3	4	4	2	3.67	2.00	5.00
	Production cost	4	5	3	4	2	2	2	4	4	3.33	2.00	5.00
	Market diversity	4	4	4	5	4	4	2	4	4	3.89	2.00	5.00
	Conversion efficiency	4	4	4	4	1	2	2	3	4	3.11	1.00	4.00
	Technical lifetime	4	4	3	4	1	2	1	3	2	2.67	1.00	4.00
	Intermittency	4	4	4	4	2	2	4	3	3	3.33	2.00	4.00
	Source diversity	2	4	5	2	4	4	3	4	3	3.44	2.00	5.00
	Reserve to production ratio	4	5	3	2	4	5	1	3	2	3.22	1.00	5.00
	Substitutability	5	5	4	5	2	4	4	3	2	3.78	2.00	5.00
	Land use	5	2	2	5	2	3	3	4	2	3.11	2.00	5.00
	Water use	2	2	2	2	2	3	3	4	2	2.44	2.00	4.00
	Emissions to air and water	4	5	3	4	2	3	2	4	2	3.22	2.00	5.00
	External health costs	4	5	3	5	4	4	3	3	1	3.56	1.00	5.00
	Employmnt effects	4	5	3	4	4	4	1	3	4	3.56	1.00	5.00
	System efficiency	5	5	4	5	1	4	2	4	4	3.78	1.00	5.00
	System diversity	5	5	5	4	2	4	2	4	2	3.67	2.00	5.00

Appendix IV: Data for Import Dependency Calculation

The following table contains detailed data on the German oil imports in 2011. Small discrepancies in the numbers might stem from rounding differences. Where different data bases provided different figures, the arithmetic mean has been used.



German Oil Imports 2011

Sourcing Country	Amount [t]	Share (S)	Risk Factor (R)	Distance (D) [km]	S*R*D [dimensionless]	Net import quota
Russian Federation	35328.00	39.08%	6.5	5426.76	13784.32	97.80%
United Kingdom	12703.00	14.05%	4.6	1034.14	668.43	
Norway	7395.00	8.18%	1.2	1043.25	102.40	
Libya	2781.00	3.08%	4.3	2823.17	373.44	
Nigeria	5431.00	6.01%	7.0	4687.57	1971.23	
Kazakhstan	7325.00	8.10%	4.8	3988.87	1551.35	
Saudi Arabia	1070.00	1.18%	6.1	4238.38	306.00	
Algeria	2761.00	3.05%	6.6	2678.64	539.93	
Azerbaijan	3070.00	3.40%	5.2	3097.23	546.92	
Egypt	1539.00	1.70%	5.4	3208.11	294.91	
Iraq	759.00	0.84%	7.9	3345.03	221.86	
Venezuela	1109.00	1.23%	7.3	8558.92	766.45	
Denmark	1200.00	1.33%	2.2	570.96	16.67	
Kuwait	157.00	0.17%	5.5	3910.55	37.35	
The Netherlands	366.00	0.40%	4.0	372.23	6.03	
Colombia	321.00	0.36%	7.0	9256.12	230.06	
Tunesia	365.00	0.40%	4.6	1924.89	35.75	
Brazil	369.00	0.41%	5.4	9442.21	208.12	
Cote d'Ivoire	569.00	0.63%	7.8	5075.08	249.15	
Angola	1257.00	1.39%	7.6	6979.87	737.58	
Italy	148.00	0.16%	5.0	1047.07	8.57	
Poland	186.00	0.21%	4.5	607.33	5.62	
Gabon	42.00	0.05%	5.1	5786.24	13.71	
Iran	821.00	0.91%	6.2	4068.98	229.10	
Mexico	365.00	0.40%	6.1	9458.14	232.94	
Equ. Guinea	42.00	0.05%	6.1	5512	15.62	
Lithuania	82.00	0.09%	6.1	998.71	5.53	
Albania	28.00	0.03%	6.2	1340.45	2.57	
Turkmenistan	104.00	0.12%	6.2	4006.88	28.58	
Georgia	25.00	0.03%	6.3	2669.18	4.65	
Congo	217.00	0.24%	6.3	5743.6	86.86	
France	4.00	0.00%	5.3	816.74	0.19	
Canada	299.00	0.33%	2.8	6758.28	62.59	
Oman	8.00	0.01%	3.9	5119.83	1.77	
UAE	354.00	0.39%	4.1	4820.3	77.39	
Cameroon	125.00	0.14%	6.9	4878.51	46.54	
Trinidad and Tobago	98.00	0.11%	4.7	7817.87	39.83	
Chad	6.00	0.01%	8.5	4043.73	2.28	
Syria	1575.00	1.74%	5.8	2921.73	295.23	
SUM	**90404.00**	**100.00%**			**23807.55**	

Source: BAFA, 2012 & 2013; EIU, 2013; DFT, (n.d.), Umweltbundesamt (2011)

The following table contains detailed data on the German natural gas imports in 2012. Small discrepancies in the numbers might stem from rounding differences. Where different data bases provided different figures, the arithmetic mean has been used.

German Gas Imports 2012						
Sourcing Country	**Amount [t]**	**Share (S)**	**Risk Factor (R)**	**Distance (D) [km]**	**S*R*D [dimensionless]**	**Net import quota**
The Netherlands	826450.00	22.13%	4.0	372.23	329.44	81.80%
Norway	1287263.00	34.46%	1.2	1043.25	431.44	
Former Soviet Union	1413482.00	37.84%	6.5	5426.76	13348.43	
Denmark	39200.67	1.05%	2.2	570.96	13.18	
France	39200.67	1.05%	5.3	816.74	45.43	
United Kingdom	39200.67	1.05%	4.6	1034.14	49.92	
SUM	**3735201.00**	**100.00%**			**38025.40**	

Source: BAFA, 2012 & 2013; EIU, 2013; DFT, (n.d.), Umweltbundesamt (2011)

The following tables contain detailed data on the German hard coal imports in 2011 and on the hard coal shares in the German heating sector. Small discrepancies in the numbers might stem from rounding differences. Where different data bases provided different figures, the arithmetic mean has been used.

German Hard Coal Imports 2011						
Sourcing Country	**Amount [t]**	**Share (S)**	**Risk Factor (R)**	**Distance (D) [km]**	**S*R*D [dimensionless]**	**Net import quota**
Poland	5139000.00	11.30%	4.50	607.33	308.89	77.00%
Czech Republic	360000.00	0.79%	3.70	385.89	11.30	
Spain	33000.00	0.07%	5.50	1617.19	6.46	
France	62000.00	0.14%	5.30	816.74	5.90	
Russian Federation	11002000.00	24.20%	6.50	5426.76	8535.32	
Norway	857000.00	1.88%	1.20	1043.25	23.60	
USA	8139000.00	17.90%	5.30	7879.28	7475.28	
Canada	1736000.00	3.82%	2.80	6758.28	722.50	
Colombia	10826000.00	23.81%	7.00	9256.12	15427.27	
South Africa	2644000.00	5.82%	7.00	9179.84	3736.70	
Australia	4280000.00	9.41%	3.60	14482.43	4907.74	
China	195000.00	0.43%	4.80	7231.98	148.88	
Indonesia	34000.00	0.07%	6.80	11018.24	56.03	
Venezuela	161000.00	0.35%	7.30	8558.92	221.24	
SUM	**45468000.00**	**100.00%**			**41587.12**	

Source: DERA, 2012 & 2013; EIU, 2013; DFT, (n.d.), Umweltbundesamt (2011); VDKI, 2012

Coal Shares in the German Heating Sector		
	Other Coal	**Hard Coal**
Industry	15.01%	84.99%
Service	0.00%	100.00%
Households	36.48%	63.52%
Total	**16.84%**	**83.16%**

Source: AGEB, 2013; ISI, 2012; LfE, 2012; RWI, 2012, Steinbach, 2013

Appendix V: Data for Price Volatility Calculation

The following table contains detailed data on the price index for natural gas. Small discrepancies in the numbers might stem from rounding differences. Where different data bases provided different figures, the arithmetic mean has been used.

Price Index Natural Gas						
Month	**Households**	$\ln\left(\frac{p_i}{p_{i-1}}\right)$	**Service Sector**	$\ln\left(\frac{p_i}{p_{i-1}}\right)$	**Industry**	$\ln\left(\frac{p_i}{p_{i-1}}\right)$
Jan 06	96.70		117.00		117.00	
Feb 06	97.30	0.62	117.70	0.60	117.60	0.51
Mar 06	97.30	0.00	117.70	0.00	118.90	1.10
Apr 06	98.10	0.82	118.70	0.85	128.50	7.76
May 06	98.50	0.41	119.10	0.34	129.00	0.39
Jun 06	98.60	0.10	119.30	0.17	130.20	0.93
Jul 06	98.80	0.20	119.80	0.42	131.10	0.69
Aug 06	98.90	0.10	119.90	0.08	131.30	0.15
Sep 06	99.20	0.30	120.30	0.33	131.30	0.00
Oct 06	102.70	3.47	124.10	3.11	136.20	3.66
Nov 06	103.40	0.68	124.80	0.56	136.70	0.37
Dec 06	103.40	0.00	125.10	0.24	137.10	0.29
Jan 07	105.90	2.39	125.00	-0.08	136.30	-0.59
Feb 07	105.90	0.00	124.90	-0.08	136.20	-0.07
Mar 07	105.80	-0.09	124.70	-0.16	135.40	-0.59
Apr 07	102.20	-3.46	120.60	-3.34	129.20	-4.69
May 07	101.70	-0.49	119.80	-0.67	128.90	-0.23
Jun 07	101.70	0.00	119.50	-0.25	128.30	-0.47
Jul 07	101.10	-0.59	118.20	-1.09	123.10	-4.14
Aug 07	101.00	-0.10	118.20	0.00	123.40	0.24
Sep 07	100.60	-0.40	118.20	0.00	123.30	-0.08
Oct 07	100.90	0.30	118.50	0.25	124.50	0.97
Nov 07	100.80	-0.10	118.30	-0.17	125.10	0.48
Dec 07	100.80	0.00	118.40	0.08	126.40	1.03
Jan 08	104.20	3.32	121.70	2.75	132.60	4.79
Feb 08	104.30	0.10	122.70	0.82	133.30	0.53
Mar 08	104.40	0.10	123.20	0.41	134.30	0.75
Apr 08	105.80	1.33	125.20	1.61	143.10	6.35
May 08	106.50	0.66	125.70	0.40	144.00	0.63
Jun 08	107.00	0.47	126.10	0.32	145.70	1.17
Jul 08	109.20	2.04	128.50	1.89	153.90	5.48
Aug 08	111.40	1.99	130.40	1.47	155.50	1.03
Sep 08	115.00	3.18	134.90	3.39	156.90	0.90
Oct 08	122.80	6.56	146.10	7.98	168.70	7.25
Nov 08	123.60	0.65	147.70	1.09	170.80	1.24
Dec 08	123.90	0.24	148.60	0.61	173.80	1.74
Jan 09	125.30	1.12	149.40	0.54	173.70	-0.06
Feb 09	124.30	-0.80	148.80	-0.40	173.10	-0.35
Mar 09	123.50	-0.65	145.70	-2.11	171.20	-1.10
Apr 09	110.80	-10.85	132.10	-9.80	149.10	-13.82
May 09	110.20	-0.54	129.70	-1.83	147.10	-1.35
Jun 09	109.70	-0.45	127.80	-1.48	143.90	-2.20
Jul 09	105.40	-4.00	121.40	-5.14	126.60	-12.81
Aug 09	104.30	-1.05	121.20	-0.16	127.00	0.32
Sep 09	103.80	-0.48	120.90	-0.25	126.70	-0.24
Oct 09	100.30	-3.43	115.90	-4.22	119.80	-5.60
Nov 09	100.00	-0.30	115.00	-0.78	119.70	-0.08
Dec 09	99.00	-1.01	114.70	-0.26	120.50	0.67
Jan 10	99.30	0.30	115.30	0.52	123.80	2.70
Feb 10	99.40	0.10	115.30	0.00	125.40	1.28
Mar 10	99.40	0.00	115.30	0.00	125.20	-0.16
Apr 10	99.60	0.20	115.90	0.52	128.50	2.60
May 10	99.70	0.10	116.20	0.26	128.20	-0.23
Jun 10	99.70	0.00	116.10	-0.09	129.40	0.93
Jul 10	99.70	0.00	116.20	0.09	133.90	3.42
Aug 10	99.90	0.20	116.80	0.52	134.80	0.67
Sep 10	100.00	0.10	117.30	0.43	134.80	0.00
Oct 10	101.00	1.00	118.10	0.68	139.60	3.50
Nov 10	101.10	0.10	118.70	0.51	140.60	0.71
Dec 10	101.20	0.10	119.10	0.34	140.70	0.07
Jan 11	102.30	1.08	119.40	0.25	142.70	1.41
Feb 11	102.60	0.29	119.20	-0.17	142.90	0.14
Mar 11	102.70	0.10	119.10	-0.08	143.10	0.14
Apr 11	102.80	0.10	119.80	0.59	146.00	2.01
May 11	103.10	0.29	119.90	0.08	146.70	0.48
Jun 11	103.10	0.00	120.00	0.08	146.50	-0.14
Jul 11	103.70	0.58	121.00	0.83	153.90	4.93
Aug 11	104.40	0.67	121.70	0.58	155.60	1.10
Sep 11	105.70	1.24	122.10	0.33	155.40	-0.13
Oct 11	107.90	2.06	125.70	2.91	164.20	5.51
Nov 11	108.30	0.37	126.50	0.63	165.30	0.67
Dec 11	108.50	0.18	127.20	0.55	165.40	0.06
Jan 12	109.40	0.83	128.00	0.63	167.80	1.44
Feb 12	109.80	0.36	128.00	0.00	168.30	0.30
Mar 12	109.80	0.00	128.30	0.23	168.80	0.30
Apr 12	109.80	0.00	128.90	0.47	173.20	2.57
May 12	109.90	0.09	128.90	0.00	173.40	0.12
Jun 12	109.90	0.00	128.90	0.00	173.20	-0.12
Jul 12	109.90	0.00	129.30	0.31	174.70	0.86
Aug 12	110.30	0.36	129.50	0.15	175.10	0.23
Sep 12	110.70	0.36	130.20	0.54	175.80	0.40
Oct 12	110.80	0.09	130.90	0.54	177.00	0.68
Nov 12	110.80	0.00	130.90	0.00	176.90	-0.06
Dec 12	110.90	0.09	131.20	0.23	175.80	-0.62

Source: Destatis, 2013

The following table contains detailed data on the price index for natural gas. Small discrepancies in the numbers might stem from rounding differences. Where different data bases provided different figures, the arithmetic mean has been used.

Price Index Oil						
Month	**Households**	$\ln\left(\frac{p_i}{p_{i-1}}\right)$	**Service Sector**	$\ln\left(\frac{p_i}{p_{i-1}}\right)$	**Industry**	$\ln\left(\frac{p_i}{p_{i-1}}\right)$
Jan 06	47.28		47.28		45.21	
Feb 06	47.77	1.03	47.77	1.03	45.50	0.64
Mar 06	52.15	8.77	52.15	8.77	47.80	4.93
Apr 06	53.87	3.24	53.87	3.24	51.20	6.87
May 06	51.69	-4.13	51.69	-4.13	49.14	-4.11
Jun 06	51.86	0.33	51.86	0.33	49.18	0.08
Jul 06	55.01	5.90	55.01	5.90	52.24	6.04
Aug 06	53.45	-2.88	53.45	-2.88	50.71	-2.97
Sep 06	48.96	-8.77	48.96	-8.77	46.40	-8.88
Oct 06	49.26	0.61	49.26	0.61	46.57	0.37
Nov 06	46.09	-6.65	46.09	-6.65	43.69	-6.38
Dec 06	46.49	0.86	46.49	0.86	43.27	-0.97
Jan 07	41.60	-11.11	41.60	-11.11	38.98	-10.44
Feb 07	43.81	5.18	43.81	5.18	40.68	4.27
Mar 07	44.22	0.93	44.22	0.93	41.98	3.15
Apr 07	47.49	7.13	47.49	7.13	44.75	6.39
May 07	47.09	-0.85	47.09	-0.85	44.07	-1.53
Jun 07	48.59	3.14	48.59	3.14	46.16	4.63
Jul 07	50.29	3.44	50.29	3.44	47.48	2.82
Aug 07	49.76	-1.06	49.76	-1.06	46.99	-1.04
Sep 07	53.27	6.82	53.27	6.82	50.05	6.31
Oct 07	52.84	-0.81	52.84	-0.81	49.78	-0.54
Nov 07	58.09	9.47	58.09	9.47	55.02	10.01
Dec 07	59.73	2.78	59.73	2.78	56.03	1.82
Jan 08	57.07	-4.56	57.07	-4.56	54.34	-3.06
Feb 08	60.34	5.57	60.34	5.57	58.16	6.79
Mar 08	63.10	4.47	63.10	4.47	61.33	5.31
Apr 08	65.97	4.45	65.97	4.45	63.71	3.81
May 08	75.22	13.12	75.22	13.12	72.98	13.58
Jun 08	78.89	4.76	78.89	4.76	76.30	4.45
Jul 08	79.85	1.21	79.85	1.21	77.82	1.97
Aug 08	69.07	-14.50	69.07	-14.50	67.02	-14.94
Sep 08	66.42	-3.91	66.42	-3.91	64.40	-3.99
Oct 08	58.62	-12.49	58.62	-12.49	56.52	-13.05
Nov 08	52.48	-11.06	52.48	-11.06	49.55	-13.16
Dec 08	41.95	-22.40	41.95	-22.40	39.00	-23.94
Jan 09	45.11	7.26	45.11	7.26	41.95	7.29
Feb 09	40.11	-11.75	40.11	-11.75	37.60	-10.95
Mar 09	37.33	-7.18	37.33	-7.18	34.53	-8.52
Apr 09	41.14	9.72	41.14	9.72	38.34	10.47
May 09	41.20	0.15	41.20	0.15	38.35	0.03
Jun 09	46.72	12.57	46.72	12.57	43.48	12.55

Price Index Oil						
Month	**Households**	$\ln\left(\frac{p_i}{p_{i-1}}\right)$	**Service Sector**	$\ln\left(\frac{p_i}{p_{i-1}}\right)$	**Industry**	$\ln\left(\frac{p_i}{p_{i-1}}\right)$
Jul 09	41.97	-10.72	41.97	-10.72	39.00	-10.87
Aug 09	46.74	10.76	46.74	10.76	43.51	10.94
Sep 09	44.17	-5.66	44.17	-5.66	41.00	-5.94
Oct 09	47.73	7.75	47.73	7.75	44.94	9.18
Nov 09	46.89	-1.78	46.89	-1.78	43.88	-2.39
Dec 09	46.11	-1.68	46.11	-1.68	43.10	-1.79
Jan 10	49.21	6.51	49.21	6.51	46.34	7.25
Feb 10	48.70	-1.04	48.70	-1.04	46.11	-0.50
Mar 10	52.95	8.37	52.95	8.37	50.25	8.60
Apr 10	55.98	5.56	55.98	5.56	53.56	6.38
May 10	56.89	1.61	56.89	1.61	54.31	1.39
Jun 10	56.26	-1.11	56.26	-1.11	54.30	-0.02
Jul 10	54.81	-2.61	54.81	-2.61	52.39	-3.58
Aug 10	54.05	-1.40	54.05	-1.40	51.33	-2.04
Sep 10	56.56	4.54	56.56	4.54	53.75	4.61
Oct 10	55.28	-2.29	55.28	-2.29	52.76	-1.86
Nov 10	57.67	4.23	57.67	4.23	55.21	4.54
Dec 10	60.10	4.13	60.10	4.13	57.35	3.80
Jan 11	63.46	5.44	63.46	5.44	60.59	5.50
Feb 11	66.07	4.03	66.07	4.03	62.22	2.65
Mar 11	70.12	5.95	70.12	5.95	67.89	8.72
Apr 11	70.59	0.67	70.59	0.67	67.93	0.06
May 11	66.54	-5.91	66.54	-5.91	63.53	-6.70
Jun 11	69.14	3.83	69.14	3.83	66.19	4.10
Jul 11	69.87	1.05	69.87	1.05	67.41	1.83
Aug 11	67.15	-3.97	67.15	-3.97	64.28	-4.75
Sep 11	69.64	3.64	69.64	3.64	67.01	4.16
Oct 11	72.61	4.18	72.61	4.18	70.33	4.84
Nov 11	75.13	3.41	75.13	3.41	72.55	3.11
Dec 11	70.79	-5.95	70.79	-5.95	68.22	-6.15
Jan 12	74.65	5.31	74.65	5.31	72.30	5.81
Feb 12	77.43	3.66	77.43	3.66	74.93	3.57
Mar 12	77.70	0.35	77.70	0.35	75.34	0.55
Apr 12	75.53	-2.83	75.53	-2.83	73.30	-2.75
May 12	72.96	-3.46	72.96	-3.46	70.53	-3.85
Jun 12	70.03	-4.10	70.03	-4.10	67.44	-4.48
Jul 12	73.71	5.12	73.71	5.12	71.34	5.62
Aug 12	77.91	5.54	77.91	5.54	75.47	5.63
Sep 12	76.98	-1.20	76.98	-1.20	74.52	-1.27
Oct 12	79.45	3.16	79.45	3.16	77.30	3.66
Nov 12	75.97	-4.48	75.97	-4.48	73.73	-4.73
Dec 12	71.65	-5.85	71.65	-5.85	69.07	-6.53

Source: Destatis, 2013

The following table contains detailed data on the price index for electricity (for geothermal heat generation technologies). Small discrepancies in the numbers might stem from rounding differences. Where different data bases provided different figures, the arithmetic mean has been used.

Price Index Electricity

Month	Households	$\ln\left(\frac{p_i}{p_{i-1}}\right)$	Service Sector	$\ln\left(\frac{p_i}{p_{i-1}}\right)$	Industry	$\ln\left(\frac{p_i}{p_{i-1}}\right)$
Jan 06	79.40		102.20		110.40	
Feb 06	79.50	0.13	102.70	0.49	113.00	2.33
Mar 06	79.50	0.00	103.00	0.29	114.30	1.14
Apr 06	79.60	0.13	103.20	0.19	114.60	0.26
May 06	79.80	0.25	104.40	1.16	114.20	-0.35
Jun 06	79.80	0.00	104.50	0.10	113.60	-0.53
Jul 06	79.90	0.13	105.00	0.48	114.40	0.70
Aug 06	80.00	0.13	105.10	0.10	115.80	1.22
Sep 06	80.00	0.00	105.10	0.00	115.30	-0.43
Oct 06	80.00	0.00	103.60	-1.44	114.50	-0.70
Nov 06	80.00	0.00	103.70	0.10	114.60	0.09
Dec 06	80.10	0.12	103.70	0.00	114.50	-0.09
Jan 07	84.00	4.75	105.60	1.82	116.50	1.73
Feb 07	84.40	0.48	105.90	0.28	114.30	-1.91
Mar 07	84.50	0.12	105.90	0.00	113.20	-0.97
Apr 07	84.60	0.12	105.90	0.00	113.80	0.53
May 07	84.60	0.00	105.90	0.00	116.20	2.09
Jun 07	84.70	0.12	106.00	0.09	116.00	-0.17
Jul 07	85.40	0.82	107.60	1.50	117.20	1.03
Aug 07	85.50	0.12	107.80	0.19	117.40	0.17
Sep 07	86.00	0.58	107.80	0.00	117.60	0.17
Oct 07	86.50	0.58	108.30	0.46	119.20	1.35
Nov 07	86.70	0.23	108.50	0.18	121.10	1.58
Dec 07	86.80	0.12	108.50	0.00	121.60	0.41
Jan 08	90.20	3.84	111.00	2.28	123.50	1.55
Feb 08	90.50	0.33	111.00	0.00	123.20	-0.24
Mar 08	90.50	0.00	111.10	0.09	124.20	0.81
Apr 08	90.80	0.33	111.60	0.45	125.00	0.64
May 08	90.90	0.11	111.60	0.00	126.90	1.51
Jun 08	90.90	0.00	111.60	0.00	131.10	3.26
Jul 08	91.20	0.33	112.20	0.54	138.60	5.56
Aug 08	91.60	0.44	112.30	0.09	135.90	-1.97
Sep 08	91.80	0.22	112.60	0.27	136.70	0.59
Oct 08	92.00	0.22	112.60	0.00	134.70	-1.47
Nov 08	92.00	0.00	112.60	0.00	130.30	-3.32
Dec 08	92.10	0.11	112.70	0.09	127.20	-2.41
Jan 09	95.00	3.10	114.30	1.41	124.90	-1.82
Feb 09	95.70	0.73	115.90	1.39	121.70	-2.60
Mar 09	96.30	0.63	116.60	0.60	119.70	-1.66
Apr 09	97.00	0.72	117.60	0.85	122.80	2.56
May 09	97.20	0.21	117.60	0.00	124.20	1.13
Jun 09	97.20	0.00	117.60	0.00	123.70	-0.40
Jul 09	97.20	0.00	118.50	0.76	123.60	-0.08
Aug 09	97.30	0.10	118.50	0.00	124.40	0.65
Sep 09	97.40	0.10	118.60	0.08	123.00	-1.13
Oct 09	97.40	0.00	118.50	-0.08	123.70	0.57
Nov 09	97.40	0.00	118.50	0.00	124.20	0.40
Dec 09	97.40	0.00	118.50	0.00	122.90	-1.05
Jan 10	98.70	1.33	120.90	2.01	122.70	-0.16
Feb 10	98.90	0.20	121.20	0.25	122.00	-0.57
Mar 10	99.30	0.40	122.10	0.74	122.10	0.08
Apr 10	99.60	0.30	122.20	0.08	123.30	0.98
May 10	100.00	0.40	122.70	0.41	123.80	0.40
Jun 10	100.00	0.00	122.70	0.00	126.00	1.76
Jul 10	100.20	0.20	122.70	0.00	125.40	-0.48
Aug 10	100.50	0.30	123.30	0.49	124.00	-1.12
Sep 10	100.50	0.00	123.30	0.00	123.60	-0.32
Oct 10	100.70	0.20	123.50	0.16	125.40	1.45
Nov 10	100.70	0.00	123.50	0.00	126.80	1.11
Dec 10	100.80	0.10	123.50	0.00	128.00	0.94
Jan 11	105.70	4.75	131.50	6.28	133.20	3.98
Feb 11	106.30	0.57	131.80	0.23	133.50	0.22
Mar 11	106.80	0.47	132.40	0.45	135.20	1.27
Apr 11	107.20	0.37	132.50	0.08	138.50	2.41
May 11	107.60	0.37	133.00	0.38	138.00	-0.36
Jun 11	107.60	0.00	133.00	0.00	138.10	0.07
Jul 11	107.60	0.00	133.00	0.00	137.70	-0.29
Aug 11	107.60	0.00	133.00	0.00	137.10	-0.44
Sep 11	107.60	0.00	133.00	0.00	137.40	0.22
Oct 11	107.60	0.00	133.00	0.00	136.40	-0.73
Nov 11	107.60	0.00	133.00	0.00	136.50	0.07
Dec 11	107.70	0.09	133.00	0.00	135.10	-1.03
Jan 12	108.90	1.11	135.00	1.49	134.90	-0.15
Feb 12	109.10	0.18	135.10	0.07	135.00	0.07
Mar 12	109.50	0.37	136.10	0.74	135.60	0.44
Apr 12	110.00	0.46	137.20	0.80	135.00	-0.44
May 12	110.10	0.09	137.20	0.00	134.20	-0.59
Jun 12	110.40	0.27	138.70	1.09	133.10	-0.82
Jul 12	110.60	0.18	138.70	0.00	132.90	-0.15
Aug 12	110.90	0.27	139.60	0.65	133.50	0.45
Sep 12	110.90	0.00	139.60	0.00	133.00	-0.38
Oct 12	111.00	0.09	139.80	0.14	133.70	0.52
Nov 12	111.00	0.00	139.80	0.00	136.80	2.29
Dec 12	111.10	0.09	139.80	0.00	136.00	-0.59

Source: Destatis, 2013

The following table contains detailed data on the average price index for biomass. Small discrepancies in the numbers might stem from rounding differences. Where different data bases provided different figures, the arithmetic mean has been used.

Price Index Biomass (Average Data)

Month	Households	$\ln\left(\frac{p_i}{p_{i-1}}\right)$	Service Sector	$\ln\left(\frac{p_i}{p_{i-1}}\right)$	Industry	$\ln\left(\frac{p_i}{p_{i-1}}\right)$
Jan 06	98.80		101.10		112.60	
Feb 06	98.20	-0.61	104.80	3.59	149.70	28.48
Mar 06	100.40	2.22	103.60	-1.15	167.90	11.47
Apr 06	100.60	0.20	109.20	5.26	158.50	-5.76
May 06	103.40	2.75	116.30	6.30	149.40	-5.91
Jun 06	108.40	4.72	119.00	2.30	189.40	23.72
Jul 06	108.60	0.18	123.10	3.39	195.80	3.32
Aug 06	110.60	1.82	128.30	4.14	113.70	-54.35
Sep 06	113.10	2.24	134.60	4.79	153.70	30.14
Oct 06	121.70	7.33	137.00	1.77	171.40	10.90
Nov 06	124.40	2.19	152.70	10.85	153.70	-10.90
Dec 06	130.90	5.09	159.70	4.48	156.10	1.55
Jan 07	138.60	5.72	162.80	1.92	194.30	21.89
Feb 07	159.80	14.23	178.70	9.32	196.30	1.02
Mar 07	164.80	3.08	176.20	-1.41	113.70	-54.61
Apr 07	164.00	-0.49	177.10	0.51	160.20	34.29
May 07	156.80	-4.49	157.60	-11.67	168.60	5.11
Jun 07	155.10	-1.09	157.20	-0.25	147.00	-13.71
Jul 07	150.80	-2.81	152.70	-2.90	155.20	5.43
Aug 07	149.30	-1.00	150.70	-1.32	197.60	24.15
Sep 07	150.00	0.47	150.70	0.00	193.00	-2.36
Oct 07	149.70	-0.20	148.70	-1.34	113.30	-53.27
Nov 07	153.50	2.51	148.00	-0.47	160.00	34.51
Dec 07	154.00	0.33	147.20	-0.54	176.80	9.98
Jan 08	151.10	-1.90	147.20	0.00	145.60	-19.42
Feb 08	152.10	0.66	161.20	9.09	160.40	9.68
Mar 08	149.40	-1.79	158.50	-1.69	198.30	21.21
Apr 08	147.70	-1.14	156.70	-1.14	194.60	-1.88
May 08	147.10	-0.41	145.30	-7.55	111.90	-55.33
Jun 08	149.40	1.55	145.90	0.41	161.00	36.38
Jul 08	146.10	-2.23	150.20	2.90	174.60	8.11
Aug 08	147.40	0.89	152.20	1.32	140.40	-21.80
Sep 08	147.60	0.14	151.60	-0.39	161.60	14.06
Oct 08	151.40	2.54	152.00	0.26	197.20	19.91
Nov 08	154.30	1.90	154.40	1.57	190.40	-3.51
Dec 08	159.20	3.13	154.10	-0.19	110.70	-54.23
Jan 09	170.20	6.68	150.80	-2.16	161.70	37.89
Feb 09	174.10	2.27	146.70	-2.76	175.20	8.02
Mar 09	175.60	0.86	146.70	0.00	138.80	-23.29
Apr 09	171.10	-2.60	145.80	-0.62	161.80	15.33
May 09	169.30	-1.06	147.30	1.02	196.80	19.58
Jun 09	164.60	-2.82	144.30	-2.06	188.10	-4.52

Price Index Biomass (Average Data)

Month	Households	$\ln\left(\frac{p_i}{p_{i-1}}\right)$	Service Sector	$\ln\left(\frac{p_i}{p_{i-1}}\right)$	Industry	$\ln\left(\frac{p_i}{p_{i-1}}\right)$
Jul 09	167.10	1.51	146.10	1.24	111.30	-52.47
Aug 09	173.10	3.53	145.20	-0.62	159.20	35.79
Sep 09	178.00	2.79	142.00	-2.23	166.50	4.48
Oct 09	181.00	1.67	149.80	5.35	139.70	-17.55
Nov 09	181.30	0.17	148.90	-0.60	167.80	18.33
Dec 09	180.50	-0.44	148.10	-0.54	195.70	15.38
Jan 10	180.10	-0.22	158.10	6.53	186.00	-5.08
Feb 10	180.00	-0.06	158.80	0.44	117.90	-45.59
Mar 10	182.90	1.60	163.60	2.98	156.70	28.45
Apr 10	179.00	-2.16	168.40	2.89	164.00	4.55
May 10	176.80	-1.24	179.90	6.61	139.40	-16.25
Jun 10	174.50	-1.31	179.90	0.00	174.40	22.40
Jul 10	174.70	0.11	179.90	0.00	193.00	10.13
Aug 10	181.10	3.60	181.70	1.00	185.50	-3.96
Sep 10	184.10	1.64	181.70	0.00	118.50	-44.81
Oct 10	185.40	0.70	186.30	2.50	160.80	30.52
Nov 10	186.40	0.54	184.50	-0.97	163.40	1.60
Dec 10	189.80	1.81	186.30	0.97	142.10	-13.97
Jan 11	195.10	2.75	187.00	0.38	176.90	21.91
Feb 11	200.00	2.48	190.40	1.80	197.90	11.22
Mar 11	198.50	-0.75	190.40	0.00	180.80	-9.04
Apr 11	198.50	0.00	187.80	-1.37	125.50	-36.51
May 11	197.90	-0.30	187.80	0.00	162.60	25.90
Jun 11	192.90	-2.56	187.80	0.00	163.50	0.55
Jul 11	189.60	-1.73	185.20	-1.39	143.90	-12.77
Aug 11	189.60	0.00	185.20	0.00	179.40	22.05
Sep 11	191.10	0.79	185.20	0.00	196.70	9.21
Oct 11	197.90	3.50	183.90	-0.70	180.10	-8.82
Nov 11	197.90	0.00	185.90	1.08	129.20	-33.22
Dec 11	198.30	0.20	187.20	0.70	165.10	24.52
Jan 12	198.30	0.00	187.20	0.00	163.70	-0.85
Feb 12	200.50	1.10	187.20	0.00	141.90	-14.29
Mar 12	201.00	0.25	187.60	0.21	183.60	25.76
Apr 12	193.70	-3.70	187.70	0.05	193.60	5.30
May 12	191.30	-1.25	182.00	-3.08	181.60	-6.40
Jun 12	188.70	-1.37	182.00	0.00	133.80	-30.55
Jul 12	189.30	0.32	177.40	-2.56	164.00	20.35
Aug 12	190.30	0.53	177.40	0.00	165.80	1.09
Sep 12	192.20	0.99	177.40	0.00	142.90	-14.86
Oct 12	200.90	4.43	175.50	-1.08	186.10	26.41
Nov 12	210.90	4.86	184.40	4.95	193.80	4.05
Dec 12	213.80	1.37	184.40	0.00	179.30	-7.78

Source: Destatis, 2013

The following table contains detailed data on the average price index for coal. Small discrepancies in the numbers might stem from rounding differences. Where different data bases provided different figures, the arithmetic mean has been used.

Price Index Coal

Month	Hard Coal	$\ln\left(\frac{p_i}{p_{i-1}}\right)$	Lignite	$\ln\left(\frac{p_i}{p_{i-1}}\right)$
Jan 06	103.60		103.70	
Feb 06	103.50	-0.10	103.70	0.00
Mar 06	104.30	0.77	103.70	0.00
Apr 06	103.60	-0.67	104.20	0.48
May 06	103.60	0.00	102.10	-2.04
Jun 06	103.90	0.29	102.10	0.00
Jul 06	101.80	-2.04	102.10	0.00
Aug 06	102.10	0.29	102.10	0.00
Sep 06	102.60	0.49	104.20	2.04
Oct 06	102.90	0.29	104.20	0.00
Nov 06	103.30	0.39	104.20	0.00
Dec 06	103.40	0.10	104.20	0.00
Jan 07	101.60	-1.76	108.00	3.58
Feb 07	101.70	0.10	108.00	0.00
Mar 07	104.00	2.24	108.00	0.00
Apr 07	104.10	0.10	105.90	-1.96
May 07	102.40	-1.65	105.90	0.00
Jun 07	102.40	0.00	105.90	0.00
Jul 07	104.80	2.32	105.90	0.00
Aug 07	105.60	0.76	105.90	0.00
Sep 07	105.60	0.00	105.90	0.00
Oct 07	107.80	2.06	108.00	1.96
Nov 07	112.30	4.09	108.00	0.00
Dec 07	119.60	6.30	108.00	0.00
Jan 08	126.70	5.77	108.50	0.46
Feb 08	126.70	0.00	108.50	0.00
Mar 08	133.20	5.00	108.50	0.00
Apr 08	149.30	11.41	106.40	-1.95
May 08	145.00	-2.92	106.40	0.00
Jun 08	155.40	6.93	106.40	0.00
Jul 08	174.40	11.53	106.40	0.00
Aug 08	185.40	6.12	102.20	-4.03
Sep 08	200.50	7.83	102.20	0.00
Oct 08	188.70	-6.07	100.10	-2.08
Nov 08	183.90	-2.58	100.10	0.00
Dec 08	178.70	-2.87	100.10	0.00
Jan 09	154.80	-14.36	106.50	6.20
Feb 09	152.60	-1.43	109.80	3.05
Mar 09	156.10	2.27	110.50	0.64
Apr 09	144.00	-8.07	109.50	-0.91
May 09	141.50	-1.75	110.70	1.09
Jun 09	131.90	-7.03	111.50	0.72
Jul 09	126.50	-4.18	110.80	-0.63
Aug 09	120.10	-5.19	110.50	-0.27
Sep 09	126.00	4.80	111.90	1.26
Oct 09	120.20	-4.71	110.80	-0.99
Nov 09	120.00	-0.17	110.80	0.00
Dec 09	126.80	5.51	110.80	0.00
Jan 10	125.10	-1.35	111.80	0.90
Feb 10	123.70	-1.13	114.50	2.39
Mar 10	123.90	0.16	115.20	0.61
Apr 10	123.60	-0.24	113.40	-1.57
May 10	130.50	5.43	114.00	0.53
Jun 10	143.40	9.43	115.70	1.48
Jul 10	143.50	0.07	114.00	-1.48
Aug 10	144.50	0.69	114.00	0.00
Sep 10	143.20	-0.90	114.00	0.00
Oct 10	141.60	-1.12	116.30	2.00
Nov 10	144.10	1.75	116.20	-0.09
Dec 10	154.50	6.97	116.20	0.00
Jan 11	169.20	9.09	119.20	2.55
Feb 11	174.60	3.14	121.70	2.08
Mar 11	172.60	-1.15	124.50	2.27
Apr 11	171.70	-0.52	123.10	-1.13
May 11	174.80	1.79	123.10	0.00
Jun 11	171.00	-2.20	123.10	0.00
Jul 11	173.40	1.39	123.10	0.00
Aug 11	173.00	-0.23	123.10	0.00
Sep 11	173.00	0.00	123.10	0.00
Oct 11	177.20	2.40	125.80	2.17
Nov 11	173.30	-2.23	125.80	0.00
Dec 11	177.30	2.28	125.80	0.00
Jan 12	175.90	-0.79	127.10	1.03
Feb 12	172.90	-1.72	127.10	0.00
Mar 12	164.00	-5.28	127.10	0.00
Apr 12	161.80	-1.35	127.10	0.00
May 12	158.40	-2.12	127.10	0.00
Jun 12	156.30	-1.33	127.10	0.00
Jul 12	152.50	-2.46	127.10	0.00
Aug 12	153.60	0.72	127.10	0.00
Sep 12	159.60	3.83	127.10	0.00
Oct 12	149.60	-6.47	128.50	1.10
Nov 12	149.60	0.00	128.50	0.00
Dec 12	149.60	0.00	128.50	0.00

Source: Destatis, 2013

Appendix VI: Data for Intermittency Calculation

The following tables contain detailed data on intermittency indicator components. For the natural availability of solar thermal energy, only average data from 2007 could be obtained. Ideally this indicator should be built on a broader data basis over several years to get a more realistic picture of intermittency.

Intermittency Data

Technology	$\frac{maintenance\ and\ repair\ costs}{investment}$	t_m	t_n	$\frac{1}{\bar{x}(degree\ of\ natural\ availability)}$
Oil	3.50%	20.00	8760.00	1.00
Natural Gas	2.50%	20.00	8760.00	1.00
Coal	4.50%	10.00	8760.00	1.00
Biogas	2.50%	20.00	8760.00	1.00
Biomass	4.50%	10.00	8760.00	1.00
Geothermal	4.00%	20.00	8760.00	1.00
Solar Thermal	1.00%	5.00	5267.00	5.21

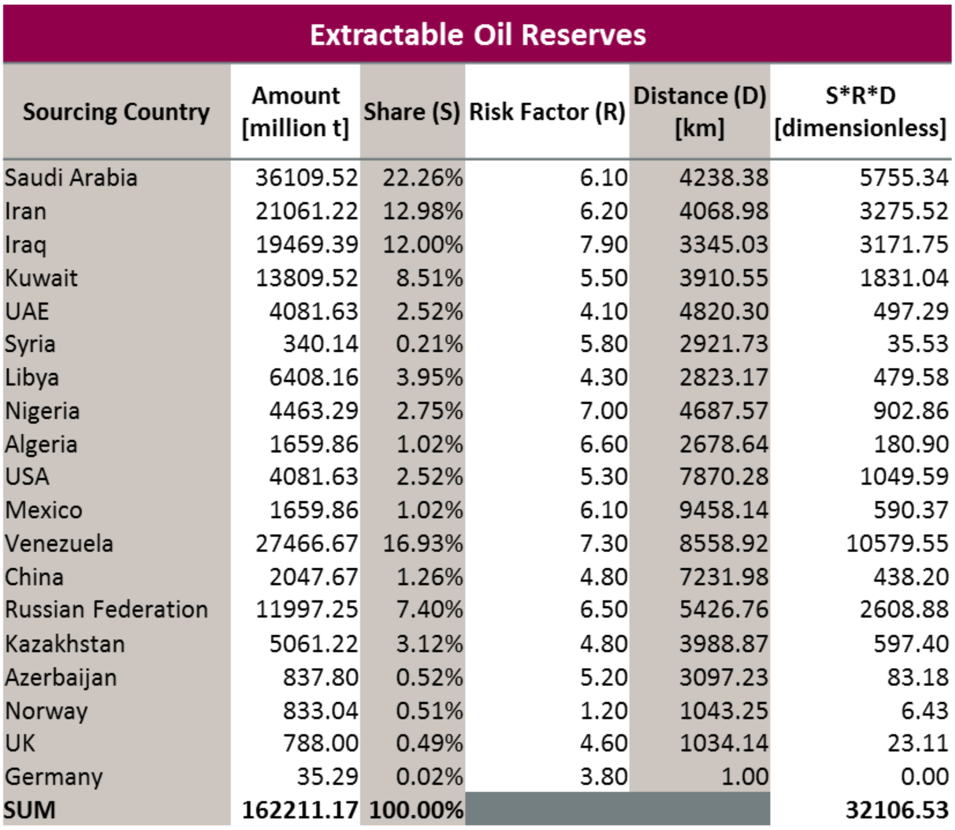
Average Intensity of Solar Radiation (Degree of Natural Availability) 2007

Hour	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
1	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
2	0.00%	0.00%	0.00%	0.00%	0.00%	0.01%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
3	0.00%	0.00%	0.00%	0.01%	0.70%	1.64%	0.70%	0.05%	0.00%	0.00%	0.00%	0.00%
4	0.00%	0.00%	0.00%	2.74%	10.60%	12.62%	8.98%	3.07%	0.13%	0.00%	0.00%	0.00%
5	0.00%	0.00%	1.89%	26.72%	31.15%	30.36%	25.51%	18.88%	5.70%	0.58%	0.00%	0.00%
6	0.01%	1.04%	17.90%	59.95%	51.38%	48.34%	42.66%	38.86%	25.17%	10.88%	0.84%	0.00%
7	2.09%	9.84%	40.95%	81.92%	63.93%	60.18%	54.06%	54.88%	43.04%	28.11%	6.40%	1.85%
8	9.78%	21.28%	56.45%	93.76%	69.96%	65.07%	59.48%	64.03%	51.76%	40.40%	13.59%	8.76%
9	15.16%	29.92%	62.88%	98.91%	70.71%	64.29%	59.32%	65.26%	50.97%	45.79%	17.33%	14.46%
10	17.88%	34.45%	63.93%	100.00%	68.22%	59.55%	55.16%	61.73%	48.96%	49.22%	20.97%	18.63%
11	19.03%	35.98%	61.79%	98.81%	66.69%	57.11%	54.13%	58.65%	44.82%	45.76%	21.23%	20.06%
12	16.66%	31.95%	55.70%	96.11%	64.43%	55.36%	52.86%	56.26%	42.85%	45.40%	18.60%	17.43%
13	12.91%	27.01%	53.45%	91.54%	60.99%	53.52%	51.46%	54.46%	42.13%	39.54%	13.66%	12.31%
14	7.72%	19.13%	48.03%	84.08%	57.97%	54.64%	51.73%	52.80%	38.82%	29.04%	6.70%	4.63%
15	1.59%	10.21%	36.84%	73.25%	51.74%	52.15%	49.16%	50.46%	32.23%	14.71%	1.03%	0.32%
16	0.01%	1.33%	15.78%	49.35%	40.15%	43.58%	40.87%	37.82%	14.79%	1.32%	0.00%	0.00%
17	0.00%	0.00%	0.99%	14.85%	21.97%	27.35%	25.81%	17.26%	1.54%	0.00%	0.00%	0.00%
18	0.00%	0.00%	0.00%	0.50%	3.94%	9.51%	7.84%	1.86%	0.00%	0.00%	0.00%	0.00%
19	0.00%	0.00%	0.00%	0.00%	0.08%	0.66%	0.43%	0.01%	0.00%	0.00%	0.00%	0.00%
20	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
21	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
22	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
23	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%

Source: SoDa, 2013; VDI, 2007

Appendix VII: Data for Diversity of Availability Calculation

The following table contains detailed data on extractable oil reserves 2011. Small discrepancies in the numbers might stem from rounding differences. Where different data bases provided different figures, the arithmetic mean has been used.

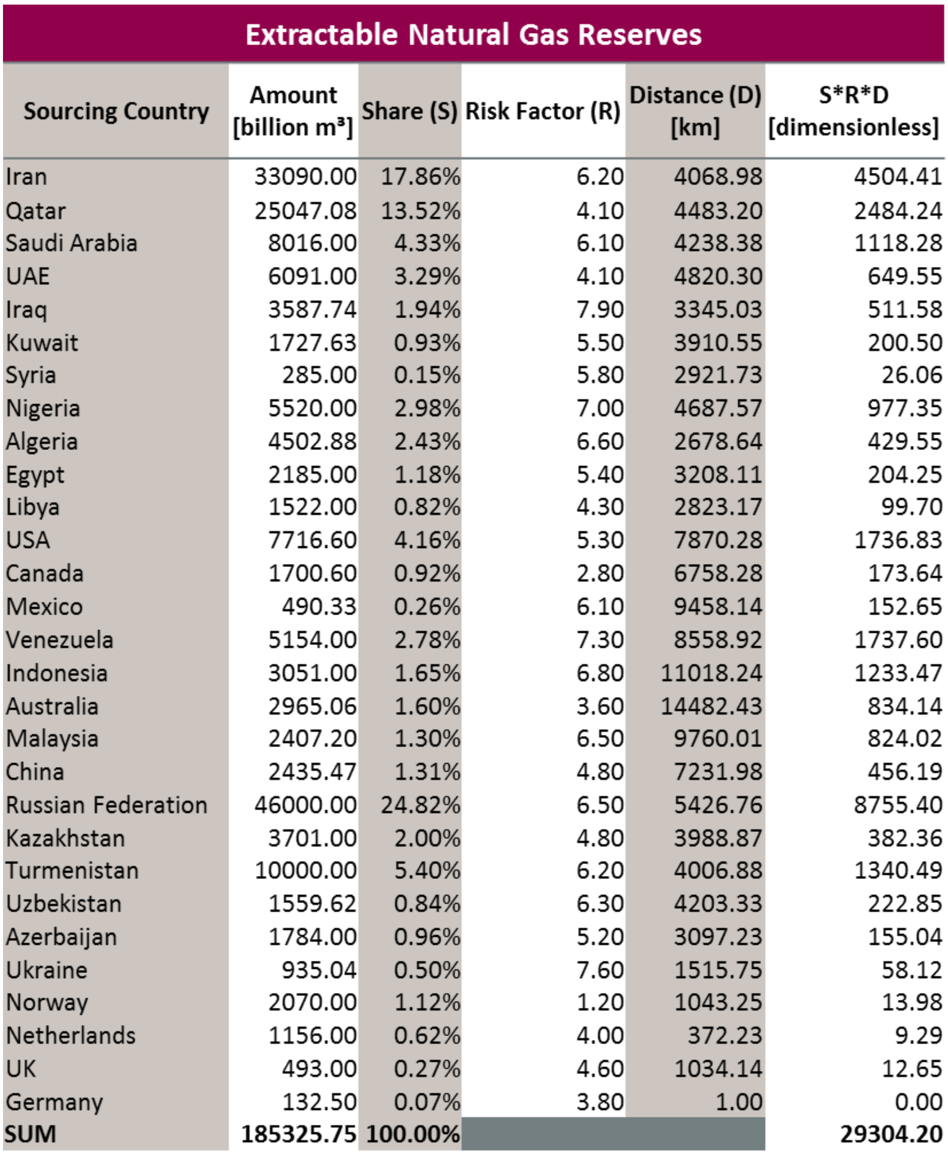


Extractable Oil Reserves

Sourcing Country	Amount [million t]	Share (S)	Risk Factor (R)	Distance (D) [km]	S*R*D [dimensionless]
Saudi Arabia	36109.52	22.26%	6.10	4238.38	5755.34
Iran	21061.22	12.98%	6.20	4068.98	3275.52
Iraq	19469.39	12.00%	7.90	3345.03	3171.75
Kuwait	13809.52	8.51%	5.50	3910.55	1831.04
UAE	4081.63	2.52%	4.10	4820.30	497.29
Syria	340.14	0.21%	5.80	2921.73	35.53
Libya	6408.16	3.95%	4.30	2823.17	479.58
Nigeria	4463.29	2.75%	7.00	4687.57	902.86
Algeria	1659.86	1.02%	6.60	2678.64	180.90
USA	4081.63	2.52%	5.30	7870.28	1049.59
Mexico	1659.86	1.02%	6.10	9458.14	590.37
Venezuela	27466.67	16.93%	7.30	8558.92	10579.55
China	2047.67	1.26%	4.80	7231.98	438.20
Russian Federation	11997.25	7.40%	6.50	5426.76	2608.88
Kazakhstan	5061.22	3.12%	4.80	3988.87	597.40
Azerbaijan	837.80	0.52%	5.20	3097.23	83.18
Norway	833.04	0.51%	1.20	1043.25	6.43
UK	788.00	0.49%	4.60	1034.14	23.11
Germany	35.29	0.02%	3.80	1.00	0.00
SUM	**162211.17**	**100.00%**			**32106.53**

Source: BMWi, 2013; DFT, (n.d.); EIU, 2013

The following table contains detailed data on extractable natural gas reserves 2011. Small discrepancies in the numbers might stem from rounding differences. Where different data bases provided different figures, the arithmetic mean has been used. The unit (m^3) differs from those of other relevant resources (t). Despite these discrepancies, relevant resources are frequently compared on the basis of their respective units by the German Federal Ministry of Economics and Technology. (BMWi, 2013).

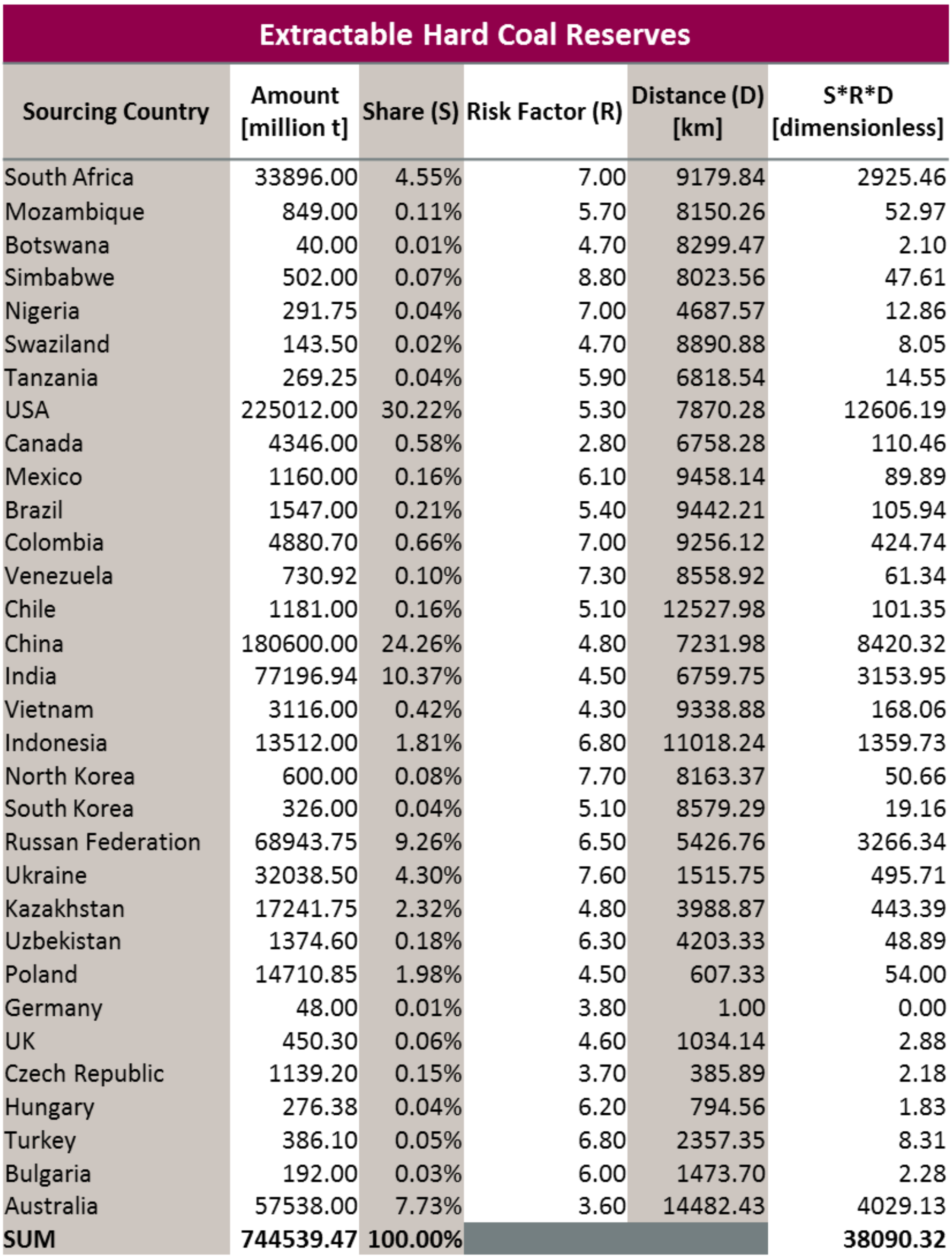


Extractable Natural Gas Reserves

Sourcing Country	Amount [billion m³]	Share (S)	Risk Factor (R)	Distance (D) [km]	S*R*D [dimensionless]
Iran	33090.00	17.86%	6.20	4068.98	4504.41
Qatar	25047.08	13.52%	4.10	4483.20	2484.24
Saudi Arabia	8016.00	4.33%	6.10	4238.38	1118.28
UAE	6091.00	3.29%	4.10	4820.30	649.55
Iraq	3587.74	1.94%	7.90	3345.03	511.58
Kuwait	1727.63	0.93%	5.50	3910.55	200.50
Syria	285.00	0.15%	5.80	2921.73	26.06
Nigeria	5520.00	2.98%	7.00	4687.57	977.35
Algeria	4502.88	2.43%	6.60	2678.64	429.55
Egypt	2185.00	1.18%	5.40	3208.11	204.25
Libya	1522.00	0.82%	4.30	2823.17	99.70
USA	7716.60	4.16%	5.30	7870.28	1736.83
Canada	1700.60	0.92%	2.80	6758.28	173.64
Mexico	490.33	0.26%	6.10	9458.14	152.65
Venezuela	5154.00	2.78%	7.30	8558.92	1737.60
Indonesia	3051.00	1.65%	6.80	11018.24	1233.47
Australia	2965.06	1.60%	3.60	14482.43	834.14
Malaysia	2407.20	1.30%	6.50	9760.01	824.02
China	2435.47	1.31%	4.80	7231.98	456.19
Russian Federation	46000.00	24.82%	6.50	5426.76	8755.40
Kazakhstan	3701.00	2.00%	4.80	3988.87	382.36
Turmenistan	10000.00	5.40%	6.20	4006.88	1340.49
Uzbekistan	1559.62	0.84%	6.30	4203.33	222.85
Azerbaijan	1784.00	0.96%	5.20	3097.23	155.04
Ukraine	935.04	0.50%	7.60	1515.75	58.12
Norway	2070.00	1.12%	1.20	1043.25	13.98
Netherlands	1156.00	0.62%	4.00	372.23	9.29
UK	493.00	0.27%	4.60	1034.14	12.65
Germany	132.50	0.07%	3.80	1.00	0.00
SUM	**185325.75**	**100.00%**			**29304.20**

Source: BMWi, 2013; DFT, (n.d.); EIU, 2013

The following table contains detailed data on extractable hard coal reserves 2011. Small discrepancies in the numbers might stem from rounding differences. Where different data bases provided different figures, the arithmetic mean has been used.



Extractable Hard Coal Reserves

Sourcing Country	Amount [million t]	Share (S)	Risk Factor (R)	Distance (D) [km]	S*R*D [dimensionless]
South Africa	33896.00	4.55%	7.00	9179.84	2925.46
Mozambique	849.00	0.11%	5.70	8150.26	52.97
Botswana	40.00	0.01%	4.70	8299.47	2.10
Simbabwe	502.00	0.07%	8.80	8023.56	47.61
Nigeria	291.75	0.04%	7.00	4687.57	12.86
Swaziland	143.50	0.02%	4.70	8890.88	8.05
Tanzania	269.25	0.04%	5.90	6818.54	14.55
USA	225012.00	30.22%	5.30	7870.28	12606.19
Canada	4346.00	0.58%	2.80	6758.28	110.46
Mexico	1160.00	0.16%	6.10	9458.14	89.89
Brazil	1547.00	0.21%	5.40	9442.21	105.94
Colombia	4880.70	0.66%	7.00	9256.12	424.74
Venezuela	730.92	0.10%	7.30	8558.92	61.34
Chile	1181.00	0.16%	5.10	12527.98	101.35
China	180600.00	24.26%	4.80	7231.98	8420.32
India	77196.94	10.37%	4.50	6759.75	3153.95
Vietnam	3116.00	0.42%	4.30	9338.88	168.06
Indonesia	13512.00	1.81%	6.80	11018.24	1359.73
North Korea	600.00	0.08%	7.70	8163.37	50.66
South Korea	326.00	0.04%	5.10	8579.29	19.16
Russan Federation	68943.75	9.26%	6.50	5426.76	3266.34
Ukraine	32038.50	4.30%	7.60	1515.75	495.71
Kazakhstan	17241.75	2.32%	4.80	3988.87	443.39
Uzbekistan	1374.60	0.18%	6.30	4203.33	48.89
Poland	14710.85	1.98%	4.50	607.33	54.00
Germany	48.00	0.01%	3.80	1.00	0.00
UK	450.30	0.06%	4.60	1034.14	2.88
Czech Republic	1139.20	0.15%	3.70	385.89	2.18
Hungary	276.38	0.04%	6.20	794.56	1.83
Turkey	386.10	0.05%	6.80	2357.35	8.31
Bulgaria	192.00	0.03%	6.00	1473.70	2.28
Australia	57538.00	7.73%	3.60	14482.43	4029.13
SUM	**744539.47**	**100.00%**			**38090.32**

Source: BMWi, 2013; DFT, (n.d.); EIU, 2013

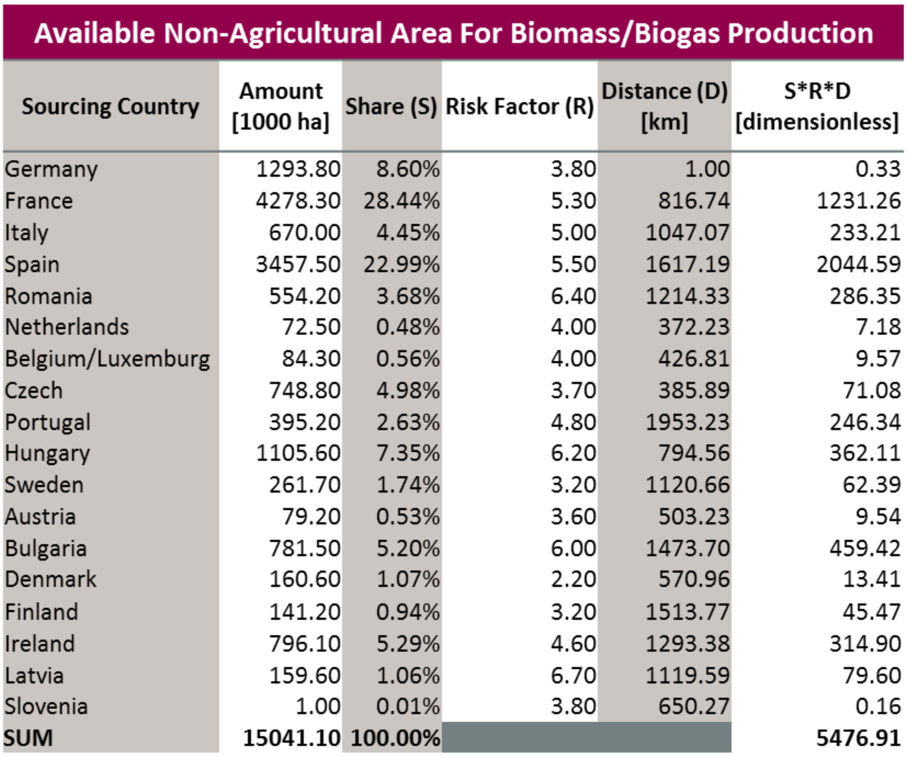
The following table contains detailed data on extractable lignite reserves 2011. Small discrepancies in the numbers might stem from rounding differences. Where different data bases provided different figures, the arithmetic mean has been used.

Extractable Lignite Reserves

Sourcing Country	Amount [million t]	Share (S)	Risk Factor (R)	Distance (D) [km]	S*R*D [dimensionless]
Niger	6.00	0.00%	7.50	3741.54	0.62
Nigeria	63.00	0.02%	7.00	4687.57	7.58
Central African Republic	3.00	0.00%	7.80	5053.70	0.43
USA	30669.00	11.25%	5.30	7870.28	4691.07
Canada	2236.00	0.82%	2.80	6758.28	155.16
Mexico	51.00	0.02%	6.10	9458.14	10.79
Brazil	5049.00	1.85%	5.40	9442.21	944.01
Ecuador	24.00	0.01%	7.70	10082.29	6.83
China	11000.00	4.03%	4.80	7231.98	1400.22
India	4846.90	1.78%	4.50	6759.75	540.65
Indonesia	9001.80	3.30%	6.80	11018.24	2473.18
Japan	10.00	0.00%	3.80	9058.55	1.26
Mongolia	1350.00	0.50%	6.10	6357.45	191.98
Thailand	1062.90	0.39%	7.00	5397.73	147.27
Vietnam	244.00	0.09%	4.30	9338.88	35.93
Russian Federation	91184.40	33.44%	6.50	5426.76	11794.53
Ukraine	2335.50	0.86%	7.60	1515.75	98.66
Albania	522.20	0.19%	6.20	832.92	9.89
Bosnia Herzegovina	1271.68	0.47%	7.50	951.02	33.26
Bulgaria	2174.00	0.80%	6.00	1473.70	70.49
Germany	40500.00	14.85%	3.80	1.00	0.56
Greece	2875.95	1.05%	6.30	1611.38	107.06
Italy	7.00	0.00%	5.00	1047.07	0.13
Cosovo	1564.20	0.57%	6.40	1238.89	45.48
Makedonia	331.65	0.12%	6.60	1369.34	10.99
Poland	4514.02	1.66%	4.50	607.33	45.24
Portugal	33.00	0.01%	4.80	1953.23	1.13
Romania	280.00	0.10%	6.40	1214.33	7.98
Serbia	7111.80	2.61%	6.60	1120.94	192.94
Slovakia	137.95	0.05%	5.50	718.11	2.00
Slovenia	315.00	0.12%	3.80	650.27	2.85
Spain	319.23	0.12%	5.50	1617.19	10.41
Czech Republic	2683.25	0.98%	3.70	385.89	14.05
Turkey	2075.80	0.76%	6.80	2357.35	122.02
Hungary	2633.31	0.97%	6.20	794.56	47.57
Australia	44219.00	16.21%	3.60	14482.43	8453.93
SUM	**272705.54**	**100.00%**			**31678.16**

Source: BMWi, 2013; DFT, (n.d.); EIU, 2013

The following table contains detailed data on extractable natural gas reserves 2011. Small discrepancies in the numbers might stem from rounding differences. Where different data bases provided different figures, the arithmetic mean has been used. The unit (ha) differs from those of other relevant resources (t). Despite these discrepancies, relevant resources are frequently compared on the basis of their respective units by the German Federal Ministry of Economics and Technology. (BMWi, 2013).



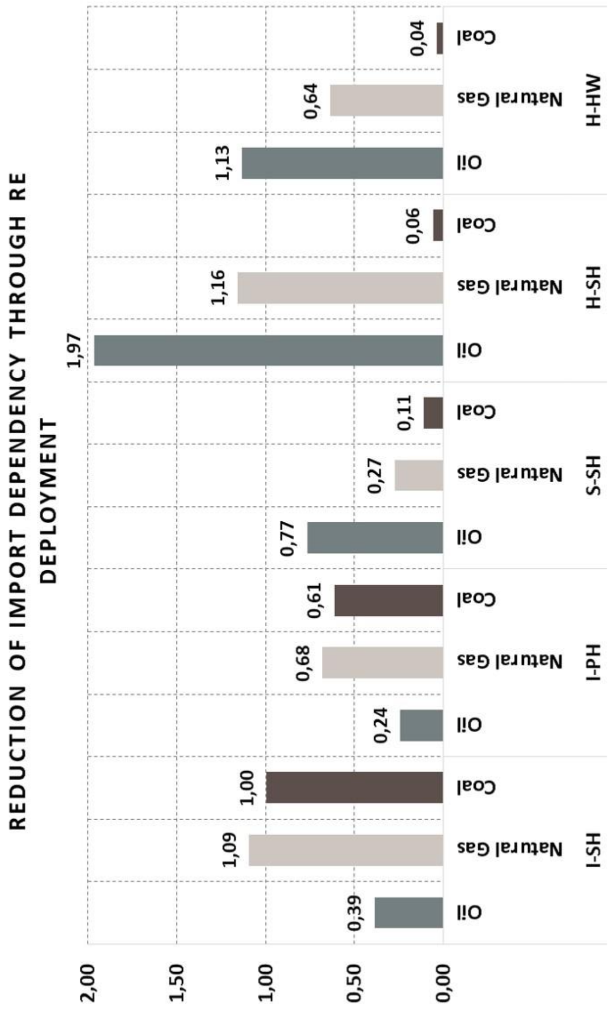
Available Non-Agricultural Area For Biomass/Biogas Production

Sourcing Country	Amount [1000 ha]	Share (S)	Risk Factor (R)	Distance (D) [km]	S*R*D [dimensionless]
Germany	1293.80	8.60%	3.80	1.00	0.33
France	4278.30	28.44%	5.30	816.74	1231.26
Italy	670.00	4.45%	5.00	1047.07	233.21
Spain	3457.50	22.99%	5.50	1617.19	2044.59
Romania	554.20	3.68%	6.40	1214.33	286.35
Netherlands	72.50	0.48%	4.00	372.23	7.18
Belgium/Luxemburg	84.30	0.56%	4.00	426.81	9.57
Czech	748.80	4.98%	3.70	385.89	71.08
Portugal	395.20	2.63%	4.80	1953.23	246.34
Hungary	1105.60	7.35%	6.20	794.56	362.11
Sweden	261.70	1.74%	3.20	1120.66	62.39
Austria	79.20	0.53%	3.60	503.23	9.54
Bulgaria	781.50	5.20%	6.00	1473.70	459.42
Denmark	160.60	1.07%	2.20	570.96	13.41
Finland	141.20	0.94%	3.20	1513.77	45.47
Ireland	796.10	5.29%	4.60	1293.38	314.90
Latvia	159.60	1.06%	6.70	1119.59	79.60
Slovenia	1.00	0.01%	3.80	650.27	0.16
SUM	**15041.10**	**100.00%**			**5476.91**

Source: BMWi, 2013; DBFZ, 2009; DFT, (n.d.); EIU, 2013

Appendix VIII: Complete Decomposition Level Analysis for Import Dependency

The following figure shows the complete decomposition level analysis for import dependency (absolute numbers).



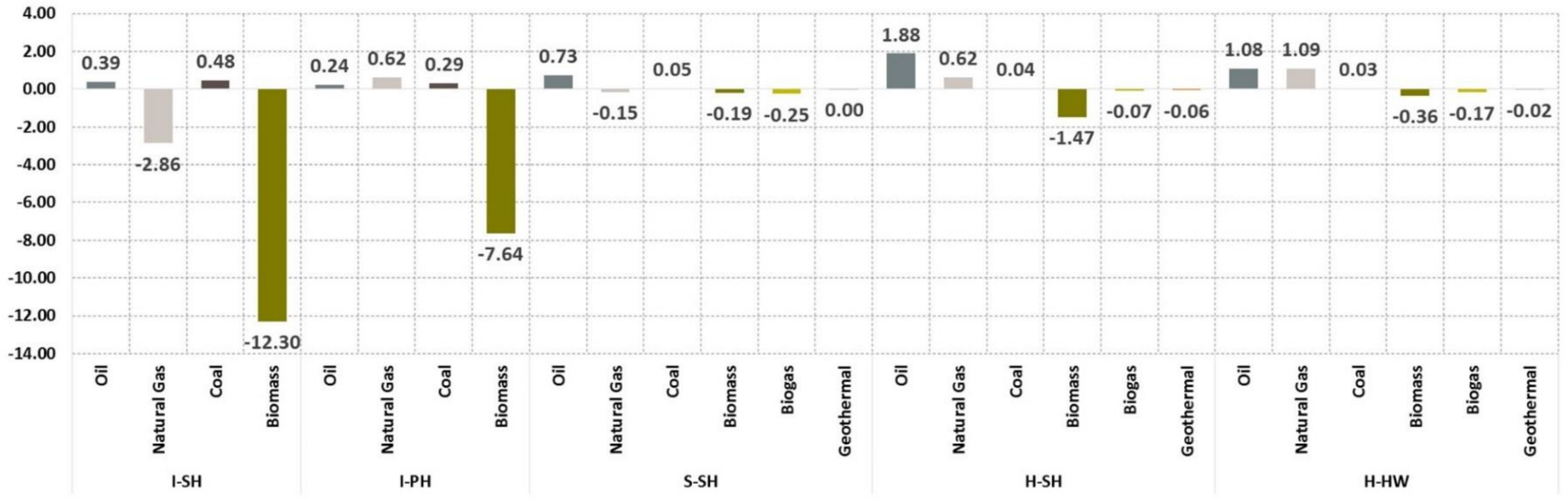
IMPORT DEPENDENCY			
Sublevel	Technology	Scenario I	Scenario II
I-SH	Oil	2.53	2.91
	Natural Gas	7.39	8.48
	Coal	2.96	3.96
I-PH	Oil	1.48	1.73
	Natural Gas	6.52	7.20
	Coal	7.73	8.35
S-SH	Oil	5.70	6.47
	Natural Gas	7.19	7.47
	Coal	2.47	2.58
H-SH	Oil	6.88	8.84
	Natural Gas	5.14	6.30
	Coal	1.53	1.59
H-HW	Oil	7.17	8.30
	Natural Gas	6.54	7.18
	Coal	0.50	0.53

Appendix IX: Complete Decomposition Level Analysis for Price Volatility

The following figure shows the complete decomposition level analysis for price volatility (absolute numbers).

PRICE VOLATILITY																												
Sublevel	I-SH				I-PH				S-SH						H-SH						H-HW							
Technology	Oil	Natural Gas	Coal	Biomass	Oil	Natural Gas	Coal	Biomass	Oil	Natural Gas	Coal	Biomass	Biogas	Geo-thermal	Oil	Natural Gas	Coal	Biomass	Biogas	Geo-thermal	Oil	Natural Gas	Coal	Biomass	Biogas	Geo-thermal
Scenario I	2.25	10.57	1.42	12.30	1.48	5.93	3.71	7.64	5.45	4.12	1.12	0.19	0.25	0.00	6.57	2.76	1.10	1.47	0.07	0.06	6.85	2.76	0.36	0.36	0.17	0.02
Scenario II	2.91	7.71	1.90	0.00	1.72	6.55	4.00	0.00	6.18	3.97	1.17	0.00	0.00	0.00	8.45	3.38	1.14	0.00	0.00	0.00	7.93	3.86	0.38	0.00	0.00	0.00

REDUCTION OF PRICE VOLATILITY IMPACT THROUGH RE DEPLOYMENT



Appendix X: Complete Decomposition Level Analysis for Production Costs

The following figure shows the complete decomposition level analysis for production costs (absolute numbers).

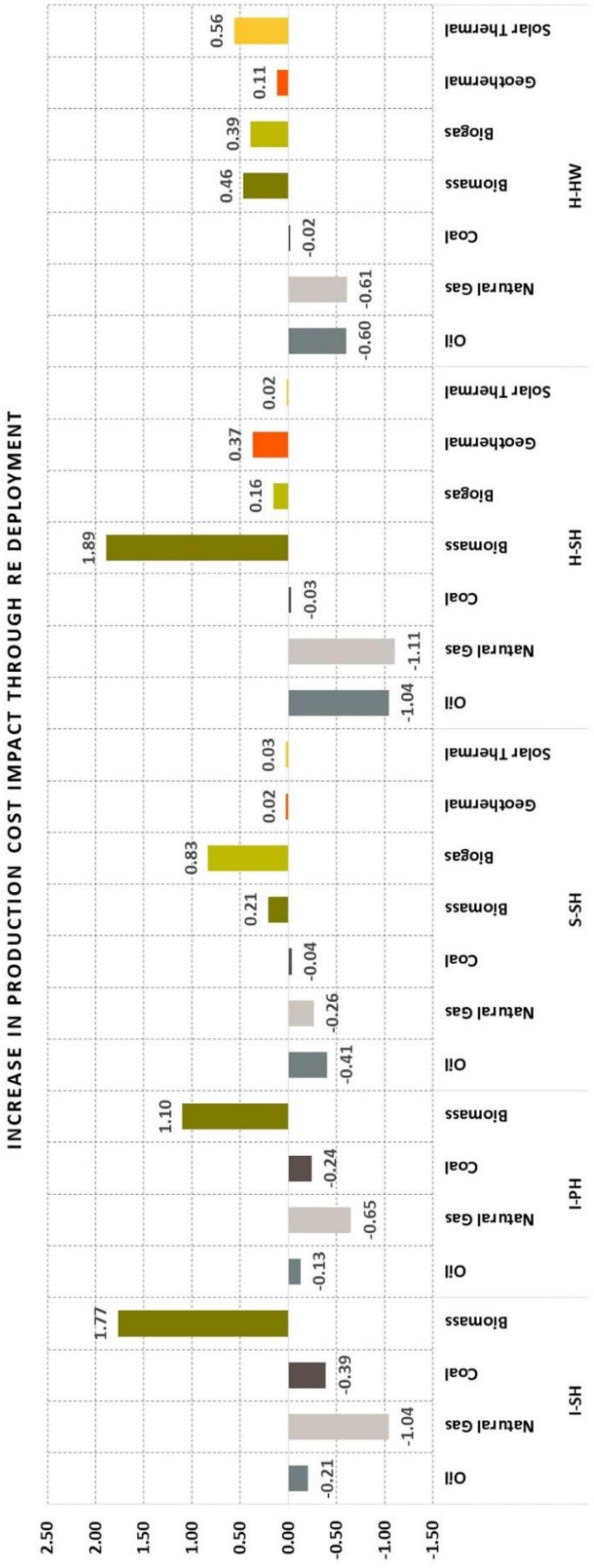
PRODUCTION COSTS

Sublevel	I-SH				I-PH			
Technology	Oil	Natural Gas	Coal	Biomass	Oil	Natural Gas	Coal	Biomass
Scenario I	1.34	7.06	1.16	1.77	0.79	6.23	3.03	1.10
Scenario II	1.54	8.11	1.55	0.00	0.91	6.88	3.27	0.00

Sublevel	S-SH						
Technology	Oil	Natural Gas	Coal	Biomass	Biogas	Geo-thermal	Solar Thermal
Scenario I	3.02	6.87	0.82	0.21	0.83	0.02	0.03
Scenario II	3.42	7.14	0.86	0.00	0.00	0.00	0.00

Sublevel	H-SH						
Technology	Oil	Natural Gas	Coal	Biomass	Biogas	Geo-thermal	Solar Thermal
Scenario I	3.64	4.92	0.80	1.89	0.16	0.37	0.02
Scenario II	4.69	6.02	0.83	0.00	0.00	0.00	0.00

Sublevel	H-HW						
Technology	Oil	Natural Gas	Coal	Biomass	Biogas	Geo-thermal	Solar Thermal
Scenario I	3.80	6.25	0.26	0.46	0.39	0.11	0.56
Scenario II	4.40	6.86	0.28	0.00	0.00	0.00	0.00



Appendix XI: Complete Decomposition Level Analysis for Conversion Efficiency

The following figure shows the complete decomposition level analysis for conversion efficiency (absolute numbers).

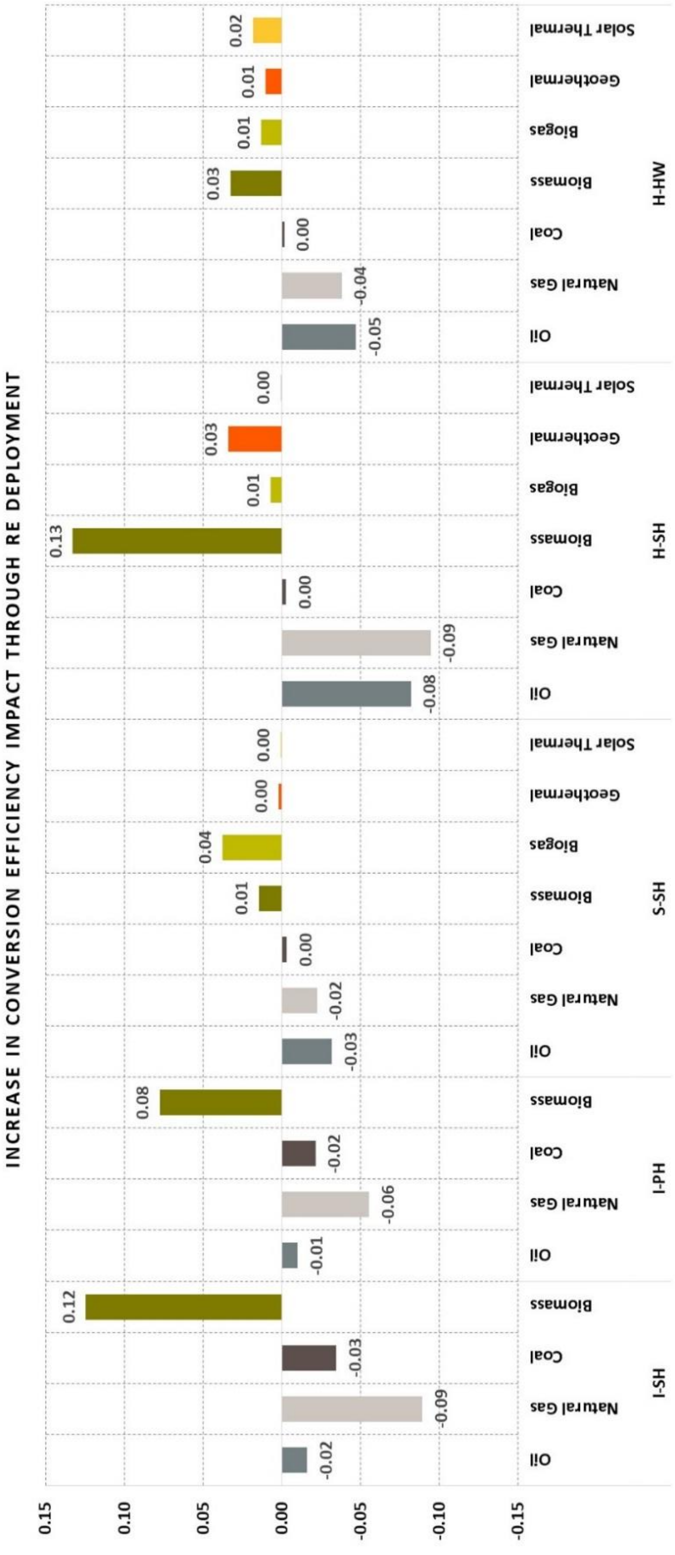
CONVERSION EFFICIENCY

Sublevel	I-SH				I-PH			
Technology	Oil	Natural Gas	Coal	Biomass	Oil	Natural Gas	Coal	Biomass
Scenario I	0.11	0.60	0.10	0.12	0.06	0.53	0.27	0.08
Scenario II	0.12	0.69	0.14	0.00	0.07	0.59	0.29	0.00

Sublevel	S-SH						
Technology	Oil	Natural Gas	Coal	Biomass	Biogas	Geo-thermal	Solar Thermal
Scenario I	0.24	0.59	0.07	0.01	0.04	0.00	0.00
Scenario II	0.27	0.61	0.08	0.00	0.00	0.00	0.00

Sublevel	H-SH						
Technology	Oil	Natural Gas	Coal	Biomass	Biogas	Geo-thermal	Solar Thermal
Scenario I	0.29	0.42	0.07	0.13	0.01	0.03	0.00
Scenario II	0.37	0.51	0.07	0.00	0.00	0.00	0.00

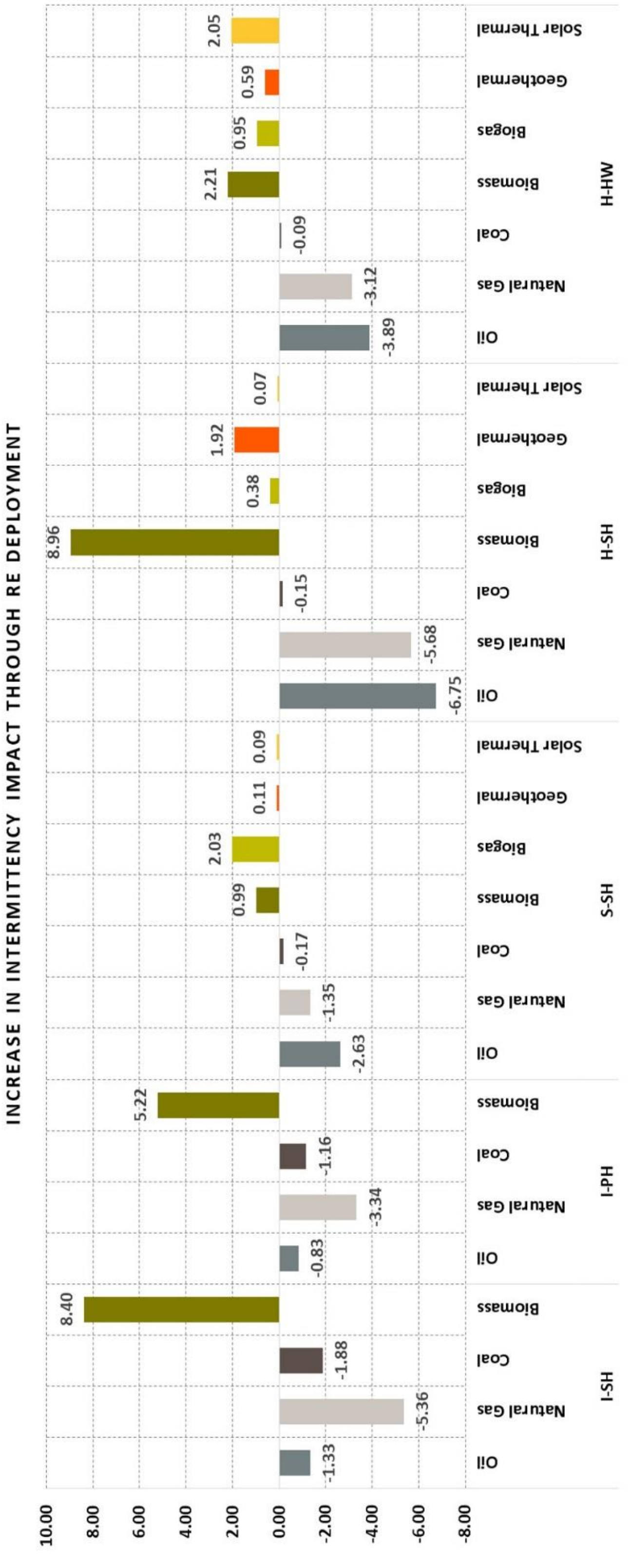
Sublevel	H-HW						
Technology	Oil	Natural Gas	Coal	Biomass	Biogas	Geo-thermal	Solar Thermal
Scenario I	0.30	0.39	0.02	0.03	0.01	0.01	0.02
Scenario II	0.35	0.43	0.02	0.00	0.00	0.00	0.00



Appendix XII: Complete Decomposition Level Analysis for Intermittency

The following figure shows the complete decomposition level analysis for intermittency (absolute numbers).

INTERMITTENCY																													
Sublevel	I-SH				I-PH				S-SH							H-SH							H-HW						
Technology	Oil	Natural Gas	Coal	Biomass	Oil	Natural Gas	Coal	Biomass	Oil	Natural Gas	Coal	Biomass	Biogas	Geo-thermal	Solar Thermal	Oil	Natural Gas	Coal	Biomass	Biogas	Geo-thermal	Solar Thermal	Oil	Natural Gas	Coal	Biomass	Biogas	Geo-thermal	Solar Thermal
Scenario I	8.67	36.27	5.59	8.40	5.09	32.01	14.59	5.22	19.56	35.29	3.96	0.99	2.03	0.11	0.09	23.60	25.25	3.87	8.96	0.38	1.92	0.07	24.59	32.11	1.26	2.21	0.95	0.59	2.05
Scenario II	10.00	41.63	7.47	0.00	5.92	35.34	15.75	0.00	22.19	36.64	4.13	0.00	0.00	0.00	0.00	30.36	30.93	4.02	0.00	0.00	0.00	0.00	28.48	35.23	1.35	0.00	0.00	0.00	0.00



Appendix XIII: Complete Decomposition Level Analysis for Diversity of Availability

The following figure shows the complete decomposition level analysis for diversity of availability (absolute numbers).

DIVERSITY OF AVAILABILITY

Sublevel	I-SH				I-PH				S-SH							H-SH							H-HW						
Technology	Oil	Natural Gas	Coal	Biomass	Oil	Natural Gas	Coal	Biomass	Oil	Natural Gas	Coal	Biomass	Biogas	Geo-thermal	Solar Thermal	Oil	Natural Gas	Coal	Biomass	Biogas	Geo-thermal	Solar Thermal	Oil	Natural Gas	Coal	Biomass	Biogas	Geo-thermal	Solar Thermal
Scenario I	0.16	2.04	0.21	0.84	0.10	1.80	0.55	0.52	0.37	1.98	0.14	0.10	0.22	0.01	0.02	0.45	1.42	0.16	0.90	0.04	0.21	0.01	0.46	1.80	0.05	0.22	0.11	0.06	0.41
Scenario II	0.19	2.34	0.28	0.00	0.24	1.99	0.59	0.00	0.42	2.06	0.14	0.00	0.00	0.00	0.00	0.57	1.74	0.17	0.00	0.00	0.00	0.00	0.54	1.98	0.06	0.00	0.00	0.00	0.00

INCREASE IN DIVERSITY OF AVAILABILITY IMPACT THROUGH RE DEPLOYMENT