A scenario analysis of

The energy use in the U.S. steel industry

Possibilities for and limitations to energy transition

By

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PREFRACE

'The finest steel has to go through the hottest fire'
– R. Nixon, 37th president of the United States

This research is conducted in light of graduation for the master program Systems Engineering Policy Analysis Management (SEPAM) at Delft University of Technology (TU Delft). The research was executed for the faculty of Technology, Policy and Management, for the section Energy & Industry. The client and host of the research project was Shell International. The research was conducted in the form of a full time internship in the Shell Scenarios team, which is part of the Future Strategy department and is located in The Hague. Shell has been using scenario planning for over 40 years to help deepen its strategic thinking. Developing and applying scenarios is part of an on-going process in Shell that encourages decision-makers to explore the features, uncertainties, and boundaries of the future landscape, and engage with alternative points of view. The team consists of around 25 people based in The Hague (Netherlands) and London (United Kingdom). The duration of the research and internship was six months, from March to August 2015.

I could not have executed the research without the help of a number of people. First I would like to specially thank Rob Stikkelman for being the main supervisor on behalf of TU Delft and direct focal point for queries; Bert Enserink for being the second supervisor on behalf of the TU Delft and providing feedback mostly focused on the scenario methodology; and Paulien Herder for chairing the TU Delft graduation committee. Second I would like to express my special appreciation and thanks to Rhodri Owen-Jones for supervising on behalf of Shell and coaching on a weekly basis; and Colette Hirstius for being a mentor with regard to the research process as well as for personal development. Finally I would like to thank all other people who provided input, reviewed the work for feedback or supported in any other context.

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EXECUTIVE SUMMARY

RESEARCH CONTEXT

In the United States (U.S.), from the year 1990 to 2014 the carbon dioxide (CO_2) emissions have increased by seven per cent and it is expected that this will continue to rise in the coming decades. In 2014, the country emitted over 5000 million metric tonnes energy related CO_2. In on-going climate debate much attention is directed towards how to rapidly de-carbonise the energy system and how to transition to sustainable energy systems. From the U.S. major economic sectors the industrial sector is, with 32% energy consumption, the largest energy consumer, and is accountable for 14% of the total U.S. CO_2 emissions. As possibilities for full energy transition in some sectors are extensively researched, less attention is directed towards heavy industry due to the complexity and high variety of these processes. However, when debating the energy mix, heavy industry's black box for energy consumption is a recurrent theme on the agenda.

Unlike the present energy system based on fossil fuels, an energy system fully based on renewable energy sources (RES) with hydrogen and electricity as energy carriers would be sustainable in terms of CO_2 emissions. The energy transition of the 21st century will need to be more rapid, however, to rapidly change the energy system and at the same time satisfy the rising energy demand is a major challenge. Lack of clarity exists with regard to the possibilities and pace of energy transition in heavy industry, but also the answer to the question whether100% decarbonisation is possible, is surrounded by uncertainty.

RESEARCH OBJECTIVE

This research focuses on the U.S. steel industry. The industry is one of the largest energy consumers in heavy industry and accounted for 128,8 million metric tons CO_2 emissions in 2014, but is also critical to the U.S. economy as steel is the material of choice for many elements of construction, transportation, manufacturing, and a variety of consumer products. This research key research question was: *What are the possibilities for and limitations to an energy transition towards the use of electricity and hydrogen as energy carriers (from RES) in the U.S. steel industry up until the year 2050?* By improving the understanding, an empirical contribution to the debate around energy transition in the steel industry and heavy industry is made. In addition, recommendations on how to enhance energy transition are provided to policymakers, and the obtained knowledge feeds into the work on the Energy Transition Climate Challenge for client Shell.

RESULTS

The results of a scenario workshop with industry experts revealed two plausible scenarios for the U.S. steel industry in 2050: Quarterback and scenario Wide Receiver (analogy with American football roles). An overview of the two scenario characteristics is presented in figure A. In the Quarterback scenario, the U.S. has developed itself as one of the active players in the sustainable steelmaking market and utilization. Visionary politicians make the decisions about what game to play and take strong action to

Scenario	Quarterback	Wide Receiver
Economy	• Squeezed economic growth • High iron ores prices • Cooperation to survive • Niche market	• Economy flourishes • Low iron ores prices • Individualism of companies • Also mass production
Policy	• Visionary politicians • Stringent environmental policy measures	• Conservative politicians • Reserved environmental policy measures
Technology	• Pushed to radically innovate	• Business as usual
Society	• Service-oriented economy • Job losses in industry	• Stay industrialized • More employment
Environment	• Environmental conservation	• Intensified pollution

Figure A: Key characteristics of the two scenarios abate the intensified stresses on the environment. Steel producers either have to radically innovate in cleaner technologies or are tackled by the high CO_2 taxes, which result in steel winners and losers. Cooperation is key in surviving the national playing field, and competition focuses on quality rather than quantity.

In the Wide Receiver scenario, the U.S. steel industry actively outmanoeuvres the deployment of environmental policy measures that heavily affect the steel industry by lobbying against it. With the low iron costs the industry quickly develops as an up to speed steel industry, with active participation in the international steel market. The environment takes some tough hits and experiences the consequences of continued pollution. In addition, with little incentives to innovate the industry only invests in incremental improvements.

Moreover, modelling the two scenarios with Shell's World Energy Model (WEM) shows that in scenario Quarterback larger energy transition occurs than in Wide Receiver. Figure B shows the energy consumption (in energy carriers) per year by U.S. steel producers for 2014 and for 2050 in the case of Quarterback and Wide Receiver. In Quarterback 59% of the total energy consumed comes from the energy carriers electricity and hydrogen, of which 27% is produced by renewable primary energy sources (e.g. wind, solar). In Wide Receiver 36% of the total energy consumed comes from electricity and hydrogen, of which 22% is produced by primary renewable energy sources.

Energy transition in the U.S. steel industry is limited by three technical factors. Firstly, the technologies currently in a progressed stage of research and development reveal that no technology becomes available that can produce steel by only consuming the energy carriers electricity and hydrogen carriers. Secondly, from the two major routes to steel, the cleaner technological route to steel is limited by the quality it can produce. Thirdly, the option to mix hydrogen in the natural gas grid is limited to 5-15% due to the fact that facilities connected to the natural gas grid are not optimized for hydrogen contents above these levels, as this can be damaging for to the infrastructure. Furthermore financial and institutional barriers exist, including the lack of funding to replace highly capital-intensive assets, lacking incentives to innovate and the presence of political uncertainty.

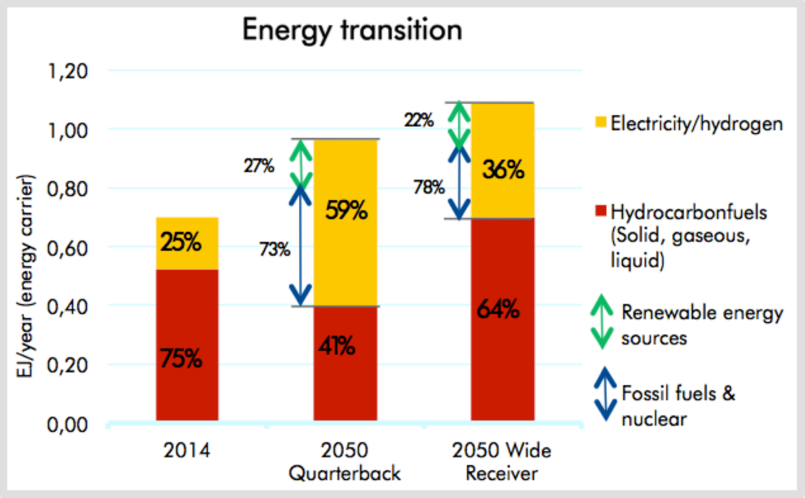

Figure B: Energy transition in the two scenarios

IMPLICATIONS OF THE RESULTS

For policymakers, the two scenarios with different energy consumption behaviour of the U.S. steel producers show that policymakers can, to some extent, trigger energy transition in the U.S. steel industry as they have the power to influence the industry with environmental policy measures. However, the current policy frameworks are not capable of successfully triggering energy transition in the industry, and a gap between today's policy environment and the policy environment in Quarterback in 2050 is revealed. Recommendations to create persistent and continuous, aligned, and balanced policy measures include a national (and also internationally aligned), long-term CO_2 abatement system and the provision of incentives and financial support to stimulate radical innovation.

For client Shell the scenarios show that there are limitations to energy transition in the steel industry and in heavy industry. By better understanding of the possibilities and limitations Shell can actively engage in the energy transition debate and the discussions about the development of a CO_2 abatement scheme. Furthermore the results show a robust demand for natural gas and it demonstrates that as the consumption of electricity and hydrogen increases, opportunities for (further) deployment of activities in these markets exist. Finally, a role for Shell to deploy carbon capture and storage (CCS) in the steel industry is identified.

DIRECTIONS FOR FUTURE RESEARCH

Next steps in this field of research would be to further explore energy transition in other parts of heavy industry. Where this research concerned a market driven country, an interesting next step would be to conduct a scenario analysis for a policy driven country (e.g. China). In addition, future research could focus on addressing the environmental policy gap between today and the year 2050 as was identified in the scenarios.

READING GUIDE

In this report, the research that resulted in these insights is described more comprehensively. An introduction to this study's topic and context are discussed in chapter 1. In chapter 2 the theoretical framework of the research is provided and in chapter 3 is elaborated on the methodological approaches. The current U.S. steel industry system is analysed and possibilities for future change are explored in chapter 4. In chapter 5 the qualitative part of the scenario analysis is conducted in which the organisation and results of the scenario workshop are discussed. Chapter 6 the quantitative part of the scenario analysis is conducted, and it describes the modelling exercises and evaluation thereof. In chapter 7 the implications of the scenario analysis for energy transition in the industry and the implications for the key stakeholders are discussed. In chapter 8 the research conclusions are presented and in chapter 9 the value of the research is discussed. Finally, in chapter 10 an evaluation of the research process and personal experiences are presented.

Throughout the report, reading guide paragraphs are provided at the end of each chapter to guide the reader through the research. In addition, as this research is insightful to multiple stakeholders, the most relevant sections for the various key stakeholders are highlighted below:

SHELL

Stakeholders from Shell are referred to chapter 1 (section 1.1) as this provides the context of the research and an introduction to the key topics; chapter 5 because the scenario workshop experiences and scenarios are useful to the Scenarios team; chapter 6 since the model experiences are useful for future enhancement of the model exercises in the Scenarios team; chapter 7 (section 7.2 and 7.3.2) because this shows the implications of the scenarios for Shell; and chapter 8 as this provides the main research conclusions.

POLICYMAKERS

Policymakers are referred to chapter 1 (section 1.1) as this provides the context of the research and an introduction to the key topics; chapter 5 (section 5.4) because the developed scenarios can support development of policy measures; chapter 7 (section 7.2 and 7.3.1) because this shows the implications of the scenarios for policymakers; chapter 8 as this provides the main research conclusions; and appendix E as this shows the key conclusions in article form for energy policy development.

OTHER STAKEHOLDERS IN THE U.S. STEEL INDUSTRY SYSTEM

Other stakeholders are referred to chapter 1 (section 1.1) as this provides the context of the research and an introduction to the key topics; chapter 4 because this provides an insightful analysis of the total U.S. steel industry system; and chapter 8 as this provides the main research conclusions.

TU DELFT

Researchers from the TU Delft are referred to chapter1 as this provides the context of the research and an introduction to the key topics; chapter 2 and 3 because these describe the theory and methods used for the research; chapter 6 since the model experiences are useful for future enhancement heavy industry scenario modelling; chapter 8 as this provides the main research conclusions; and chapter 9 because this discusses the scientific and social value of the research.

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LIST OF ABBREVIATIONS

AISI	American Iron and Steel Institute
BF	Blast furnace
BOF	Basic oxygen furnace
Btu	British thermal units
CAPEX	Capital expenditures
CCS	Carbon capture and storage
CO_2	Carbon dioxide
DOE	Department of Energy
DRI	Direct reduced iron
EAF	Electric arc furnace
EIA	United States Energy Information Administration
ES	Energy Service
ESE	Energy Service Efficiency
ETCC	Energy Transition Climate Challenge
EPA	United States Environmental Protection Agency
GDP	Gross Domestic Product
GHCF	Gaseous hydrocarbon fuels
HFS	Hydrogen Flesh Smelting
HRC	Hot rolled coil
IEA	International Energy Agengy
IPCC	Intergovernmental Panel on Climate Change
LHCF	Liquid hydrocarbon fuels
MJ	Megajoule
MOE	Molten Oxide Electrolysis
NREL	National Renewable Energy Laboratory
OPEX	Operation expenditures
PRB	Population Reference Bureau
PSH	Paired Straight Hearth
R&D	Research and development
RES	Renewable energy sources
SHCF	Solid hydrocarbon fuels
STEEP	Society, Technology, Economy, Environment, Policy
SWOT	Strengths, Weaknesses, Opportunities, Threats
TFC	Total final consumption
TJ	Terajoule
TPE	Total primary energy
ULCOS	Ultra–Low CO_2 Steelmaking
US	United States
WEM	World Energy Model
WSA	World Steel Association

1. INTRODUCTION

1.1 RESEARCH CONTEXT

1.1.1 ENERGY TRANSITION IN U.S. HEAVY INDUSTRY

Today we live in an era of energy volatility and transition. Much attention is focused on how to rapidly de-carbonise the energy system and how to transition to sustainable energy systems (EPA, 2015; IPCC, 2014). Most historical energy shifts have lasted over a century or longer and were stimulated by resource scarcity, high labour costs, and technological innovations (Solomon & Krishna, 2011). However, to significantly abate stresses on the environment from pollution, the energy transition of the 21st century will need to be more rapid. Rapid change of the energy system, and at the same time satisfying the rising energy demand is a major challenge.

Unlike the present energy system based on fossil fuels, an energy system based on renewable energy sources (RES) with hydrogen and electricity as energy carriers would be sustainable in terms of carbon dioxide (CO_2) emissions (Barbir, 2009). Technological and associated institutional transformations in energy end-use are the fundamental drivers of historical energy transitions. Hence by shifting end-use applications towards electricity and hydrogen as the prime fuel source, the global energy system is gradually undergoing a decarbonisation transformation (Grubler, 2012; IEA, 2014). The benefit of hydrogen is that it produces only water vapour and no other gaseous byproducts when used as a reducing agent or fuel (DOE, 2002b). The same accounts for electricity, which also does not emit CO_2 when consumed at the end of the value chain. Despite these advantages a transition to cleaner energy carriers is constrained by technological barriers, as well as institutional and financial barriers (DOE, 2002b; NREL, 2014).

In the case of the United States (U.S.), from the year 1990 to 2013 the carbon dioxide emissions have increased by seven per cent (EPA, 2015), and the U.S. Energy Information Administration (EIA) states that this will number will continue to rise in the coming decades (EIA, 2014a). In 2014, the country emitted over 5000 million metric tonnes energy related CO_2. These numbers raise serious concerns and emphasise the need for change in the U.S.

From the U.S. major economic sectors – which are industrial, transportation, residential and commercial - the industrial sector is, with 32% energy consumption, the largest energy consumer, and is accountable for 14% of the total CO_2 emissions (EIA, 2014d; EPA, 2014). Whereas the future possibilities and limitations for the use of electricity and hydrogen (from here onwards called clean energy carriers) in the transportation, residential and commercial sector are extensively debated and researched, less attention is directed towards heavy industry. This includes refining, chemicals, pulp & paper, coal, cement, and primary metals (e.g. aluminium and steel) (EIA, 2014a; McDowall & Eames, 2006; Sugiyama, 2012). The complexity and high variety of heavy industry processes are the key reasons for the lack of knowledge. However, in on-going debate about the energy transition, heavy industry's black box for energy consumption is a recurrent theme on the agenda.

Current literature explores long-term scenarios for industry and cleaner fuel use from the demand viewpoint (Ishikawa, Glauser, & Janshekar, 2010), or, explores the supply of electricity and hydrogen from RES (McDowall & Eames, 2006; Sugiyama, 2012). A number of scholars are concerned with integration of the demand and supply systems, but have a limited focus on industry and focus on a specific region (Jacobson et al., 2014; Wei et al., 2013). Also, often research approaches an issue from one perspective (e.g. technical or economical), leaving out other perspectives such as policy and the influence of stakeholders. However, in the world of ever-growing system complexity, actor inter-dependability, dynamic nature of stakeholders, and evolving changes in the system environment, the field of systems engineering shows more prominence. This looks at systems from a complex socio-technical approach (Sage & Armstrong, 2000). A research gap can be identified that concerns understanding of the use of clean energy carriers in the long-term future of the U.S. heavy industry as a system, including primary energy production and final energy consumption, combining a technical, economical and multi-actor approach.

1.1.2 CLEAN ENERGY CARRIERS IN THE STEEL INDUSTRY

Even though relatively little comprehensive research is conducted with regard to the use of cleaner carriers in heavy industry, the idea that there are possibilities for a transition towards cleaner carriers in the future is generally recognized. However, the questions can be asked what those possibilities exactly are, and whether or not limitations exist; is a 100% transition technically and practically possible or are there limits to the use of clean fuels? The technologies may be constrained with the use of fossil fuels for certain process steps. Secondly, the question is at what pace will such a transition actually take place.

Taking into account the current best available technologies and pilot technologies, it is expected that certain heavy industries have higher potential to incorporate clean energy carriers in the technological processes than other industries. For instance, to produce aluminium already a significant quantity of electricity is necessary, which could possibly be supplied by RES in the future, but the use of hydrogen fuel has limited potential (EIA, 2014a). On the other hand, the bulk chemical and refinery industries show potential for increased use of electricity as well as hydrogen fuel, but due to the complexity and variety of production processes this varies significantly per system.

Analysing the electricity and hydrogen use in the steel industry, the electric arc furnace consumes electricity. In addition, new technologies are being piloted (e.g. HISarna) that allow more fuel flexibility including the use of hydrogen (IEA, 2014). However, the U.S. steel industry (including iron production), being one of the largest energy consumers in the manufacturing sector, relies significantly on natural gas and coal coke and breeze for fuel, and accounted for 128,8 million metric tons CO_2 emissions in 2014 (EIA, 2014a, 2014b). The industry is critical to the U.S. economy; steel is the material of choice for many elements of construction, transportation, manufacturing, and a variety of consumer products (EIA, 2014b). Because the steel industry shows potential for electrification and also use of hydrogen, but is currently a relatively closed system with the use of conventional energy carriers, it is an interesting case to research the possibilities for and limits to an energy transition, and is therefore the focus of this research.

1.1.3 SHELL AND THE ENERGY TRANSITION CLIMATE CHALLENGE

Whilst much attention is focused on decarbonizing the energy system, less is focused on how to provide the future energy needed to enable a reasonable quality of life for a growing global population. This unbalanced discussion has led to energy policy paralysis, volatility and uncertainty. In Shell's work in the long-term strategy department on the Energy Transition Climate Challenge (ETCC), the aim is to better understand the future energy system. Analysing the U.S. is relevant to Shell as this is an interesting and representative case to analyse the dynamics and behaviour of actors in future energy system in a market driven country. By better understanding the possibilities for and limitations to an energy transition in various sectors, Shell aims to play an active role in creating dialogue with important stakeholders (e.g. policymakers), to add realism to the debate, and ultimately aims to collaboratively secure a sustainable and abundant energy future for all.

Moreover, the steel industry is interesting to Shell, as it is a key energy consumer and (potential) customer for Shell's products and services. An energy transition will affect many stakeholders in the energy system. Shell, being an energy provider of oil and natural gas, is one of those stakeholders that could be affected as its core business concerns fossil fuels. Increased deployment of RES puts pressure on the fossil fuel market. Hence, in order to get an idea of what the future energy system and demand entails, understanding the pace and consequences of the energy transition, is essential for Shell. Questions such as 'is there a continuous role for fossil fuels?' and 'what role will Shell play in the transition?' are key to answer. This thesis project contributes to the ETCC work and sheds light on one piece of the puzzle of understanding of the future energy system, as it focuses on the U.S. steel industry. A separate research deliverable - which is not included in this report because of confidentiality – is created that serves as a knowledge source to management.

1.2 INTRODUCTION TO SCENARIOS

The aim of this section is to define what a well-suited higher-level methodological approach is for a research problem with these features. To do so the following approach is taken. Firstly, the nature of the research is identified by means of the book Verschuren & Doorewaard (2005). This is to help understand what higher-level methodologies could be an optional approach to consider. Next, the optional approaches are evaluated concerning their advantages and disadvantages, and subsequently the best-suited high-level method is chosen. In addition, the limitations to the chosen high-level approach are described.

1.2.1 NATURE OF THE RESEARCH

This research can be categorized as a practice-oriented research, which means the aim is to provide knowledge and information that can contribute to an intervention in order to change an existing situation. Following the research stages defined by Verschuren & Doorewaard (2005), this research focuses on the research stages *problem analysis* (exploring the tension between a current and desired situation) and *diagnosis* (background and the causes of the identified problem), which have 'setting the agenda' and 'creating dialogue' as one of the main objectives (Verschuren & Doorewaard, 2005). One of the key characteristics of the research question is that the research is long-term oriented, namely up until 2050. Also, the research takes a system perspective in a system that is complex in nature (e.g. multi-actor and socio-technical system) and is surrounded by uncertainties (e.g. environmental policy, steel demand, etc.). These three characteristics ask for a methodology that is capable of dealing with deep uncertainties and a complex system, in a long-term time frame.

1.2.2 SCENARIO ANALYSIS METHOD

Relatively few techniques deal with complexities and deep uncertainties in a long-term time frame. System Dynamics is used for simulating dynamically complex issues and analysing the resulting non-linear behaviours over time (Series & Sterman, 2003). However, the method is less suitable for a long-term horizon (Featherston, 2012). Other potential methods are Exploratory Modelling and Analysis or Agent Based Modelling, which also use computational experiments to analyse complex and uncertain issues (Kwakkel & Pruyt, 2013). However, critics argue that in these highly quantitative methods social forces and less quantifiable forces are difficult to incorporate.

A different technique is *scenario analysis*, which is primarily concerned with understanding external, complex and uncertain environments (Wilkinson & Kupers, 2014). By examining the external drivers and driving forces of a system a number of possible future worlds - called scenarios - can be developed and described. These scenarios are a valuable tool that help organizations to prepare for possible eventualities, and makes them more flexible and more innovative (Amer, Daim, & Jetter, 2013). Also, it is used by policymakers in order to form or test long-term policy.

In scenario analysis a qualitative and quantitative approach can be taken. It is by combing both qualitatively and quantitatively research into a more comprehensive outcome, which makes it possible to incorporate the effect of social forces (Amer et al., 2013). Qualitative methods are considered appropriate for research with a large scope and long time horizon, while quantitative methods are generally considered useful for narrowly focused research with a shorter time frame. However, the two methods can compliment and strengthen each other as is highlighted in figure 1 (Pillkahn, 2008). The scenarios practitioners in Shell often combine the two approaches, for example in their 'New Lens Scenarios' (Bentham, 2014).

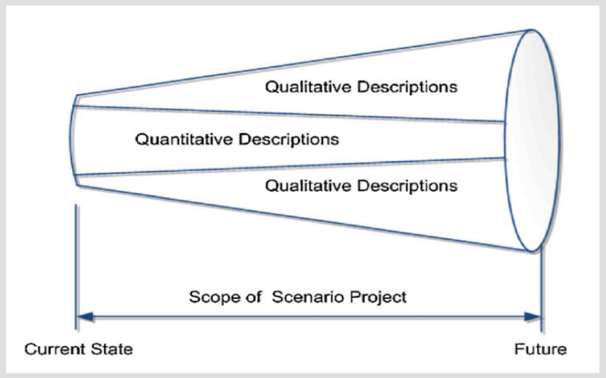


Figure 1: Combining qualitative and quantitative scenario analysis (Pillkahn, 2008)

This research follows the same higher-level approach and aims to answer the research question by means of combining a qualitative and quantitative approach. The lower-level approaches are not necessarily the same as the Shell methodology, as for each most suited approach for this particular research is chosen. In chapter 3 elaborates the various types of scenario analysis, and which specific approach this research takes.

Some limitations to the scenario analysis methodology exist. Firstly, there is the issue of the unknowables (Schoenmaker, 1995). Three classes of knowledge exist: (1) things we know, (2) things we know we do not know, and (3) things we do not know we do not know. Scenario development is especially helpful at supporting knowledge development of type 2, but for type 3 this is extremely difficult. Secondly, scenarios do not predict the future. They explore multiple plausible future situations with the purpose of extending the sphere of thinking of the participants in the scenario development process (Wilkinson & Kupers, 2014); and considering long time periods, they provide a useful means of capturing the broad dimensions of change (McDowall & Eames, 2006). Since the aim of this research is not to forecast, but rather to understand the possible effects of external drivers on the steel industry with many uncertainties and in the long-term, this is judged to be a suitable method for analysis.

1.3 RESEARCH FRAMEWORK

1.3.1 OBJECTIVE AND SCOPE

This study's objective is to understand what the possibilities for and limitations to an energy transition are towards the use of electricity and hydrogen as energy carriers (from RES) in the U.S. steel industry up until the year 2050. This is done by conducting a scenario analysis for the U.S. steel industry by means of a scenario workshop and by modelling the scenarios with the Shell World Energy Model (WEM). By improving the understanding of the possibilities and limitations, an empirical contribution to the debate around the energy transition in the steel industry as being part of heavy industry is made, and recommendations to the U.S. steel industry, including policymakers and the client are provided. The scenario analysis is conducted from the perspective of the steel producers, but the implications and conclusions are drawn more widely. Based on the behaviour of the steel producers, the implications for the energy transition in general, policymakers and finally the client Shell are discussed.

In addition to the empirical contribution to the energy transition debate, the modelling with the WEM is analysed. Based on this analysis a user framework and various recommendation are provided in order to enhance future similar research.

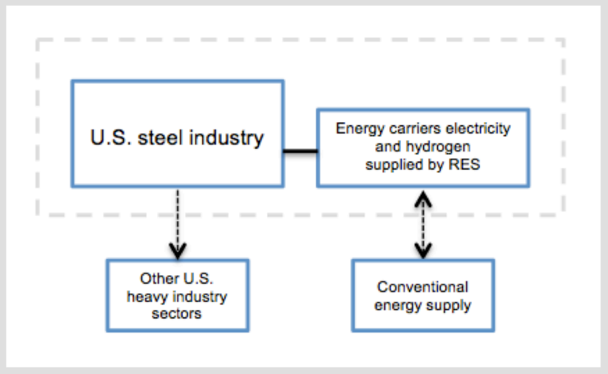


Figure 2: Scope of the research

In figure 2 the scope and the system boundaries of the research are shown. The grey dotted lines present the system boundary. In this research the term *steel industry* describes the production of iron and the production of steel. The mining of the ores and the continued production of the steel to the final products - including casting, rolling, coating, but also further manufacturing – are not subject to the main research focus. The research is conducted for the steel industry in the U.S. The U.S. is addressed on a country wide level. Other heavy industries and other countries are not subject to the main research, however, the steel industry is an international market, with a lot of international trading of the ores, and of the steel products itself. Therefore it is also important to take the world economy and trade flows into consideration. Especially countries such as China affect the steel market in the U.S for example. In the research discussion the study's conclusions are drawn to a broader perspective in which also other industries or countries are addressed.

The total energy system is addressed, including primary energy production, energy carrier transport, and final consumption. However, the focus is on the final transport, the energy carriers electricity and hydrogen, and primary energy supply from RES. In addition, there are a number of technologies and measures available to abate CO_2 emissions for the different iron and steel making processes. These include minimising energy consumption and improving the energy efficiency of the process, changing to a fuel-energy source that emits less CO_2 or capturing the CO_2 and storing it underground, which is a technology called carbon capture storage (CCS) (Carpenter, 2012). This research focuses primarily on CO_2 abatement by changing to another fuel-energy source combination with a lower CO_2 emission factor.

1.3.2 RESEARCH QUESTION AND STEPS

The research objective and scope have resulted in the formulation of the following research question: *What are the possibilities for and limitations to an energy transition towards the use of electricity and hydrogen as energy carriers (from RES) in the U.S. steel industry up until the year 2050?*

In order to answer the research question the following steps are undertaken:

1. Define what theory and methodologies can be supportive to conducting a scenario analysis
2. Analyse the environment of the U.S. steel industry system
3. Develop qualitative scenarios by means of a scenario workshop
4. Model the scenarios with the World Energy Model and evaluate the modelling exercises
5. Assess the implications of the scenarios for the U.S. steel industry and the energy transition
6. Identify the possibilities for and limitations to an energy transition towards the use of electricity and hydrogen from RES as energy fuel in the U.S. steel industry up until the year 2050
7. Discuss and evaluate the research (process)

More detailed explanation of the methodology in each step is given in chapter 3 *Lower-level methodological approaches.*

1.3.3 RESEARCH FRAMEWORK AND DELIVERABLES

For this study the following research framework with the data flows is used, see figure 3. In the figure also the research deliverables are presented. In order to obtain the basic knowledge needed for the scenario workshop four approaches are taken. By analysing theory the question of 'how' to find answers to the research question is addressed. For example, how to find drivers of the U.S. steel industry? Or how conduct a scenario analysis? With literature review, desktop research and expert correspondence the questions of 'what' and 'why' is addressed. For instance, what are the drivers for the steel industry? And, why are these the drivers of the steel industry? The data obtained by the first round of research is complemented with data found and developed in the scenario workshop, which results in a number of scenarios. After the development of the scenarios additional research is done to provide the inputs for modelling. Next the quantitative analysis can be conducted, and finally the outcomes of both the qualitative and quantitative analyses are evaluated.

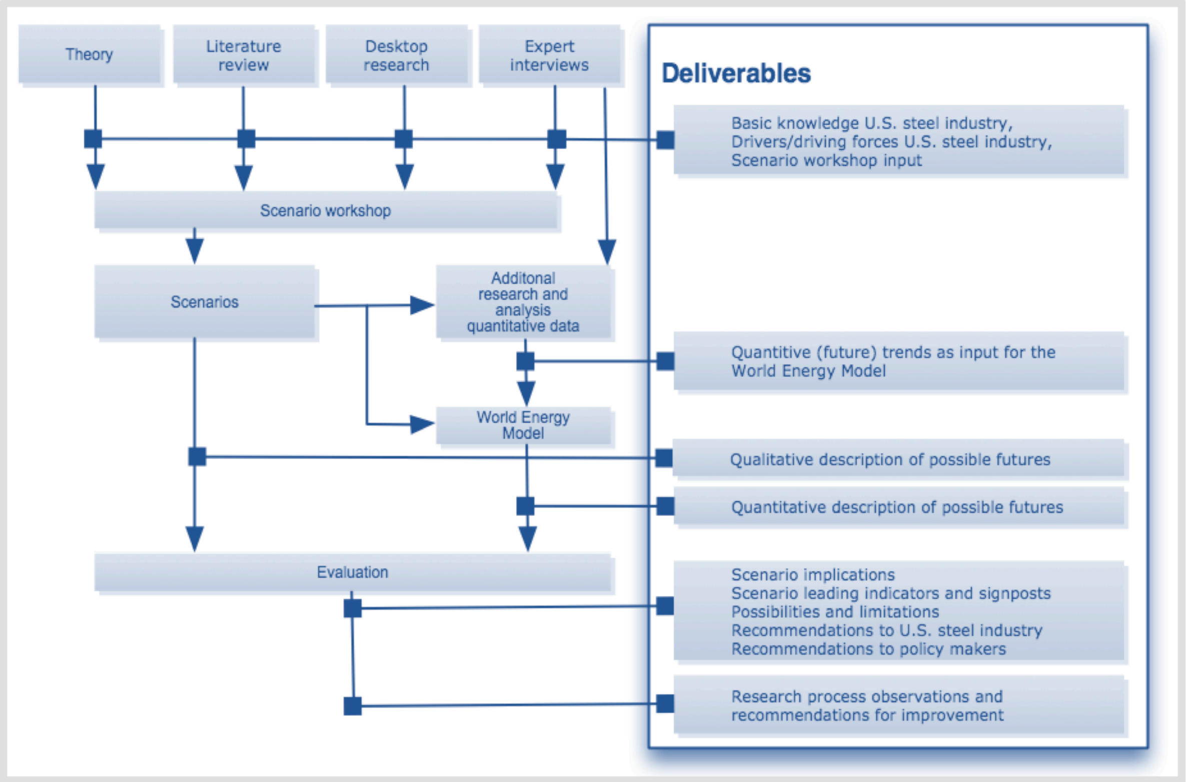


Figure 3: Research framework with data flows

2. THEORETICAL FRAMEWORK

In this chapter a theoretical view is taken concerning *how* to answer the research question. As many approaches for conducting a scenario analysis exist, a literature review is conducted in order to identify the supportive theories and methodologies. The current state-of-the-art of scenario analysis is evaluated and the most suitable approach for conducting a scenario analysis for this research is defined. The literature review results in a theoretical framework that forms a basis for the subsequent research. To conduct the literature study the approach in figure 4 is followed.

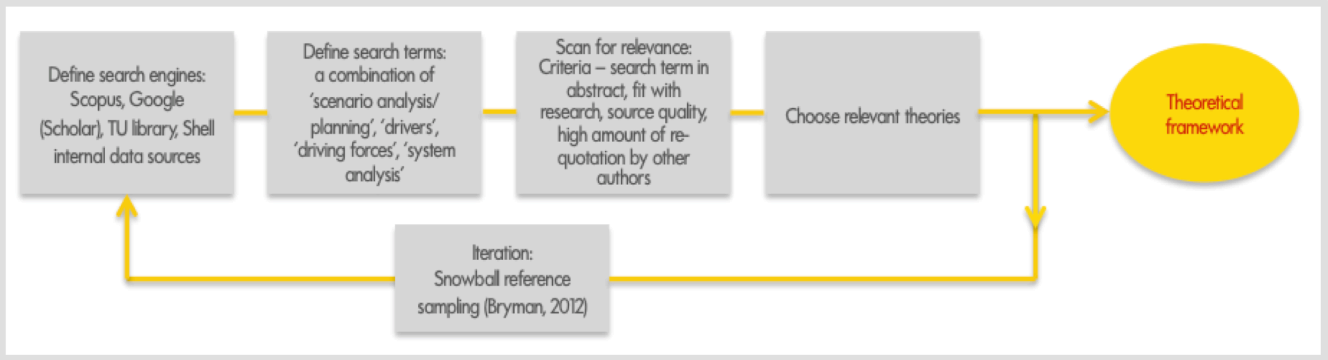


Figure 4: Literature study approach

In chapter 10 *Research Evaluation,* a critical view is taken towards the framework and methodology as well as the resulting outcomes. In addition the tensions between the theory, the practical scenario workshop and the modelling exercises are evaluated therein.

2.1 SCENARIO PLANNING

Over 45 years people have been practicing scenario planning. Notwithstanding, no single clear definition of scenario planning or scenario analysis exists (Bradfield et al., 2005). Herman Kahn, one of the founding fathers of scenario planning, defines scenarios as '*a set of hypothetical events set in the future constructed to clarify a possible chain of causal events as well as their decision points*' (Kahn & Wiener, 1967). For the purpose of this research this definition is embraced. Scenario planning stimulates strategic thinking and helps to overcome thinking limitations by creating multiple futures. Scenario thinking is both protective and entrepreneurial, in which the future is scanned for threats and opportunities (N. Hughes, 2013). The benefits of using scenarios can be described as improving the decision-making process, identification of new issues and problems that may arise in the future, and initiating a public debate (Amer et al., 2013). In general scenario-building techniques focus on defining the issues, identifying the key drivers, stakeholders, trends, constraints and other important issues in a systematic way, and ranking of these items by importance and uncertainty.

In the military, scenario techniques been employed by military strategists throughout history, generally in the form of war game simulations (Amer et al., 2013). Later in the 1960s the scenario technique was extensively used for public policy analysis, social forecasting, and decision-making. The use has increased significantly during the last decade (Rigby & Bilodeau, 2007). Nowadays, increasing innovation and change in the world has increased the importance of identifying future trends and expected business landscape. Hence increasing emphasis is being placed on the use of scenario planning techniques, because of its usefulness in times of complexity and uncertainty (Schoenemaker, 1991).

Scenario planning can be used for various system levels (e.g. worldwide, industry, corporate). In many cases it has been successfully used at national level, and it has been applied extensively at corporate level. At corporate level scenario planning approach is more popular among large size companies. Shell is considered the best-known and most celebrated user of scenarios in the world for business context. Usage of scenarios helped the company to cope with the oil shock and other uncertain events in 1970s (Bentham, 2014; Coates, 2000). Scenarios are generally used for long range planning for ten years or more, and the majority of scenario users belong to capital intensive industries (Amer et al., 2013).

2.2 SCENARIO APPROACHES

Although there is no single approach to scenario planning, literature review reveals that the methodologies for generating scenarios have many common characteristics. The scenario literature can be distinguished in three broad categories: trend based, actor based and technical feasibility approaches. Notwithstanding the categories, scholars stress that these should be combined to obtain a systemic view of the technological, societal and cultural interactions of a socio-technical system as it evolves through time (Hughes, 2013). *Integral scenario* methods are generally more useful methods because they can achieve higher quality outcomes, provide richer options, and provide deeper insights into the nature and dynamics of a system (Slaughter, 1999). Taking this into account, this research takes an integral approach and combines the three viewpoints.

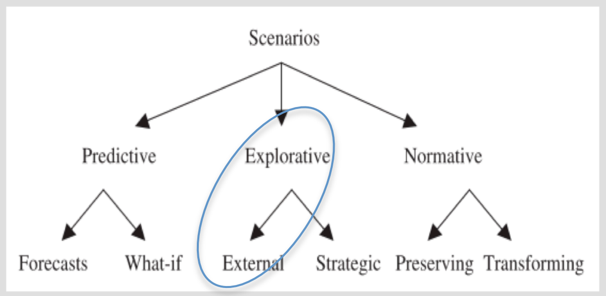


Figure 5: Scenario types and research focus (source: Börjeson et al., 2006)

In general, three types of scenarios exist: (1) predictive, (2) explorative, and (3) normative (see figure 5) (Börjeson et al., 2006). In predictive studies scenarios are developed with the aim to predict what the future looks like, whereas normative scenarios are goal directed and respond to policy planning concerns (e.g. in order to achieve desired targets). *Explorative scenarios* are plausible futures, but often have the objective to initiate debate rather than predicting the future. This method is therefore used in this study. Also, the explorative type stands out as having more structured approaches to thinking about drivers. Explorative research can be divided into external and strategic oriented. Strategic includes factors that are controllable by the actor in question, while external factors – interesting for this study - are outside the scope of influence of the actor (Börjeson et al., 2006).

Amer et al. (2013) identified three major approaches for the development of scenarios, namely (1) intuitive logics, (2) probabilistic modified trends methodology and (3) La prospective (Bradfield et al., 2005). This research follows the *intuitive approach* for the development of scenarios, because the method results in a qualitative set of equally plausible scenarios in narrative form with strategic options, implications, and early warning signals (Amer et al., 2013). The intuitive logic approach assumes that business decisions are based on a complex set of relationships among the technological, economic, political, social, resource, and environmental factors, and cannot be easily modelled (Huss & Honton, 1987). The intuitive method - also referred to as the 'Shell approach' - now dominates the scenario development in the U.S. and many other countries (Bradfield et al., 2005).

A popular scenario building model often cited in literature is the one presented by Schwartz (1991), which belong to intuitive logics approach. Schwartz describes in detail each step of his scenario building model consisting of eight steps and suggests to plot scenario drivers to develop various scenarios (Schwartz, 1991). For the qualitative part of this research the steps by Schwartz are executed.

Section 1.3 on introduction of scenarios, already revealed that a scenario analysis can be conducted qualitatively or quantitatively. This study follows a *combined qualitative and quantitative approach* in order reach a more comprehensive outcome. Explorative external scenarios can be generated qualitatively by surveys, workshops or with the Delphi method (Börjeson et al., 2006). For this research a *scenario workshop* is organized. The benefit of workshops is that it can facilitate broadening of the perspectives, since decision-makers, stakeholders and experts can be included in the process. Moreover, workshops can increase the acceptance of decisions or scenarios among the participants, and it is also possible to include techniques that liberate the creativity of the human mind (Oreszczyn & Carr, 2008). Critical for the success of the workshop is the cognitive diversity of the workshop participants. The reason for that is the impact of individual differences in ways of perceiving and judging of content within the scenario planning workshops (Franco et al., 2013).

To support the qualitative scenarios with quantitative data, a *model exercise with Shell's internal scenario model* is conducted. The most common quantitative methods are Interactive Cross Impact Simulation, Interactive Future Simulations, Trend impact analysis (TIA), and Fuzzy Cognitive Map (Amer et al., 2013). Shell's model is partly in accordance with the TIA in that it collects time series data, conducts extrapolation, and qualitatively writes narratives. However, the Shell approach does not gives probabilities to events occurring over time. Strictly quantitative methods are often criticized because these methods rely solely on historical data and assume that same trends will prevail in future. The combined qualitative and quantitative methodology is further explained in chapter 3 *Methodological approaches.*

2.2.1 SCENARIO STEPS

The theory by Schwartz (1991) was chosen to serve as a red line throughout the research. He identified eight general steps to develop scenarios (see box 1). Below each of the steps is explained more comprehensively. The explanation in *italic* is retrieved from the theory by Schwartz. To enhance the understanding of each step, additional literature was found to support the theory by Schwartz. In the case more explanation is required additional theory is presented under each of the relevant steps.

BOX 1: SCENARIO STEPS BY SCHWARTZ (1991)

Step 1 - Identify the focal issue or decision
Step 2 - Identify key forces in the local environment
Step 3 - List the driving forces
Step 4 - Rank key factors & driving forces by importance and uncertainty
Step 5 - Select scenario logics
Step 6 – Flesh out the scenarios
Step 7 - Explore implications
Step 8 – Select leading indicators and signpost

STEP 1 - IDENTIFY THE FOCAL ISSUE OR DECISION

In the first step a specific decision or issue is defined, and subsequently build out to the broader environment. A focal question is developed that is answered with the following scenario steps.

STEP 2 - IDENTIFY KEY FORCES IN THE LOCAL ENVIRONMENT

Secondly, the key forces that influence the success or failure of the focal question are identified, and the considerations that will shape the outcomes are defined. These include facts about customers, suppliers, competitors, etc.

A number of authors came up with methods to structure the process of identifying key forces. Analysing the market in which the problem owner operates is a first step to find the key forces. Aaker (1996) outlined the dimensions important for a market analysis. In table 1 these dimensions and the explanations are shown.

Dimension	Explanation
Market size	Based on current sales and potential (future) sales. Data available from governments, trade associations, or major market players
Market growth rate	Extrapolation of historical data. Demographic information and sales growth in complementary products are important factors
Market profitability	See Porter's five forces model explained below
Industry cost structure	Includes fixed and variable costs
Distribution channels	Existing distribution channels, trends and emerging channels, channel power structure
Market trends	Changes in the market. Can include changes in price sensitivity, demand for variety, and level of emphasis on service and support, regional trends
Key success factors	Those elements that are necessary in order for the industry to achieve its marketing objectives. For example, economies of scale, access to resources or technological progress

Table 1: Market analysis dimensions by Aaker (1996)

In this research the dimensions in table 1 are analysed to get a market overview. The distribution channels are discussed together with the sub-sections market size and growth rate. In analysing the market profitability Porter's (1990) model is supportive. The model is primarily of use on a firm level, but the models can also be applied on a wider industry level. The five forces model (see figure 6) provides a simple framework for assessing and evaluating the competitive strength and position of a business organisation (or in this case industry). The theory is based on the concept that there are five forces that determine the competitive intensity and attractiveness of a market. Porter's model of five forces helps to identify where power lies in a business situation. This is useful both in understanding the strength of an industry's current competitive position, and the strength of a position that an industry may look to move into in the future.

In addition to the market analysis, a stakeholder analysis is conducted in order to identify the key stakeholders in the system. A useful model to map the map the stakeholder dependencies is the method that Bryson (2004) uses (see figure 7). In the power-interest matric a stakeholder is mapped on two axes: the level of power, and the level of interest. Identifying which stakeholders have high power, high interest, or both helps to identify key forces in the system.

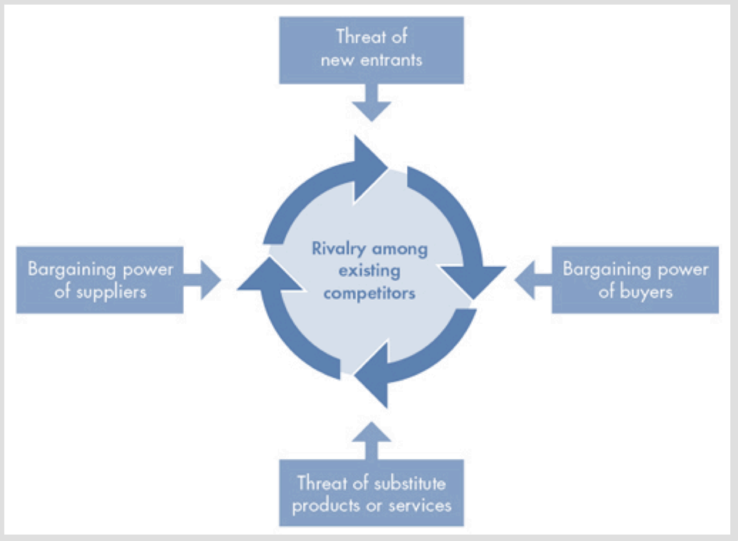


Figure 6: Porter's five forces model (Porter, 1990)

Figure 7: Stakeholder grid (Bryson, 2004)

STEP 3 - LIST THE DRIVERS/DRIVING FORCES

Thirdly, in this step the macro-environmental forces behind the micro-environmental forces from step 2 are defined. The major trends and trend breaks are analysed.

In order to identify drivers (e.g. CO_2 price) or driving forces (e.g. high CO_2 price) of a system it is important to understand the complexity of a system. In figure 8 a simplified projection of the industry and its surroundings is presented. In this research the analysis is conducted from the perspective of steel producers in the system, hence these are the clients. Players and competitors are other actors in the system (e.g. energy producers). When dealing with complexity in business environments, a distinction can be made between three levels of complexity: (1) internal, (2) transactional environment, and (3) contextual environment (Vasconcelos & Ramirez, 2011). From the latter two, being both external, the transactional environment refers to that part of the environment that the organization can influence and is a major player in it. The contextual environment is that part of the environment that has repercussions for an organization but on which it has little or no influence (Wilkinson & Kupers, 2014). Institutions in this type of environment are called referees and context setters (e.g. policymakers).

Moreover, every organization is propelled by particular driving forces. Some of these are internal (e.g. competency of management) and some are external (e.g. policy), and shape the future of the organization (Schwartz, 1991). Hence, to understand the future of the steel industry and the possibilities of electrification and use of hydrogen, the drivers the steel industry has influence over should be examined, and, even more importantly the

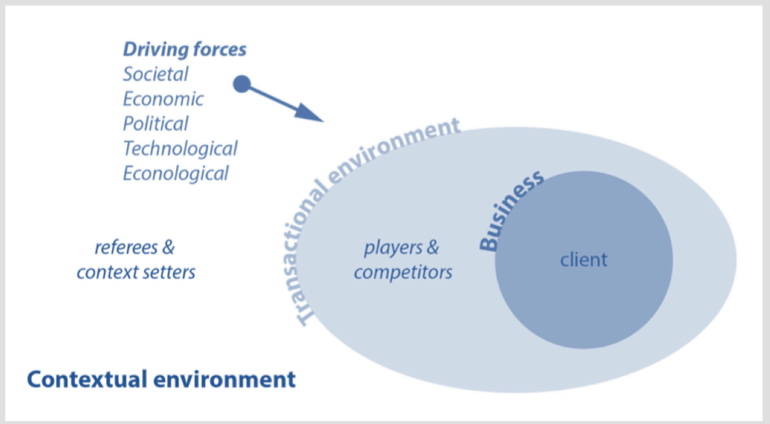


Figure 8: The U.S. steel industry and its surroundings (van der Heijden, 2005)

fundamental drivers of which the industry has no influence over should be assessed. The processes and tools used by scenario practitioners to find these driving forces are basically generic and include desk research, individual and group brainstorming and clustering techniques. A contextual environment analysis can be conducted using the Society, Technology, Economy, Environment, Political (STEEP) framework (Bradfield et al., 2005), in which the system is analysed from multiple viewpoints.

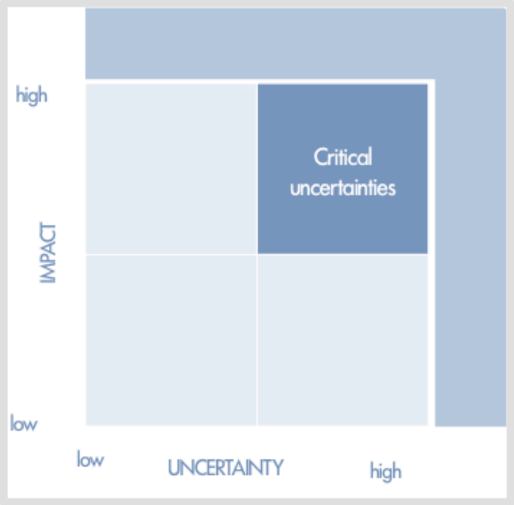


Figure 9: Defining the critical uncertainties

STEP 4 - RANK KEY FACTORS & DRIVING FORCES BY IMPORTANCE AND UNCERTAINTY

In step 4 two or three key factors and driving forces are identified that are both most important and most uncertain.

In this step critical uncertainties are identified, which will form the bases of the scenarios. This can be done by drawing a two-dimensional ranking space which indicates on the one hand the level of impact and on the other the level of uncertainty (Postma & Liebl, 2005; Schwartz, 1991) (see figure 9). The critical uncertainties are the drivers that can be categorized as having a high impact on the system and having a high level of uncertainty.

STEP 5 - SELECT SCENARIO LOGICS

From the ranking of step 4 the axes along which the eventual scenarios will differ can be drawn. Determining these steps is among the most important in scenario development. Proliferations of scenarios should be avoided by choosing only a few scenario critical uncertain drivers. The final narrative will usually be more subtle than the simple logics would suggest.

The chosen critical uncertainties are usually polarized on axes (e.g. energy prices high/low). It is important that two polar scales are the same and not too broad or too narrow. Subsequently the polarized axes can be 'tested' against each other to see what scenarios are formed and to finally create a scenario framework (see figure 10). A scenario framework usually has two axes or more. The more axes the more critical uncertainties are included, but the more complex the framework becomes and a higher variety of scenarios is created.

In the reviewed literature no precise response to the question of how many future scenarios are optimal was found. Various researchers have recommended different number of alternative scenarios usually ranging between two to six scenarios (Amer et al., 2013). Table 2 shows the advantages and disadvantages of various numbers of scenarios. It is important to develop a manageable number of scenarios, that best captures the dynamics of the situation and communicates the core issues effectively (Mietzner & Reger, 2005). Also, the number of scenarios developed significantly depends upon how many critical uncertainties of the future environment are considered to create scenarios (Amer et al., 2013). Assigning probabilities to scenarios should be avoided, as this is not the purpose of this type of scenario development.

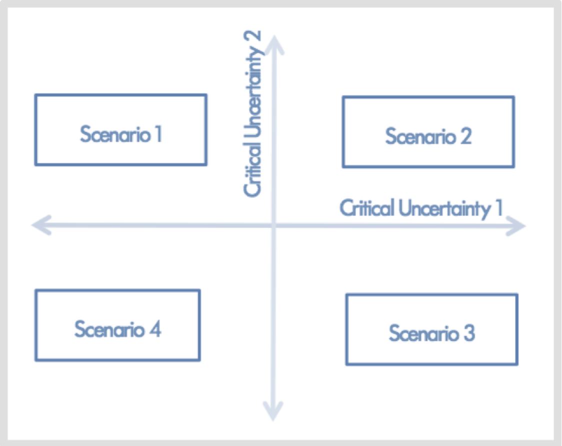


Figure 10: Scenario framework

Number of scenarios	Implications
1	Most likely scenario. Although it is convenient for strategy formulation, it will not yield any alternative or future options
2	Usually based on two extreme situations (optimistic and pessimistic), which are difficult to handle in the context of evaluation
3	Recommended by many researchers, but there is a risk of focusing on the middle (most likely) scenario
4	Possible, good cost-benefit ratio
5	Possible
More than 5	Possible, but cost of development and evaluation of all scenarios will be very high

Table 2: Evaluation of scenario analysis number (Pillkahn, 2008)

A scenario should be tested on the following features: plausibility, recognisability from signals in the past, inclusion of 'good' and 'bad' aspects, internal consistency, challenging, consequentiality, and memorability (Shell, 2015). The features of a good scenario can be helpful when 'testing' axes and defining what scenario framework to continue with.

STEP 6 – FLESH OUT THE SCENARIOS

The logics in step 5 give the skeleton of the scenarios. Now the key factors and trends listed in Steps 2 and 3 must be added. Each key factor and trend should be given some attention in each scenario.

In addition it is important to pay a great deal of attention to naming the scenarios. Successful names telegraph the scenario logics. For example the latest Shell scenarios are called Mountains and Oceans, representing top down governing, and more market driven respectively.

STEP 7 - EXPLORE IMPLICATIONS

Return to the focal issue or decision in Step 1. The following questions can be asked: How does it look in each scenario? What vulnerabilities have been revealed? Is the strategy robust across all scenarios? How could it be adapted to make it more robust?

The decision to move on to other strategic options will be contingent on how they play out in the different scenarios, and hence depends on the way the external environment actually develops (Shell, 2008). It may be that for certain aspects of the steel industry, whichever scenario might occur, whatever events the future may hold, the implications of a particular strategy seem certain to remain the same. This may suggest to steel producers or policymakers that there is a set of actions that they can or should implement fairly immediately and securely. A helpful tool to explore the scenario implications is the strengths, weaknesses, opportunities and threats (SWOT) framework. This framework can be used for every scenario and from the perspectives of the problem owner of the scenario analysis.

STEP 8 – SELECT LEADING INDICATORS AND SIGNPOST

In the latest step the leading indicators and signpost are defined. In the future the indicators and signposts will help to decide which scenario is closest to the course of history.

Defining implications for strategic development of the decision makers is a long-term process, consisting of monitoring the external world for indications and events that are moving in a particular direction. Decision makers can use their scenarios almost like a map to structure their discussions, guiding their thinking about the future. Identified leading indicators and signpost are intended to help to respond faster and more effectively to changes in their business environment. Decision makers can scan the environment for indications that the dynamics in the scenarios, and therefore underpin their decisions or strategy, are actually happening. Watching for signals means that rather than being forced to react to unexpected events after they have happened, decision makers can begin to anticipate the development of situations (Shell, 2008).

2.2.2 READING GUIDE

The theoretical framework that was developed in this chapter serves as the framework for continuation of the research. It partly provides the answers to *how* to answer the research question. The identified theories are used in the subsequent steps of the research. How exactly the theories are incorporated in the research and what lower-level methodological approaches are taken in the various research steps is explained in the next chapter.

3. (LOWER-LEVEL) METHODOLOGICAL APPROACHES

In the first chapter a brief introduction about the higher-level methodology applied – a scenario analysis – was given. Now that in the preceding chapter a better theoretical understanding is obtained of the main methodology, this chapter elaborates further on the lower-level methodologies that are used (from now on called methodologies). In the first section the approaches for data collection are presented. In the second the approaches for data analysis are shown. Finally, the steps to validate the research are shown.

3.1 DATA COLLECTION

In table 3 an overview of the lower-level methodologies for data collection, the required data and the methodological limitations is presented per research step.

Research steps	Methodology	Data required	Limitations to approach
1. Define what theories and methodologies can be supportive to conducting a scenario analysis	Literature review, desktop research Why: theoretical background necessary for further research; efficient way to quickly gain information	Theory on scenario analysis, driving forces, system analysis, and other complementary theories *Sources*: TU Library, data bases (Scopus, etc.), Shell library, Journals, reports, Google (Scholar)	Complete overview of all literature is difficult to guarantee due to fragmented literature of multidisciplinary nature; only theoretical approach is taken, practice may lead to other findings
2. Analyse the U.S. steel industry system for key forces in the environment	Analyse by means of supporting theory, literature review, desktop research, correspondence with expert steel industry (e.g. TATA steel) Why: combine both theoretical approach with practice to get complete overview	Theory on U.S. steel industry and driving forces; qualitative and quantitative data on the U.S. steel industry *Sources*: data bases, Google (Scholar), reports, Energy Information Administration (EIA), Department of Energy (DOE)	Various theories and/or data sources can be inconsistent or conflicting; necessary data might be unavailable; correspondent might provide biased insights
3. Develop scenarios by means of a scenario workshop	Scenario workshop Why: obtaining qualitative data, bring experts knowledge in; time efficient, comprehensive and creative development of scenarios	Input about driving forces, uncertainties, scenario storylines, implications *Sources*: experts in steel, the U.S., RES, or system integration	Workshop participants can be biased; workshop is only qualitative oriented
4. Translate qualitative scenarios to quantitative data with the WEM and evaluate the modelling exercises	Literature review, expert correspondence (e.g. Shell), desktop research, World Energy Model Why: obtain quantitative data; find missing inputs for model, because of in-house knowledge Shell	Excel files, assumptions, quantitative trends steel industry; *Sources*: experts Shell, data bases, reports, Energy Information Administration (EIA), Department of Energy (DOE), Google (Scholar)	Data model might be unclear, and knowledge can be tribal within Shell and not documented; possibility that qualitative steel case and quantitative model do not align
5. Assess the implications of the scenarios for the U.S. steel industry and the energy transition	Evaluation of outcomes questions 3 and 4	Findings and evaluations of previous questions	
6. Answer the research question about the possibilities for (and limitations to) an energy transition	Evaluation of outcomes questions 2, 3, 4 and 5	Findings and evaluations of previous questions	
7. Discuss and evaluate the research (process)	Evaluation of outcomes questions 5 and 6	Findings and evaluations of previous questions	

Table 3: Overview research methods

In the table a number of methodological limitations to the data collection is acknowledged. These limitations are addressed with extra attention by using sources of significant quality, namely from scientific sources or from experts. Also, multiple sources should be used to validate the data. With regard to the workshop it is important to know the background and interest of the participants. For the

WEM it is key to start in time with understanding the model and finding the data necessary. By being aware of the limitations the effects of the limitations can be minimized.

3.2 DATA ANALYSIS

Research step 2 to step 5 require more explanation with regard to data analysis. For each step a description of the approach is provided, an outline is presented, and the methodological justification and limitations are discussed.

3.2.1 STEP 2: ANALYSE THE U.S. STEEL INDUSTRY SYSTEM

This step serves to obtain profound background knowledge of the system and to discuss the key forces in the system environment. Key forces are crucial powers in the environment that determine success or failure of the industry. In order to do so two routes are taken (see figure 11). In the first route the U.S. steel industry is analysed. From the literature review, desktop research and correspondence with industry experts, relevant data about the U.S. steel industry is obtained, and key forces are identified. Subsequently the key forces are discussed in the corresponding S.T.E.E.P. analysis. In the second route the energy system in the U.S. is analysed. From the data obtained key forces are discussed. Also, the possibilities for and limitations to an energy transition to cleaner energy carriers are addressed.

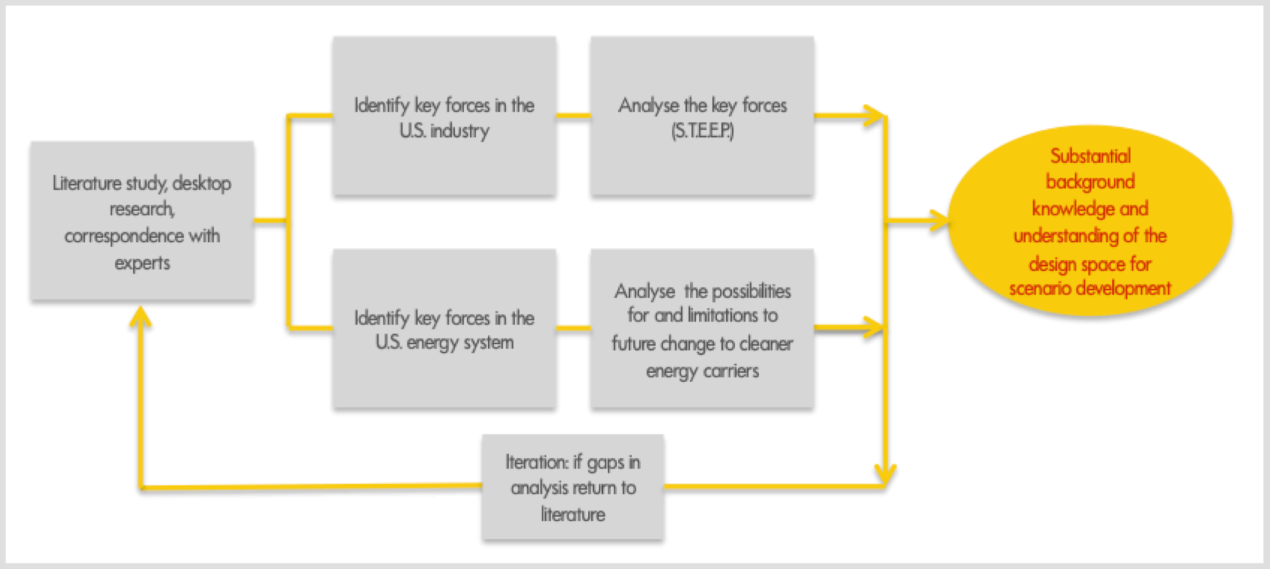


Figure 11: Method for analysis the U.S. steel industry for key forces

In the approach iteration takes place when in the analysis certain gaps come forward that require more attention. When full understanding of a force has not been reached, one returns to the first step where the data is gathered.

Furthermore, the *actors* within the system are analysed – as part of the societal analysis. An actor is defined as *'a social entity, a person, or an organization, able to act on or exert influence on a decision'* (Enserink et al., 2010). The actors are analysed by means of a stakeholder analysis (Bryson, 2004), in which actors are mapped to characterize actors and to identify the types of relationships the problem owner (in this research: the steel producers) typically establishes with the actors in the each of the four quadrants as explained in chapter 2. *Theoretical framework*. This is done by conducting the following steps, which are a selected number of steps from the actor analysis steps defined by Enserink et al. (2010):

(1) Make an inventory of the actors involved
(2) Drafting problem formulations of actors
(3) Rate the level of actor interest in the industry (low to high)
(4) Rate the level of actor power in the industry (low to high)
(5) Map the actors in the stakeholder grid as shown in the theoretical framework chapter

By following the approach in figure 11, substantial background knowledge of the industry and the energy system is obtained. In this research step exploring the possibilities for a energy transition can be regarded as exploring or extending of the design space in which the scenario development takes place, whereas the definition of the limitations sets clear design space boundaries or constraints for the development of scenarios.

3.2.1.1 REFLECTION ON LIMITATIONS

Thorough understanding of the U.S. steel industry system is required in order to be able to develop future scenarios. However, a balance between the level of depth and the broader scope must be found. Whereas on the one hand a scenario analysis requires insights on the focal question from various perspectives in order to capture all drivers on the system, on the other hand, a significant level of depth to understand the differences within the system is required. A limitation is revealed, as the level of depth is confined. For example, by taking the system scope at the country level, regional differences are not taken into account. For this chapter it is key to identify the most important forces without going into too much unnecessary detail.

In step 3, hereunder to be explained, the findings drawn from the industry analysis and energy system analysis are brought together, and form the basic understandings necessary for organization of the scenario workshop.

3.2.2 STEP 3: DEVELOP SCENARIOS BY MEANS OF A SCENARIO WORKSHOP

The primary method in step 3 is the organization of a scenario workshop with industry experts. Around 30 carefully selected industry experts are approached with an invitation for the workshop. The participants are selected based on the following criteria. The participant has:

- Expertise in the steel industry
- Expertise in conventional energy use in heavy industry
- Expertise in renewable energy in heavy industry
- Expertise in energy system integration
- Knowledge of the United States policy and institutional climate

Participants need to fulfil a minimum of three criteria in order to participate. Furthermore, considerations are relevant: 1) support and participation from managerial levels is essential; 2) a broad range of functions and divisions should be represented; 3) imaginative people with open minds who can work well together as a team is key (Rotmans et al., 2001). Two facilitators and one note taker are required to guide and support the workshop. A pre-reading document is send to the participants prior to the workshop to inform them about the event formalities and to provide them with background knowledge about the focal question. This pre-reading document is presented in appendix A). The focal question of the scenario workshop has been identified prior to the workshop and states: *how will U.S steel producers change their energy use between now and 2050?* In the workshop itself the following steps are followed (see figure 12).

Figure 12: Qualitative scenario analysis

With regard to the workshop itself, in the first exercise the participants are firstly asked to *identify drivers*. The step of identification of key forces in the local environment is skipped in the workshop, due to time considerations and because these are already analysed research step 2 (chapter 4). Two presentations by industry experts are provided in which the experts present the main drivers according to them to warm up the participants. After that a plenary discussion follows in which for each of the S.T.E.E.P areas relevant drivers are identified. A driver is taken into account if it complies with the following criteria, based on the description of determination of driving forces in scenarios by Enserink et al. (2010) (1) it is a driver in the contextual environment, (2) the force cannot be influenced by a single actor in the industry or by factors inside the system, and (3) it influences the already distinguished factors. The identified drivers are captured on magnetic hexagons and subsequently grouped according to an overarching theme in order to shorten the list of drivers. This results in a list of *key drivers* that captured all drivers.

Secondly, the participants are asked to *rank the driving forces by importance and uncertainty* as described in the theoretical framework chapter. This is done by means of a plenary discussion. The aim is to capture the two to three most critical uncertainties in order to keep the scenario logics manageable for the scenario participants, as this results in two or three axes.

Thirdly, in the step *select scenario logics,* the critical uncertainties are polarized along axes. For each critical uncertainty a sliding scale is created (e.g. the price of supply the polarised scale can be identified as low and high). After the development of separate axes, the axes are tested in different sets to create a x/y(/z)-axes plane to see what sets of scenarios come out of the various combinations of axes. The objective is to find a set of axes that results in scenarios with the following features: plausible, recognisable from signals in the present, include 'good' and 'bad' aspects, internally consistent, challenging, consequential, and memorable (Amer et al., 2013). For this exercise the group of participants is split up in two groups. After testing a couple of axes, each group chooses their best set of axes. Thereafter a plenary discussion follows to decide upon the final set of axes.

Fourthly, when the scenario framework is established the *scenarios are fleshed out*. This is done by asking questions such as 'What will the world look like in each scenario?' The answers are established based on knowledge of the industry and on intuition, as in this exercise the explorative intuitive scenario approach is pursued. The list of drivers can be used as a checklist, as for every driver the question 'what if the system is in scenario X, what would driver Y looks like?' can be asked and subsequently the driving force of a certain driver can be established (e.g. high economic growth versus low economic growth). The result is a storyline of system features in each scenario for the U.S. steel industry in 2050. This step is done in two separate groups whereby each group fleshes out half of the scenarios from the framework. This way the groups can go more into depth in only a couple scenarios rather than having to address all of them. In the workshop the key characteristics for each scenario are developed, and after the workshop the key characteristic are further elaborated on and are the full storylines consolidated. Finally, the scenarios get names because this helps to emphasize with the scenarios and to more easily refer to them.

3.2.2.1 REFLECTION ON LIMITATIONS

The workshop set-up is based on experiences shared by Shell's scenario experts in the Scenario team, as well as on other sources of information. The scenario experts where helpful in explaining the steps one can execute in a scenario workshop and what considerations are important to take into account when organizing a workshop (e.g. analysing the interest of the participants). However, a limitation to following the exact Shell methodology is that because of their years of experience the process possibly has much features of standardization, excluding the on a case-by-case difference required. Also, as Shell finds itself in the business environment, scientific features can be lacking. Because of these limitations also other sources of information for organizing a scenario workshop were obtained. A scenario expert from the TU Delft was asked to share the experiences about scenario workshops organized within TU Delft context. In addition, scientific literature about scenario workshops is studied.

Moreover, scientific literature shows that an advantage of a workshop is that it can facilitate broadening of the perspectives, since industry experts and stakeholders of any kind can be included in the process (Börjeson et al., 2006). However developing scenarios through a workshop also has limitations. As the exercises are conducted in groups there is the risk of groupthink. This limitation is addressed by means of inviting experts with various backgrounds so that every issue there is touched upon from multiple views, and by splitting up the group in smaller groups in a number of exercises.

Also, with regard to the exercises executed in the workshop both structure and creativity are important for the quality of scenarios, but there is a tension between the two (van Vliet et al., 2012). Structuring of the workshop is necessary in order to give the participants some guidance. Especially since some of the experts might not be scenario practitioners or may not automatically apply 'scenario thinking'. In order to address this issue a couple of Shell's scenario practitioners are invited to the workshop to sometimes pull the discussion 'out of the box' when necessary. However, care should be taken in structuring the output in order not to harm creativity too much (van Vliet et al., 2012). To maintain creativity, a good balance between structuring and leaving room for creativity should be found.

Furthermore it is the responsibility of the facilitators to let the discussions flourish and provide support where needed.

Furthermore, the number of participants has to be optimised; on the one hand one should aim to have a large amount of people participating in order to bring in significant levels of knowledge from various perspectives, while on the other hand the group must be manageable in terms of resources. Therefore the aim is to find 15-25 participants for the workshop.

A last limitation is the duration of a workshop (namely five hours) due to the usually full schedule of experts. As a result the narratives have to be flashed out on an individual basis by the researcher. This limitation is addressed by sending the final narratives to all participants for validation, and to adjust the scenarios based on the received comments accordingly.

3.2.3 STEP 4: TRANSLATE SCENARIOS TO QUANTITATIVE DATA WITH WEM

In this step the qualitative narratives are modelled with the WEM to complement the scenario narratives with quantitative data. In figure 13 the approach is outlined. First the knowledge and understanding of the WEM are obtained, with the help of Shell scenario experts and by exploring the model by means of trial-and-error. This is done this way because no user guide for the model exists nor is explained how and what drivers serve as input for the model. Next, the modelling strategy and exercises are defined. The drivers resulting from the workshop form the inputs for the narratives and will also be key in modelling the scenarios. However, possibly a mismatch between the qualitative scenario narratives and the translation to model parameters exists. In this step is analysed how the identified drivers would serve as input in the model. In the third step the assumptions are explained. Accordingly the model is run and the results are analysed. Finally, as no user guide exists for how to implement the drivers in the model, this research aims to develop a framework and several recommendations for similar future research and modelling with the WEM. The experiences obtained in the second step in figure 13 serve as input for this. Ultimately, research step 4 results in qualitative data for the scenarios, a WEM framework for the scenario modelling in the steel industry, and recommendations for future use of the WEM in other heavy industry.

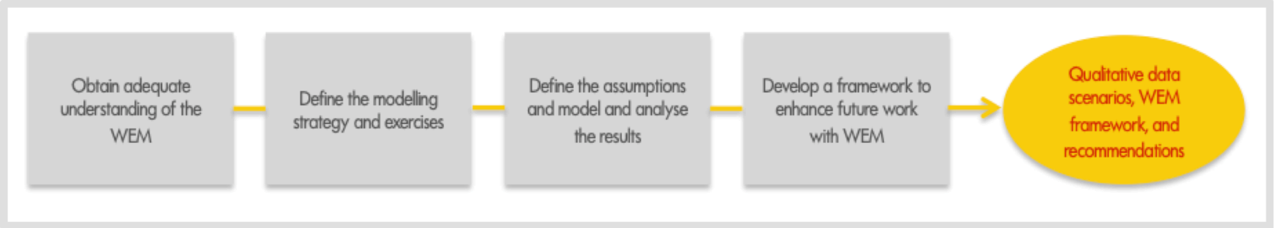


Figure 13: Translating the qualitative narratives to qualitative data

3.2.3.1 REFLECTION ON LIMITATIONS

Advantages of modelling of scenarios on a computer based model are that it is more rigorous and precise than for example a conceptual model, and that it is logically coherent and can include and process large amounts of data (Börjeson et al., 2006). However, in a model that simulates a complex multi-actor system, limitation exist with regard to the number of causal relations that can be included. In this model the energy system in the scenarios are modelled, in which only a number of causal relations are included. This results in the possibility that certain drivers might not be implementable in the model. Also, certain drivers can be hard to quantify (e.g. public pressure) which makes it difficult to model. These limitations are addressed by creating a framework that provides support in the step of transforming drivers to input, which can be used for future similar research.

3.2.4 STEP 5: ASSESS THE IMPLICATIONS OF THE SCENARIOS

In figure 14 the approaches for analysing the implications of the scenarios is shown. Firstly, the implications for the problem owners, the steel producers, are analysed. A Strengths, Weaknesses, Opportunities, and Threats (SWOT) analysis is conducted from the perspective of the steel producers in order to understand what the effect of the scenarios – the external environment - is on the strategic considerations of the steel producers in the transactional environment. In this section is returned to the focal question: how will the U.S. steel producers change their energy use between now and 2050? Based on this the implications for the energy transition are discussed.

In addition, two other important stakeholders are addressed, namely policymakers and Shell. A key stakeholder in the system is the policymaker as it has significant power to influence the system and have high interest, and is considered of paramount importance in energy transitions (Grubler, 2012). Therefore, one section in chapter 7 *Implications* is addressed to policymakers in which recommendations are provided - based on the steel industry playing field in the both scenarios - how they can enhance the energy transition. With regard to Shell it is analysed what the scenarios imply for the company's strategy and what role Shell can play in the transition. Thereafter, leading indicators and signposts are identified by analysing for each key driver what events could create specific external driving forces that push the system in the direction of one of the two scenarios. Finally, these steps result in knowledge necessary to answer the research question and serve as guidance for using the scenarios.

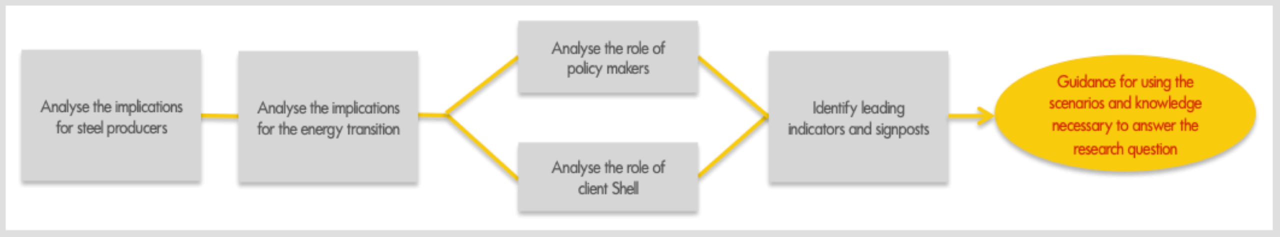


Figure 14: Assessing the implications of the scenarios

3.2.4.1 REFLECTION ON LIMITATIONS

As the focus of this research is on the change in energy use of the U.S. steel producers the scenario analysis is conducted from the perspective of the U.S. steel producers. However, the implications of the research for policymakers and for Shell are discussed as well. This requires some logical reasoning as no thorough scenario analyses are conducted from their perspective. In order to address this limitation with regard to drawing conclusions for Shell, the scenarios and implications for Shell are extensively discussed and validated with Shell's Scenarios team. Validation of the implications with U.S. policymakers is out of the scope of this research, but it is recommended that in future research a next step would be to test the scenarios for policy development in cooperation with U.S. policymakers.

3.3 VALIDITY OF RESEARCH

3.3.1. VERIFICATION AND VALIDITY OF QUALITATIVE SCENARIO ANALYSIS

In the qualitative part of the scenario analysis the research data is verified by means of using multiple data sources. Literature study, desktop research, steel expert correspondence and a scenario workshop are combined in order to address the issue at hand from multiple perspectives. Supportive quantitative data in the scenarios (e.g. the share of renewable energy in the electricity grid) are validated by means of comparing the data with other sources (e.g. International Energy Agency versus U.S. Energy Information Administration).

Since scenarios concern statements about the future, validation is disputable. The scenarios can however be tested for having the features of a good scenario. Bradfield et al. (2005) developed scenario evaluation criteria for the intuitive method. The scenarios have to be coherent, comprehensive, internal consistent, novel, equally plausible, and underpinned by rigorous structural analysis and logics. Shell (2008) also includes the criteria: a scenario has to be recognisable from signals in the present, includes 'good' and 'bad' aspects, challenging, consequential, and is memorable. After the development of the scenario fundamentals in the workshop, the fleshing out of the narratives is further deployed on an individual basis by the main researcher. To validate the scenarios each of the workshop participants are asked to critically assess the scenarios based on the criteria and provide comments by e-mail for improvement. These comments are subsequently included in the final scenario narratives.

3.3.2 VERIFICATION AND VALIDITY OF QUANTITATIVE SCENARIO ANALYSIS

In the quantitative part of the scenario analysis the qualitative narratives are translated to quantitative data by means of the WEM. The WEM is an existing model and as Shell frequently uses and updates this model, it is assumed that the model is verified. To double-check whether the model works properly for heavy industry various test runs are conducted. A number of trial-and-error tests are conducted to better understand the model. For every scenario parameter it is checked what the impact is on the model output by testing multiple inputs. Then it is checked whether the results are expected and what the cause is of any unexpected result. Thereafter the parameters are adjusted in line with the scenarios. With regard to the built-in scenario parameters the various data sets are analysed and tested for each scenario in order to find the most suitable data set. The WEM settings, inputs and final results are validated by means of expert opinion. In the Shell Scenario team a number of scenario experts that built the model or work with the model on a daily basis are asked to check the results with the scenario narratives.

A challenge lies in how to the draw the right conclusions of the model. As the model results show plausible futures, rather than probable futures, no output can be assumed as the given future. Since the model analyses the future system in the long run, many assumptions need to be made, bringing a lot of uncertainty to the results. Therefore, the results should be used as a starting point for discussion instead of taking the results as the truth.

3.3.3 READING GUIDE

At this point the theoretical framework and the methodological approaches for every research step have been discussed. In this chapter the lower level methodological approaches in every research step were comprehensively explained. For every following research step this chapter serves as a guide for how to execute these steps. In the following chapter this report continues with execution of the second research step: analyse the U.S. steel industry system for key forces in the environment.

4. THE U.S. STEEL INDUSTRY SYSTEM

The aim of this chapter is to analyse the transactional environment of the U.S. steel industry system, and to ''identify and discuss the key forces in the environment'', which is the second step of the scenario analysis as defined by Schwartz (1991). Firstly, a closer look is taken with regard to what the U.S. steel industry entails by means of a number of analyses from the various perspectives. Secondly, the research goes more into depth about the energy system and it analyses what the possibilities are for change in the steel industry in the future with regard to the use of cleaner energy carriers. This chapter serves to explore the design space for the scenarios and set boundaries by identification of limitations in the system. After reading this chapter one should have profound knowledge of the U.S. steel industry and energy system, and understanding of the key forces on the industry.

4.1 S.T.E.E.P. ANALYSIS OF THE STEEL INDUSTRY

In this section the current U.S. steel industry system is analysed. Key forces and the expectations and/or uncertainties of the key forces are discussed. The S.T.E.E.P. framework is used to analyse the system from multiple perspectives, namely from a social, technological, economical, political and an environmental perspective.

4.1.1 THE SOCIETY AND STEEL

4.1.1.1 ECONOMICAL GROWTH VERSUS ENVIRONMENTAL CONSERVATION AND DE-INDUSTRIALIZATION

For the steel industry tensions between economic growth versus de-industrialization and environmental conservation exist. Over the last two centuries, the U.S. as a society has been transformed from a predominantly rural, agricultural nation into an urbanized, industrial one. Following the thee sector theory (see box 2) the society finds itself currently predominantly in phase 2. However, gradually the country is moving towards phase 3, in which re-industrialization occurs and activities are shifted to provision of services. Usually, a transition to a next phase goes hand in hand with growth in Gross Domestic Product (GDP).

> *Box 2*: Three sector theory
> *Phase 1*: economy constitutes basic forms of activities in extraction of raw materials
> *Phase 2:* economy industrializes and involves mostly manufacturing activities
> *Phase 3*: the economy reaches saturation, and activities become more service oriented (Fisher et al., 1939)

The demand for steel is closely related to growth in GDP and economic growth of a country or region. The more economic growth, the wealthier people get, the more money they have for consumption of products such as cars. A trend is visible of people continuously want to have more and the newest products or bigger products (e.g. cars, houses). In addition, urbanization is an important source for changes in steel use in the society, because more construction material is necessary when people who live in the city instead of in rural areas. Underpinning this transformation are the economies of scale that make concentrated urban centers more productive. Over the last 200 years the ration of Americans living in urban areas changed from one out of twenty to four out of five in the 2000s. Furthermore, every year around 75 million people are added to the - already over seven billion - people living on this planet (PRB, 2014), who will also need cars and houses.

However, economic prosperity generally comes with a cost for the environment as production processes lead to stresses on the environment, especially in the case of steel. Hence, on the one hand a shift is visible where the economy gradually moves away from industrialization, and on the other, trends such as growth in population and urbanization demand more steel production from the steel industry. A challenge for the U.S. lies in finding a balance between economic growth and conservation of the environment. Today this balance has not been found yet. Economical health and having a job sit higher on the priority list than the environment. It is expected that in the coming decades the societal trends of growth in GDP, population and urbanization will continue to push through, but until what level is highly uncertain.

4.1.1.2 ANALYSIS OF THE STAKEHOLDERS IN THE SYSTEM

To obtain a better understanding of the actors and the interdependencies between actors in the system a stakeholder analysis is conducted. The analysis is conducted from the perspective of the steel producers, who have relatively high power and high interest in the industry. The full analysis is presented in appendix B1. The stakeholders are evaluated based on their power on the one hand and interest in the steel industry on the other. Accordingly the stakeholders are plotted on the axes (see figure 15).

The actors in the first quadrant (upper left) should be kept satisfied as they have high power but less interest. The second quadrant (upper right) should be managed closely as these actors have a lot of power and have high interest. This includes for example U.S. policymakers and iron ore suppliers. The third quadrant (lower left) should be monitored, as they have less power and interest than the actors in the other quadrants. For example, the end consumer and iron and steel producers outside the U.S. The fourth quadrant (lower right) should be kept informed, as they do not have much power, but are interested in the steel industry. The actors in the system are addressed throughout the following sections.

Figure 15: Stakeholder grid for the U.S. steel industry

4.1.2 TECHNOLOGICAL ANALYSIS OF THE U.S. STEEL INDUSTRY

In the following sections the technological process of iron and steel making is explained. Firstly, an overview of the current state-of-the-art technologies is provided, where after certain parts of the process are highlighted more comprehensively. In addition the energy fuel consumption and energy demand of each of the technologies is analysed. Finally, the technologies under research and development (R&D) are identified.

4.1.2.1 CURRENT STATE-OF-THE-ART

4.1.2.1.1 Integrated iron & steel and electric arc furnace process the two routes to steel

Steel production can be distinguished into primary steelmaking, which is new steel production primarily from iron ores, and secondary steelmaking in which steel is produced solely from recycled steel. The most common two ways to produce steel are the integrated iron and steel process and the electric arc furnace (EAF) route (see figure 12). In the integrated route iron from the iron ore is extracted in the blast furnace (BF). The molten product is mixed with recycled steel, and refined with oxygen in the Basic Oxygen Furnace (BOF). In the EAF route, recycled steel and iron from Direct Reduced Iron (DRI) are the main input materials. The open hearth furnace route is more capital intensive and less productive, and is not used in the U.S. The secondary production process has some restrictions regarding the quality of the steel it can produce. Therefore producing facilities are often combined with a DRI process to improve quality. Since the integrated and EAF route are mostly used in the U.S. this research considers only those two routes.

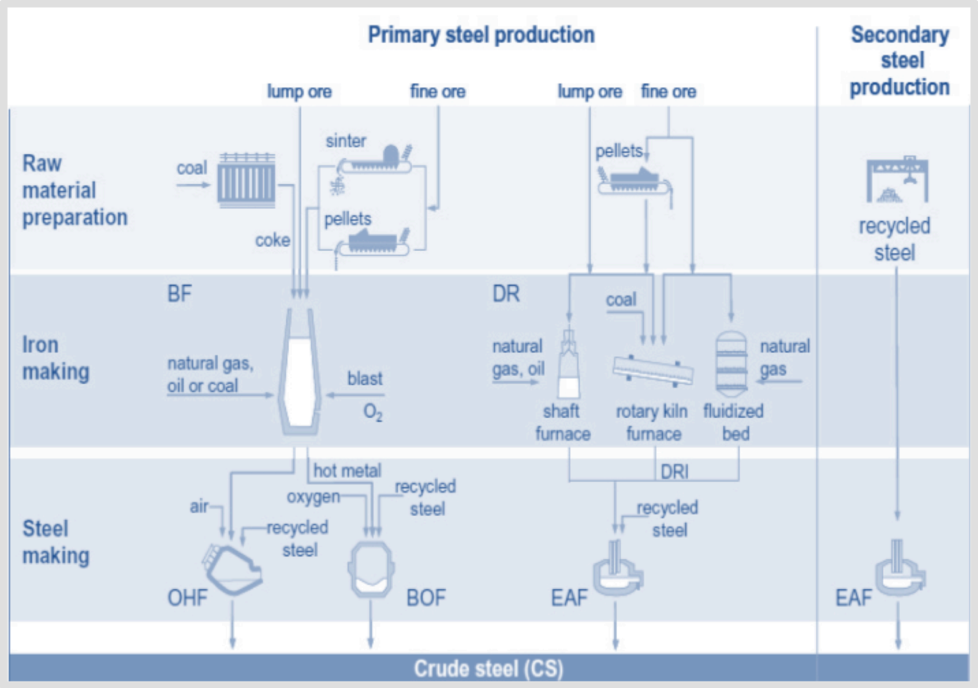


Figure16: Primary and secondary steel production (Pardo, et al. 2012)

The integrated route is the most widely used process, accounting for about 70% of the world crude steel production in 2010 (Carpenter, 2012). In the U.S. however is EAF steelmaking the dominant route, responsible for just over 60% of production in the U.S., with the balance coming from the integrated process (see figure 17) (AISI, 2010). In the last years the ratio EAF/BOF routes has slightly increased. For example, U.S. Steel Corporation have changed some of their BFs to EAF and are currently researching the possibilities to continue these changes for other BFs (Hughes, 2014). Also, companies such as Nucor, Severstal North America are investing billions in the DRI technology to combine with the EAF (Zeus Intelligence, 2014).

In the coming decades it is expected that this ratio is continuing to increase, for reasons such as the smaller CO_2 emission rates of the EAF route and the lower operation expenditures (OPEX) and capital expenditures (CAPEX) of the EAF. Also, the EAF can be started and stopped at will without exposing the mill to excessive costs associated with the shutdown or start-up process (Miller, 2015). The question for the coming decades is in what pace this transition towards more EAFs continues, what the limit is to this transition and when the increase of the EAF route is saturated.

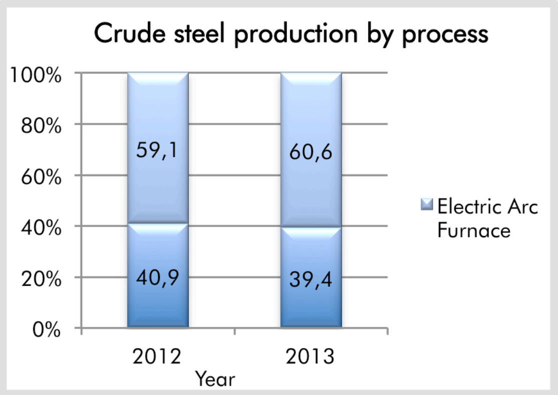


Figure 17: Crude steel production by process (AISI, 2010)

4.1.2.1.2 Producing iron with a BF or a DRI process

Now that the two main routes to steel are broadly explained, a more in depth analyses of the various steps is made. When iron is extracted from iron ore it is never pure and contains other elements. It reacts with oxygen and therefore an extraction process with high temperatures is necessary to obtain iron in its metallic form. Two common practices for extracting iron (or also called 'hot metal') are using a BF that produces liquid iron (in the integrated route), or the DRI that produces solid iron (in the EAF route).

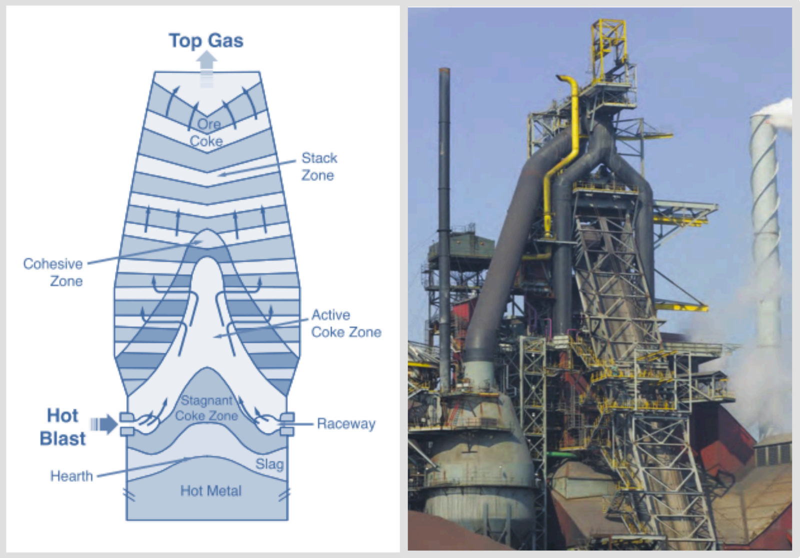


Figure 18: Blast furnace (AISI, 2010)

In a BF, which is a enormous shaft furnace top fed with iron ore, coke, and limestone, the coke combusts after hot air is blown in through an opening in the bottom of the furnace, producing heat and CO gas (see figure 18). The heat melts the charge and the CO removes the oxygen from the iron ore producing hot metal, which then flows to the bottom of the furnace. Periodically, the hot metal is tapped from the furnace into transfer cars and transported to BOF, where it is refined into steel. It is characterized as semi-continuous; it is a batch process that is processing for twenty minutes, and then has a ten minute stop, but because a number of batch processes is constantly running with different starting times the process becomes close to continuous (Jäger, 2015). The blast furnace is the most energy-intensive step in the integrated steelmaking process, generating 43% of the total CO_2 emissions (EPA, 2012). For these reasons, effort is put into improving the energy efficiency of the blast furnace and developing alternative iron making processes. Furthermore, coke making is an energy and capital-intensive process. Therefore, significant research has been devoted to using coal directly in the BF and thus minimizing or eliminating the use of coke all together. Large improvements in the BF are difficult to accomplish due to its high level of reached sophistication and because the process is highly complex (AISI, 2010).

DRI production processes convert natural gas and iron ore pellets into high quality DRI, a feed used alongside steel scrap to produce various steel products in electric arc furnaces. In iron production through DRI, either natural gas or coal feedstock can be used, but in the U.S. large part utilizes natural gas due to the cheap gas prices (Zeus Intelligence, 2014). In the process hydrogen and CO – produced by 'cracking' natural gas – is used to reduce the iron ore. DRI can utilize natural gas contaminated with inert gases, avoiding the cost of inert removal, however such gases can decrease thermal efficiency of the conversion process. It is a solid-state process in which the impurities are removed from the liquid iron in the blast furnace to form a slag remain in the DRI product. The DRI is further refined in the EAF (Walker, 2012). The resulting DRI is an iron product with about the same content as pig iron, the conventional steel-making feedstock.

4.1.2.1.3 Steelmaking with a BOF or EAF

In steelmaking with a BOF, the molten steel that comes from the BF is poured into a BOF vessel where it is mixed with scrap steel at an approximately 75%/25% ratio (EPA, 2012). With pure oxygen being blown into the mixture a high temperature is reached and molten steel is produced. In steelmaking with an EAF recycled scrap metal and a small amount of iron are melted and refined using electrical energy. In the EAF charged material is heated by means of an electric arc. Both the BOF and EAF are (partly) recycling processes. Steel products contain on average 65% recycled steel, with the overall recycling rate being 88 per cent (Schmitt, 2014). The energy intensity of scrap melting is much lower than producing primary steel from iron ores, therefore much attention in research is focused on improving the ability to recycle scrap.

4.1.2.1.4 Wide variety and quality of steel products

The integrated route and EAF route generally produce different type of products with different qualities. Both routes produce molten steel in excess of 1650 °C (>3000 °F) (AISI, 2010). Through continuous casting machines the molten steel is solidified and then goes through a series of hot and cold rolling processes to produce various shapes. These shapes, coated or uncoated, are sold to manufacturers who produce a myriad of steel products, for example automobile bodies. The products that result from the steel production processes can vary significantly, e.g. tubes, plates, or thin layers for cans, depending on the requirements of the customers. The integrated and EAF route usually produce slightly different products, due to the small differences in chemical compositions. The integrated route is mostly used for more large-scale production, whereas the EAF route can also be used for smaller scale production.

It is expected that in the coming decades the steel profile and customer requirements for steel products and quality will change drastically in some applications. For example, there will be a need for light-weight applications due to environmental requirements and a need for high-strength steels for safety and power applications. The demand for corrosion resistant alloy tubes will also increase (McKinsey & Company, 2013a). These changing customer requirements offer steel makers opportunities to de-commoditize and sell more value-added offerings. As demand patterns change, competition between metals will increase, making product innovation a more important source of differentiation for steel companies (McKinsey & Company, 2013b). An important question to be answered in the coming decades is whether all routes for steelmaking can produce these products or whether there are limits to this, with for instance, the EAF.

4.1.2.2 ENERGY FUEL MIX & ENERGY DEMAND

Now that a basic understanding of the steelmaking processes is obtained, a closer look is taken towards the energy use of the processes. Firstly, the energy fuel use of the current technologies is analysed, first for the integrated route and subsequently the EAF route. It is examined what and how much energy is necessary to produce one tonne of steel. Secondly, the relationship between the energy fuel consumption and the energy demand is explained.

There are two types of fuel use in steel production; fuel consumed for energy (energy carrier), and fuel consumed for feedstock. Fuel consumed as energy includes all energy used for power, heat, and electricity generation, regardless of where the energy was produced. Grid electricity is included in the energy consumed as a fuel, but grid electricity does not include electricity from onsite generation or combustible fuel sources. The second, fuel used as a feedstock, is the energy used as a raw material for purposes other than for heat, power, and electricity generation. For instance, in the steel industry coal is used as a raw material to produce coal coke (EIA, 2014b). Also, in some processes energy fuels are used as reducing agents, whereby an element or compound loses an electron to another chemical species in a redox chemical reaction, for example coal in the BF process. This research takes both types of energy use into account. All feedstock that is not energy related, such as iron, is called non-energy feedstock.

4.1.2.2.1 Energy fuel mix of the integrated route: mostly coal

In this section the energy use of the integrated route is analysed. Usually around 50% of an integrated facility's energy input comes from coal, 35% from electricity, 5% from natural gas and 5% from other gasses (WSA, 2013). Coal is mostly used as a feedstock. It is baked in a heated oven to produce coke and breeze. This process allows for the impurities of the coal to be burned off while not allowing the carbon content of the coal to burn. Coke and breeze are used for two purposes: to fuel the blast furnace, and to deoxygenate the iron ore and turn it into wrought iron. It is the addition of limestone (non fuel feedstock) to the blast furnace along with the heat from the coke and breeze that turns the wrought iron into pig iron (EIA, 2014b). In a sinter plant electricity, gas and iron ores (non fuel feedstock) are consumed for iron making. In an oxygen plant the oxygen is produced for the BF, and is electricity consumed.

Moreover, the term 'integrated steel plant' is used because of the way that the separate processes are integrated together. Besides the coke ovens, a mix of technologies delivers heat, including burners, boilers and turbines. Over 99% of the by-product gases from one process are captured and reused in the process (AISI, 2010). For instance, the CO produced can be "post combusted" to CO_2 in order to produce addition energy that can be used in the BOF to melt more scrap. By-product gases typically contribute 60% to total energy and are used either as a direct fuel substitute or for the internal generation of electricity, complementing the electricity purchased from the grid. Alternatively, gases can also be sold for power generation. They are flared only if no other option is available (Parsons Brinckerhoff & DNV GL, 2015). In the integrated route, except for the BF, most processes are heated by burners. These burners are generally fired by natural gas or process gas, but occasionally could also be fired by oil. Traditional burners are air-fuel fired. This increased use of oxygen increases the fuel efficiency, but also increase NO_x formation. Furthermore, the natural gas is used for energy in furnaces and power generators. It is used as energy and reducing agent in the BF.

In figure 19 an overview of the in- and outflowing energy necessary to produce one ton of steel of a typical integrated plant is presented. The energy intensity of the primary steel production route varies between 14 and 23 GJ per tonne of crude steel (Pardo et al., 2012). This variation is influenced by the iron ore and coal quality, the steel grade and the material efficiency. The practical minimum energy use (i.e. the sum of chemical energy, hot metal carbon content and energy in the hot metal) has been reported as being 10.4 GJ/tonne crude steel produced. The world best practice energy intensity was determined to be 14.8 GJ/tonne crude steel produced (Parsons Brinckerhoff & DNV GL, 2015).

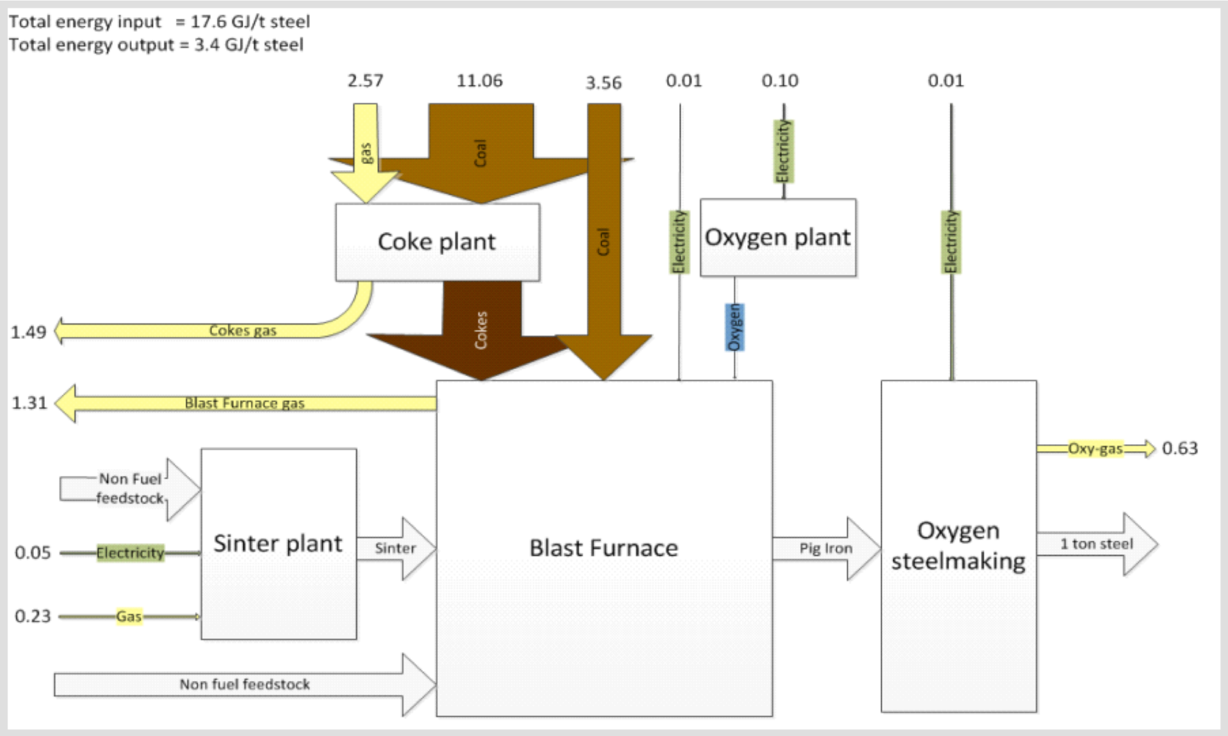


Figure 19: Energy consumption in the integrated route in GJ/tonne of steel (Shell, 2014)

4.1.2.2.2 Energy fuel mix of the EAF route: mostly natural gas and electricity

Next the energy use of the EAF route is analysed. The primary energy source in the EAF melting process is electricity. Electric arcs create very high temperatures that melt the scrap. Oxy-fuel burners can be used supplement the heat input into EAFs. The EAF also emits large quantities of CO gas at high temperatures. These can be post combusted order to produce addition energy that can be used in the EAF to increase productivity and reducing the electrical energy required by 50 to 100 kWh per tonne of steel (EPA, 2012). Boilers at EAF plants, where there are no by-product gases, are generally used to provide process steam. They are usually fired on natural gas or oil, although oil is used rarely now. Burners used as direct process heaters are traditionally air or fuel-fired (Parsons Brinckerhoff & DNV GL, 2015).

From the two other processes in this route the DRI production process is mostly energy intensive. For the process before the EAF process step coal or natural gas can be used, but in the U.S. this is mostly gas due to the shale gas availability. The DR plant also consumes some electricity. The (non fuel) feedstock is newly produced iron, because a certain share of new iron is required to maintain the steel quality. Finally, in the pellet plant the process of compressing or moulding iron ore into the shape of a pellet takes places, which consumes electricity and natural gas, and iron ores as (non fuel) feedstock.

In figure 20 an overview of the in- and outflowing energy necessary to produce on ton of steel of a typical EAF plant is presented. The energy intensity of this route ranges from 9.1 to 12.5 GJ per tonne of steel (Pardo et al., 2012). Currently, the world best practice energy intensity for a EAF it was determined to be 2.6 GJ/tonne (Parsons Brinckerhoff & DNV GL, 2015).

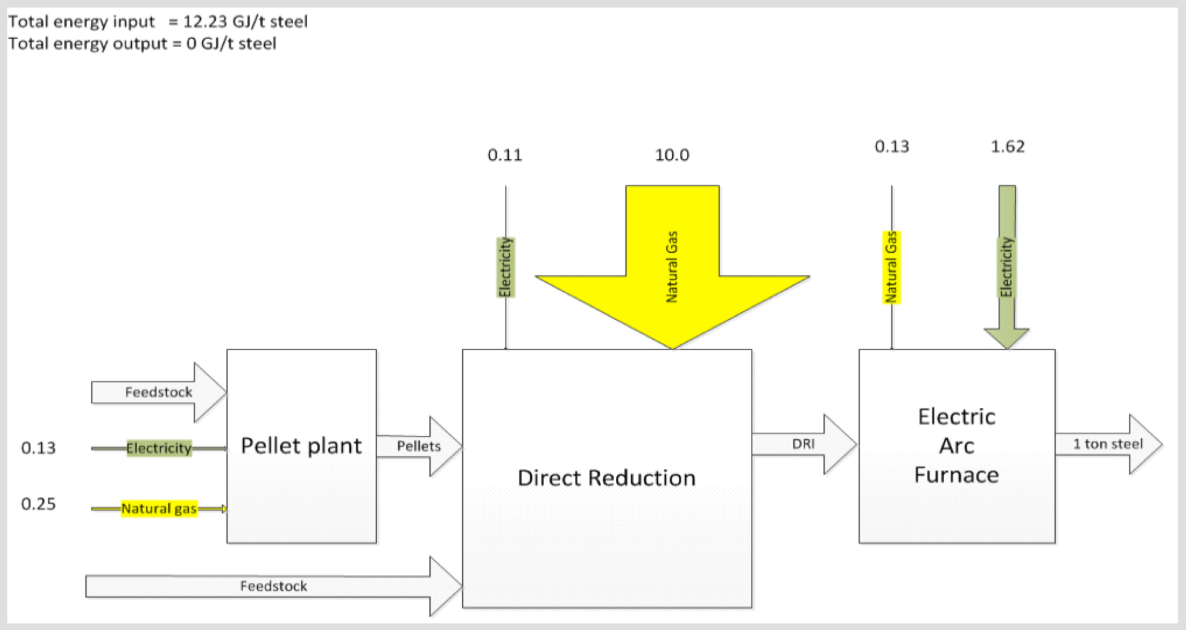


Figure 20: Energy consumption in the EAF route in GJ/tonne of steel (Shell, 2014)

4.1.2.2.3 Total industry energy demand decreased but more reduction is demanded

In the previous section the fuel mix to produce one ton of steel was presented. The total energy fuel demand of the industry depends on two main factors, namely the technologies (e.g. efficiency and fuel type) in use described in the variable energy input/tonnes of steel and the amount of steel that needs to be produced (see box 3). The amount of steel to be produced is closely related to the steel demand. To get an idea of the distribution of the total U.S. steel industry's energy fuel consumption, figure 21 gives an overview of the share of each type of fuel of the total energy fuel consumed. It shows that nearly all of the industry's fuel consumption came from coke and breeze, natural gas, 'other' and electricity together. The 'other' fuel constitutes for around 99 per cent of two major by-product fuels, namely coke oven and blast furnace gases. In the last years the steel industry in the U.S. used over 1.1 quadrillion Btu (quads) of energy as fuel (EIA, 2014b).

Box 3: Total energy fuel consumption

In order to calculate the total energy fuel that is used by the steel industry the following formula can be used:

Total energy fuel consumption = amount of steel produced * energy fuel input/tonnes of steel

The U.S. steel industry has reduced its energy intensity per ton of steel shipped by over 30% since 1990. Today's technologies are relatively efficient and its operations are asymptotically approaching a practical minimum, namely 10,4 9,1 GJ/tonnes of crude steel for the integrated route and 9,1 GJ/tonnes of crude steel for the EAF route technologies. Energy efficiency can be improved through operational benchmarking activities and continuous adoption of improved practices and equipment as they are developed. However, only marginal improvements can be expected following this path. To achieve major improvements (e.g. 30–50% energy reductions) radical, transformational technologies that replace or eliminate today's processes are required (AISI, 2010).

The expectations for the future amount of energy fuel consumption depend on both the technologies and the steel demand. The future technological developments are further discussed in the following section called 'Research & development', and the future of the steel demand is analysed in section 4.1.3.1.

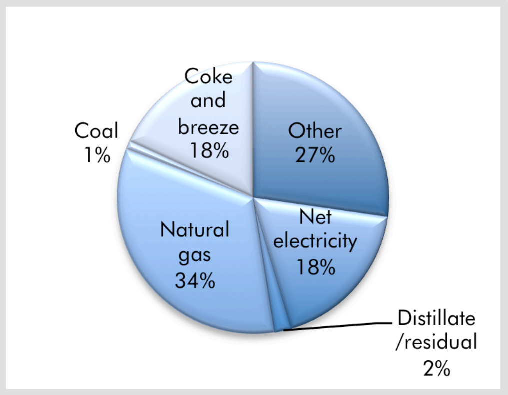


Figure 21: Industry energy fuel consumption (EIA, 2014b)

4.1.2.3 RESEARCH & DEVELOPMENT

To get an understanding of the energy fuel use in the future, not only the current state-of-the-art technologies should be analysed, but also the possible changes in technology in the coming decades should be examined. A distinction can be made between incremental (e.g. small efficiency improvements) and radical innovations (e.g. change in technology). In this research only the radical innovative technologies are considered, because incremental improvements will not significantly change the energy fuel mix and use. Significant further decarbonisation needs breakthrough technologies (Parsons Brinckerhoff & DNV GL, 2015). Breakthrough technologies can only be put on-stream via adequate funding in Research & Development (R&D), pilot, demonstration and deployment.

4.1.2.3.1 U.S. and Europe key pioneers in technological development

In order to identify the newest radical technologies the first step was to examine in what type of institutions the R&D occurs (e.g. on a company level, in universities or in separate institutes). The most important R&D for the steel industry is conducted in the following countries and institutes: the European Union (EU) (ultra low CO_2 steelmaking, or ULCOS), the U.S. (the American Iron and Steel Institute (AISI), Technology Roadmap Program & CO_2 Breakthrough Program), Canada (the Canadian Steel Producers Association), South America (ArcelorMittal Brazil), Japan (COURSE50), Korea (POSCO), China (Baosteel) and Taipei (China Steel) and, Australia (Bluescope/One Steel and HIsmelt). For the U.S. steel industry both the R&D by the AISI as well as the R&D conducted by ULCOS in the EU are considered to be the most crucial for the U.S. steel industry (Jäger, 2015). The AISI in the U.S. is important because it focuses on technologies especially useful for the industry in the U.S. The ULCOS program is one of the front runners in the area of clean steel technology development and new technologies developed will likely diffuse to the U.S. relatively quickly. Therefore, this research focuses on the technologies under R&D in the ULCOS and the programs by the AISI.

The AISI programs are a public private partnership between AISI and the U.S. Department of Energy (DOE), Office of Industrial Technology. The program is designed to increase energy efficiency, increase the competitiveness of the North American steel industry, and improve the environment. ULCOS is a consortium of 48 European companies and organizations from fifteen European countries that have launched a cooperative R&D initiative to enable drastic reduction in CO_2 emissions from steel production. The aim of the ULCOS program is to reduce the CO_2 emissions by at least 50 per cent. R&D is considered to be a relatively non-competitive area; the sector must cooperate to tackle decarbonisation together, but this will depend on availability of funding. Both of the institutions are sponsored by governmental organizations, but most of the funding comes from the steel companies themselves.

4.1.2.3.2 Currently seven radical technologies under R&D

In the ULCOS program and through AISI seven relevant radical technologies that under R&D where identified:

- Paired Straight Hearth furnace (by AISI)
- Suspension Reduction of Iron Ore Concentrates (Hydrogen Flash Smelting) (by AISI)
- HIsarna (by ULCOS)
- Molten Oxide Electrolysis (by AISI)
- Electrolysis (ULCOWIN) (by ULCOS)
- Top gas recycling blast furnace (by ULCOS)
- Carbon capture storage (by ULCOS)

In the second part of this chapter the technologies are further elaborated on.

In general, it is expected that in the coming decades a share of the current capital stock will be replaced by new technologies. The question is when the new capital will be installed and what technologies are used. What the exact cost will be of each of the technologies when they become commercially available is unknown at this point in time. For this research is assumed that the radical technologies all require a high investment, but that the choice for a technology is not based on the price difference between the technologies. The choice to invest is based on whether there is money available to invest, and on what the optimum technology is considering the operating costs.

4.1.3 ECONOMIC ANALYSIS U.S. STEEL INDUSTRY

In this sub-section the economic forces that influence the energy fuel use in the U.S. steel industry are analysed. The glory days of the steel boom before the financial and economic crisis in 2008-2009 are over. The question is now what new market developments and trends can be expected. A market analysis is conducted touching upon each of the outlined dimensions by Aaker (1996).

4.1.3.1 MARKET SIZE & MARKET GROWTH RATES

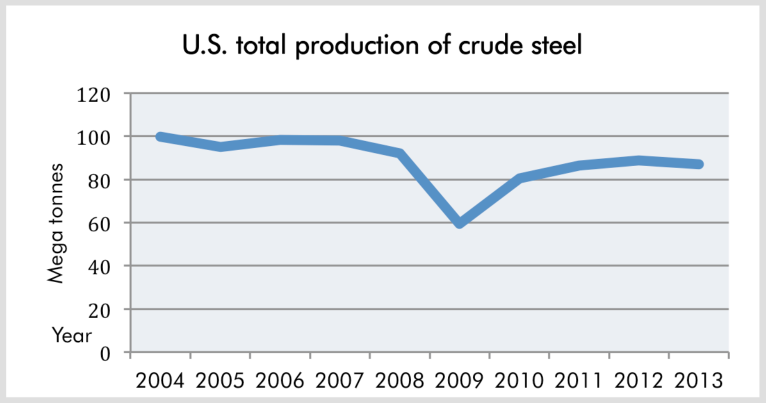


Figure 22: U.S. total production of crude steel (EIA, 2014b)

The U.S. steel industry mostly operates in its national market, but also takes part in international trade. Over the past decade, demand in the U.S. has been uncertain. Finished steel demand has been volatile and varied between 68 (2009) and 142 (2006) mega tonnes (McKinsey & Company, 2013b). In the years 2008-2009 a decrease in production is visible (see figure 22), which was a result of the financial crisis. In 2013 the production level has increased again, but has not yet reached the level it had before the crisis. In figure 23 is shown in what market the steel produced in the U.S. is consumed. It shows that the construction and the automotive sector are the two largest steel customers. The price of steel in the U.S. was around $650-700 per metric ton in the last couple of years (McKinsey & Company, 2013b). Steel is generally cheaper in China and Russia. If too much steel is imported the price of the imported steel will have a negative effect on the U.S. steel price level. The price of exported steel is mainly determined by other countries (Shell, 2015a).

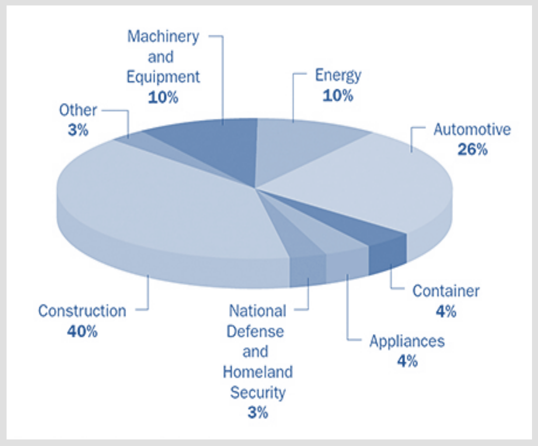


Figure 23: Steel shipment by market classification (Schmitt, 2014)

The U.S. has a negative trade balance; it imports more than it exports. The export of U.S. (semi-) finished steel products steel products has slowly increased in the last ten years (see figure 24). In the years of the crisis can be seen that the import of steel was significantly affected, while the export of steel remained almost unaffected. The U.S. exports mostly to North (excluding the U.S.) and South America. In addition, smaller numbers are exported to the EU, Africa, the Middle East, and Asia (WSA, 2014). The EU and Asia are the biggest players in the steel industry. International trade flows are affected by the regional imbalances due to exchange rate differences and cost advantages (e.g., Brazil), country development combined with local consumption trends (e.g., Russia), and surplus capacity and change of addressable markets (e.g., Europe to U.S.).

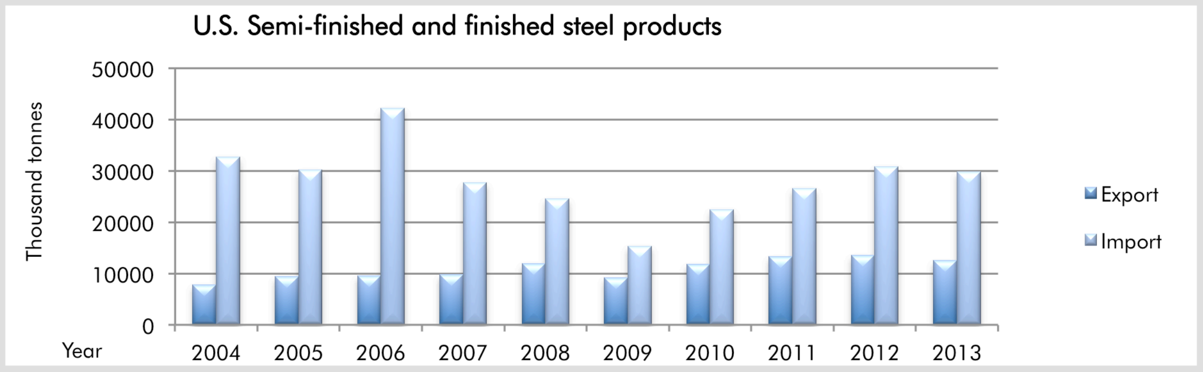


Figure 24: U.S. Semi-finshed and finished steel products (WSA, 2014)

The market growth rate in the U.S. has been relatively low over the last years. The steel demand is closely linked with the economic growth, and as was explained in the societal analyses the U.S. is moving closer towards the saturation phase of economical growth, in which slower economic growth is feasible visible. The U.S. per capita consumption of steel is 300-400 kg/person, which is less steel-intensive than other developed economies. On average, the U.S. has a roughly 10% lower demand per capita than does Western Europe (McKinsey & Company, 2013b).

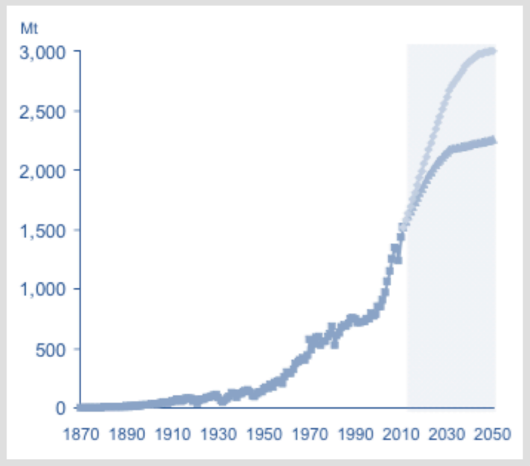


Figure 25: Long term perspective of steel demand in U.S. (WSA, 2013)

It is expected that in the coming decades the U.S. steel demand will slowly increase, since the U.S. is currently less steel-intensive than other developed economies and continued population growth takes place (McKinsey & Company, 2013b). Remaining uncertainties are when the level of full demand saturation will be reached, and what at this point the per capita consumption is. The World Steel Association (2013) estimated the future steel demand, showed in figure 25. The x-axis shows the years and the y-axis shows the total steel demand in mega tonnes. The figure shows the deep uncertainty for the level of growth in the years up to 2050. For the demand the development of the construction and automotive sectors in the future is important. Furthermore, the energy sector develops a higher demand for steel in the future if a trend with more gas use and renewable energy use pushes through, whereby products such as steel pipes and panels increase in demand.

Moreover, the worldwide steel demand is also expected to continue to grow, and emerging regions will continue to define the global growth path for the industry. It is worth highlighting Mexico's role as potentially the largest source of demand growth for steel in the U.S. in this decade. China, being one of the biggest growing economies today, will also experience growth in demand. However China also increases its steel production. The size of Chinese demand fluctuations alone could be as large as the total demand in Europe.

4.1.3.2 INDUSTRY COST STRUCTURE

4.1.3.2.1 CAPEX: relatively high

The steel industry is highly capital intensive, and installations have a relative long lifetime. For example, a BF has a lifetime of 50 to 60 years and to reline a BF to a EAF costs around $100 million or more (EY, 2013). In 2013, 95% of the capacity in the U.S. was older then 25 years (McKinsey & Company, 2013a). Based on this, it can be expected that large part of the capacity requires replacement in the years 2030-2050. For most steel companies the next step up will be to increase productivity and the resource and energy efficiency of existing assets through better processes and to invest selectively in advanced production assets and technologies (McKinsey & Company, 2013b). One of the most important barriers to decarbonisation and energy efficiency is lack of funding for investments as the return of investment is not attractive enough or there is a lack of capital available (Parsons Brinckerhoff & DNV GL, 2015). However, companies in the U.S. are generally short term driven, and lacking incentive for innovation and investment in new technologies prevails. This means that the coming decades present installed capacity will most likely continue to operate. Potential new technologies have to compete against a settled and well working system (Jäger, 2015). Besides, with degreasing margins less money is available for investments.

4.1.3.2.2 OPEX: volatile

In the past few years, soaring raw material costs and price volatility have been major challenges for the steel industry. Steel prices responded more slowly than production costs, leading to reduced margins or losses (EY, 2013). Within the entire steel value chain, profitability is challenged and margins move to mining (McKinsey & Company, 2013b). Hence, keeping the operating costs low is highly important for the steel industry. The two largest parts of the cost of steel production are the energy fuel and the non-energy fuel feedstock.

Firstly, the energy fuel constitutes 20 to 40 per cent of the total OPEX, of which 97 per cent coming from electricity, natural gas, coke and breeze, and coal. Electricity is the largest expenditure and accounts for approximately 32 per cent of the total energy expenditures in this industry (EIA, 2014b). This is mostly due to the increasing share of EAFs. The recent discovery and increased production of oil and natural gas from domestic shale formations has substantially changed opportunities for the domestic steel industry. Affordable natural gas is presenting all steelmakers with new options for how to make their products more efficiently (AISI, 2015a). Steelmakers such as Nucor, Severstal North America and others are investing billions in the construction of new DRI plants across the country. Companies like Nucor have been able to lock-in long-term gas supply agreements to supply their DRI projects. This guarantees stability for such projects, and makes them easier to secure financing (Zeus Intelligence, 2014).

Secondly, besides energy, the non-energy fuel feedstock iron ores and scrap constitutes a high share of the costs. In figure 26 the iron ore price of the last couple of years is presented. It shows that the iron ore price is highly volatile. The steady decline is caused by a decrease in demand for iron ores from the Chinese, resulting in an oversupply on the market. Due to its fluctuations the iron ore price can have a large effect on the profit margins in the steel industry. There are several economic reasons to use scrap rather than iron ore in steel making. These economic reasons stems from the fact that steel scrap has already been refined and therefore requires minimum energy to be expended for further processing, which contributes enormously to a company's economy and consequently to the environment. The price of scrap is linked to the price of iron ores; scrap will always be slightly cheaper than iron ores, but if the price for iron ore goes up, the price for scrap also increases.

Figure 26: Iron ore price from 12-2009 to 7-2015 (Infomine, 2015)

It is expected that in the coming decades the most successful steelmakers will be those ''that take a more integrated approach to understanding how iron, coal, and scrap affect their margins, produce opportunities for innovation and growth, and create new challenges for how they manage risk'' (McKinsey & Company, 2013b). The shale gas boom in the US is will continue, and will have a significant impact on the coal business. Due to the low costs of shale gas coal becomes less cost competitive compared to natural gas, leading to a significant drop in coal demand and declining prices. Remaining uncertainties are to what degree the steel industry will invest in new technologies, and what the total OPEX of those new technologies will be. The implementation of new technologies will be costly, not only because of the investments involved, but also because of the possible higher operating costs (Eurofer, 2013).

4.1.3.3 MARKET PROFITABILITY AND TRENDS

To get a feeling for the market profitability the theory by Porter (1990) is used, in which five driving forces are discussed. In the following paragraphs these five forces are addressed.

- *(1) Supplier power: relatively low due to availability of substitute suppliers*

For the steel industry raw materials and scrap are the two most important inputs in the process. While structural scarcity was acute some years ago, today the raw materials scarcity looks less troublesome (McKinsey & Company, 2013b). In the short term, the iron ore industry faces oversupply risks as projects are under way, and despite some delays and cancellations, it is unlikely that the majority will be put on hold. In the medium to long term, new investments are needed in order to satisfy global iron ore demand, also as a consequence of the depletion of existing mines (McKinsey & Company, 2013b). The U.S. iron ore sales are characterized by long-term supply agreements with various price adjustment provisions (Team, 2014). The mineral reserves of the U.S. mining companies is sufficient for current rates of extraction as well as potential for future growth. China's iron ore consumption largely determines iron ore prices. U.S. iron ore companies' costs per ton of iron ore produced is much higher than that of mining majors worldwide, such as Rio Tinto, BHP Billiton and Vale, which leverage their economies of scale and high quality, low cost reserves (Mining-technology, 2014). Therefore, for U.S. steel companies it can be attractive to look at other companies worldwide to buy iron ores from.

Rising raw materials prices are likely to make scrap increasingly attractive. However, on a global level, strong growth in the scrap supply will be seen mainly after 2020. This is to a large degree driven by China (McKinsey & Company, 2013b)(McKinsey & Company, 2013b)(McKinsey & Company, 2013b). Much of the produced steel products remain in use for long duration (on an average 15–19 years) (Birat et al., 2006; Matsuno et al., 2007). China's steel demand is expected to peak at the same time as the start of end-of-life scrap supplies from the construction boom of the 2000s, generating a massive scrap supply. Only after 2020 scrap levels be high enough to decrease the need for iron ore. While there is already equilibrium or even excess supply in mature regions such as Europe, the U.S., and Japan, the change in supply in emerging regions, particularly China, will dramatically shift the global scrap balance in the future.

It can be concluded that in the coming decades there is not enough quantity of recycled steel available to meet the growing demand of steel worldwide just by secondary steel making route alone. In general can be stated that for iron ore and scrap as well as for other feedstock, such as energy or coal, many suppliers exist, so it is relatively easy to buy from a different supplier. Therefore, it can be concluded that there is relatively low supplier power. In the coming decades it is expected that this remains approximately the same.

- *(2) Buyer power: relatively high due to increasing product quality demand*

Steel producers comply their production according to consumer steel requirements. A broad trend that can be identified is a changing face of the customer regarding product quality. In addition, some seek technically advanced solutions, particularly in automotive, where body and chassis weight could fall by up to 40% over the next 20 years, requiring steel makers to provide high-strength products – or lose out to lightweight materials. The power and sophistication of steel buyers is growing. Consumers increasingly seek the lowest price anywhere in the world, resulting in structurally higher steel trade flows. Hence, the product mix can be expected to shift accordingly to more value added (McKinsey & Company, 2013b). Furthermore, current massive global steel overcapacity is estimated at nearly 600 million net tonnes, which is over six times U.S. raw steel production (AISI, 2015b). This overcapacity, combined with sluggish world demand and import barriers in other markets, has resulted in high levels of steel imports into the U.S. market. Hence, buyers find themselves in a luxurious position.

It can be concluded that the buyer currently has significant power, as the buyer set requirements in terms of the product quality. Also, there are many steel producers in the market so the buyer can easily order steel from a different producer. In the coming decades it is expected that the buyer power will increase more.

- *(3) Competitive rivalry: high due to the high number of steel producers in the market*

Steel producers compete mostly on the basis of costs. However, due to the increased quality requirements from customers also quality becomes more important. In appendix B2 an overview of the steel plants of North America is presented. It shows that over 40 steel producers are distributed throughout the U.S. Many producers have multiple plants, throughout the U.S. and internationally. A very small share of the producers has integrated facilities, but these plants produce significantly higher amounts of steel compared to the EAF plants. In addition, there are a number of independent steel producers who have one plant, these

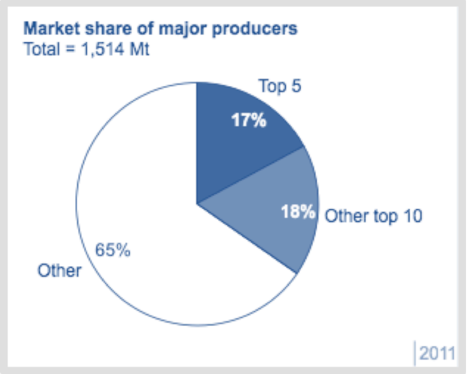


Figure 27: Market share of major producers in the U.S. (2011 data) (Shell, 2014)

are mostly EAF producers. Figure 27, which shows the market share of the major producers, reveals that the top five largest producers are responsible for 17% of the steel production. In general, plants always run on maximum capacity, with the result that prices go down due to an oversupply on the market. Currently this is already the case (Jäger, 2015). It can be concluded that the competitive rivalry is relatively high, due to the diffused market share. Furthermore, because the U.S. steel market is closely linked to the international market international competitor dynamics also affect the industry, which makes it a challenging market to operate in. In the area of R&D, companies participate in collaborative programs in order to combine knowledge for innovation, and there is less competitive rivalry visible.

- *(4) Threat of substitution: significant by materials such as aluminium and carbon fibre*

The largest threat of substitution for steel is aluminium, especially in the automotive industry. Automakers' demand for aluminium, which is lighter than steel, is growing rapidly as manufacturers push to improve fuel efficiency (Hughes, 2014). Aluminium has already taken a strong position in the premium class segment, in chassis and powertrains as well as in body structures. Although the aluminium price has been two to three times as expensive as steel in the last decade, the gap between the two is shrinking (McKinsey & Company, 2013a). Furthermore, carbon fibre is identified as a new material to replace some of the steel used for the support structures of electric vehicles (McKinsey & Company, 2013a). It can be concluded that there is significant threat of substitution by other materials.

- *(5) Threat of new entry: high from steel producers in emerging economies*

If the demand for steel continues to rise in the U.S. or worldwide it can be attractive to step into the market. The U.S. and Europe might reach a level of saturation in the coming decades, but for emerging economies, such as China and India, the demand for steel will continue to rise for at least some decades. Furthermore, there is the possibility for international steel companies to start up a facility in the U.S. due to the low natural gas costs because of the shale gas production. The growing economy and increasing steel producing capacity in China is however a threat to the U.S. steel market, as greenfield plants can often produce steel for a lower cost price (McKinsey & Company, 2013a). Even though some attractive features in terms of demand are present, the market has some entry barriers as well. Firstly, the market is highly competitive and most companies have been in the market for years, and developed a lot of know-how. Secondly, due to the highly capital intensive market, entry requires a big investment. Only for the EAF route the investment is lower as steel production on a smaller scale is possible. It can be concluded that the threat of new entry is considerable medium and high, nationally and on an international scale respectively.

- *Conclusion of Porter’s five forces analysis*

From the Porter analysis can be concluded that currently the market is struggling with profitability. In the highly competitive market a low price is key, but with the current market changes and the feedstock and energy fuel price dynamics, the industry needs to adapt in order to remain in the market. In general can be noted that the strength of the U.S. currency compared to other currencies will have significant influence in all the five forces, especially due to the international character of the steel market. It is expected that in the coming decades the market will remain to be highly competitive, with strong international influences. The market profitability will slightly change, but how exactly depends on many aspects.

4.1.3.4 KEY SUCCESS FACTORS

As a result of the economic recession, maturity of the market, and increasing global competition, the current actors in the system are focused on business continuity, value-added projects, investing in growing markets (e.g. India), and increasing production efficiency. In today’s market success of the industry depends on its ability to access growing international markets, to reduce emissions, take advantage of economies of scale and to obtain a reliable source of key feedstock and to compete on price. In addition, R&D and innovation should be a non-competitive area enabling good cooperation and cross-company learning.

4.1.4 POLICY ANALYSIS U.S. STEEL INDUSTRY

In this sub-section the U.S. steel industry is analysed in terms of policy measurements that affect the market. It can be remarked that the U.S. is a market driven country rather than a policy driven country. One generally believes that market forces result in significant competition and that limited policy forces are necessary. Since for most governmental positions elections take place every four years politicians have a short-term focus. Below firstly the general market policy measures that have influence are analysed, and secondly the environmental policy measures are discussed.

4.1.4.1 COMPETITION AND INTERNATIONAL TRADE POLICY

The U.S. government has an incentive to support the steel industry, as it ensures economic prosperity for the nation in terms of for example jobs. Nationally, the government's objective is to stimulate competition between the steel producers in order to drive down the market prices for consumers. However, the steel producers find themselves in a difficult climate and there is a current oversupply in the market. Some of these challenges cannot be resolved at the company level. In certain parts of the industry the entire industry landscape needs to change because demand is smaller than the industry capacity. These cases call for policymakers and industry to work out reframing actions and paths to migrate the steel industry to a new structure that restores competitiveness.

Internationally, several measures account, mostly governed by the World Trade Organization (WTO), which strives for equal global trade. In some countries state intervention is more common than in the U.S., which leads to – by the U.S. experienced - tensions with regard to international trade. Trade distorting foreign government policies, such as import barriers, subsidies, investment restrictions, and state-supported enterprises, act as barriers to exports and investment. To give an example, in China's non-market economy the state supports the production of steel and steel-containing products, which may lead to unequal forces on the international trade market. Other major steel producers including Brazil and India also continue to use subsidies, tax and trade policies, and investment restrictions to protect their markets and expand their steel production and exports. Currently no effective trade policy to combat these trade practices has been developed for the U.S. steel companies. In the coming decades it remains of paramount importance to keep track of the world politics and foreign policies in order to understand what affect this has on the U.S. steel market (AISI, 2015b).

4.1.4.2 ENVIRONMENTAL POLICY

Significant attention focuses on how to rapidly de-carbonise the energy system. From two biggest carbon emission abatement principles, carbon taxation and a cap and trade system, the U.S. has been mostly supportive to carbon taxation. However, there is no nationwide carbon tax levelled in the U.S.; only a few states have introduced a tax. The government has not been able to secure support for legislation to set either a price or a limit on greenhouse gas emissions. A number of states have introduced CO_2 abatement schemes. For example, since 2013 California has an emissions trading scheme. However, the functioning of those systems is questionable as the costs only constitute only a couple per cent of the total costs (Ho et al., 2008).

Moreover, the domestic industry has reduced its energy intensity by 28 per cent since 1990 through incremental innovations, while reducing its greenhouse gas emissions by 35 per cent over the same time period (AISI, 2015a). However if the industry wants to further decrease the level of pollution, radically changes in the technologies are required. Given the highly competitive market for steel, along with the significant investment challenge facing the sector to reduce emissions, the policy context needs to carefully balance industrial regulation and investment support. It has been emphasised that a long-term energy and climate change policy framework alongside policy support for industrial competitiveness is key to investor confidence in cleaner energy technologies (Parsons Brinckerhoff & DNV GL, 2015).

In the last couple of years, the U.S. Environmental Protection Agency, which is the main environmental regulatory body in the U.S., has undertaken an aggressive regulatory agenda, proposing a substantial number of new regulatory initiatives. Current measures that apply are the Clean Power Plan and Clean Air Act.

To conclude, it can be stated that for both general market policy and environmental policy a lot of uncertainty for future policy measures exists. There is a lack of trust in policy by the sector, which results in that the sector acts more on a short term basis, rather than making long term commitments (e.g. large investment in a certain technology). It is expected that in the coming decades a number of regulatory measures continue to be developed and put into practice in the iron and steel industry, in areas including air, water, toxic chemicals, and solid waste. Many of these new regulations will create permitting obstacles for investment in new and renovated facilities and impose significant additional costs on domestic steel producers.

4.1.5 ENVIRONMENTAL ANALYSIS U.S. STEEL INDUSTRY

Release of CO_2 emissions can occur at the beginning of the value chain where the energy is produced (e.g. oil refining), during transport (leakage), and at the end of the value chain when the energy is consumed (e.g. incineration of coal). The steel industry is mostly concerned the latter type of pollution. The steel industry is facing some tough environmental challenges as a number of technical barriers to decarbonisation prevail.

McKinsey & Company (2013a) calculated the CO_2 footprint (in tonnes of CO_2) of both the integrated route and the EAF route when producing one tonne of steel (see figure 28). It shows that the integrated route with the blast furnace technology emits more than three times as much CO_2 than the EAF route, where the BF the biggest emitter is due large share of fossil fuels that is burned. Over the last years the industry has put significant effort in decreasing its CO_2 emissions. However, a big issue is that the energy reduction efforts are already close to the theoretical limit. This means that breakthrough radical technological innovations are necessary to further abate CO_2 pollution (WSA, 2013). Parsons Brinckerhoff & DNV GL (2015) identified non-technical barriers to decarbonisation: global competition from lower-cost producers, shareholders demand quick payback, availability of capital or competition for funds, increasing electricity and gas prices, slow rate of capital stock turnover. Furthermore, steel customers primarily make decisions on costs, not on carbon emissions. Whereas on the one hand higher carbon costs provide incentives to invest in cleaner technologies, on the other increasing cost of carbon can result in an uneven playing field compared to countries where no or a lower carbon price applies.

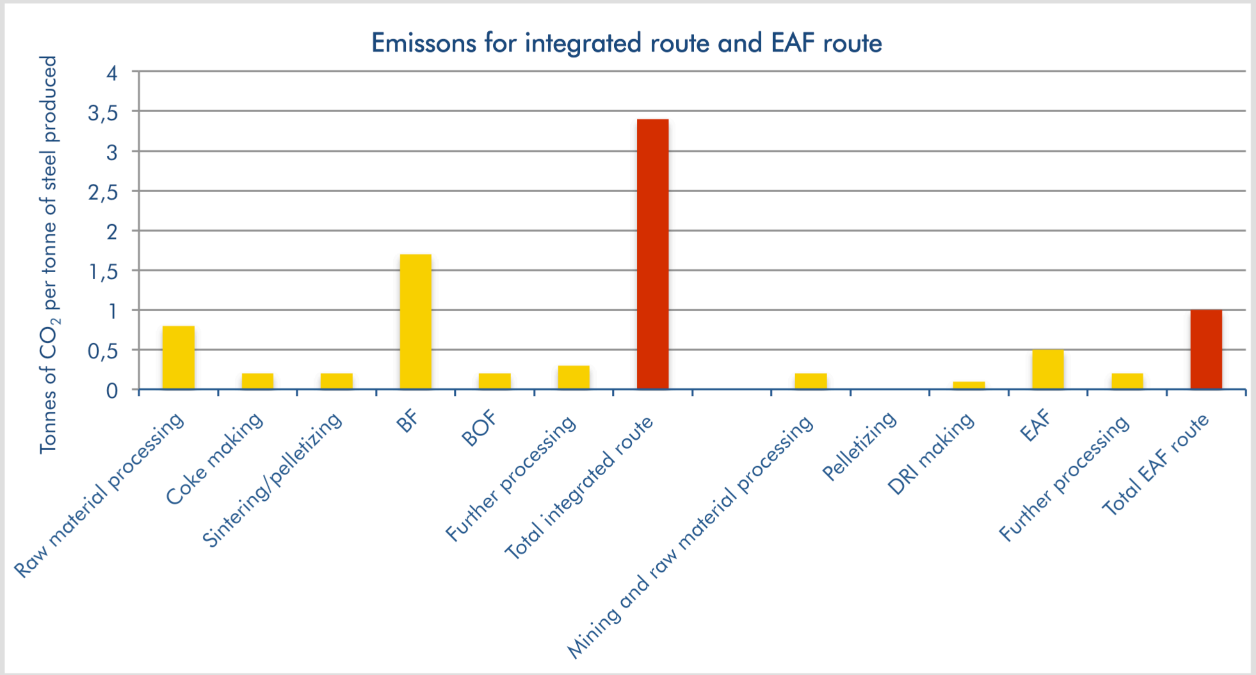


Figure 28: CO_2 emissions per route: integrated (left) and EAF (right) (based on McKinsey & Company, 2013a)

As stated before, today we live in an era of energy transition, but for the steel industry this transition has currently not taken off yet as in other sectors such as transport. What exactly the pace of energy transition will be in the steel industry is unknown. In any case, further de-carbonisation brings along some serious challenges for many stakeholders in the market. In section 4.2 the research goes more into depth about the energy system and the future possibilities for change towards the use of cleaner energy carriers.

4.2 FUTURE USE OF CLEANER ENERGY CARRIERS

In this section the energy system within the U.S. steel industry system is discussed more into depth, because the research focuses on the energy use in the steel industry. For each of the three sub-systems in the energy system – final consumption, transport through energy carriers, and primary energy production - a closer look is taken at the possibilities for and limitations to change in the future, and in specific the increased use of the energy carriers electricity and hydrogen, and the share that comes from RES.

4.2.1 THE ENERGY SYSTEM TODAY SETS THE CONTEXT FOR THE FUTURE

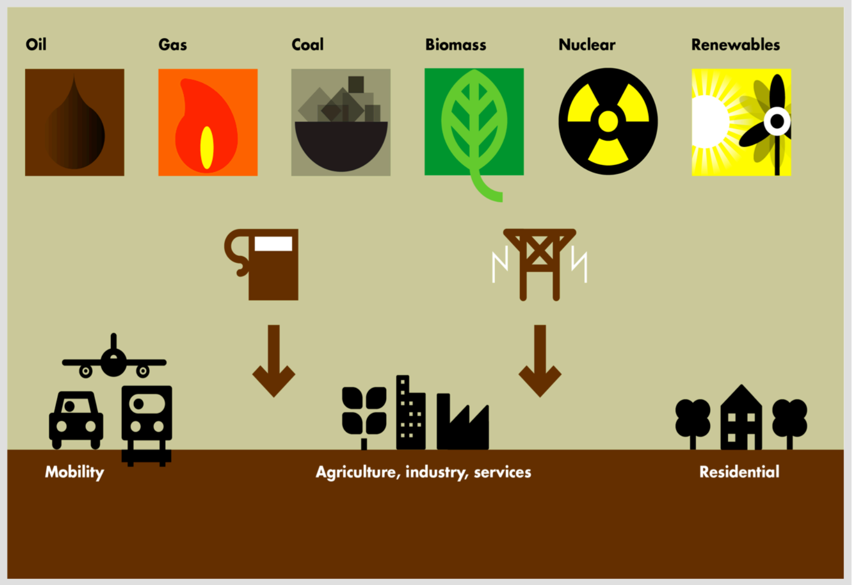


Figure 29: Overview of the energy system (Shell, 2014)

To better understand what causes a change in energy use it is important to take a system perspective and look at the energy system as a whole. The energy system in general can be distinguished in three sub-systems (see figure 29). Firstly, energy is produced through various types of energy production, including energy production through oil, gas, coal, biomass, nuclear and renewables (Haigh, 2014). All forms energy production together form the *Total Primary Energy* (TPE). The primary energy is transported through energy carriers (or called energy fuels); through electricity or fuels (e.g. gasoline or hydrogen). Finally, the energy is used in the residential, industry & services, or transport sectors. The total consumption of energy is called the *Total Final Consumption* (TFC). The TPE and TFC are not the same, due to efficiency losses during conversion and transportation. This research considers all three stages of the energy system, and thereby focuses on steel industry as the final energy consumer. The ultimate aim to analyse the change in energy fuel use, and look at the share of energy fuels that comes from electricity and hydrogen, and even more specific the share of those energy carriers that comes from renewable energy sources.

Moreover, the energy supply by primary energy sources is influenced by the total energy demand and the choice for energy fuel by the final consumers. The energy carriers that are available through the variety of energy sources in turn influence the final consumer. Thus in order for the steel industry to change its energy fuel mix both the steel industry must change its demand for energy carriers, and the energy carriers must be available in an (cost) efficient form. This research mainly focuses on the change in demand from the steel industry side, and touches upon the question around the availability of the electricity and hydrogen as energy carriers from renewable energy sources. The choice for energy fuel in the steel industry depends on the technological development of the processes, but also other factors such as economic factors (e.g. price) and policy (e.g. CO_2 pricing). In the following sub-sections each of the three sub-systems is addressed more into depth.

4.2.2 CLEAN ENERGY CARRIER USE

The following categories for energy carrying carriers can be distinguished: solid hydrocarbon fuels (SHCF), liquid hydrocarbon fuels (LHCF), gaseous hydrocarbon fuels (GHCF), electricity (commercial or distributed with solar photovoltaic), hydrogen, heat (commercial or distributed solar thermal), and biomass (commercial or traditional). Over the last years only a couple of these fuels are used in the steel industry. In figure 30 the historical final energy use per energy carrier in the U.S. steel industry is presented (based on Shell's internal EIA data). It shows that mostly SHCF (e.g. coal), GHCF (e.g. natural gas), and some electricity is consumed. Also, over the years the energy consumption has decreased due to more efficient technologies, while the total steel production in the U.S. remained relatively constant. In the 1980's the effects of back-to-back recessions and a torrent of foreign steel caused the dip in energy. Later the energy use increased again, due to the increased tonnes of steel produced.

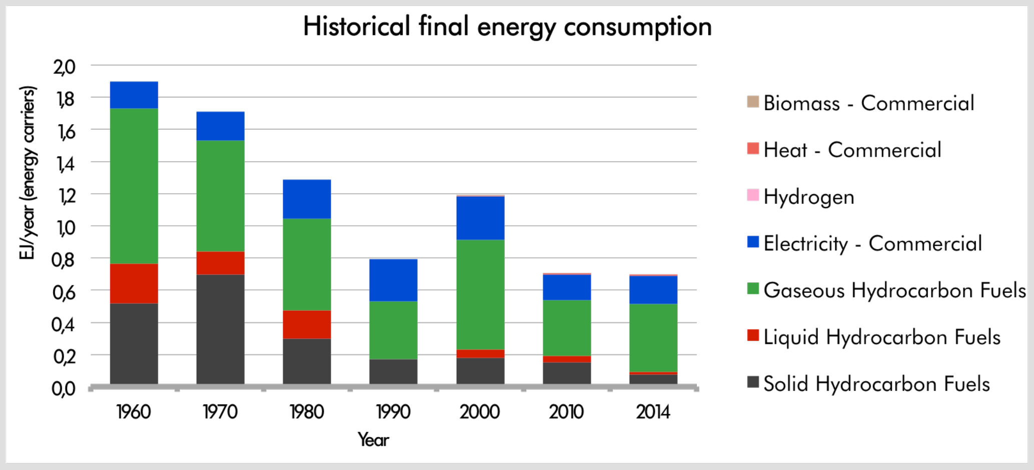


Figure 30: Historical final energy consumption of the U.S. steel industry per energy carrier

Hydrogen and electricity are interesting energy carriers as they generally release less CO_2 when consumed. As energy carriers can originate from various primary energy sources, whereby there is a difference in how much CO_2 is released during production, the choice for an energy carrier can make a difference in the CO_2 emissions in the whole value chain for which the steel industry is (in)directly responsible. Also, there is a difference in the amount of CO_2 emissions that is released during consumption of the energy. For example, if liquid or gaseous hydrocarbon fuels are burned for energy consumption a higher amount of CO_2 is formed than if it would be electricity (see box 4). Electricity and hydrogen have generally the lowest intensity factor, as those energy carriers can be produced with renewable energy sources. The intensity factor decreases when the grid is more decarbonised, which means a higher share comes from renewable energy sources (Parsons Brinckerhoff & DNV GL, 2015). For example for 1MW of electricity, the higher the share of electricity from wind turbines - rather than for instance from a gas turbine plant - the lower the intensity factor.

In the case of hydrogen, besides direct use of hydrogen as an energy carrier, it can be mixed with natural gas to make the natural gas 'cleaner', and decreases the CO_2 intensity factor (Birat, 2013). Blending hydrogen into the existing natural gas pipeline network has been proposed as a means of increasing the output of renewable energy systems, such as large wind farms. However, many technologies connected to the grid are not built for the use of hydrogen. If hydrogen is mixed with the natural gas and it is burned the flame has a higher temperature and a different flame speed. If implemented with relatively low concentrations - less than 5%-15% hydrogen by volume - this strategy of storing a delivering renewable energy to markets appears to be viable without significantly increasing risks associated with utilization of the gas blend for the consumer. However, the appropriate blend concentration may vary significantly between pipeline network systems and natural gas compositions and must therefore be assessed on a case-by-case basis as there are currently no existing guidelines for the preparation for injection of these networks (Melaina et al., 2013).

***Box 4:* CO_2 intensity factors**

The CO_2 intesity factors are helpful to estimate the level of pollution of an energy consumption activity. The formula that can be used is the following: $Emission_{activity} = Activity * Emission\ intensity_{carrier}$. If the activity is kept the same, the higher the intensity factor the more emissions are polluted. Shell uses the following numbers in the WEM:

SHCF	LHCF	GHCF	Electricity commercial	Heat commerical	Hydrogen
0.0481	0.0659	0.0478	0.0203	0.0585	0

Table 4: CO_2 intensity factors U.S. in $g(CO_2\text{-eq})/MJ$

4.2.3 FINAL CONSUMPTION OF THE STEEL INDUSTRY

4.2.3.2 TECHNOLOGIES CURRENTLY UNDER R&D

In the steel industry the type of technologies are decisive for the amount and type of energy use. Whether or not a steel process can use electricity or hydrogen depend on the technology that is used. Hydrogen and electricity can both fulfil a reducing agent role and an energy-carrying role. The carbon-hydrogen-electron triangle graphically represents the relation between carbon, hydrogen and electrons as reducing agents and shows some alternative iron making processes (Birat, 2013) (see figure 31). Their distance from the carbon apex indicates the reduction in CO_2 achievable via the various reduction methods. For example electrons can be provided by electricity, for which the corresponding process is the electrolysis of iron ore (Parsons Brinckerhoff & DNV GL, 2015).

Hydrogen can be used to provide the chemical function of reducing oxide ores. This is traditionally done with carbon from fossil fuels, but with hydrogen reduction of iron ore has steam as a gas product instead of CO_2. The extent to which coal can be replaced is dependent on the iron making process. Hydrogen can fulfil an energy role when it is mixed with natural gas. However, current technologies are optimized with natural gas use and not with hydrogen.

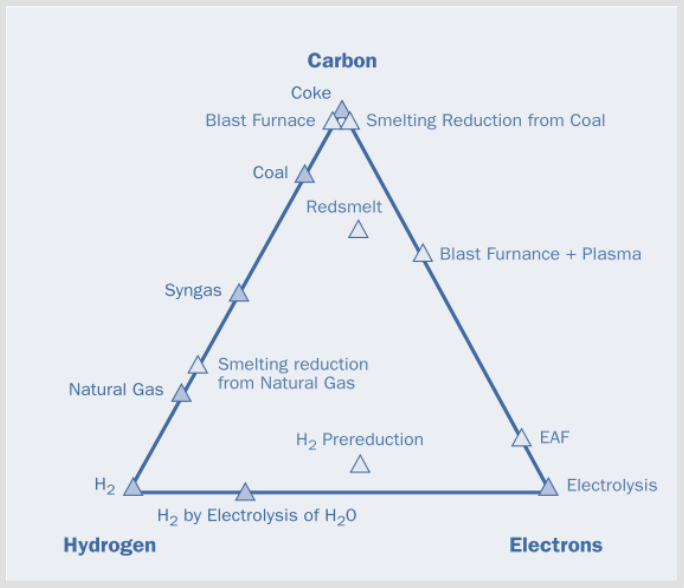


Figure 31: Reducing agents triangle (AISI, 2010)

Currently a number of R&D projects are conducted that show possibilities for future improvements; some with more use of electricity of hydrogen. The projects could lead to commercially available new technologies in the future, and to get a better understanding of the future choice for technology all technologies under R&D are analysed more into depth. In table 5 the technologies are listed and briefly described. Per technology the main improvements are stated. In the second column an overview is given of the technology's advantages, in the third column the disadvantages or barriers for deployment is shown. Finally in the right column the status of each technology as described in the literature is presented. Accordingly, to each technology a technology readiness level (see box 5) was allocated, also shown in the right column.

Box 5: Technology readiness levels

Technology readiness levels (TRL) is a method for estimating technology maturity. TRL are based on a scale from 1 to 9, with 9 being the most mature technology. See appendix B3 for an elaborate explanation of each level.

Technology	Advantages	Disadvantages or barriers for deployment	Technology readiness level (TRL)/ status
Iron making			
Paired Straight Hearth (PSH) furnace - coal based DRI and molten metal process for replacement of BF and coke ovens; for integrated or EAF route. It is an improved, high-productivity form of DRI. It has three major energy inputs, coal in the composite pellets, sensible heat in preheated combustion air and gaseous fuel (Lu, 2006; Vehec, 2014)			
	+ Use coal in stead of coke; 30% reduction in energy use; CO_2 emissions decrease 33% per ton of hot metal produced; lower capital and manufacturing costs; efficiency of 11,5 GJ/tonne of steel	- Technological and cost barriers	TRL 6/ Demonstration project in process, next step commercial plant; mid term
Suspension Reduction of Iron Ore Concentrates (Hydrogen Flash Smelting (HFS)) - iron is produced by a suspension reduction technology that uses hydrogen as the reducing agent/fuel and fine iron oxide concentrates in a suspension reduction process; for integrated or EAF route (Sohn, 2008)			
	+ Less CO_2 emissions (even when natural gas or coal is used); reduction in carbon dioxide emissions 39% and 69% of the Blast Furnace value; 38% less energy than the blast furnace process; efficiency of 12,06 GJ/tonne of steel	- Technological and cost barriers - Hydrogen cost inefficient	TRL 6/ Larger scale test phase; next step is to do more systematic tests in bench scale and to commission a industrial-scale pilot plant; long term
HIsarna - technology based on bath-smelting; combines coal preheating and partial pyrolysis in a reactor, a melting cyclone for ore melting and a smelter vessel for final ore reduction and iron production; uses a Cyclone Converter Furnace			
	+ Less coal use; less CO_2 (20 % reduction of CO_2/t-hot rolled coil (HRC) without carbon capture and storage (CCS); reduction of up to 80% in CO_2/t HRC is possible with CCS); flexible process allows partial substitution of coal by biomass, natural gas or hydrogen; 20% improvement in energy efficiency	- Technological and cost barriers	TRL 7/ Pilot plant by Hoogovens (Netherlands) from 2010; mid term

Steel making			
Molten Oxide Electrolysis (MOE) – technique uses high temperature electrolysis to make liquid metal and oxygen from a metal oxide feedstock; produces molten steel; extreme form of molten salt electrolysis; replaces coke ovens and BF (Urquhart, 2013)			
	+ Electricity use; use of carbon-free anodes; no production of CO_2 (if electricity from renewables); production of O_2 that has commercial value; produce molten steel in single unit; significant capital costs savings; higher steel purity; also viable for small scale production; efficiency of 12,6 GJ/tonne of molten steel	- High cost and it only works with consumable or highly expensive and rare anode materials such as iridium; might not have much competitive advantage to replace the existing route	TRL 5/ In 2007 first tests conducted; laboratory scale tested, next step pre-pilot; due to inexpensive coal and BF developments pathway not pursued by AISI; Massachusetts Institute of Technology now responsible for research; long term
Electrolysis (ULCOWIN) This process produces direct reduced iron from iron ore by means of alkaline electrolysis; leads directly to final products (Pardo et al., 2012)			
	+ Use of only electricity; lower CO_2 emission if electricity if carbon content of electricity is low; efficiency of 15-20 GJ/tonne of steel	- Technological and cost barriers	TRL 5/Least developed process route currently being studied in ULCOS; Technology proven on a very small scale; commercial application decades away/ expected 2040
Top gas recycling blast furnace (with CCS) - separation of the off gases so that the useful components can be recycled back into the furnace and used as a reducing agent (Pardo et al., 2012)			
	+ 26% coke saving/ton hot metal from the current BF coke consumption; 15% reduction of CO_2/t-HRC without CCS; up to 50% CO_2 reduction with CCS.	- Technological and cost barriers	TRL 8/ Combination of the modified BF and CCS plant was successfully tested in 2007; commercially test phase; expected year 2020
Other			
Carbon Capture Storage (CCS) – a technique for capturing carbon dioxide emitted from large point sources and compressing it. CCS also includes transporting it to a suitable geological storage site where it is injected into a stable geological formation, generally more than one kilometre below the surface (Pardo et al., 2012)			
	+ Emissions reduction potential ranges between 0.5 gigatonnes to 1.5 gigatonnes of CO_2/year	- Requires large space; financial barrier (CO_2 price too low), if CO_2 level higher than 40-60 euro per ton economically feasible; technical barriers process consumes significant amount of energy (e.g. lower energy efficiency)	TRL 8/ Technical feasibility of each individual element of CCS technology has been demonstrated, but the economic viability and technical integration and scale-up needed for routine industrial application requires significant research and demonstration; expected in 2020

Table 5: Radical technologies under R&D

From the technological analysis was found that the technologies MOE and ULCOWIN would significantly change the energy fuel mix towards a higher share of electricity. How much higher the share of electricity from the total energy use to produce one tonne of steel becomes is currently not known for full-scale installations. In addition, the technologies HFS and HIsarna enable a slightly increase the use of hydrogen. For both technologies it is unclear in the literature what share of hydrogen is used as a reducing agent and what share is used as an energy fuel. How much higher the share of hydrogen from the total energy use to produce one tonne of steel becomes is also currently not known for full-scale installations.

The CCS technology is a special case in this list of technologies under R&D, as the technology does not concerns steel production, but aims to abate CO_2 as it captures and stores the emissions underground. Although this technology does not results in transition in energy consumption, it is an important technology in the abatement of CO_2 in the future and is therefore taken into account. The deployment rate of this technology is uncertain as technical (e.g. safety) as well as financial and institutional (e.g. protest by society) barriers exist.

4.2.4 ELECTRICITY AND HYDROGEN FROM PRIMARY ENERGY SOURCES

In the previous sub-section was described what possible future technologies can (partly) consume electricity and hydrogen as energy fuel. However, in order to incentivise the investment and use in those type of technologies, cleaner carriers have to be available and for reasonable costs. In addition, it is preferred that the carriers that the steel producers consume are produced with RES, because of the lower CO_2 intensity. For primary energy sources the following distinction can be made: wave, tidal, wind, solar (thermal/photovoltaic), geothermal (engineered/hydrothermal), biomass (traditional/commercial), biofuels (marine/first generation/second generation), hydro-electricity, nuclear, coal, natural gas and oil (Shell, 2015b). This research does not go into very much depth about the type of primary energy sources used, but it distinguishes between the share of RES and non-RESs.

4.2.4.1 SUPPLY OF ELECTRICITY

4.2.4.1.1 Electricity through the grid only partly from RES

One option for steel producers is to retrieve electricity from the electricity grid. In the grid nearly ten per cent of the total electricity generated in the U.S. comes from renewable sources. Another nineteen per cent comes from nuclear and about 25 per cent from natural gas. Approximately 40 per cent of the total electricity generated was coal-based (Mehta & Kumar, 2013). In 2014, the total consumption of RES was about 9.6 quadrillion British thermal units (Btu) (EIA, 2014c). In figure 32 can be seen that biomass, hydroelectric power, wind and solar/photovoltaic are the major sources of renewable primary energy. In the coming decades the decarbonisation of electricity supply has an important contribution to make to overall sector decarbonisation (Parsons Brinckerhoff & DNV GL, 2015).

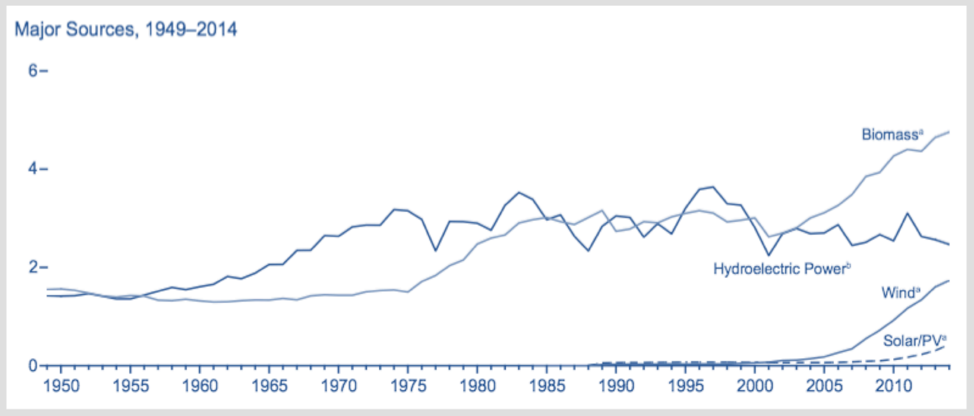


Figure 32: Renewable energy consumption in quadrillion Btu (EIA, 2014c)

4.2.4.1.2 Self supply of electricity only with non-RES

Another option for steel producers is to supply electricity themselves. Currently this already exists for plants that have a lot of unused process gasses that still have value thermodynamically. For example, TATA Steel cooperates with energy supplier Nuon, which uses its gases to produce electricity. In some cases, the steel producer owns the energy plant. The produced electricity can in turn be used in the production process. However, most plants need more electricity than they can produce themselves (Jäger, 2015). This is especially true in the case of the EAF route, where all energy necessary comes from third parties.

In the future steel producers might invest in wind turbines or solar panels for own use, but these energy sources have to compete with cheap produced electricity from the grid or produced by the steel producer himself, which leads to fewer incentives for investment. Also, electricity from RES can be used in a steel plant, but the steel plant cannot fully depend on RES due to volatility of the sources. Thereby other issues such as the required space or location for the sources might provide barriers for steel producers.

4.2.2.1.3 Electricity system integration barrier for RES deployment

Due to the volatile character of RESs barriers for further deployment exist. Today no all-round solution to the problem of intermittency has been found. Technological developments such as Smart Grids, electrical batteries and demand response programs might provide a solution in the future. However, waiting with the start of a process for a cheap electricity price (e.g. with demand response) is not reasonable for the steel industry. Only if significant overcapacity in the market exists, time management with demand response might become attractive.

4.2.4.2 SUPPLY OF HYDROGEN

Full benefits of hydrogen as a clean, versatile, and efficient fuel may be realized only if hydrogen is produced from RES (Barbir, 2009). Three major forms of hydrogen production exists. Firstly, steam methane reforming accounts for 95 per cent of the hydrogen produced in the U.S. This is a catalytic process that involves reacting natural gas or other light hydrocarbons with steam to produce a mixture of hydrogen and CO_2. This method is the most energy-efficient commercialized technology currently available. Secondly, partial oxidation of fossil fuels in large gasifiers is another method of thermal hydrogen production. It can be applied to a wide range of hydrocarbon feedstocks, including natural gas, heavy oils, coal and solid biomass. The main by-product is CO_2. Thirdly, it can be produced by using electricity in electrolysers to extract hydrogen from water (e.g. Power-to-Gas). Currently this method, which is the only method that does not realises CO_2, is not as efficient or cost effective as using fossil fuels in steam methane reforming and partial oxidation. Nevertheless, it would allow for more distributed hydrogen generation and open possibilities for using electricity made from renewable and nuclear resources. The primary by-products are oxygen from the electrolyser and carbon dioxide from electricity generation (Koerner, 2015). Currently hydrogen is used in the steel industry for both primary metal production and secondary metal processing, for example in furnaces as backfill gas and for heat treating (Ishikawa et al., 2010).

4.2.4.2.1 Three methods to supply hydrogen

One way for hydrogen supply is by pipeline, however, currently hydrogen pipelines only exist in a number of industrial areas. In the grid nearly 96% of all hydrogen is derived from fossil fuels, with natural gas being by far the most frequently used with an estimated 49%, followed by liquid hydrocarbons at 29%, 18% from coal and about 4% from electrolysis and other by-product sources of hydrogen (Ishikawa et al., 2010). Currently the steel industry often obtains hydrogen via coke making, which results in hydrogen as a by-product, or through a steam methane reformer on-site (Ishikawa et al., 2010). However, if hydrogen will play a larger role in the future enlargement of the hydrogen infrastructure is necessary.

4.2.2.2.2 System integration hydrogen barrier for deployment

The U.S government is devoting large efforts and resources toward developing a hydrogen energy to replace fossil energy. However, the transition to a hydrogen economy could take several decades (DOE, 2002a). Hydrogen production costs are high relative to conventional fuels (McDowall & Eames, 2006). With most hydrogen currently produced from hydrocarbons, the cost per unit of energy delivered through hydrogen is higher than the cost of the same unit of energy from the hydrocarbon itself. Compared to the large-scale, well-developed production and delivery infrastructures for natural gas, oil, coal, and electricity that keep the energy prices low, make it challenging for hydrogen to meet these low prices (DOE, 2002b).

In addition, effective design and implementation of a hydrogen-based energy system requires a whole system approach, which includes production, storage, delivery, and conversion. Development of national and international codes and standards, collaborative R&D, and technology validation through demonstrations by government/industry partnerships are necessary for further hydrogen deployment (DOE, 2002b; Koerner, 2015). Strong policies are needed for hydrogen to deploy and to play a major role within the future low carbon energy system.

4.2.5 READING GUIDE

In this chapter the key forces the transactional environment of the U.S. steel industry were analysed. The industry is characterized with energy and capital intensive production processes, fierce competition, low profit margins, changing market dynamics, uncertainty about future policy measures, and the challenge of CO_2 abatement. The analysis also touched upon the question around the future development of forces and it reveals that some forces are more surrounded by uncertainty than others. The obtained knowledge serves as input for the organization of the scenario workshop. In addition the analysis resulted in profound background knowledge for development of the scenarios.

In the energy system analysis the question concerning the possibilities for and limitations to an energy transition to the use of cleaner energy carriers is addressed. It shows that with the possible future availability of technologies currently under R&D it can be possible to move (partly) to the consumption of cleaner carriers in the industry. The possibilities extend the design space for the scenarios development and give an idea of what could be possible in the future. The defined limitations provide clear boundaries to the design space. In the next chapter the two findings are brought together and form the basis of the next step: organize a scenario workshop.

5. DEVELOPING SCENARIO NARRATIVES IN A SCENARIO WORKSHOP

In this chapter the results of the development of scenarios by means of the scenario workshop with industry experts are presented. After approaching 30 industry experts, thirteen experts agreed to participate. The experts collaborated a full afternoon to explore and develop scenarios to answers to the following question: *how will U.S steel producers change their energy use between now and 2050?* The main conclusions are presented in the following sections, but a more extensive report of the workshop can be found in appendix C1. The final result of the scenario workshop is two scenario narratives.

5.1 LISTING THE DRIVING FORCES

In the workshop each of the five S.T.E.E.P. areas were discussed. Drivers for each area were identified, the lists of which are presented per area in the upper part in figure 33. Subsequently, the drivers were written down on magnetic hexagons and in a collaborative session grouped on a whiteboard in order to select the overarching key drivers. Ultimately this resulted in six key drivers, presented at the bottom of figure 33. Which key driver captures which driver is shown in appendix C2.

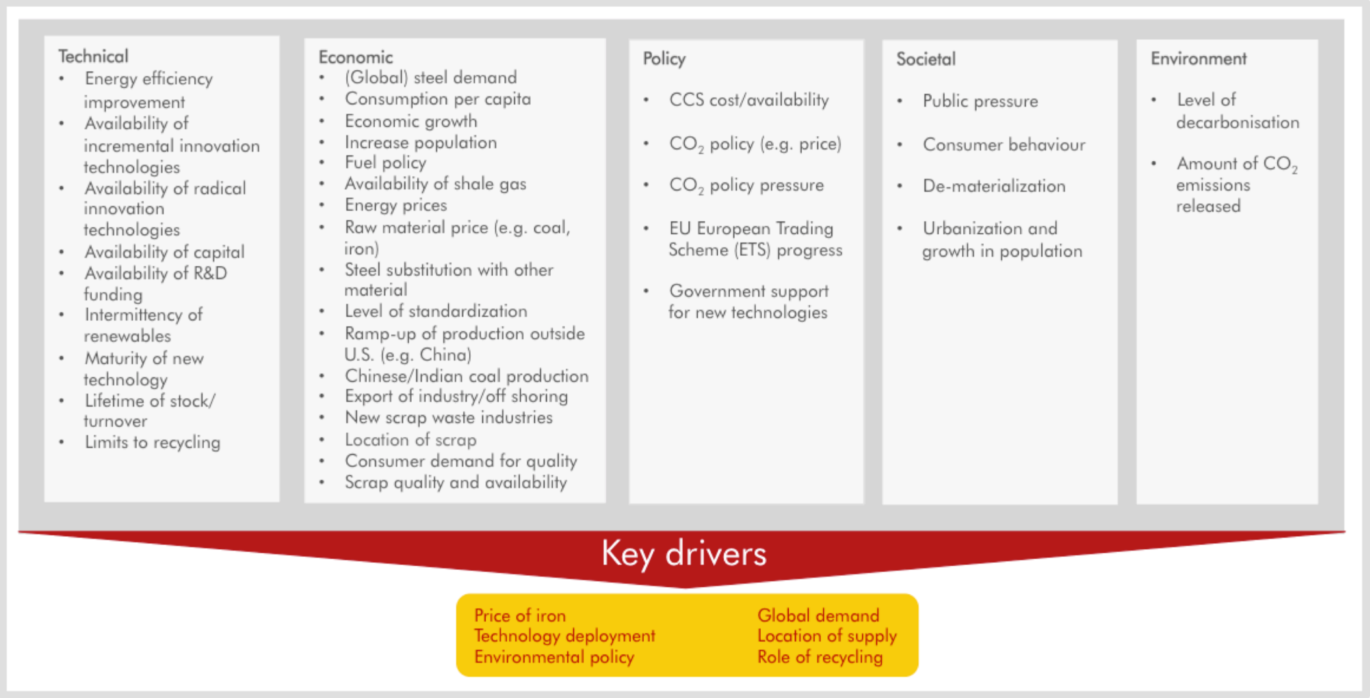


Figure 33: Identified drivers and the key drivers

Reflecting on the exercise and results, it can be stated that a comprehensive list of drivers has been established. At times, some steering was required in order to focus the discussion to new S.T.E.E.P. areas that were not addressed extensively yet in the former parts of the discussion. Also, participants were sometimes not fully able to directly name a driver. In that case, their supportive stories helped the facilitators to identify a driver. Grouping the drivers to key drivers was challenging, as the drivers were often interdependent and could be categorized in multiple groupings. Notwithstanding, all participants agreed on the six key drivers that were considered to have the biggest effect on the system, and captured most of the drivers.

5.2 RANKING OF DRIVING FORCES TO FIND CRITICAL UNCERTAINTIES

After this phase in the scenario building, the key drivers were ranked on their level of uncertainty and level of impact (see figure 34). The driver *location of supply*, which captures the drivers concerning differences in competitive advantages due to location regarding for example prices (e.g. energy, feedstock), was ranked relatively low on both axes. The same accounts for the key driver *role of recycling*, which captures every driver related to recycling (e.g. availability, price, and limits to recycling). *Technology deployment* and *global demand* both scored high on one the axis and somewhat lower on the other. The *price or iron ores* scored semi-high on both axes, and environmental policy scored relatively high on both impact and uncertainty. The latter four key drivers are identified as critical uncertainties and are further explained in the next step. The reason to also include *technology deployment* and *global demand*, two key drivers that are not fully in the red square, was that including them means that ore separate polarized axes can be formed, and additional scenario frameworks can be tested on the criteria for 'good' scenarios.

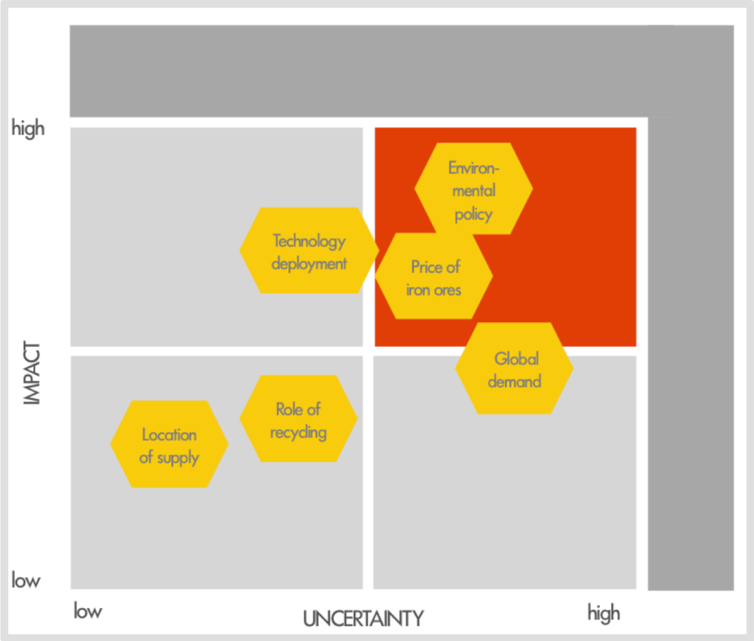


Figure 34: Ranking the key drivers

Reflecting on the exercise and results, it can be concluded that this was a relatively easy step as the framework provided good support for the participant's thinking about uncertainty and impact of certain key drivers. The non-critical uncertainties were not used for the development of the scenario framework. However, these will be discussed in the scenario narratives described later in section 5.4.

5.3 SELECTING SCENARIO LOGICS

Next, the critical uncertainties were polarized on axes. Firstly, the price of iron ores was polarized from 'low' to 'high'. The price of iron ores is an important driver as it has large effects on the margins in the business. A low iron ore price results in lower costs and thus a higher profit margin for steel producers, whereas a high iron ore price results in higher costs and hence a lower profit margin.

Secondly, the technology deployment axis was polarized with 'deteriorated' on the one hand and 'enhanced' on the other. Technology deployment captures the drivers concerning availability of incremental or radical innovations, availability of capital and funding for R&D, and governmental support for R&D. Deteriorated technology deployment means that less effort is put in R&D and that innovative technologies become commercially available at a later stage. Enhanced technological deployment means more effort is put into R&D due to, for example, extra government support or high capital availability in steel producing companies.

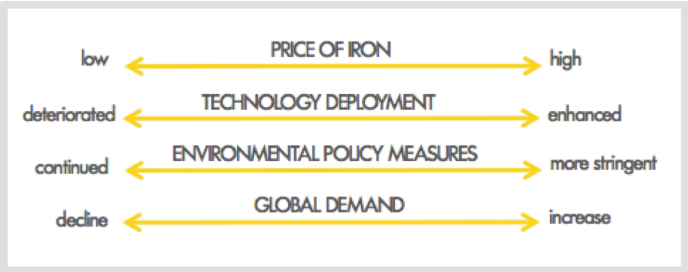


Figure 35: Polizing of drivers on axes

Thirdly, environmental policy measures axis was polarized with 'continued' and 'more stringent'. The continued polar means that the environmental policy measures are deployed at the same pace over the last couple of years. The more stringent polar means that environmental policy measures are developed quickly to a more stringent environment for the industry. This critical uncertainty captures issues such as CO_2 policy and costs, government support for new technologies and CCS costs and availability.

Finally, global demand was polarized with ‘decline’ on the one hand and ‘increase’ on the other hand. This critical uncertainty captures the total steel demand, which comprises of global and national steel demand. Related drivers include threat of substitutes, consumption per capita, and demand for quality. Decline in (global) demand means people have a lower need for steel, for example it has been substituted for another material. Increase in steel demand means more people want to buy steel, for example due to growth in GDP.

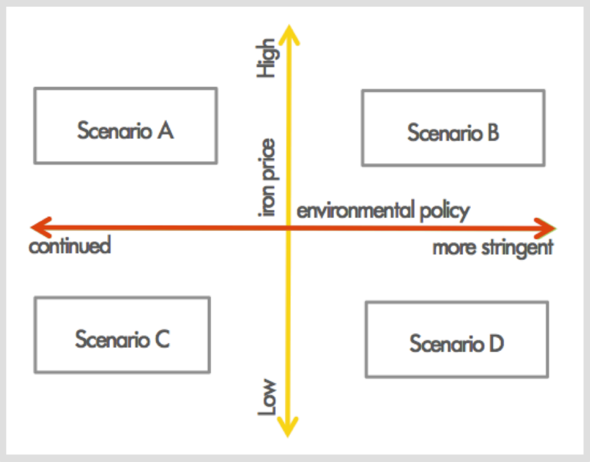


Figure 36: Scenario framework

Now that the axes were polarized, the axes could be ‘tested’ to see to what scenarios they would lead to. This was done by subsequently testing with two and three axes. Each of the two participant groups came up with a different set of axes, but ultimately it was decided to continue with the scenario framework in figure 36.

Reflecting on this exercise and results, it was one of the most important but also most challenging steps. This is where the participants had to start using their imagination and think ahead about what types of scenarios would emerge and judge whether this complied with the features of a good scenario according to Amer et al. (2013). The two groups ended up with two different scenario frameworks. With a plenary discussion was agreed that the framework in figure 36 leads to more challenging scenarios. After the workshop was decided by this project’s main researcher - in consultation with the client Shell – that is continued with only scenario B and C in order to flesh these out more in depth rather than all four in limited depth.

5.4 FLESHING OUT THE SCENARIOS – THE U.S. STEEL INDUSTRY IN 2050

In the following section the narratives of the two scenarios are fleshed out. The two scenarios are named Quarterback and Wide Receiver, in analogy with American football roles (see box 6). Firstly, the U.S. steel industry in 2050 is explored using the Quarterback scenario. The question ‘’what if the iron price is relatively *high* and environmental policy is developed in a *faster pace* (compared to today) to a stringent environmental policy environment?’’ is answered. Secondly, future of the U.S. steel industry in 2050 in the Wide Receiver scenario is explored. The question ‘’what if the iron price is relatively *low* and environmental policy developed in the *same pace* as today to a low stringent environmental policy environment?’’ is answered. The list of drivers is used as a checklist and for every driver it is analysed what the driver might look like in a particular scenario. The line of reasoning is presented in appendix C2.

BOX 6: AMERICAN FOOTBALL ROLES

Quarterback	vs.	Wide Receiver
•Throws the ball		•Catches the ball
•Plans a specific strategy		•Takes a situation as it is
•Forethoughtful		•Backward looking
•Quality (throwing)		•Quantity (meters)
•Address obstacles		•Run around obstacles

5.4.1 QUARTERBACK SCENARIO

In Quarterback the U.S. has developed itself as one of the active players in the sustainable steelmaking market and utilization. Even though the U.S. is market driven by nature, visionary politicians make decisions about what game to play and take strong action to abate the intensified stresses on the environment with government intervention. However, this greener environment comes with a cost for the steel industry. Steel producers either have to radically innovate in cleaner technologies or are tackled by the high CO_2 taxes; this results in steel winners and losers. Although the CO_2 emission decreases in the U.S., some ‘carbon leakage’ occurs when a number of steel producers move their production to less policy stringent areas. Cooperation is key to survive the national playing field. Internationally the U.S. have difficulties to stay in the low price steel market, and focus more on the better quality steel products.

5.4.1.1 SQUEEZED ECONOMIC GROWTH AND MARKET PROFITABILITY

A lot is changed in the nature of the economy and the market size in the years leading up to 2050. The more stringent environmental policy slows the increase in population and urbanization down to some extent. The policy has serious effect on the industry, and the industry takes some hits along the way towards a cleaner production process. The government interventions are not well received by most in the industry, but the industry does not have enough power to oppose the strong measures. Due to the high capital-intensive industry character in combination with the long lifetime of capital, the industry has to pass through a period of increasing stringent policy measures, while still coping with old technologies. Some companies even have to replace part of their technologies before the end-of-life time of the existing capital. Companies are still struggling with its profitability. A number of steel producers take the step to move their production to cheaper parts of the world, where not only a higher demand is visible and cheaper iron is available, but more importantly the environmental costs, such as CO_2 tax, are significantly lower. The steel producers that remain in the U.S. are producing high value added steel products that are light weighted or have extra high strength qualities.

A professor from the Technical University of Delft stated: *‘‘with more stringent environmental policy measures steel producers stop their operations and transfer them to less stringent regulation areas’’. Also a manager from an international steel producer noted: ‘‘if we cannot afford it, we move to areas where there is no carbon tax’’*

The environmental policy also affects the steel buyers. The construction sector and automotive sector import parts of their low quality steel products from other countries, due to the lower price. A small number of low costs automotive companies also move abroad in order to be located in the vicinity of cheaper steel producers. The trade balance turns more negative. However, the relative strength of the U.S. dollar is high in Quarterback, which benefits the international trade at least to some extent. China evolves into the main centre of steel production, and sets the international steel price at a low level. Furthermore, level of saturation of the U.S. steel-use-per-capita curve the saturation level has been reached. This means not only top-down but also bottom-up pressure is exercised on the industry.

‘‘When there is more focus on sustainability the economic model should be changed: we have to standardize, for example the size of car doors. If a car door is broken, just change it with a standardized new one’’ – said a leader from an international steel producer

The increase in iron ore prices has big effect on the industry cost structure. High feedstock prices, and in particular the price of iron, drag down the profit margins. In addition to that the high carbon tax which needs to be paid for every ton of CO_2 that is emitted causes a higher cost per tonne of steel. In other areas in the world, such as China and India, the environmental discussion has also reached a significant level, but has not yet led to such stringent environmental policy as in the U.S. leads to a competitive disadvantage for producers in the U.S and to geopolitical tensions. Hence, in order to keep the costs low the industry is obliged to cut costs wherever possible. With the implementation of new technologies more automation and standardization was introduced. This decreases the costs for labour force significantly. Furthermore, all scrap that becomes available is re-used, because this remains a relatively cheap way to produce steel.

The market profitability is squeezed. Customers have increased market power, as they require low cost and high quality steel and due to the higher U.S. price buyers go find their products more easily abroad. The competitive rivalry is high, and steel producers find themselves in a difficult operating environment. Some producing facilities even have to close down. Also, the threat of substitution of steel with aluminium has increased, because more customers require light material, and can more easily switch to aluminium as it has now reached around the same price level of aluminium. In the U.S. the new entry is confined, but on the world steel market steel producers from upcoming economies will continue to enter the market and provide cheap steel. The key success factors for steel producers are adapting to the environmental policy measures, invest in green technologies, and produce steel for a low price and high quality.

‘‘There is no money available, so it is a hard game to play’’ – stated a partner in an innovation and sustainability consultancy firm

5.4.1.2 STRINGENT ENVIRONMENTAL POLICY BRINGS CHALLENGES TO THE MARKET

''A set of rules should reduce the emissions. It requires a significant works from the government'' – explained a partner in an innovation and sustainability consultancy firm

Over the years U.S. citizens acknowledged the environmental problems and environmental politicians received more and more votes. Today the government has environmental health as a high priority issue on the political agenda. With stringent measures the government tries to force heavy industry to innovate and invest in cleaner technologies. Steel producers pay a high CO_2 tax for emissions. The policymakers set strict goals on an announced timeline. Even though these strict goals lead to many issues for steelmakers, one can argue that less political uncertainty is present: companies know where they stand and what to expect.

The government acknowledges the changing effects of their strict policy measures on the market environment and agrees to financially support the industry with funding for R&D for cleaner technologies to sweeten the blow. However, the level of support is not high enough for all steel producers to survive the stringent policy measures. Policymakers are in a continued struggle in terms of how to provide the right incentives to trigger companies to innovate and decrease pollution, but not incentivise them to move production abroad or even push them out of the market.

Furthermore policymakers have to deal with the downside of stringent environmental regulation: slowed down economic growth and loss of jobs. Politicians embrace the idea of de-industrialization, but this transition goes slowly. Internationally, the U.S. steel industry experiences problems due to the competitive advantage of areas with less or no policy regulations. To address this international imbalance the U.S. government lobbies for international cooperation to develop a unilateral environmental policy system.

A professor from the TU Delft noted *''look at Pittsburgh, it used to be a dirty industry, but now it's very successful because it invested in R&D and technology''*
- Pittsburgh was the centre of the American steel industry, and is still known as "The Steel City," but transitioned in the twentieth century to an economy with enhanced industrial robots and shifted jobs to health care and higher education.

5.4.1.3 HIGH TECHNOLOGICAL EFFICIENCY AND RADICAL INNOVATION

Due to the more stringent environmental policy a lot of pressure is exercised on the steel industry for technological innovation. The high carbon tax, together with the high iron ore price cause the production costs to being so high that the business is near to non-profitable. Hence innovation in cleaner technologies is necessary to survive. Fortunately, the green government supports the industry with funding and subsidies for R&D. The strict policy measures require radical innovations due to the high production costs. Therefore the steel producers are forced to replace capital, sometimes even before the end of lifetime of the working capital. Since the iron ores are expensive the focus for innovation is on technologies with less use of iron ores. In addition, the choice for the type of energy carrier is considered important, because cleaner fuels result in less CO_2 emissions, which in turn means that less carbon tax needs to be paid. The use of shale gas based technologies is attractive due to the low costs of the gas. In addition, to survive the more stringent policy measures and capture part of the remaining release of CO_2, CCS is actively deployed.

Collaborations, such as the AISI, are of major importance in R&D for new technologies. Furthermore, technologies diffuse from Europe to the U.S (e.g. HIsarna). The share of the EAF route is slightly higher, due to the low production costs and because the process is cleaner than integrated steelmaking. However, the limit of the increased share of the EAF route is reached. The share of the integrated route has slightly decreased but because, among other things, most of the EAF's need a significant share of newly produced steel, this technology cannot be discarded completely. Instead, investments are made in new technologies, in alternative technologies in the integrated route and in new ways of electric steelmaking. With the new technologies such as MOE or ULCOWIN better quality steel can be produced.

In figure 37 the technology mix is presented per year and per technological category (for assumptions see appendix C3). In appendix D5 it is described what technologies fall under each category. The figure shows that from the year 2020 onwards there are steady innovations in radical technologies, and that the old fashioned integrated route is partly replaced by new technologies. The result of years of innovation is high technological efficiency. Besides, with the new technologies it is possible to produce high quality and light weighted or high strength steel products.

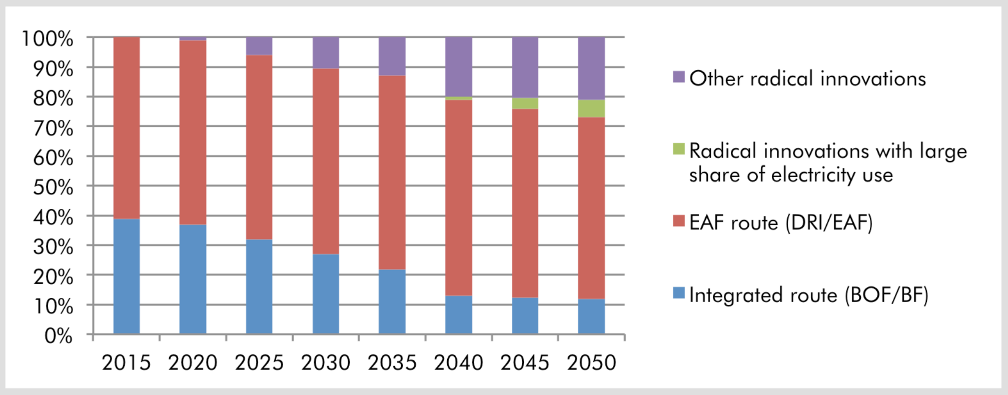


Figure 37: Technology mix in Quarterback

5.4.1.4 MORE SUSTAINABLE SOCIETY BUT JOBS SACRIFICED

Over the years people have slowly started to change their mind-sets, and today acknowledge the importance of sustainability. Also the government puts significant pressure on the society to live a more sustainable life. People act more sustainably and also ask this from the producers of the products they use. Still, customers are only willing to slightly pay more for greener products. Society puts significant pressure on the steel industry in terms of CO_2 abatement. Some parts of the U.S. take sustainability to the next level and even lower their steel consumption in light of de-materialization and the 'sharing-economy' trend.

On the other hand, the population that is negatively affected by the trend of the closing down of parts of industry is not so pleased. A significant number of steel industry workers lost their jobs, and had to be re-skilled. Today, people slowly are starting to find new purposes in life. The heavy industrialized based activities are slowly being replaced by more consumption-service oriented industries.

In figure 38 the changes of stakeholder power and interest over the years up until 2050 in Quarterback are presented. A number of stakeholders require closer management (top right square). This includes the U.S. policymakers and collaborative institutes as they have increased power in Quarterback. In 2050 collaboration provides the means to survive the difficult climate. This means that steel producers need to pay more attention to close stakeholder management. Iron ore suppliers in the U.S. have less power as their prices are high and the steel industry looks for alternative ways of steel production. The steel producers themselves have significantly less power in this scenario, as they have to obey to the stringent environmental policy measures and the possibilities for substitutes are more apparent. The dependability on actors is larger because cooperation in certain areas (e.g. R&D) is necessary to survive the market dynamics.

Figure 38: Changes in stakeholder positions in Quarterback

5.4.1.5 ENVIRONMENTAL CONSERVATION

With the stricter and effective measures, the U.S. steel industry emits less CO_2 and the decarbonisation of the environment is noticeable to a considerable extent. CCS is deployed significantly and captures a share of the CO_2 emissions that is emitted by the older technologies. Moreover, less coal is used, in favour of cleaner energy fuels. One of the benefits of the stringent policy is the faster development of an infrastructure with improved integration and higher share of renewable energy to the electricity grid, and the development of a hydrogen economy and infrastructure. Because clean electricity and hydrogen are available for a reasonable cost, in combination with a high carbon tax that needs to be paid for emissions, steel producers invest in technologies with more electricity and hydrogen use. However, one important remark has to be made: lower levels of pollution are reached in the U.S., but as a number of operations move to less stringent regulation areas this still is a loss to the environment.

5.4.2 WIDE RECEIVER SCENARIO

In Wide Receiver the U.S. steel industry keeps outmanoeuvring the deployment of environmental policy measures that heavily affect the steel industry by lobbying against it. In the market driven economy the industry's big players suppress policymakers with the message that steel industry growth results in economic wealth. With the low iron costs the industry quickly develops an up to speed steel industry, which also actively runs in the international steel market. However, increased steel production has a downside. The environment takes some tough hits and experiences the consequences of continued pollution. In addition, with little incentives to innovate the industry only invests in incremental improvements.

5.4.2.1 ECONOMIC GROWTH AND INTERNATIONAL MARKET PARTICIPATION

Over the last decades the U.S. economy unfolded itself in an accelerating pace. With a low iron price and limited environmental policy constraints the steel markets finds themselves in the optimal climate to flourish in their production. The steel market size grows significantly due to the increase in population in the U.S. and participation in the international market as the U.S. steel market can compete with lower steel prices. On the other hand, the U.S. dollar currency in Wide Receiver is relatively low, which creates barriers to trade. Still the U.S. exports to South America, Africa and Europe. The biggest competitor in the market is China, which produces cheaper and better quality steel. With continuing urbanization the per capita use of steel is high, while it does not reach standardization due to the cheap availability of steel. The construction and automotive industry in the U.S. also experience a blossom in their sector, and therefore remain located in the U.S. The industry costs structure is characterized by low cost iron ore, resulting in high profit margins. Other feedstock, such as coal, is also available for a low cost. The largest share of the costs is accounted to the energy fuel. Every now and then a mismatch between supply and demand exists due to the ineffective regulated market, resulting in price volatility. The shale gas deployment reaches its top level and is optimally utilised by steel producers that design their production process accordingly. A carbon tax that needs to be paid for every tonne of CO_2 emissions is approximately five percent of the total costs this incentive is ignored.

''Steel companies have no incentive to innovate'' – stated a professor from the Technical University of Delft

A big flow of scrap becomes available worldwide. As the scrap price follows the iron ore price and cheap shale gas is available not only the integrated route, but also the EAF rout is profitable. In terms of investment, due to the high margins companies have money available to reinvest in new technologies. However, producers have little incentive to do so if enough profit can be made with the technologies they currently use. The only incentive to innovate is to become more efficient and produce better quality steel in order to stay ahead of competitors nationally and internationally.

''Because of shale gas, steel companies move to gas-based steel making.'' – stated a leader from an international steel producer

The market profitability is high, which attracts new entry in the market. The product focus is slowly moving from quantity to quality due to consumer demand for higher quality steel. Less threats of substitution from other materials exist, because steel is amongst the cheapest material of its kind. Only in terms of demand for lightweight and high strength materials the competition is higher, nationally as well as internationally. Moreover, key success factors in the sector are productivity and economies of scale. Lazy behaviour due to high profit margins is a risk, and those steel producers that wait and see will or have been pushed out of the market. The importance of innovation is underestimated, but will be necessary to become more efficient.

5.4.2.2 NO STRINGENT ENVIRONMENTAL MEASURES BUT POLITICAL UNCERTAINTY

Governments, by their nature, are slower to act than the speed of daily life often requires. This also goes for the case of the steel industry in Wide Receiver. Environmental pollution is acknowledged, but no central functioning system to abate the emissions is developed. Some states developed carbon tax policies but these are too low to have a significant impact on the environment. The politicians have economic growth higher on the agenda than the environment, and therefore increased steel production is championed. The green politicians are put under pressure by the big industry players, who continue to lobby to be exempted from any environmental policy measures. However, how long the political climate remains in this sphere is unknown. With the environmental damage becoming more visible, it is only a question of time until the next government election or governmental decision towards a cleaner pathway is made. This leads to a lot of uncertainty in the industry.

> *‘‘With a malfunctioning policy system there is no incentive for CCS because the price that needs to be paid is based on a calculation with the inflows, the chemical reactions, and then the resulting CO_2 output. So a producer has to pay anyways, because CO_2 is produced’’* – noted a leader from an international steel producer

Furthermore, because of the high profit margins little governmental support for new technologies is provided. Thus steel producers have to invest in R&D themselves or with collaborative institutions, such as the AISI. Also, due to an increase in international trade, the international trade policy becomes more important. Because China experiences competition from the U.S. it is trying to obstruct American products and creates barriers to trade for trading. This leads to severe geopolitical tensions. The paradox for government leaders is very applicable here: the greater the forces of globalisation, the less autonomous power of national governments.

5.4.2.3 LACK OF INCENTIVE TO INNOVATE AND MOSTLY INCREMENTAL INNOVATIONS

In Wide Receiver a lack of incentive to innovate prevails; business as usual is the way to act. Steel producers only invest small amounts in incremental R&D, because they do not feel the need to innovate radically. Also, the government provides limited funding, slowing down the R&D processes for new radical technologies. To stay ahead of competitors companies invest in incremental improvements that save costs due to improvement in efficiency, and if that improvement emits less CO_2 that is a nice extra. The transition to new technologies goes slowly because steel producers are not likely to change the capital before the end of lifetime.

> *‘‘Investment in new technologies is reluctant because new technologies compete with good working capital’’* – stated a leader from an international steel producer

As long as the iron ores have a relatively low cost, steel producers have the incentive to produce steel in an integrated fashion. However, the shale gas revolution has pushed through, making lots of cheap gas available. This also results in a significant share of EAF steelmaking. The scrap that becomes available is therefore widely used. In the final years in the journey to the year 2050 a small number of radical new technologies became available in the U.S., in addition to technologies that diffused from Europe. Moreover, due to the continued heavily steel use, around 2030-2040 a big flow of scrap becomes available worldwide. CCS is deployed only limitedly. A malfunctioning environmental policy system resulted in gaps in the system, providing less incentive for steelmakers to invest in the technology. The result of the lack in innovation is a very limited transition to cleaner technologies.

In figure 39 the technology mix is presented per year and per technological category (for assumptions see appendix C3). In appendix D5 it is described what technologies fall under each category. The figure shows that only very limited innovation in radical technologies takes place, and that cheap production with the integrated route continues.

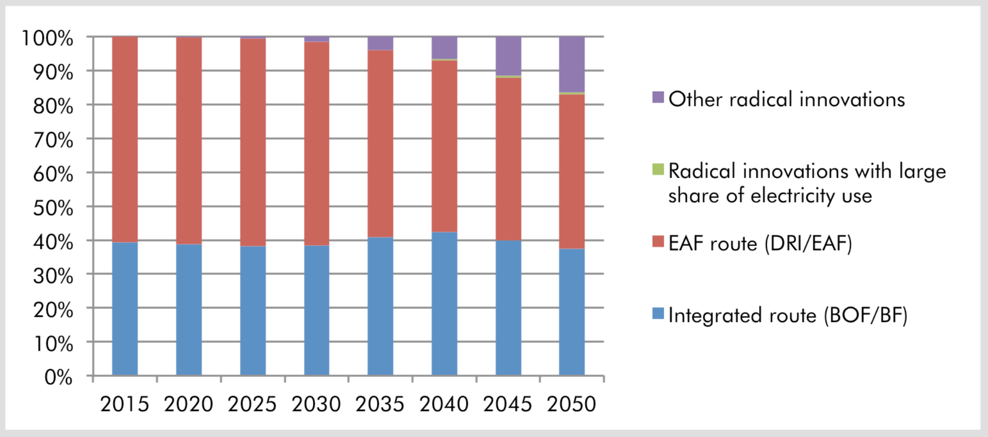


Figure 39: Technology mix in Wide Receiver

5.4.2.4 SOCIETY WANTS BIG AND MORE

Growth in population and urbanization leads to increased demand for steel products. The U.S. citizens pay a great deal to have the newest gadgets, the biggest cars, and a large house with a garage. But to be able to afford all that the Americans need jobs. And in with those jobs, products are developed. Economic growth is at the core of this vicious circle, and slowing the growth in wealth down because the environmental damage is unwanted by society. A shift towards a service-oriented economy is postponed. The demand for a growing economy and jobs is put first, instead of the environment.

> "*We are all green until it costs a penny"* – noted a manager of an international steel producer

Environmental groups have formed themselves and exercise pressure on the government as well as the industry. Every now and then the steel producers face environmental activists obstructing the daily business. Notwithstanding, the mainstream of the American society does not undertake any real action. It appears that change of behaviour takes a long time.

> *''Humanity only changes its mindset after a crisis or war event.''* – argued a manager of an international steel producer

In figure 40 the changes of stakeholder power and interest over the years up until 2050 in Wide Receiver are presented. The steel producers themselves have significantly more power in this scenario, as their business flourish. The U.S. policymakers have slightly lower power as the steel industry ensures a significant share of GDP and employment. Substitute producers have less power as the steel can be produced cheaper resulting in a larger price difference with its substitutes. Iron ore suppliers have increased power and interest, as there is more demand for their product. In general an environment with higher competition between actors is present and for steel producers less dependencies on other actors exist.

Figure 40: Changes in stakeholder positions in Wide Receiver

5.4.2.5 POLLUTED ENVIRONMENT

In Wide Receiver the environment bears the brunt for the economic growth and increased steel production. Large amounts of CO_2 emissions are released to the sky every day. CCS is deployed limitedly, and is relatively expensive. Coal is one of the main inputs as much of the steel is produced via the integrated route. In terms of the supply of cleaner energy carriers, only a small share of the electricity grid and hydrogen supply originates from RES. The development of a renewable energy infrastructure stagnates due to a lack of funding and support. Also, the 'hydrogen economy' plans by the government did not push through, with the result that the hydrogen price remains relatively high. Only distributed solar energy is deployed to some extent by the steel producers, due to the relatively low costs of the panels and the easiness to install. Hydrogen is mostly made by means of steam methane reforming, and the cost of hydrogen produces through electrolysis is still much higher than other energy sources.

5.4.3 READING GUIDE

In the scenario workshop two plausible scenarios – Quarterback and Wide Receiver – for the U.S. steel industry are sketched. The scenarios can be regarded as two plausible external environments in which the industry might find itself in 2050. But what does this mean for the system in both scenarios? In

Quarterback strong environmental policy measures and the high iron ore prices have a strong effect on the steel industry business, resulting in a difficult operating climate for the steel producers but also enhanced CO_2 abatement due to significant radical innovation in cleaner technologies. Additionally, other stakeholders in the system experience the pressure by the stringent environmental policy measures and cooperation is key to survive the tense market climate.

In Wide Receiver environmental policy has less effect on the steel business, and due to the lower iron prices the steel producers can produce steel with lower costs and thus can increase market share; mostly nationally and some internationally. However, steel producers have little incentive to innovate in cleaner technologies, resulting in stronger levels of pollution.

The question now is what exactly the effect of these external forces is on the steel producers in the system. To what extent will the steel producers change their energy use in the two scenarios? In the next chapter the energy system is further analysed by means of modelling with the WEM. The qualitative data aims to complement the qualitative scenarios.

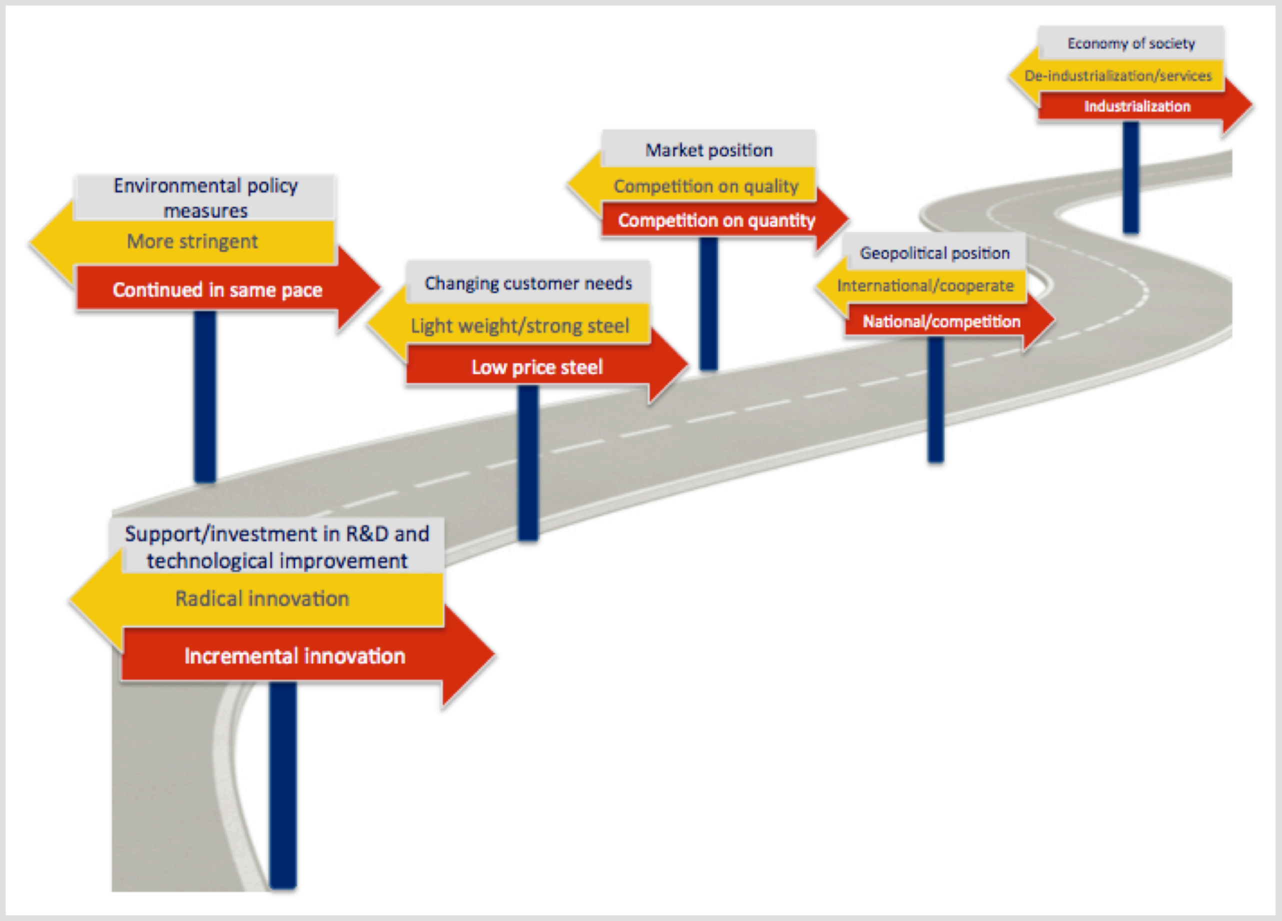


Figure 41: The route to 2050: two plausible scenarios

6. MODELING THE SCENARIOS WITH THE WORLD ENERGY MODEL

The aim of this chapter is to model - and explain how to model - the defined scenarios with the WEM in order to support the scenarios with quantitative data. Adequate understanding of the model is obtained, after which the modelling strategy and key assumptions are defined. Results are modelled and discussed accordingly. Finally, with the modelling experiences obtained, the suitability of the WEM for modelling of scenarios for an energy transition in heavy industry is tested and recommendations for further enhancement of the model are provided.

6.1 HOW THE MODEL WORKS

6.1.1 MODEL BASICS

The WEM is designed to model the long-term transformation of the energy system. The continuous and deterministic model can be categorized as a predictive or forecasting model (Sage & Armstrong, 2000). The dynamics are modelled from a population-level, rather than from an agent-based perspective. It does however include a choice module (to be explained in section 6.1.2.2) in which choices for energy are based on energy utility. In figure 42 a basic representation of the model is shown. The WEM was developed in the years 2005 to 2008 and has been in use ever since. It is an existing sophisticated and complex model; the model engine can be seen as a black box in which a nation's demand is matched with the supply of energy available, given certain preferences (the choice module) on the producer as well as on the energy consumer side. As it is not the aim of this research to adjust the model engine's calculations, but only to make adjustments to the inputs in order to generate output data, this black box remains for the large part unrevealed. As a starting assumption it is assumed that the model is validated and works. Only basic understanding of the black box is necessary to define the inputs, and will be explained in the next section. In this research is focused on the scenario inputs. If adjustments are required in the historical data this is also conducted. The constant variables are kept the same.

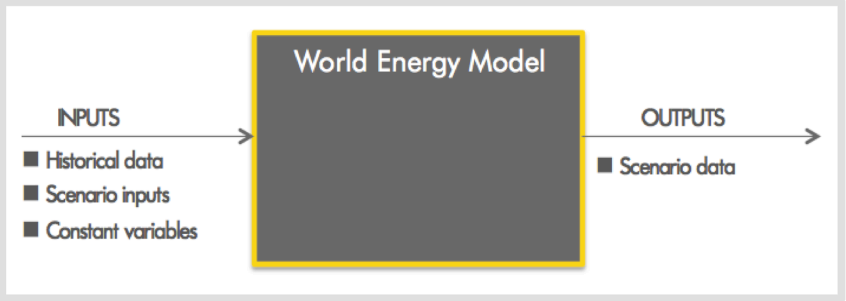


Figure 42: Basic representation of WEM

6.1.2 WEM STRUCTURE

The WEM integrates econometric and technical modelling with its scenario methodology to derive dynamic energy outlooks. It is developed in Excel and is a framework of linked spreadsheets, including 1) a bank of historical data, 2) scenario inputs, 3) the model engine itself, and 4) output spreadsheets with generated results in tables and charts (see appendix D1). The historical data includes the years 1960 to today and the scenario data includes the years from today to 2050. The WEM is a balancing model (energy supply and demand as explained in more detail in the paragraph below), using algorithms and linear extrapolation to first calculate current year+1, then in turn uses these results to calculate current year+2, etc.

The WEM comprises of three principal components (see figure 43): the Energy Ladder, Energy Choice and Energy Supply modules. It is a partial equilibrium model, in which the feedback from the supply module ensures a balancing of supply and demand based on a given nation's preferences, and where prices play a core role. Furthermore the model includes the following economic principles: (1) income (measured in GDP per capita) and prices affect total demand for energy services, (2) cost influences market shares of energy, (3) competition of technologies and markets, (4) innovation, (5) government policies, (6) incentives, and (7) societal barriers. In the following paragraphs each of the tree principal components is briefly discussed. For a full explanation of the model methodology is referred to Haigh (2014).

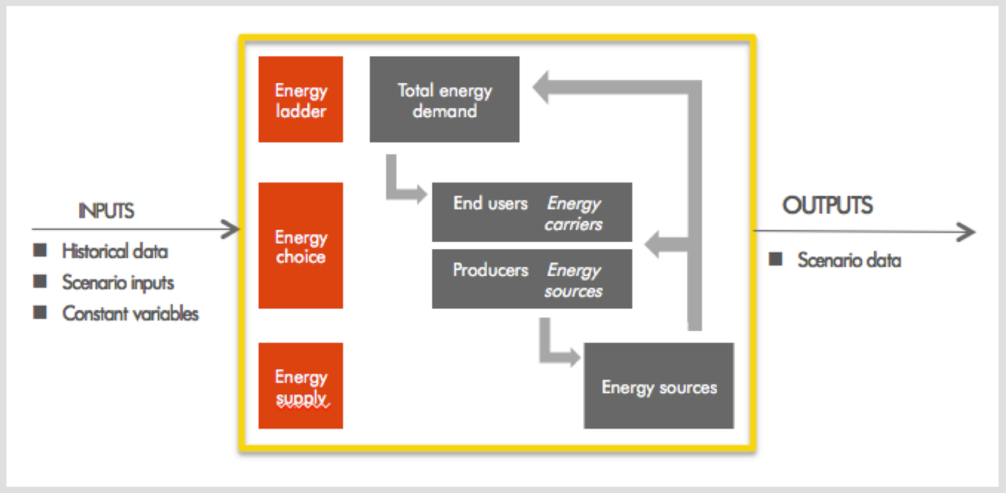


Figure 43: Opening up the black box: the model engine

6.1.2.1 THE ENERGY LADDER

The Energy Ladder represents the way aggregate energy demand responds to changes in prices and incomes (GDP). The assumption is that as people get richer they will want to use more energy. However, this is not a linear relationship: it tends to follow an S-curve. Country A might be on a different point on the S-curve than country B, or might follow an entirely different S-curve. Figure 44 shows an example of a number of energy ladders from various countries, in which the energy consumption for different GDP levels per capita is presented. For example, the upper blue line presents the energy ladder of the U.S. (USA). After income, price is the second most important factor determining the long run energy demand in a country. A series of economic estimations using fixed effects panel data regressions is ran to establish the relationship between energy demand and income and price, while controlling for unobserved variables such as technological change.

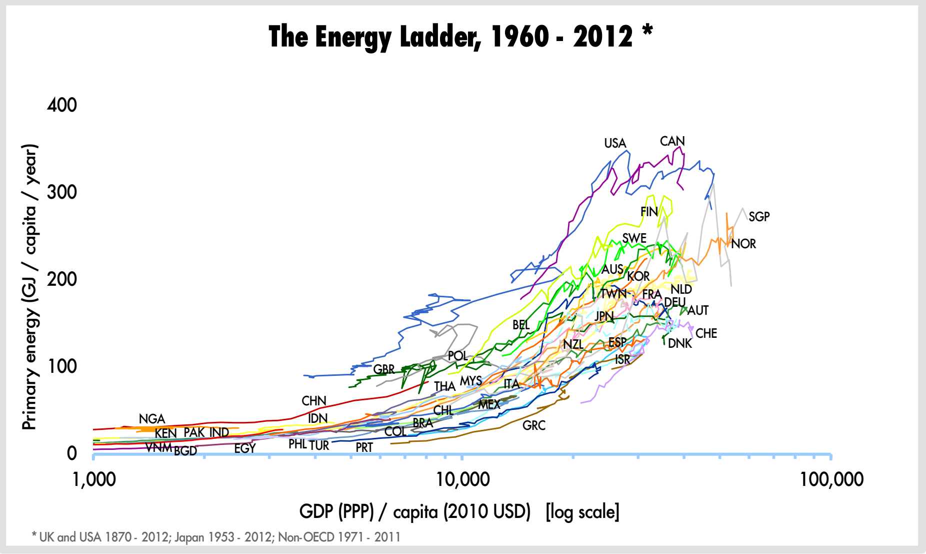


Figure 44: Example of energy ladders of various countries (from the WEM)

6.1.2.2 THE ENERGY CHOICE

The Energy Choice is a two-stage process to determine the energy mix. In the first stage, the final forms of energy (electricity, gasoline) to different end-use sectors are assigned (heavy industry, transport, residential heating, etc.). The second stage takes the demand for these energy carriers and seeks to meet those by drawing on the energy sources. The WEM uses the multinomial logit discrete choice methodology, which is a behavioural approachwhich represents how people choose between technologies and how they change their choices in response to prices, preferences or policies. It takes a generalised price (utility) for each energy type available. The formula (for every energy type) that is used is:

(1) Generalized costs (utility) = 'fuel convenience factor' + X_1** energy cost +* X_2** unitised capital costs*

(2) Energy cost = operating costs / efficiency

with X_1 and X_2 being parameter estimates. The fuel convenience factor represents the end-user's choice for energy carriers for other reasons than cost of the energy or the cost of the equipment to run it. For example, people can prefer cooking with gas rather than with coal, resulting in a negative factor for coal.

6.1.2.3 ENERGY SUPPLY

The Energy Supply is a representation of the supply potential for each of the energy sources (e.g. oil, wind energy). It is a combination of build-rate constraints, physical supply potential, cost-of-supply curves for renewables, and scenario-dependent supply outlooks.

6.1.3 THE ENERGY SYSTEM

6.1.3.1 SEGMENTATION

In the WEM the energy system is built up in the sub-systems as explained in section 4.2.1 (see also appendix D1). Figure 45 shows this segmentation more comprehensively. The steel industry is captured by the yellow box *industry & services* under *heavy industry.*

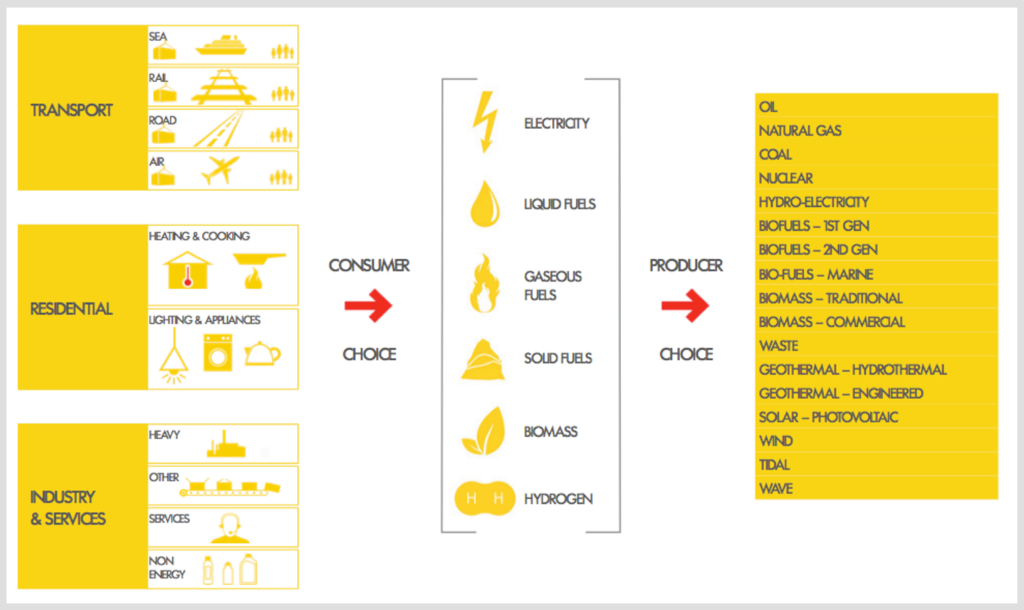


Figure 45: Segmentation of WEM

6.1.3.1 ENERGY SERVICE VERSUS ENERGY DEMAND

In order to link the choice for energy with economic measures in the model an important variable is used, called *energy service*. The economic estimation is based on final energy demand, measured in terajoule (TJ). However, the requirement for a user is for energy service. This is for example the kilometres an agent can travel by car rather than the MJ of gasoline, diesel, gas or electricity consumed to do so. The *Energy Service Efficiency* (ESE) is the end-users' efficiency in using energy carriers. This value is important when comparing technologies. In this research the energy service efficiency in mega joules (MJ) per tonnes of steel is key. The following formula applies:

*(3) TFC (MJ) = Energy service (in tonnes of steel) * ESE (in MJ/tonnes of steel)*

With the historical data the WEM calculates the ESE as the TFC and the energy service are known. However, for the scenarios (the future years) the TFC is unknown and depends on changes in the ESEs and hence, a data set with ESE inputs is required.

6.1.4 MODEL INPUTS

6.1.4.1 HISTORY INPUTS

Historic data inputs (1960-today) for TFC and TPE is provide by the International Energy Agency (IEA) for TFC and TPE is used. The WEMs segmentation is based on the categorization of this data and is therefore well aligned. This research focuses on the steel industry. However, as the WEM is a top-down model, the level of depth is confined. In the WEM, the steel industry would fall into the heavy industry sector, which is the most in depth the model goes with regards of sectors. Hence, one step more into depth is necessary to model the steel industry. Therefore, historical input data in the model for heavy industry is replaced by historic data from the steel industry (also provided by the IEA). How this is done is presented in appendix D2.

6.1.4.2 SCENARIO INPUTS

Drivers of a system are key for the development of qualitative scenarios as well as for modelling of the scenarios, as the drivers define the data trends that serve as input for the model engine. In total 72 parameters serve as scenario input for the WEM calculations. The full list of parameters and explanation is presented in appendix D3. For each of the parameters standard data sets with scenario data from today to 2050 are already implemented in the WEM. This data is withdrawn from various sources, including the EIA and Ecofys. For every parameter a choice can be made between two to four data sets. A choice is made for every parameter by adjusting the buttons linked to the spreadsheets in the scenarios Excel file. By analysing the trends in the data sets, the best corresponding data set for a scenario can be chosen. However, some data sets require manual adjustments in order to make them more specific to the subject of interest. When this is necessary a new data set is created and implemented in the model. Each driver can affect the calculations through one or more parameter inputs in the model, depending on the driver and the parameters available. A challenge lies in the synthesis of the drivers defined in the scenario workshop and the set of parameter inputs that is available to include drivers in the WEM.

6.2 MODELLING STRATEGY AND ASSUMPTIONS

To model the scenarios the following steps are taken:

1) Take the list of identified drivers and decide for each of the drivers through which parameter the effect of the driver is included in the model. Drivers that do not have a causal relation with one of the parameters are not included at this point.
    - This step is shown in appendix C2.

2) Check for these parameters the data sets that are available, and check whether or not manual adjustment of a data set is necessary.
    - This step is shown in appendix D4.

3) If manual adjustment is necessary, define how this should be done.
    - This step is explained in section 6.2.1.

4) Choose for the parameters that were not linked to a specific driver, which is the most suitable data set for the corresponding scenario.
    - This step is also shown in appendix D4.

5) Model the results and validate the results. This is conducted by running a number of tests and the output is validated with the WEM experts.
    - This step is discussed in a separate section (section 6.3).

6) Reflect on the modelling exercises and discuss why certain drivers did not match with the parameters in the model and provide recommendations for future similar research. Also, discuss how the drivers would affect the results obtained.
    - This step is explained in a separate section (section 6.4).

6.2.1 MANUAL ADJUSTMENTS OF DATA SETS

6.2.1.1 ENERGY LADDER INPUT ADJUSTMENTS

In terms of energy ladder inputs, the three-step method for calculating the ESE - the total energy use per tonne of steel - is adjusted and explained below. The aim is to create a data set from today to 2050 with the ESE values per year. The accompanying Excel file is presented in appendix D5.

- *(1) Energy efficiency (MJ/tonne of steel)*

First, the energy efficiency of the analysed technologies under R&D was identified. The analyses of technologies currently under R&D in section 4.2.2.2 formed the basis for the step. A data set with the energy efficiency per year and per technology had to be created. For simplification, it is assumed that four technology pathways are available in the future, namely the current available integrated route and the EAF route, as well as two paths of radically changing technologies that become available in the future. The latter two routes are segmented in *electrical*, which are the technologies that have electricity as their central energy fuel focus (including MOE and ULCOWIN), and *other*, which are the technologies that have another type of energy fuel as their central focus (including TGR, PSH, HIsarna, and HFS). When data could not be found for certain years, linearization (to the years where data was available) was applied for the years that were unknown.

Even though CCS was also on the list of technologies under R&D that were analysed, it is not included in the following calculations, because the technology is not applicable to the ESE calculations for the steelmaking process. The development around CCS in each scenario is included in other scenario inputs in the model, including 'CCS end-user' and 'CCS producer' (see appendix D4). It is assumed that the development of total energy use per tonne of steel per technology is the same for both scenarios. Also, the technologies become available at the same time in both scenarios. Finally, the outcome is a table with the efficiency per year (2014-2050) per each of the four technology pathways.

- *(2) Split of efficiency per energy carrier*

The WEM requires a split of energy efficiencies per fuel type. However, in literature the fuel mix of the technologies under R&D is not specified; often only a percentage improvement or new level of energy efficiency is provided. In the WEM the choice for a fuel type is simplified and is – in addition to economic considerations - based on the how much MJ of that fuel is necessary to produce one tonne of steel. For example, if compared to fuel A, fuel B needs more MJ to produce one tonne of steel, than fuel A has the preference in the model calculations with regard to the technical aspect of choice.

Because in literature the mix of technologies under R&D are not described, and because the WEM simplifies significantly in this respect, big assumptions have to be made in this step. It is chosen to link each of the fuel types to one technology pathway (see table 6). For all four technological pathways it is decided what fuel type is closely related to that pathway. For technology A and B this is relatively easy as they can be linked with the highest share of energy fuel. For technology C and D this is slightly more difficult; the technological pathway is linked to that fuel type that is radically different from the others in that particular pathway. For solid hydrocarbon fuels, heat and biomass an approximation was made of the fuel efficiency. A lower efficiency was assumed, so that the WEM automatically chooses other types of fuels for the energy use. This is line with the assumption that these kind of fuels are usually not used in steel production.

Energy carrier	Appointed energy efficiency
Liquid hydrocarbon fuels	Technology A
Solid hydrocarbon fuels	Low efficiency
Gaseous hydrocarbon fuels	Technology B
Electricity – Commercial	Technology C
Hydrogen	Technology D
Heat – Commercial	Low efficiency
Biomass – Commercial	Low efficiency

Table 6: Simplification of energy service efficiencies

- *(3) Energy service efficiency (tonne of steel/MJ)*

To obtain the energy service efficiency of a specific fuel type, 1 was divided by the efficiencies from above.

6.2.1.2 ENERGY CHOICE INPUT ADJUSTMENTS

In the scenario inputs with regard to the choice, manual adjustment for the parameter *fuel convenience factor* for certain energy carriers is necessary. If the factor is positive this has a positive effect on the utility and if the factor is negative the energy carrier gets a lower utility. To represent the policy measures focusing on cleaner energy fuel use (e.g. hydrogen), the fuel convenience for hydrogen is set higher, which means there is a positive preference for hydrogen and this is reflected in the final utility. Other drivers that are represented through fuel convenience factors are government support for new technologies, and mandatory fuel policy. How the fuel convenience factor is adjusted is presented in appendix D6.

6.2.1.3 ENERGY SUPPLY INPUT ADJUSTMENTS

No manual changes were made on the supply side of the scenario inputs, since this was not the focus of the research. Only the standard scenario input buttons where changed, and followed logically from the scenario storylines (see appendix D4).

6.3 MODELLING AND VALIDATION OF THE RESULTS

A systematic approach was taken for the modelling. One parameter at a time was adjusted, and subsequently the effect of this change on the output was analysed. For every parameter a relatively high value and a relatively low value were tested. By doing this, the range in the final output graphs where the driver could have effect on became visible. With trial-and-error the input data is adjusted in line with the scenario narratives.

If the output varied significantly with the scenario, a reverse engineering strategy was pursued. Changes in inputs as a result of the reverse engineering had to be checked for compliance with the drivers. In case of non-compliance, there were three possible options: (1) the adjustment of the data was too significant, (2) there was an error in the data or (3) there might have been a constraint or error in the model (e.g. theoretical limits of a technology) that affects the data. In this case more in depth research is necessary or WEM experts need to be consulted. The first occurred a number of times (e.g. during the adjustments of the fuel convenience factor). The second occurred a couple of times when a small typo was made, but this often could be resolved easily. The third option was not experienced. The final results of the modelling are presented in appendix D7.

For validation of the results a number of tests were conducted during the modelling and after the modelling of the scenarios. Starting with testing a very high value and very low value a first step towards understanding the effect of changing a value was obtained; the output range became visible. As an additional step for every adjustment, the effect of a 10% change in a variable on the model output was considered. If this was above 200%, then additional research was performed to confirm this. Finally, the results were checked with WEM experts.

However, the question remains: are the results acceptable? This is a difficult question to answer as the results show scenarios and not predictions. Indeed, the results are plausible, but no probabilities can be assigned to the likelihood of each scenario occurring. A reasonable range of uncertainty to consider in the output graphs is around 0.2 EJ/year (energy carrier).

6.4 REFLECTION ON THE MODELLING EXERCISES

In this section is reflected on the suitability of the WEM for these types of problems. It is analysed to what extent translating the qualitative scenarios (based on drivers) about energy transition to qualitative data through parameters in the WEM is possible. The U.S. steel industry scenario modelling exercise is seen as a pilot case for modelling a sub-industry of heavy industry. Experiences are drawn to a wider perspective, in order to enhance future research with the WEM in other heavy industries (e.g. aluminium or pulp and paper).

6.4.1 GENERAL CONSIDERATIONS

During the modelling exercises a number of considerations came forward. Firstly, due to the limited segmentation of the model, if the WEM is used for a more detailed segmentation than heavy industry it requires adjustments in historical data to align it with the specific industry at hand. The IEA has data available that is more segmented than the level of segmentation in the WEM. This data can be acquired from the IEA. One disadvantage is that the data is not publically available and a fee needs to be paid in order to access the data.

Secondly, long-term data is necessary for the scenario inputs. Whereas for certain parameters data sources provide long-term data with predictions or scenarios (e.g. Ecofys or IEA), for some parameters these data sets do not exist. In this case the data sets need to be newly created and this requires significant research efforts and time. For example, much research about the newest technologies under R&D had to be conducted for the ESE steel production assumptions. Also, the data available is often incomplete and does not provide a parameter value for every year under consideration. This requires assumptions to be made, for example about the rate of innovation.

Thirdly, the *fuel convenience factor* is a parameter that can be easily manipulated to directly influence the output results, as this factor affects the utility of an energy carrier and thus the choice for this energy carrier. However, this is also an ambiguous parameter as multiple drivers could affect the fuel convenience factor at the same time, potentially resulting in contradicting forces. The challenge therefore lies in deciding how much to in- or decrease this factor (from -10 to 10). The effect should be tested with trial-and-error in order to obtain the outputs that seem to fit best. However this judgement is relatively ambiguous.

Finally, the model is relatively user friendly and necessary data can be easily adjusted. As the model is based in Excel the links between data can be easily tracked. Regardless of the level of complexity due to the many parameters included and its long term focus, the model only takes a couple of minutes to run. This makes it possible to run the model many times and to analyse the effect of one adjustment on the model outputs. The scenario outputs automatically show in the various output graphs in the output file, which is convenient for analysing the output.

6.4.2 SYNTHESIS OF THE QUALITATIVE DRIVERS AND THE WEM

6.4.2.1 TESTING THE SUITABILITY OF THE WEM

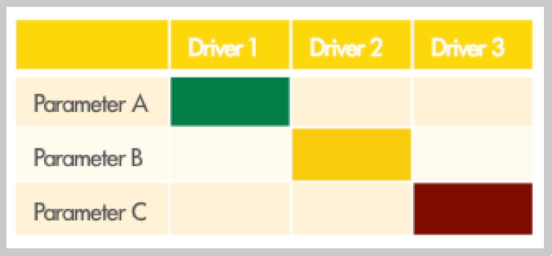
During the modelling exercises some difficulties were experienced in translating the drivers from the workshop to the WEM parameters. For some drivers a mismatch existed with the model parameters, and as a result some drivers were difficult or not possible to implement in the model. This raises questions about the suitability of the WEM for this specific case of quantifying long-term energy scenarios for the U.S. steel industry, but also about the suitability to similar type of problems in other heavy industries. The aim of this section is to test whether or not the WEM is suitable for translating and linking qualitative drivers - of energy transition problems in heavy industry - to the parameters that are built in the model. In this section the challenges in content or availability of data inputs are not included in the analysis as this can vary per industry. The focus is on linking the drivers to the parameters, and the ability of the WEM to link all drivers to at least one of the parameters so that the effect of the drivers is incorporated in the model calculations.

Darmani et al. (2014) conducted an in-depth literature review concerning literature that identified drivers for the development of renewable energy technologies (and the energy sector's technological transition, and analysed what the drivers are that are relevant for this transition. This resulted in an overview of the typical systemic drivers and a comprehensive typology and categorization of drivers. This is categorization is relevant for testing the suitability of the WEM because (1) although the typology is made for drivers that affect 'renewable energy technologies and energy sector's technical transition' and not for 'energy transition to cleaner energy fuels' this implies practically the same (2) it provides a useful overview of all drivers that could be relevant in the case of energy transition, and (3) it provides a framework to cluster the drivers from the workshop in order to analyse for every driver category whether or not this category was implementable in the WEM.

In the following paragraphs is explained how the suitability of the WEM is analysed and how the typology is used.

6.4.2.2 THE CASE OF THE U.S. STEEL INDUSTRY

In this step is - for each driver for change in energy use in the U.S. steel industry that was identified in the scenario workshop - analysed if and through which parameter it can be included in the model. A framework was created with the WEM parameters vertically and the drivers horizontally. For each of the drivers was checked whether it had a causal relation with one or more of the parameters. If this was the case a colour was given to the linking square. In appendix D8 the framework and colour coding is presented. Three colour codes exist (see figure 46 for an example):



	Driver 1	Driver 2	Driver 3
Parameter A	🟩		
Parameter B		🟨	
Parameter C			🟥

Figure 46: Linking the drivers and parameters

1) Green: in this case the drivers that had a direct link with at least one of the parameters and could thus be included in the model calculations through this parameter.

2) Grey: in this case it was ambiguous if the driver had a direct link with a parameter. For example, it occurred that a driver did have causal effect on a parameter, however, that this parameter was also the effect of many other causes (e.g. the effect of availability of R&D funding on the churn rate). What also occurred was that a driver did not have a direct link with a parameter, but could have an indirect affect on a parameter (E.g. government support for technologies leads to better commercial technologies and thus to a higher energy service efficiency). Another option was that a driver did not have a direct effect on a certain parameter but that a parameter could be used to represent the effect of a certain driver (e.g. price of iron ores affects the choice for the integrated route, and coal prices also affect the choice for integrated route, so by changing the coal prices the price of iron can be indirectly included through the coal price). These options are relatively ambiguous and were therefore not included in modelling the scenarios in this research.

3) Red: these drivers had no direct link with one of the parameters and were not included in the modelling. The reason for this could be the drivers were or outside the scope of the model (e.g. ramp-up of production outside the country of research) or that the driver concerned a too detailed level (e.g. consumer demand for quality). Another option was that the driver was both a cause and result (e.g. CO_2 emissions), which made it difficult to implement. Finally, the driver could be difficult to quantify or was too unclear (e.g. consumer behaviour).

The framework that was developed can be used in future similar scenario research for the steel industry, because it shows for typical steel industry drivers through what WEM parameter the drivers can be included in the calculations and that certain drivers cannot be included in the model. This could save time and efforts. Also, it supports to better understand what the model advantages and lacking features are, which helps to enhance analysis of the outputs.

6.4.2.3 GENERALIZING TO HEAVY INDUSTRY AND TYPOLOGY

Subsequently the drivers of energy transition in the U.S. steel industry are analysed to see if they are only applicable for the steel industry or that they are also applicable to heavy industry in general. If this is not the case, it is analysed if the driver can be rewritten to a more generalized driver so that it applies to heavy industry in general (e.g. *steel demand* becomes *demand for product*). The full list of generalized drivers is shown is appendix D9.

After that the generalized drivers are categorized according to the typology by Darmani et al. (2014). The results are presented in figure 47. The same colour coding is used to reflect the possibilities for matching the drivers with the WEM parameters.

By analysing the typology overview, conclusions for certain parts of the categorization, and thus the type of drivers the WEM can include, can be drawn based on the U.S. steel industry case study that was conducted. In general, drivers with regard to *actor's competencies* and *energy policy institutions* are well implementable in the WEM. Drivers concerning *soft institutions* (market and social norms) and *regional attributes* are cannot be implemented in the WEM. For drivers regarding *economy*, *technology specifications* and *technological infrastructure*, no direct link with a parameter is visible. These drivers can be implemented through other non-directly related parameters, however this is highly ambiguous.

No statements can be made with regard to the categories *targets*, *structure*, *strength of supply chain network*, and *societal network*, because in the U.S. steel industry case no drivers were identified in the scenario workshop and tested for inclusion in the model. It could be the case that in other heavy industries drivers in these categories are present, and that they can or cannot be easily implementable in the model.

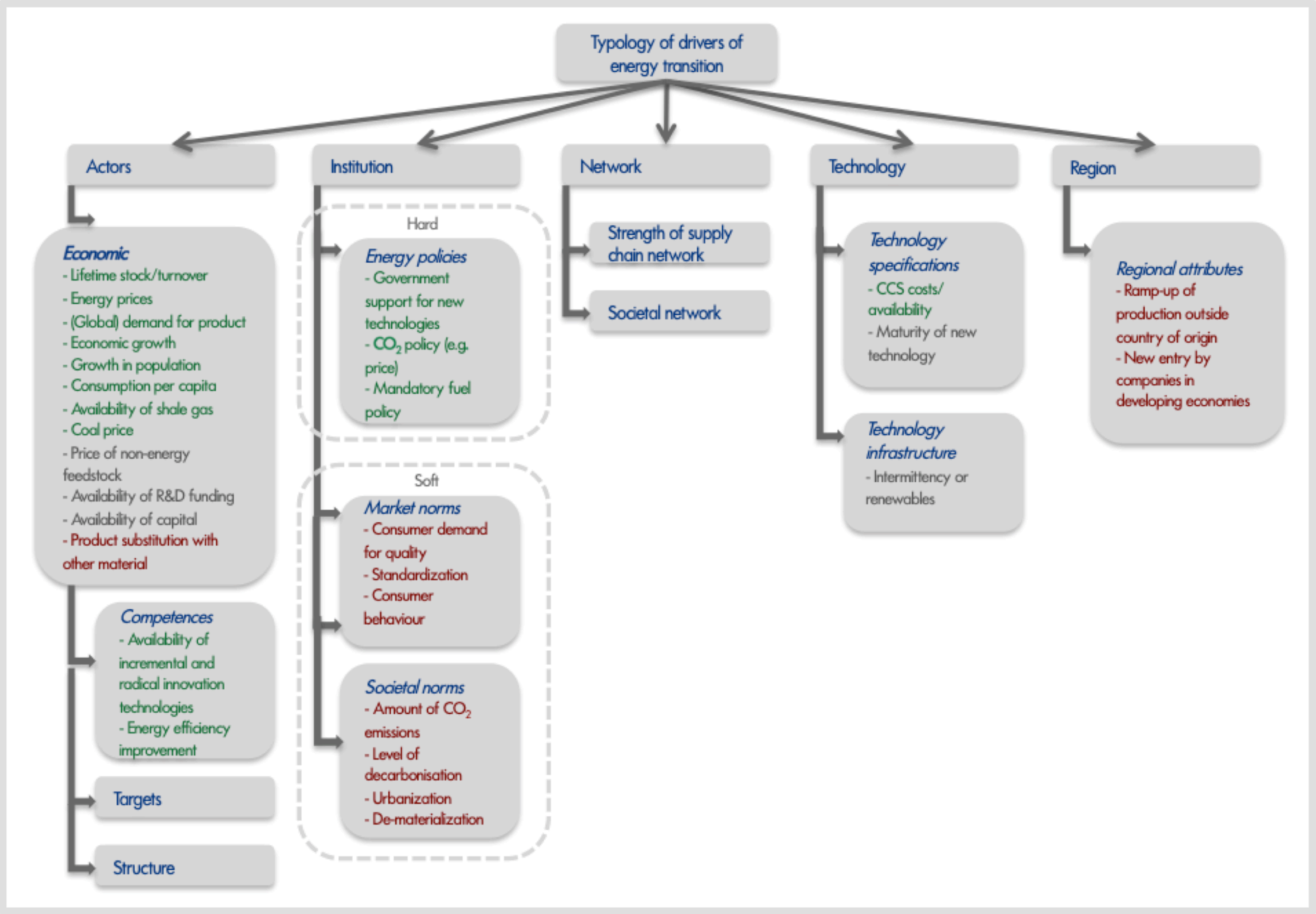


Figure 47: Typology of drivers of energy transition in heavy industry

6.4.2.4 RECOMMENDATIONS FOR FUTURE USE OF THE WEM FOR HEAVY INDUSTRY

For similar future research with the WEM about energy transition in heavy industry the following recommendations are provided. Firstly, the inclusion of drivers concerning soft institutions is not possible in the WEM. Therefore, if in a heavy industry sector many soft drivers play an important role the WEM is less suitable for modelling the scenarios, and is recommended to not use the WEM.

Secondly, incorporating drivers with a regional attribute origin cannot be implemented in the WEM as the model analyses only at country level (or region level) and no trade flows between countries (or regions) are included. It is recommended that for research whereby international drivers play a large role first an extra module should be built in the model. This module should reflect forces of international drivers on the system. The building of such a model is feasible as they have similar existing types of models in Shell. This would only require time and efforts to be invested.

Thirdly, a big improvement in the model could be made if an extra step that defines the demand for a product can be added. By doing this various parameters that can have affect on the demand (e.g. substitution for other material or urbanization) can be linked to it, where after the energy use can be calculated. This is however relatively challenging as the model bases its demand calculations on TFC and ESE (see formula 3) and it includes no inputs on energy service. This step requires relatively big changes in the model.

Finally, since the WEM is a multi-usable model for various countries and industries, the chance that certain identified drivers are cannot be linked to one of the parameter inputs is highly probable. Therefore it is important to take a moment to re-evaluate the output and analyse what effect non-included drivers could have had on the output graphs.

6.4.3 RE-EVALUATION OF U.S. STEEL INDUSTRY OUTPUT

For the U.S. steel industry a significant number of drivers could not be included in the model. Firstly, an important driver was the iron ore price, which could not be implemented in the model. However, since this driver was one of scenario framework axes, the full scenario narratives and driving forces were based on this driver, and by implementing the other drivers it was indirectly included in the model.

Secondly, the steel industry is a global market but in the WEM the international forces could not be modelled. If these driving forces were included in the model, the energy use would probably be lower as ramp-up of steel production in emerging economies would exert significant pressure on the U.S. steel market.

Thirdly, the driving forces that were too detailed could not be modelled. For example, in the model the product was steel, but it does not distinguishes between various qualities of steel. For the driver *consumer demand for quality* one could argue that for higher quality steel more energy is necessary and thus in Quarterback the energy carrier use increases.

But what if the model was able to also incorporate the non-included drivers? What would the affect be on the output results? That is difficult to say, because some have a positive effect on the energy carrier consumption and other a negative effect. In general can be concluded that the WEM is quite suitable for modelling large part of the U.S. steel industry drivers, but for a number of drivers it is not possible to include them in the model.

6.4.4 READING GUIDE

In this chapter the synthesis of the qualitative scenarios based on drivers and the quantitative modelling with the WEM was analysed. The modelling experiences are shared to enhance future research. The modelling results showed what the energy consumption behaviour of the steel producers and the energy system look like in the two scenarios. In the next chapter the results and implications are analysed.

7. IMPLICATIONS OF THE SCENARIOS

The aim of this section is to explore what the implications of the scenarios are (step 7 from Schwartz, 1991). Following this research's methodology, the implications for three stakeholders and the energy transition is addressed. Firstly, the implications for the key stakeholders of this research, the steel producers are analysed. In this section is returned to the focal question: *how will the U.S. steel producers change their energy use between now and 2050?* Based on this the implications for the energy transition are discussed. In addition, the interfaces between the steel producers and two other important stakeholders are addressed, namely policymakers and Shell (see figure 48). And finally, scenario signals and signposts are identified.

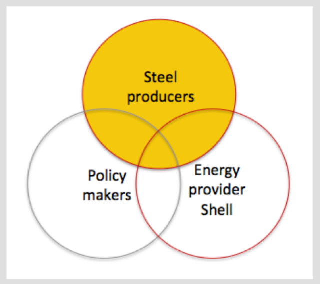
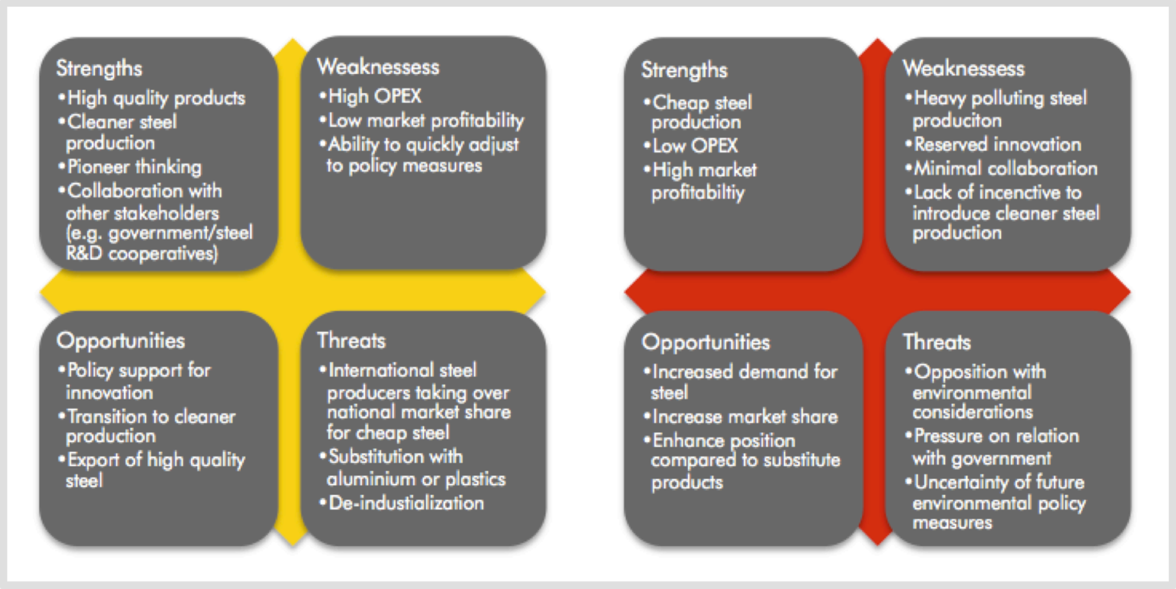


Figure 48: Interfaces between three important stakeholders in the steel industry

7.1 SCENARIOS FOR THE U.S. STEEL PRODUCERS

7.1.1 FROM CONTEXTUAL ENVIRONMENT TO TRANSACTIONAL ENVIRONMENT

The scenarios sketch two possible contextual environments for steel producers. But what does this mean for the steel producers in the system? A SWOT analysis is conducted to analyse the position of steel producers in the system in Quarterback and Wide Receiver (see figure 49). For steel producers in Quarterback strengths and opportunities lie in high quality and cleaner produced steel, whereas weaknesses and opportunities include high OPEX and intense competition. For steel producers in Wide Receiver strengths and opportunities lie in low OPEX and increased market share, whereas the weaknesses and opportunities include lack in innovation and environmental opposition.



Strengths
- High quality products
- Cleaner steel production
- Pioneer thinking
- Collaboration with other stakeholders (e.g. government/steel R&D cooperatives)

Weaknesses
- High OPEX
- Low market profitability
- Ability to quickly adjust to policy measures

Opportunities
- Policy support for innovation
- Transition to cleaner production
- Export of high quality steel

Threats
- International steel producers taking over national market share for cheap steel
- Substitution with aluminium or plastics
- De-industialization

Strengths
- Cheap steel production
- Low OPEX
- High market profitabiltiy

Weaknessess
- Heavy polluting steel produciton
- Reserved innovation
- Minimal collaboration
- Lack of incenctive to introduce cleaner steel production

Opportunities
- Increased demand for steel
- Increase market share
- Enhance position compared to substitute products

Threats
- Opposition with environmental considerations
- Pressure on relation with government
- Uncertainty of future environmental policy measures

Figure 49: SWOT analyses for steel producers in the Quarterback scenario (left) and Wide Receiver scenario

7.1.2 CHANGING ENERGY USE OF STEEL PRODUCERS

The scenarios sketch the contextual environment of the system. The question remains though how the U.S. steel producers will change their energy use between now and 2050 as a result of a changing contextual environment. Firstly, modelling the total final consumption in the U.S. steel industry with the WEM for both Quarterback and Wide Receiver shows the following result (see figure 50).

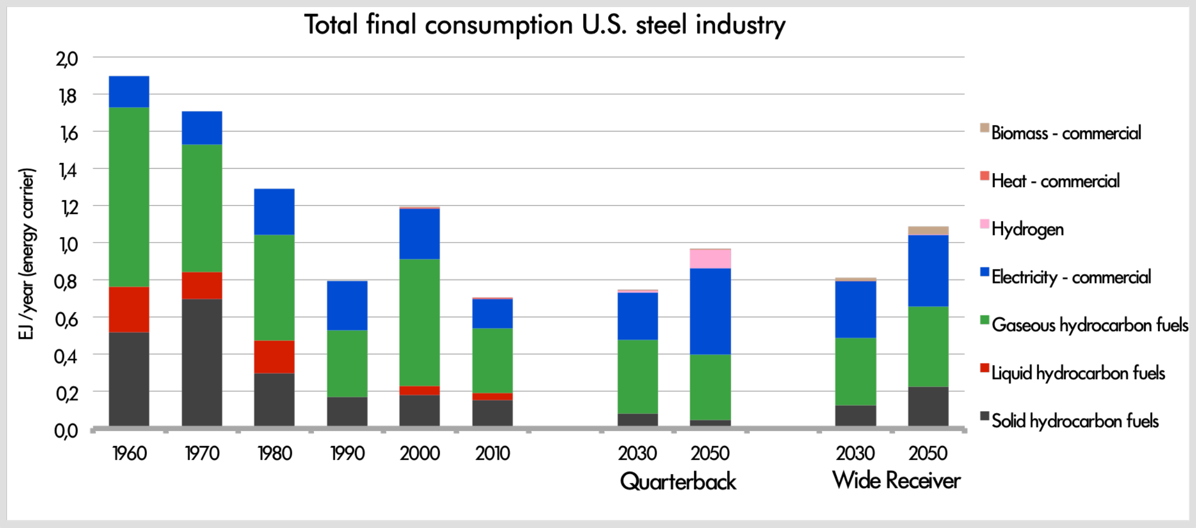


Figure 50: Total final consumption U.S. steel industry; historical (left), Quarterback (middle) and Wide Receiver (right)

For Quarterback the modelling shows that the industry changed from high hydrocarbon fuels (including coal) and natural gas use, to mostly electricity and natural gas. Only a small share of coal is used in 2050 and hydrogen was introduced as an energy fuel, mixed with natural gas, and as a reducing agent. Where the energy use mostly declined up until 2010, in the years to 2050 it increased again due to among other things growth in population, GDP and urbanization. Slightly lower than one exajoule (EJ) per year is consumed.

For Wide Receiver it shows that a large share of the energy carriers comes from electricity and natural gas. The use of coal in the integrated route increased, as the steel demand rose. In addition, commercial biomass is used for additional process heat. Hydrogen is only used as a reducing agent in improved integrated routes, but not as an energy carrier. The energy use rises above the one EJ of energy per year.

Secondly, the origin of the energy carriers in modelled with the WEM. Figure 51 shows the primary energy consumption by the U.S. steel industry up until 2050 for both scenarios. It shows that in Quarterback a relatively high share of the electricity and hydrogen from the grid comes from renewable energy. Around 25 per cent of the energy is produced by renewable energy technologies, with a high share coming from photovoltaic and wind energy. 75 Per cent of the primary energy production comes from mostly natural gas, coal and nuclear energy. Approximately 40 per cent of the hydrogen is made from electricity.

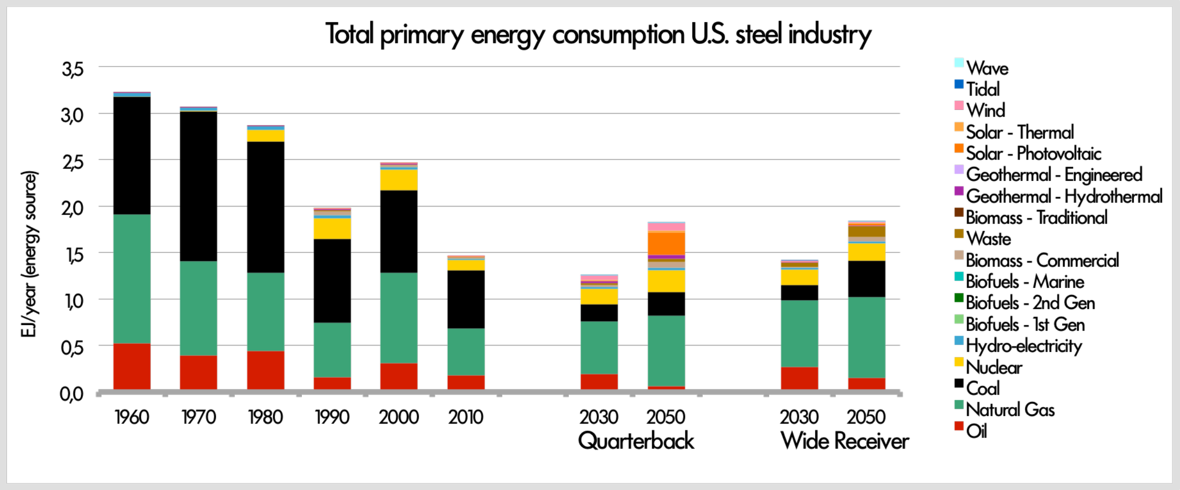


Figure 51: Total primary energy consumption by the U.S. steel industry; historical (left), Quarterback (middle) and Wide Receiver (right)

For Wide Receiver it shows that the transition to energy from RES has been disappointing; less than fifteen per cent of the electricity comes from RES. The renewable infrastructure is limitedly deployed. Natural gas, and in particular shale gas has been fully deployed and concerns the largest share of primary energy production.

7.2 IMPLICATIONS FOR THE ENERGY TRANSITION

Returning to the overarching theme of this research - the energy transition – the two scenarios show quite diverse outcomes for the change in energy fuel use mix from today to the year 2050. Thus the relevant question is what the implications of the two scenario’s are for possible energy transition and ultimately decarbonisation.

Quarterback is the scenario that leads to a more beneficial outcome in terms of the energy transition. In this scenario the energy transition has been put in motion, mostly with the effort of the government. Technologies based on primarily coal inputs have been party discarded and replaced by technologies that are electricity or natural gas (and partly) hydrogen based. The pace of the transition is slowed down due to the slow development of technologies that can use cleaner technologies together with the fact that the turnover rate of the highly capital intensive facilities is low. Even with a relatively hard push by the government change to the cleaner energy fuels electricity and hydrogen can only be partly established with the technologies currently in the prospect for development. Especially hydrogen does not have a large role as an energy fuel as only a small share can be mixed with natural gas.

In the case of Wide Receiver the energy transition in the industry can almost be neglected. The shale gas revolution has increased the share of electric arc furnaces, and thereby the use of natural gas and electricity, but a large part remains the production of steel via the dirty integrated route. It can be concluded that in Wide Receiver the energy transition has not taken off yet, mainly again do to slow technological development and low turnover rate, but more importantly by the lack of incentive to innovate by the industry.

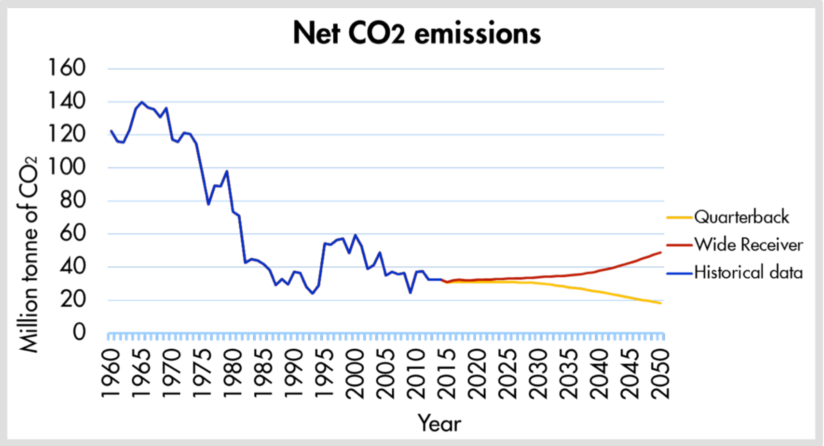


Figure 52: The net CO_2 emissions for the two scenarios

In figure 52 the CO_2 emissions of the steel industry in both scenarios are shown. In Quarterback the number of CO_2 emissions is significantly lower than in Wide Receiver. In this ‘green’ scenario the emissions fist stay constant for a number of yeas, and then slowly decrease after a number of years of stringent climate policy. This is striking because also in the scenario the energy use increases significantly. However, here the benefits of energy transition are visible; with more electricity and hydrogen as energy carriers less CO_2 is emitted. In addition, the deployment of CCS plays a role in the decreasing CO_2 emissions. In Wide Receiver the number of emissions also stay constant for a number of years, but slowly increase later due to the increase in demand due to population and GDP growth leading to increase in steel production. Since only incremental innovations took place the industry is not able to address the pollution problems.

Moving from the demand for energy to the choice for an energy fuel, there are a number of parameters that have significant impact on the utility in the years up to 2050, and hence on the choice for fuels. The most important ones being energy fuel costs, availability of funding and technologies (efficiency and fuel mix), and other influencing factors such as policy. In Quarterback the infrastructure for cleaner energy fuels such as electricity and hydrogen is further developed than in Wide Receiver, resulting in lower costs for those types of fuels, which in turn provides a better incentive to choose these fuels. This is closely linked with the stringent policy measures, which provide an even higher incentive. In Wide Receiver environmental policy measures are less stringent, and dirty fuels such as coal remain to be a cheap and easy fuel source. Furthermore, in Quarterback there is a higher incentive to invest in R&D and in new facilities, leading to a higher turnover rate. In Wide Receiver the turnover rate is lower due to lack of incentive to invest in improvements.

Finally, in the energy system the primary energy production also contributes to the resulting total CO_2 emissions from the energy use for the steel industry. This was not the focus of the research, but it can be assumed that in Quarterback a progressive green government will also put forward more stringent policy measures for primary production, with more renewable energy sources. However, the issue of volatility and intermittency is an important factor for the utility of consumption of fuels, which gives a high factor of uncertainty to the use of electricity and hydrogen, which include features of volatility if they origin from renewable energy sources. It can be assumed that in Wide Receiver combatting this problem is more actively addressed than in Wide Receiver. In addition, it should be noted that in theory it would be possible to produce all electricity and hydrogen used in the 'clean' steel producing technologies with coal and natural gas, which would abolish for a large part the efforts committed in the steel industry since the CO_2 is emitted in the beginning of the value chain in stead of in the end.

To conclude, what should be noted is that the steel industry can decide to some extent about what energy fuels they are using - e.g. choice for technologies – but large part of the choice is effected by many other factors - such as price of the fuels or the share of the grid that comes from renewable energy sources - on which the steel industry itself does not always can have an influence on. Therefore, in order for the energy transition to pursuit it is important to take a system perspective and to analyse the energy system as a whole, rather than an isolated energy consumer. Energy consumption, choice for energy and primary energy production are interconnected, and for an energy transition to take place each part of the system requires adjustments. This asks for a change in mind-set from the society as a whole.

7.3 INTERFACES WITH TWO IMPORTANT STAKEHOLDERS

7.3.1 ROLE OF POLICYMAKERS IN THE ENERGY TRANSITION

What policy recommendations can be derived from the research and developed scenarios? In the two scenarios a significant difference is visible with regard to the behaviour of steel producers and subsequently the extent to which energy transition is possible; in Quarterback steel producers consume cleaner energy and is greater energy transition visible. The policy environment in Quarterback provides the incentives to drive the industry towards cleaner energy consumption and as a results faster and larger energy transition. Comparing today's policy environment with the policy environment in Quarterback it shows that significant changes occurred as the environmental measures are more intensified. Hence a gap between today's policy environment and the policy environment in Quarterback in 2050 can be revealed.

Quarterback reveals that policymakers can trigger energy transition in the U.S. steel industry as they have significant power to influence the industry with policy measures. Grubler (2012) identified three characteristics of successful policies and energy innovation systems that drive energy transition; measures must be *persistent and continuous*, *aligned*, and *balanced*. However, it is argued that in the current system policy frameworks in place invariably do not meet these criteria and require adjustments in order to successfully trigger energy transition in the industry (Grubler, 2012).

How should environmental policy measures be developed in order for it to provide the required incentives to trigger energy transition, but at the same time support economic growth in the industry? Taking into account the three characteristics of successful policies and energy innovation systems that drive energy transition developed by (Grubler, 2012), firstly, the measures must be *persistent* and *continuous* in that a long term CO_2 abatement system should be established that provides the right incentives for steel producers to radically innovate and that creates an equal play ground for all players in the market. With a vigorous, but clearly shaped long-term plan, the industry has more certainty about the future playing field and can adjust its strategy accordingly. The CO_2 price needs to be at least significantly higher in order for it to provide the incentives to invest in cleaner technologies.

Secondly, the measures need to be *aligned* - nationally and internationally. Aligning policies nationally is key as knowledge generation via R&D and applied knowledge generation and validation through early market applications can diffuse through other parts of the country, in order to create a competitive advantage compared to other nations. Aligning policies internationally is important to prevent 'leakage' of steel producers that move or start their business in areas with less stringent environmental policy measures, and to stimulate an equal playing ground. Active participation in national and international climate debate to collectively develop the necessary measures is key.

Finally, the policy measures need to be *balanced* in that the measures should be established taking into account the challenges that the steel producers need to face when stringent measure take effect. In order to prevent the steel industry from immediate extinguishment with the stringent policy measures policymakers should start the discussion with instead of for the steel industry, even though in the first place steel producers might be reluctant to change. Collaborative effort is necessary to develop new technologies and to establish funding for R&D and deployment. The government has an important role here as the steel industry already encounters low profit margins and has less room to manoeuvre.

In order to be able to provide more detailed policy recommendations further research is required. This could focus on energy transition in other parts of heavy industry. The question is whether in other highly energy intensive industries, with other processes, limitations for energy transition exist as well. Also, the revealed policy gap and the detailed design of policy measures to enhance energy transition require more attention. The scenarios can support in future research to 'test' measures for robustness, for example with regard to the deployment of CO_2 pricing schemes.

7.3.2 THE ROLE OF SHELL

Today Shell is primarily active in the U.S. steel industry as an energy carrier producer of oil and natural gas and with electricity trading in the wholesale market. As a stakeholder a number of important considerations for the position of Shell in the future market are revealed in this research.

In the future there are three areas of shared interest of Shell with the two other stakeholders; steel producers and policymakers. Firstly, for Shell – just as for steel producers and policymakers - it is of paramount importance to map the future demand for energy. As an energy company Shell feeds energy into the electricity grid and natural gas whole sale grid. Since the steel industry is one of the key consumers of energy in the U.S. their demand influences the total energy demand from the grid, and indirectly from Shell significantly. Hence understanding of the possibilities for and limitations to an energy transition to other carriers than oil and gas is essential for the long-term development of strategy.

The scenarios show that no oil is consumed in the steel industry, but that the use of natural gas increases, in Wide Receiver slightly more than in Quarterback. For natural gas it can be concluded that the long-term demand is robust.

With regard to electricity, Shell is currently involved in electricity trading in the wholesale market in the U.S., and the two scenarios affect this in two ways. Firstly, in both scenarios the electricity consumption increases, which brings more opportunities for traders. Secondly, the origin of the electricity mix changes as in the future the share of RES in the grid is higher. This can bring in other dynamics in the trading market due to the highly volatile character of RES. Hence it is advised for traders to organize an annually long term outlook review with Shell's Scenario strategy team to monitor the long term electricity related developments.

In terms of hydrogen, Shell could consider roles in the hydrogen production, infrastructure, or trading as many synergies with the core business of Shell exists. With years of experiences in natural gas Shell developed many competencies in gas production, infrastructure and maintenance of such systems. This strategy, however, is only robust in the steel industry in scenario Quarterback, as hardly any hydrogen is consumed in Wide Receiver.

Secondly, with regard to the interface between Shell and steel producers, Shell could play a role in the CCS market. As Shell has experience with underground gas systems and built up significant competencies, it could provide services to the steel producers whereby Shell is responsible for the CCS facilities in order to bring down the CO_2 emissions from the steel industry. Quarterback would provide more possibilities for commercial deployment of CCS, since the stringent environmental policy measures result in a higher CO_2 price, which in turn results in a higher incentive to put the emissions under the ground instead of paying for them to release them in the air. In Wide Receiver steel producers have less demand for CCS due to the relatively cheap CO_2 prices. Moreover, care should be taken in stakeholder management with steel producers as tensions between Shell and industry might arise. Where Shell prefers to see higher prices for CO_2 so that coal becomes more expensive than natural gas, the steel producers prefer to maintain the cheaper coal prices as this contributes significantly to the OPEX in the integrated route.

Finally, it is important for Shell to closely monitor and communicate with policymakers. As it aims to be a taught leader in the energy transition it should actively engage in the debate around the energy transition and the discussions for the development of a CO_2 abatement scheme. It is important to bring realism to the debate, as this research shows that limitations to an energy transition exist in the steel industry. This shows that energy transition can be more difficult in heavy industry compared to for example the transport sector, which is important for policymakers to be aware of when developing environmental policy that can affect Shell's business. In Quarterback stakeholder management with policymakers is of greater importance than in Wider Receiver, as in the first scenario the policymakers have more interest in the steel market and have more power in the market.

7.4 LEADING INDICATORS AND SIGNPOSTS

The final step (8) in conducting a scenario analysis by Schwartz (1991) is identification of leading indicators and signposts for the scenarios. Strategic development is a continuous process and decision makers should consistently monitor the external environment for indications and events that are moving in a particular direction. Identification of leading indicators and signpost help decision makers to use the scenarios to structure discussions and guide the thinking about the future.

In table 7 for every key driver a number of events that push the industry system towards one of the two scenarios. Certain events are specific to Quarterback and others to Wide Receiver. In addition is described how or what to monitor in the environment for the occurrence of such events. The list of events includes, but is not exhaustive to, the following leading indicators and signposts.

Key driver	Event Quarterback	Event Wide Receiver	How/what to monitor?
Price of iron ores	Price increases to higher than USD 150	Price decreases to lower than USD 50	Iron ore price indices
Environmental policy	Election of visionary politicians	Election of conservative politicians	Political news (e.g. CNN, NBC news)
	CO_2 price (tax or cap and trade) increases up to USD 70	CO_2 price stays below USD 70	Carbon Tax Centre; CO_2 price index
	International pressure for CO_2 abatement on U.S.	Reserved international pressure for CO_2 abatement on U.S	Outcomes climate conferences (e.g. United Nations); steel industry news (Forbes)
	Governmental support for R&D in cleaner technologies	No governmental support	Development of policy measures for subsidies; communication with collaborative steel institutes (AISI)
	Steel companies going bankrupt due to stringent policy measures	Steel producers do business as usual	Statistical data with number of steel companies (AISI)
Technology deployment	Break through of clean technologies (e.g. MOE, ULCOWIN)	Delayed break through of clean technologies	Inform with collaborative steel institutes or other steel producers;
	Renewable energy sources ±20-30% share of the grid	Renewable energy sources ±5-15% share of the grid	U.S Energy Information Administration
	Facilities are replaced before end-of-lifetime	Facilities are replaced at end-of-lifetime	Inform AISI; steel industry news (e.g. Forbes)
(Global) demand	Reserved urbanization	Significant urbanization	Statistical data U.S citizens per city (www.gov.org)
	Aluminium price around same as light-weight steel price	Significant price difference steel and aluminium	Price indices aluminium and steel
	High share of U.S. steel producers operate in niche market	High share of U.S. steel producers compete on lower quality high quantity steel production	Market analysis (e.g. McKinsey steel market review)
Location of supply	Competitive advantage of producing in U.S. is minimal	Competitive advantage of producing in U.S. is mediate	Analyse operating environments international steel producers
Role of recycling	EAF route produces significant high quality steel	EAF route produces significant lower quality steel	Measure quality steel and compare with integrated route; communicate with buyers
	Increase scrap import	Scrap abundant in market	Statistical data scrap import/export; scrap price index

Table 7: Leading indicators and signposts

7.4.1 READING GUIDE

At this point the scenarios analysis is completely conducted. The implications of the scenarios for the steel producers were analysed. Subsequently the effect of their behaviour with regard to energy consumption on the energy transition, client Shell and policymakers was discussed. In the last step of the scenario analysis leading indicators and signpost were identified that can be used by the industry stakeholders. In the final three chapters, the research conclusions, the value of the research and the research evaluation are discussed.

8. RESEARCH CONCLUSIONS

A scenario analysis was conducted in order to analyse the future energy consumption in the U.S. steel industry. Two scenarios– Quarterback and Wide Receiver – for the year 2050 were developed and the implications were analysed. An overview of the key characteristics is provided in figure 53. In this chapter is returned to the main research question: *What are the possibilities for and limitations to an energy transition towards the use of electricity and hydrogen as energy carriers (from RES) in the U.S. steel industry up until the year 2050?*

Scenario	Quarterback	Wide Receiver
Economy	• Squeezed economic growth • High iron ores prices • Cooperation to survive • Niche market	• Economy flourishes • Low iron ores prices • Individualism of companies • Also mass production
Policy	• Visionary politicians • Stringent environmental policy measures	• Conservative politicians • Reserved environmental policy measures
Technology	• Pushed to radically innovate	• Business as usual
Society	• Service-oriented economy • Job losses in industry	• Stay industrialized • More employment
Environment	• Environmental conservation	• Intensified pollution

Figure 53: Key characteristics of the two scenarios

8.1 POSSIBILITIES FOR ENERGY TRANSITION

Analysing the two scenarios revealed a number of possibilities for consumption of cleaner energy carriers. Figure 53 shows the possibilities for energy transition in the two scenarios. Quarterback is the scenario that leads to a more beneficial outcome in terms of the energy transition as it shows that a significant transition to cleaner carriers is possible: 59% clean carriers in 2050 compared to 25% in 2014. In this scenario the energy transition has been put in motion, primarily with the push by the government. The integrated process that requires mostly coal inputs is party discarded and replaced by technologies that are more efficient and electricity or natural gas (and partly) hydrogen based (e.g. innovative EAF route technologies). An increase of the use of hydrogen is visible as this is mixed in the

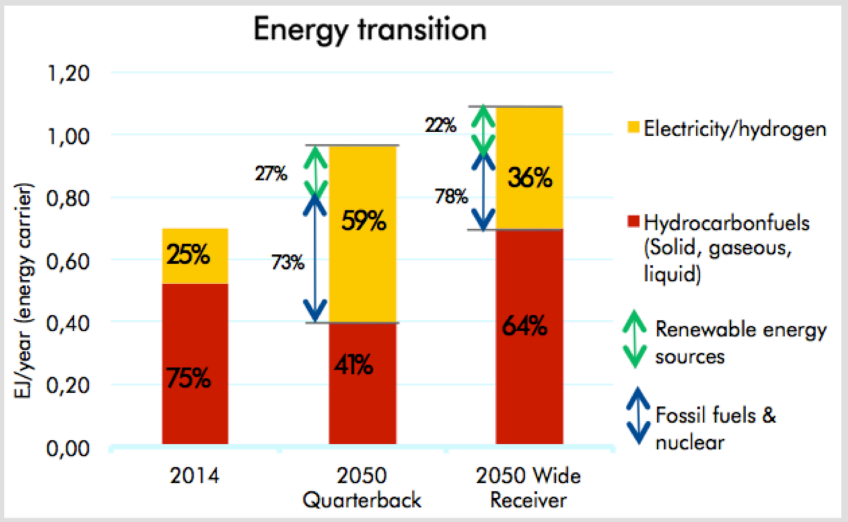


Figure 54: Energy transition in two scenarios

gas grid. In addition, hydrogen is used as a reducing agent in a number of technologies (e.g. HIsarna).

In the case of Wide Receiver the energy transition is highly reserved: 36% clean carriers in 2050 compared to 25% in 2014). Less stringent environmental policy measure did not provide enough incentives for significant change. Along with the low iron prices this resulted in continued production via the integrated route. The shale gas revolution has increased the share of the EAF, and thereby the use of natural gas and electricity, but a large part remains the production of steel via the polluting integrated route. Minimal radical innovation took place, and if it did the primary reason was the end-of lifetime of installed capacity. Hydrogen is used as a reducing agent in innovated integrated production, but not as an energy fuel mixed with natural gas in the grid.

Even though the use of electricity and hydrogen increases, this does not automatically means that these carriers come from the renewable primary energy sources. In the energy system the primary energy production also contributes to the resulting total CO_2 emissions from the energy use for the steel industry. Although primary energy production was not the main focus of the project it can be assumed that in Quarterback a progressive green government will also put forward more stringent policy measures for primary production. This results in possibilities for further deployment of RES and the infrastructure, as policy measures provide the incentives for cleaner production in the market and can organize and coordinate renewable energy production more centrally. The results of modelling with the WEM show that in Quarterback of the electricity and hydrogen that is consumed 27% comes from RES, with a high share coming from wind energy and photovoltaic. In Wide Receiver minimal central renewable energy production will be deployed. Modelling showed that of the electricity and hydrogen consumed, 22% comes from RES. Distributed solar energy will be the main renewable energy source, because this is easy to implement on an individual basis and for relatively low costs.

To summarize, in both scenarios possibilities for energy transition are visible. However, scenario Quarterback these possibilities are significantly greater due to on the one hand the replacement of installed technologies with radical innovations and on the other an enhanced renewable energy infrastructure.

8.2 LIMITATIONS TO ENERGY TRANSITION

Transition to the use of cleaner carriers is limited by a number of technical factors. Firstly, the technologies currently in a progressed stage of R&D reveal that no technology becomes available that can produce steel by only consuming clean energy carriers. Secondly, in terms of energy use it would be better to fully move to the use of the EAF route. However, the integrated route can produce better quality steel than the EAF route in which more (contaminated) scrap is recycled. Hence transition to production only via the EAF route is not possibly up until 2050, because the reviewed technologies under R&D cannot deliver the highest quality steel. Thirdly, mixing the hydrogen in the natural gas is limited by the fact that facilities connected to the grid are not optimized for hydrogen in the natural gas. As long as technologies are not adjusted accordingly, hydrogen more than 5-15% by volume results in damage and reduced efficiency.

Moreover, it should be noted that - in theory - it would be possible to produce all electricity and hydrogen used in the 'clean' steel producing technologies with fossil fuels, which would abolish for a large part the efforts committed in the steel industry since the CO_2 is emitted in the beginning of the value chain instead of in the end. In terms of energy transition in the full chain from production to consumption, the share of the clean carriers that comes from RES also limits the transition. In Quarterback this share lies around 25%, and in Wide Receiver this is only approximately 15 per cent.

Furthermore, the pace of the transition is slowed down due economical and institutional factors. Low churn rate of the highly capital-intensive facilities delays the process of replacement by new and cleaner technologies. As long as there is no economical incentive steel producers will keep do their business as usual. In Quarterback the availability of funding for investments is a significant issue. Mainly economical barriers play an important role. For Wide Receiver the policy uncertainty and lacking incentives for innovation cause issues in the industry, and would certain institutional measures be a way to overcome barriers (e.g. a CO_2 abatement system). In terms of primary energy production, funding for RES is an economic barrier for deployment. First of all the infrastructure must be in place, and secondly also the system integration is necessary to resolve the issue of intermittency. This requires both the necessary technological changes (e.g. smart grids) and institutional adaptions such as the common standards.

To conclude, the scenario analysis showed insights for key stakeholders, but above all, it helped to understand the possibilities for and limitations to an energy transition in the steel industry. In both scenarios, full decarbonisation of the industry with electricity and hydrogen is not possible in 35 years from now. The steel industry can decide to some extent about what energy fuels they are using (e.g. choice for technologies) but large part of the pace of an energy transition is affected by many other factors – for example the share of the grid that comes from RES - which the steel industry itself cannot always influence. Therefore, in addressing questions concerning the energy transition, it is of paramount importance to take a system perspective from which the energy system as a whole is addressed, rather than the steel industry as an isolated energy consumer. Energy consumption, choice for energy fuels and primary energy production are interconnected, and for an energy transition to take place each part of the system requires adjustments. In the coming years the scenarios can be used as a platform for further discussion, and creating common understanding and a coherent vision of how to decarbonise together as an industry.

9. DISCUSSION

This chapter discusses the value of the scenarios and findings about the energy transition. The links between the research findings, key societal issues, and scientific debates are discussed. Thereafter the limitations of the research are addressed and finally, recommendations with directions for future research are made.

9.1 SOCIETAL VALUE

The findings have a number of societal implications. As the population yearly keeps increasing and the demand for energy rises, CO_2 abatement is a necessity. From number of conferences can be concluded that climate change and CO_2 abatement are hot topics (Our Common Future, 2015; UN, 2014). The big question is in what pace and to what extent of the decarbonisation will take place. In both scenarios is visible that in the coming 35 years the steel industry remains a large emitter of CO_2. A question that can be raised is whether or not this will lead to significant changes for society in the long run. Will society keep bearing the costs for pollution, or can a disastrous environmental event change turn the behaviour of U.S. citizens around? Will the U.S. eventually shift to a fully service-oriented industry, and what does this mean for the economy?

The scenarios serve as a platform for further debate concerning the energy transition, and can stimulate prioritizing the issue on business and political agendas. The CO_2 problem is a society wide issue, and should therefore be tackled in the total energy system; a systematic approach is required. Every actor is a small part of the system and in order to address the CO_2 problem common understanding and shared goals should be created. The scenarios support in doing this.

The scenarios are also valuable for other countries, as it is representative for other market driven countries in general, and in specific established economies compared to the U.S. The reason for this is that the identified drivers often also apply in other market driven countries. For example the scenarios are valuable for a countries in Europe. The project findings are less representative for more policy driven countries such as China, as many other drivers play a role in these cases. The scenarios can be used for testing of robustness of a strategy, for example when a certain long run strategy or policy measure needs to be developed.

An important remark needs to be made; the scenarios could also have a complete adverse effect on the industry's energy transition. In Wide Receiver the steel industry leads to enhanced economic growth for the U.S as a strong position on the world market is obtained. This could, for example, for policymakers provide the incentives to develop policy measures that push the industry towards Wide Receiver. Especially due to the market driven nature of the economy and short-term focus of politicians. This raises concerns with regard to the energy transition, but also again stresses the tension between economic growth and environmental conservation and the challenges in that respect.

9.2 SCIENTIFIC VALUE

In this research scientific knowledge and in-practice expertise are brought together and is the best of both worlds combined. However, this resulted also in challenges with regard to combining various approaches and techniques. Especially when translating the scientifically obtained qualitative scenario narratives to quantitative inputs for the practical WEM mismatches were experienced. Shell has been using scenario planning for over 40 years to help deepen its strategic thinking and the WEM serves as a practical and suitable model to support scenario development. However, the scientific integrity and the suitability for future research about energy transition in other heavy industries were challenged. An assessment of possibilities to translate and link the identified drivers to the WEM parameters was conducted.

Firstly, a steel industry WEM framework was developed, which can be used in similar future research about the steel industry. Using this framework can save time and efforts. Also, it supports to better understand what the model advantages and lacking features are, which helps to enhance analysis of the outputs.

Secondly, the typology from Darmani et al. (2014) was used to get an overview of possible origins of drivers for energy transition. The identified drivers were tested for suitability in the WEM and categorized in the typology.

From this a number of important considerations and recommendations came forward for the use of the WEM for heavy industry. The model includes and links a tremendous amount of knowledge about the global energy system. With the availability of many parameter inputs and long-term data sets the model can easily and quickly generate future energy projections. However, the model has certain limitations regarding the number of drivers it can include in the model through the number of parameters. Since the WEM is a multi-usable model for various countries and industries, there exists a possibility that certain identified drivers cannot be linked to one of the parameter inputs due to the wide nature of drivers. It was found that the model is well suited for drivers that concern actor competencies or energy policy institutions. For heavy industry research where soft institutions or regional attributes drivers play a key role the WEM is less suitable to model the scenarios. The model can be improved by adding a number of parameter inputs to include more economical drivers and by adding an extra module to include the regional attributes driving forces.

9.3 REFLECTION ON RESEARCH LIMITATIONS

This research has a number of limitations that requires some attention. Firstly, the definition of the scope of the research – the U.S. steel industry – raises the question: is there one steel industry? The answer is no. In terms of steel producers, one can distinguish based on features including company size, number of plants, nationally versus internationally origins, type of production process, quality of steel, quantity produced and location. The scenarios are limited by the scope and depth of the research. On the one hand a wider scope including all international trade flows would enhance the research, and on the other hand, more depth concerning regions or stakeholders would be desirable. However with the research's timeframe a balance between scope and depth had to be found. Quarterback and Wide Receiver - as they are currently presented - can be used for further development or 'testing' of a more specific and robust strategy by actors in the system.

Secondly, some remarks about the qualitative research methodology can be made. With an explorative intuitive approach the scenarios were based on current knowledge and drivers that impact the U.S. steel industry today. A limitation to this approach is that for example currently unknown driving forces or black swan events (e.g. big climate events or war) are not included in the scenarios. The scenario workshop proved to be a fruitful source of data. However, it must be noted that although some participants worked for American steel companies (e.g. ArcelorMittal), no actors with a U.S. residency participated in the workshop. Therefore, an extra validation step with U.S. policymakers and steel producers is possible for further enhancement of the research.

Thirdly, in terms of the scenarios, they are plausible futures and are not predictions. The actual future can slightly differ from the scenarios. What would also be possible is that in the first decades the U.S. is similar to one scenario, and that in the subsequent decades the industry flows over towards to the second scenario. In this case it is possible that the U.S. moves from Wider Receiver to Quarterback in the long term.

Finally, the conclusion of the modelling of the scenarios with the WEM can be questioned. Many assumptions had to be made and as the model is based on linear calculations dependencies and feedback loops are not adequately captured. Furthermore, since the model is an energy model certain non-energy related drivers could not be implemented in the model directly. Also dynamics between countries are not considered, which can lead to lacking insights. Although the results ask for some nuance, the results – in the end - do support the aim to create dialogue and discussion.

9.4 DIRECTIONS FOR FUTURE RESEARCH

With regard to the energy transition, the research results have some insightful scientific implications, and build further on other research about the energy transition in general and steel industry specific. However, the scope of this project has some limitations as it sheds light on only one piece of the puzzle of understanding the dynamics of the energy transition. In order to obtain a full understanding of the future energy system future research can conduct similar research but focus on other heavy industries. The question is whether in other highly energy intensive industries, with other processes, barriers for a transition exist and whether the conclusions drawn for the steel industry can be are representative for other industries as well. Presumably, in certain heavy industries the change to a higher share of clean energy fuels can be achieved more easily than others. For example in the aluminium industry the production process already utilizes a high share of electricity. Other interesting industries are: cement, refineries, pulp and paper, and chemicals and plastic industries.

In addition, similar scenario analyses can be conducted for other countries and compared with the scenarios for the U.S. For example, China would be an interesting country to analyse, as they currently utilize older and more polluting steel plants, but do have more policy-oriented market in which it is more common for the government to intervene in the market more heavily.

Furthermore, in terms of the U.S. steel industry, the finding that an energy transition this industry is limited and that full decarbonisation in the steel industry is not possible, at least up until the year 2050, raises some concerning questions. The most beneficial scenario - in terms of the energy transition – is Quarterback. But how do you make sure the future looks more like Quarterback rather than Wide Receiver?

In this research a policy gap is revealed between today and the year 2050. A challenge lies in front of decision-makers regarding how to bridge this gap. What policy measures are necessary? Since availability of funding for R&D and investment is a large barrier in the industry, improved funding schemes by U.S. government should be deployed. In addition, the scenarios can support in research regarding CO_2 abatement schemes and further deploy measures accordingly.

10. RESEARCH EVALUATION

In the past six months of research several insights were obtained. The aim of this chapter is to reflect on the research - on the content as well as on the process and personal experiences – and share the experiences with other researchers in order to enhance future research. It is described to what extent certain steps provided support and where certain gaps or mismatches were experienced.

10.1 REFLECTION ON CONTENT

In this section the theory and methods that were used are critically evaluated and recommendations for improvement are provided. The project combined both elements of qualitative research and quantitative research, which proved to be complementary but also resulted in some frictions.

10.1.1 REFLECTION ON QUALITATIVE SCENARIO ANALYSIS

The scenario analysis steps developed by Schwartz proved to be a helpful tool to overall structure the research. However, in the theory each step is shortly described. This leaves a lot of space open for a variety of methods for further execution, but this also brings along ambiguities. The supporting theories from other authors that were identified in Chapter 2 *Theoretical framework* were helpful in resolving some of these ambiguities and providing a foundation for how to execute each step. For example how to set up and structure the search for forcers and drivers is not specified. The economical perspective with the five forces model by Porter (1990) proved to be helpful.

In the step 'fleshing out the scenarios' the usefulness of a scenario analysis were drivers are identified become obvious. The identified drivers were extremely helpful in writing the narratives by means of going over the list of drivers and for each of the drivers to check what the driver would look like in each of the scenarios. However, in rare cases it was difficult to include the driver in the scenarios, because it was unclear - based on the scenario framework with the axes - how the driver would develop. The scenario workshop has proved to be an efficient and effective method to collect input for the scenario analysis. It led to fruitful discussions that brought forward additional information to the literature research with more practical insights. The steps identified by Schwartz (1991) where used to structure the day. However, one additional step was conducted. The list of drivers that was created by the participants was grouped according to theme, by means of magnetic hexagons. Subsequently per group a key driver was identified. By doing this, the long list of drivers was shortened to the six main drivers. This was very helpful in the next step, where the participant had to identify the critical uncertainties.

In terms of testing the critical uncertainties along axes to form scenarios, it was helpful to visualize the result of various combinations of axes by means of large flip overs and sticky notes, and it guided the participants to decide about the final set of axes. In the steps that were taken a right balance was to found between explorative thinking and partly constraining the output with frameworks, as was stressed by van Vliet et al. (2012). The limited duration of the workshop might have led to less sophisticated discussion in some steps, but with all those experts together in one room even in a couple of hours a lot of interesting conclusions came forward. Besides the individual literature study provided the complementary knowledge needed for the final scenario development. Nevertheless, it is recommended – if possible - to extend the workshop duration to at least one or two days to get more comprehensive results.

With regard to the group of participants, a good balance between the various backgrounds of the participants was established. This led to a lot of variety in input, as was also stressed in the research by van Vliet et al. (2012). Especially in the step fleshing out of the scenario narratives people with different backgrounds brought forward input from multiple angles. The criteria for inviting participants were helpful, but it is recommended that one criterion is added: the ability to think in scenarios. For some participants it was difficult to emphasize with various futures and this slightly constrained the creative thinking of the total group.

10.1.2 REFLECTION ON QUANTITATIVE ANALYSIS

In general one can conclude that the WEM is a sophisticated and well-built model and is very useful to quantify all kinds of long-term energy scenarios. Also, it is easy to work with as it is developed in Excel. Also, as it has many data sets for parameters already built-in from which inputs can be chosen. Per input variable a choice of usually around two to five data sets with small differences (e.g. higher or lower growth) was available. If an inputs required manual adjustments this was also possible. It is quite comprehensive as it includes all three interconnected layers of the energy system - energy consumption, carriers, and primary production – and includes many variables. The main challenge in using the model is not the complexity of the model itself, but translating the knowledge of the energy system to the right numbers and data to serve as WEM inputs. Some difficulties were experienced with when modelling specific for the U.S. steel industry.

Firstly, the model can be used for almost all countries in the world, and distinguishes between various sectors. However, because the model analyses one country at a time international trade flows could not be taken into account. This resulted at some points in struggles with the research scope, because from the qualitative analysis international forces could be included, but in the WEM it could not.

Secondly, for some drivers it was not possible to include them in the WEM. Therefore the synthesis for the qualitative and quantitative analysis did not proceeded flawless. To figure out how the WEM works and how to include the drivers was an interesting, but also time consuming process.

Finally, as input data is key for the model output quality, difficulties arise when limited data is available. For example, an important manual adjustment concerned the technology deployment in the scenarios. In order to calculate the energy service efficiency the mixture and type of future technologies had to be estimated. This was difficult as today cannot be said what the ‘winning’ technologies will be in the future. Also, for current technologies under R&D the literature described the technology’s efficiencies, but did not disclose any information about what the share of each energy fuel will be. In sum it was a challenge to find well-established data about the future, and due to lack of data certain big assumptions had to be made.

To conclude, even though the WEM cannot include all drivers, and requires a lot of assumptions to be made it is an extremely sophisticated and useful tool for quantification of qualitative narratives. It provides significant insights in the developments of the energy system, and provides useful output graphs. Putting numbers to the scenarios results in more tangible scenarios, and it can extend the comprehensiveness of the qualitative scenarios. Nevertheless it is always important to make the remark that the scenarios are not predictions but plausible futures. But in the end of the day the overall aim of the scenarios is to create discussion, which is achieved with the WEM.

10.2 REFLECTION ON PROCESS AND PERSONAL EXPERIENCES

Conducting an six months scientific research individually, writing a plus 50 page report, diving into a complete new - to me - industry and at the same time interning full time at a top international energy company was quite a challenge. The development of a research question and research set up is key, but I considered it as one of the most difficult phases. Once the structure is clear the - in my opinion - fun part can start: the execution of the research. I especially enjoyed organizing the workshop and the actual modelling with the WEM.

What I have learned is that in the end everything comes down to structure in such a big project, because without structure you easily loose track. For me keeping a logbook with to do lists, giving themes to weeks, and having ‘zoom-out’ days, in which I focused on the red line of the report, helped me to structure the process. Furthermore, this project confirmed that I am a team worker rather than an individualist and that I feel more comfortable in a business role rather than a scientific role.

To conduct the research in the Shell Scenarios team was an exceptional opportunity and experience. It was a good way to take a sneak peak in the business environment of such a big international company and to experience the differences with university life. A challenge for the project was stakeholder management as university and Shell had different interests in certain areas. All in all, it was an interesting and fun project to do and hopefully it provides the foundations necessary to pursuit my passion for energy in a career in the energy market.

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Scenario Workshop

Future of the U.S. Steel Industry

13th of May, 2015

Shell International, The Hague

1. WELCOME AND EXPLANATION OF CONTEXT

Dear participant,

First of all, thank you very much for attending the scenario workshop on the 13th of May. I am delighted that you are willing to attend and contribute to the discussion about the future of the steel industry. In front of you, you find the pre-reading document for the scenario workshop. The workshop is organized in light of my six months graduation project for my study program Systems Engineering Policy Analysis Management at the TU Delft. The project is conducted in association with Shell, and in particular with the Scenarios team within Shell. In this document more information about the research topic and the day itself can be found.

The higher objective of the research is to understand what the possibilities for and limitations to an energy transition are towards the use of electricity and hydrogen from renewable energy sources as energy fuel in the U.S. steel industry up until the year 2050. During the workshop we will try to find answers to the following focal question:

How will the U.S. steel industry change its energy use between now and 2050?

By improving the understanding of the issue at hand, an empirical contribution to the debate around the energy transition in the heavy industry can be made, and recommendations to the U.S. steel industry and policymakers are provided. At the end of the workshop day, I – in cooperation with all participants – hope to have developed a set of future scenarios for the U.S. steel industry, and to have discussed what the various implications are of those scenario outcomes.

Some practical considerations for the day:

- The route description to the Shell International office in The Hague can be found in the appendix of this document. The entrance for the workshop is C-16.
- If you are traveling by car and need a parking space, please let me know as soon as possible so I can reserve one for you. The entrance of the parking is at the Groenhovenstraat.
- (Reasonable) travel costs are covered by Shell.
- Lunch will be provided. If you have a special diet, please inform me a.s.a.p.

For any other inquiries, please contact me by email quirine.dechesne@shell.com or by phone 06-22277247.

Once again my great thanks for being willing to attend, and I am looking forward to meeting you all on the 13th of May!

Kind regards,

Quirine Dechesne

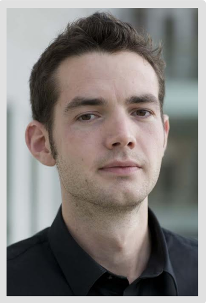
2. BIOGRAPHIES

FACILITATING

Quirine Dechesne - Shell/TU Delft

Quirine is a student in Systems Engineering Policy Analysis Management at the TU Delft. Currently she is conducting her graduation research at Shell, as part of the Scenarios team. Quirine holds a bachelor degree in Science & Innovation Management (Utrecht University), and studied abroad in the United States, Germany and Taiwan. As extracurricular activities, she worked as a business analyst at a consultancy firm and did an internship at Cofely (GDF Suez). Furthermore, she was the president of Utrecht University Model United Nations, which is a debating organisation that participates in contest in Cambridge and Harvard.

Rhodri Owen-Jones - Shell



Rhodri is an Energy Analyst in Corporate Strategy and Planning, having joined Shell in 2008. In his current position, Rhodri is heavily involved in the quantification and modelling of the Shell New Lens Scenarios, as well as communicating the resulting work to a wider global audience. His work also includes modelling global long-term energy supply and demand, analysing and advising senior leadership on short-term oil and gas market developments as well as managing a joint research project on future Indian energy pathways. Next to that, he is Business Advisor to the Executive Vice President of Strategy in the RDS Group. Rhodri has previously worked in Production Engineering at NAM BV as well as coordinating and running a Europe-wide benchmarking exercise of Shell's European assets.

Jort Rupert - Shell

Jort is an intern at Shell Scenarios and works on the environmental footprint of oil and gas production. During his master programme Energy Science at Utrecht University, he co-founded a consultancy company, was a board member of study association NRG and completed the honours programme of the European Institute of Technology & Innovation. His last internship was in Tokyo at Nissan Motor Corporation where he studied the market creation of the fuel cell electric vehicle.

PARTICIPANTS

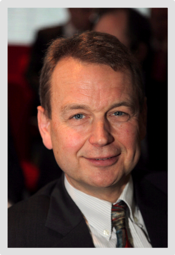
Gerard Jägers - TATA Steel

Gerard is the programme manager on energy efficiency of Tata Steel IJmuiden. He has master degrees in mathematics (Technical University Delft, 1974) and economics (University of Amsterdam). The main part of his career he worked at the Steel works in IJmuiden, in logistics, production management, technology, management of education and energy. It is his ambition to maintain a leading position in the world steel industry in energy consumption and CO_2 emission. Next to the implementation of technical measures work is done on increase of waste heat recovery e.g. in district heating systems. Also, TATA Steel participates in the international European ULCOS project (ultra low CO2 steel making) of which the pilot plant Hisarna is located in IJmuiden.

Margot Weijnen - TU Delft

Margot is full professor of process and energy systems engineering at TU Delft, since 1995. She is the founding and scientific director of the Next Generation Infrastructures Foundation, a public/private knowledge centre for cross-sectoral and interdisciplinary research on infrastructure systems and services, established in 2001. Since 2013 she is a member of the Netherlands Scientific Council for Government Policy (WRR). She is and has been engaged in numerous advisory and supervisory positions to the Dutch government, the European Commission and Dutch industry.

Hans Wiltink - De Gemeynt/Institute for Sustainable Process Technology



Hans is trained as an architectural engineer (TU Delft) and business administrator (Rotterdam School of Management) and has held positions at Fokker and Dutch Broadcasting Company. He is partner in the consultancy firm De Gemeynt with a focus on innovation and sustainability, initiating and advising companies and government. He is also involved in several projects for the ISPT, Institute for Sustainable Process Technology.

Burkard Schlange – Shell

Burkard holds a degree in Electrical Engineering from Technical University of Braunschweig. After joining Shell in 1991, his activities included refinery projects and operations, commercial power, restructuring /divestment and natural gas supply & operations. In his current role as Senior Researcher in the Energy Futures Team, his focus area is energy system integration and storage.

Erik Saat - Entrepreneur

Erik obtained an MSc degree from the Faculty of Mechanical Engineering at the TU Delft in 1998. His field of specialisation is Energy supply and conducted his graduation research assignment at ABB Power Plant Laboraties in Connecticut, USA. In 2004 he co-founded a carbon consulting and CO_2 trading house with a strategic focus on large heavy industry such as steel, power and cement in Eastern Europe including Russia. In 2008 Erik obtained an MBA degree from RSM Erasmus University through the OneMBA programme. From 2013 to 2014 he executed a seed investment in the first large scale wind park in Indonesia and spent six months in Singapore to manage the start-up. Since 2015 Erik is back in the Netherlands and focuses on small to medium size investment opportunities in start-ups and companies seeking growth capital in the European energy sector.

Emiel Sanders - Shell

Emiel has an academic background in International and Health economics. He started working 5 years ago within Shell and gained experience in reporting roles, commercial finance advisory roles, both Upstream and Downstream. He is currently working as business analyst in the European Gas Strategy team. Prior to Shell he worked at the Dutch ministry of Finance and as a junior researcher at Johns Hopkins University.

Oscar Kraan - TU Delft/Leiden University/Shell

Oscar is a PhD Researcher under supervision of Gert Jan Kramer in Shell's Energy Futures team, part of Future Energy Technologies. The project has started in April 2014 and is a collaboration between Shell, the Leiden University and the Technical University in Delft. He works on modelling of the energy transition with a relatively new modelling method, agent-based modelling with which he takes bounded rational, heterogeneous actors (individuals, cities, governments) and their interaction as starting point.

Simon Spoelstra - Energy research Centre of the Netherlands

Simon studied Applied Physics at the University of Twente and did a master in the area of heat and mass transfer. He started at ECN in 1989 and is since 1997 involved in the field of industrial energy savings. In 2001, the focus shifted towards the use of heat in industry where he has managed several technology development projects on industrial heat pumps. He presently holds the position of Innovation Manager Industrial Heat and is responsible for the development of heat pumps & storage technologies as well as energy efficiency analyses of industrial processes.

Arzu Feta - TATA Steel

Arzu did her bachelor studies in Physics at Amsterdam University College and her master studies in Energy Science at Utrecht University. She is currently working as an intern in the Energy Efficiency team at Tata Steel IJmuiden. Arzu is developing a model that integrates the different waste heat sources of the site and optimizes the waste heat utilization. Before this, she worked on analysing the electricity demand response potentials of Tata Steel IJmuiden.

Eric De Coninck – ArcelorMittal

Eric, after graduating in civil engineering from the State University of Gent (1977–1982) continued as a researcher in the lab of a paper mill. Afterwards (1983) he joined N.V. Sidmar, currently ArcelorMittal. Working as a maintenance manager in the rolling mills, as a production manager in the steel plant, and project engineer within the company and its affiliations (Bremen), he was appointed in 2008 as Chief Operating Officer in charge of the Upstream industrial operations of the Liège plant in 2008 and COO of the Fos sur Mer steel mill, in charge of engineering and industrial operations in 2009. In 2011 he became Project manager at the

ArcelorMittal Ghent plant, in 2012 he was appointed AM FCE CTO Business Development director, in charge of new technologies, including the sustainability projects of the ArcelorMittal group within the AM Innovation department.

Nick Hubbers – Eneco

Nick is part of the Fundamental Analysis team within the Corporate Strategy department of Eneco. The team is responsible for scenario development and fundamental market analysis at Eneco.

Derk Straathof - Eneco

Derk is part of the Fundamental Analysis team within the Corporate Strategy department of Eneco. The team is responsible for scenario development and fundamental market analysis at Eneco.

Eric Puik – Shell

Eric is a senior energy advisor in the Shell Scenarios team.

GUEST SPEAKER

Wim Thomas – Shell

Wim leads the Energy Analysis Team in Shell's Global Scenario Group. His team is responsible for worldwide energy analyses and long-term global energy scenarios. It advises Shell companies on a wide range of energy issues, including global supply and demand, regulations, energy policy, pricing and industry structure. He has been with Shell for almost 25 years. He previously held positions in drilling operations, subsurface reservoir management, and commercial and regulatory affairs in gas. Wim is a UK member to the World Petroleum Council and World Energy Council's energy scenario group and was chairman of the British Institute of Energy Economics in 2005. He holds a postgraduate degree in Maritime Technology, Delft University, the Netherlands.

3. AGENDA

The agenda of the day is presented below. On the day itself further in detail explanation about the group exercises will be provided.

- 11:45 - 12:00 Register at reception
- 12:00 – 12:45 Opening with lunch and presentation by RDS Chief Energy Advisor Wim Thomas
- 12:45 -13:00 Scenarios: an introduction
- 13:00 – 15:00 Group exercise: trends, drivers, and axes
- 15:00 – 15:15 Break
- 15:15 – 15:30 Group exercise: report back on axes
- 15:30 – 16:45 Group exercise: scenario development and implications
- 16:45 – 17:00 Wrap-up

4. PRE-READ

Today we live in an era of volatility and transition. Following the reports of the Intergovernmental Panel on Climate Change (IPCC) significant consensus about the damaging effects of increased carbon dioxide (CO_2) emissions on climate change exist (EPA, 2015; IPCC, 2014). With intensifying climate stresses there is an urgent call for decarbonisation of the energy system, and a transition to cleaner technologies and energy supply. However, how to rapidly change the energy system but at the same time satisfy to the raising energy demand is one of the largest challenges. For energy companies - such as Shell - it is highly important to get a better understanding of these dynamics to be able to adapt to the changing environments.

4.1 HEAVY INDUSTRY IN THE U.S.

Looking at the United States (U.S.), from the year 1990 to 2013 the carbon dioxide emissions have increased by seven per cent (EPA, 2015), and the U.S. Energy Information Administration (EIA) states that this will number will continue to rise in the coming decades (EIA, 2014a). In 2014, the country emitted over 5000 million metric energy related CO_2. From the U.S. major economic sectors – which are industrial, transportation, residential, commercial - the industrial sector is, with 32% energy consumption, the biggest energy consumer, and is accountable for 14% of the total U.S. CO_2 emissions (EIA, 2014d; EPA, 2014). These numbers raise serious concerns and emphasise the need for change in the U.S.

The design of systems that use cleaner energy fuel (e.g. electricity or hydrogen) and the development of renewable energy technologies to create those energy fuels - such as wind turbines, solar cells or Power-to-Gas - show potential for a change to a cleaner energy system. By shifting end-use applications towards electricity as the prime fuel source the global energy system is gradually undergoing a decarbonisation transformation (IEA, 2014). Furthermore, hydrogen holds the potential to provide a clean, reliable, and affordable energy source. The benefit of hydrogen is that it produces only water vapour and no other gaseous by-products when used as a reducing agent or a fuel. However, currently the design and implementation of a 'hydrogen economy' is constrained by a number of uncertainties, such as costs and uniform codes and standards (DOE, 2002b). The energy transition requires relatively radical changes and therefore a long-term perspective is required.

Whereas the future possibilities for electrification and use of hydrogen (from here onwards called cleaner fuels) in the transportation sector and residential sector are extensively debated and researched, there seem to be less attention directed towards the potential for using cleaner energy fuel from renewable energy sources (RES) in industry (McDowall & Eames, 2006; Sugiyama, 2012). This is especially surprising for the heavy industries – including refining, chemicals, pulp & paper, coal, cement, and primary metals (e.g. aluminium and steel) – who are classified as the biggest emitters in industry (EIA, 2014a). The complexity and variety of the heavy industry processes is one of the reasons for the lesser research focus.

To conclude, a research gap can be identified that concerns research about understanding the use of cleaner fuels in the long-term future of the U.S. heavy industry as a system, including the supply RES supply side, combining technical, multi-actor and policy perspectives.

4.2 CLEANER ENERGY FUELS IN THE STEEL INDUSTRY

Even though relatively little comprehensive research is done with regard to the use of cleaner fuels in heavy industry, the idea that there are possibilities for a transition towards cleaner fuels in the future is recognized. A remaining question is however to what extent heavy industry can incorporate cleaner fuels in the process; is a 100% transition possible or are there limits to the use of clean fuels?

Taking into account the current best available technologies and pilot technologies, it is expected that certain heavy industries have higher potential to incorporate cleaner energy fuels in the technological processes than other industries, which are for instance constrained by the use of fossil fuels for certain process steps. To produce aluminium already a lot of electricity is necessary, which possibly could be supplied by RES in the future, but the use of hydrogen fuel has limited potential (EIA, 2014a). The bulk chemical and refinery industry show potential for increased use of electricity as well as hydrogen fuel, but due to the complexity and variety of production processes this varies significantly per system.

In the steel industry, for example the electric arc furnace consumes electricity, and new technologies are piloted (e.g. HISarna) that allow for more fuel flexibility including the use of hydrogen (IEA, 2014). Currently, the U.S. steel industry (including iron production), being one of the largest energy consumers in the manufacturing sector, relies significantly on natural gas and coal coke and breeze for fuel, and is accounted for 128,8 million metric tons CO_2 emissions in 2014 (EIA, 2014a, 2014b). The industry is critical to the U.S. economy; steel is the material of choice for many elements of construction, transportation, manufacturing, and a variety of consumer products (EIA, 2014b). Because the steel industry shows potential for electrification and also use of hydrogen, but is currently a relatively locked-in system with the use of conventional energy fuels, it is an interesting case to research the possibilities for and limits to an energy transition, and is therefore the focus of this research.

To summarize, the project focus is the following:

- The U.S. steel industry – included is the iron & steel production, excluded is ore mining and further casting/rolling/manufacturing of the steel. The country focus is the U.S., but since the market is highly international other areas will also be important to analyse.
- The energy fuel use – the focus of the project is on the energy carriers electricity and hydrogen, but to understand the choice for the energy mix and the fuel use other energy options are just as well taken into account.
- The system is analysed from multiple perspectives, e.g. technological, economical, environmental, policy and societal developments.

5. FURTHER READING

If you would like to read more on the topic and in order to be fully prepared, the following materials can be studied:

- Steel market analysis by McKinsey:
  http://www.google.co.uk/url?sa=t&rct=j&q=&esrc=s&frm=1&source=web&cd=6&ved=0CDkQFjAF&url=http://www.mckinsey.com/~/media/mckinsey/dotcom/client_service/Metals%20and%20Mining/PDFs/Scarcity%20and%20saturation_no8_2013.ashx&ei=0cY0VY2OKojXaq_1gbgH&usg=AFQjCN

- A technology roadmap for the steel industry by the American Iron and Steel Institute:
  https://www.steel.org/~/media/Files/AISI/Making Steel/TechReportResearchProgramFINAL.pdf

- Decarbonisation and energy efficiency in the steel industry:
  https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/416667/Iron_and_Steel_Report.pdf

- Renewable electricity future study by National Renewable Energy Laboratory:
  http://www.nrel.gov/docs/fy13osti/52409-ES.pdf

- Outlook for hydrogen as an energy carrier:
  http://www.c2es.org/docUploads/10-50_Ogden.pdf

- National Hydrogen energy roadmap:
  http://www.hydrogen.energy.gov/pdfs/national_h2_roadmap.pdf

6. REFERENCES

The references were provided to the participants, but are left out in this appendix because the references are included in chapter 11 *References.*

APPENDIX B1 - STAKEHOLDER ANALYSIS

Stakeholder	Interests & objectives
Iron & steel producers in the U.S.	Earn high profits by processing iron into semi-finished and/or finished steel products and selling those products to customers. Buy a defined quality iron ore for the lowest price, and sell a defined quality product for a high price. E.g. the biggest steel producers ArcelorMittal, United States Steel Corporation, and Nucor Corporation. See for all U.S. producers appendix B2.
Iron ore suppliers in the U.S.	Earn high profits by mining iron ore from the earth's crust and selling it to iron and steel producers.
Iron & steel producers outside the U.S.	Earn high profits by processing iron into semi-finished and/or finished steel products and selling those products to customers. Buy a defined quality iron ore for the lowest price, and sell a defined quality product for a high price. E.g. Nippon Steel & Sumitomo Metal Corporation (Japanese), Hebei Steel Group (Chinese), Boasteel Group (China), Wuhan Steel Group (China).
Iron ore suppliers outside the U.S.	Earn high profits by mining iron ore from the earth's crust and selling it to iron and steel producers. Subtract iron ore and sell for highest price.
Energy and feedstock fuel suppliers	Earn high profits by selling energy carriers to steel producers
Buyers semi-finished and finished steel products	Earn profits by manufacturing or construction with semi-finished or finished steel products. Buy a defined quality product for the lowest price, and sell a defined quality product for a high price.
End consumers	Consume good quality products (sustainable, high strength, low weight) for a low price
Substitute producers (plastics, aluminium, cement, ceramics)	Earn profit by producing a product and selling it to buyers for a high price
Cooperative steel institutes (e.g. American Iron & Steel Institute)	Serve as the voice of the American steel industry, speaking out on behalf of its members in the public policy arena and advancing the case for steel in the marketplace as the material of choice; play a leading role in the R&D development and application of new steels and steelmaking technology; provide a forum for the exchange of information on technical matters and operations among member companies; serve as a source of information on the steel industry to suppliers, customers, and various government entities
U.S. policymakers	Create policy measures to protect the national market, competition in the market, ensure economic growth and jobs, and protect the environment
Non U.S. policymakers	Create policy measures to protect the national market, competition in the market, ensure economic growth and jobs, and protect the environment
U.S. Environmental Protection Agency	Protect human health and the environment by writing and enforcing regulations based on laws passed by Congress
U.S citizens (the public)	Live in a high quality environment (no pollution, high quality infrastructure and products)

Table 8: List of stakeholders with their interest and objectives

Stakeholder	Power (low-high, 1-4)	Interest (low-high, 1-4)	Scenario Quarterback (power – left, interest - right)		Scenario Wide Receiver (power – left, interest - right)	
Iron & steel producers in U.S.	4	4	Lower	Same	Higher	Same
Iron ore suppliers in U.S.	3	4	Lower	Lower	Higher	Higher
Iron & steel producers outside U.S.	2	3	Same	Same	Same	Same
U.S. Iron ore suppliers outside U.S.	2	3	Higher	Higher	Same	Higher
Energy and feedstock fuel suppliers	2	3	Same	Same	Same	Same
Buyers semi-finished and finished steel products	3	4	Lower	Lower	Same	Same
End consumers	1	2	Same	Same	Same	Same
Substitute producers (e.g. aluminium)	3	3	Higher	Lower	Lower	Same
Collaborative steel institutes (e.g. American Iron & Steel Institute)	3	4	Higher	Same	Lower	Same
U.S. policymakers	4	4	Higher	Same	Lower	Same
Non U.S. policymakers	2	1	Same	Same	Same	Same
U.S. Environmental Protection Agency	2	4	Higher	Same	Lower	Same
U.S. citizens (the public)	1	1	Same	Same	Same	Same

Table 9: Stakeholder grid analysis

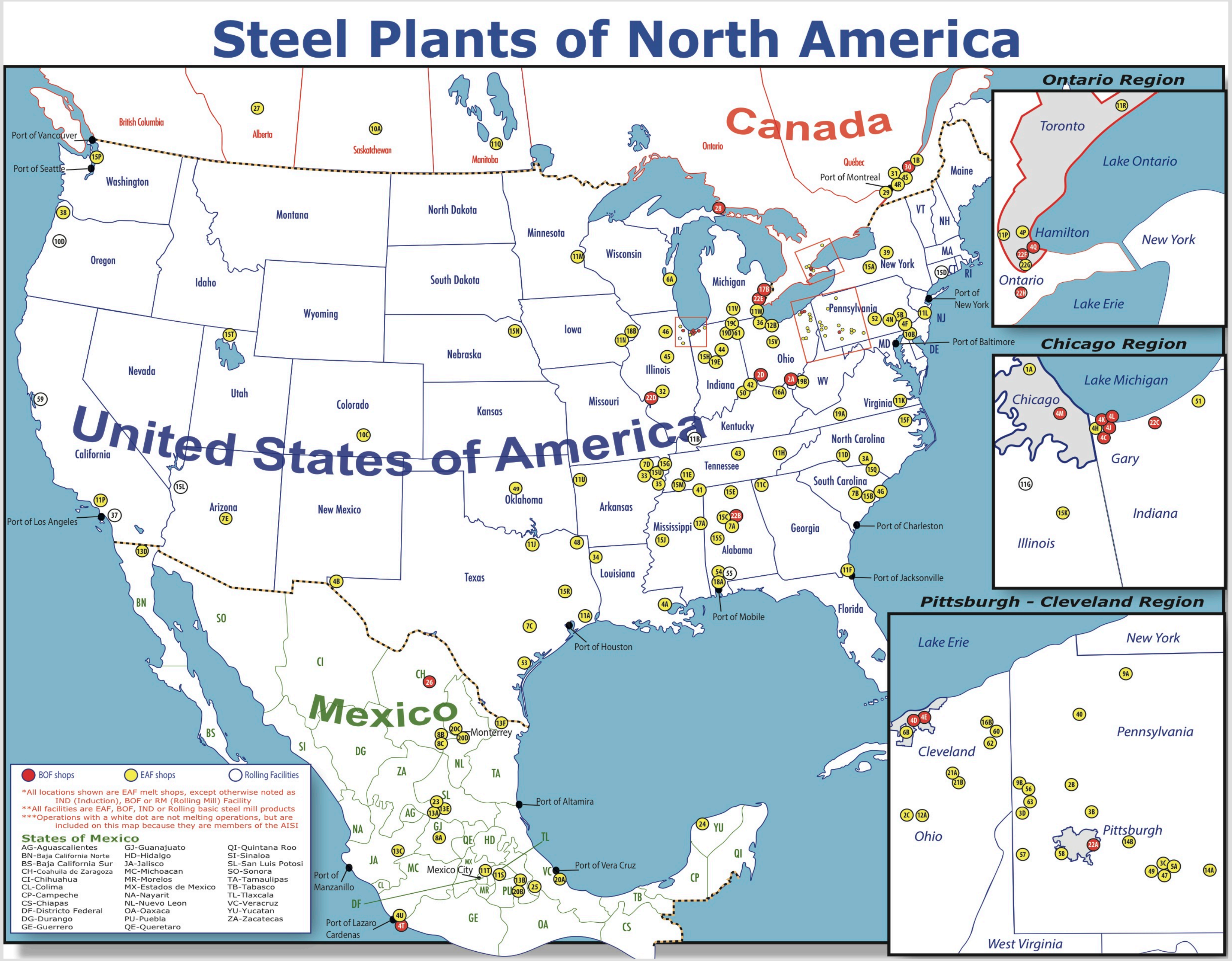
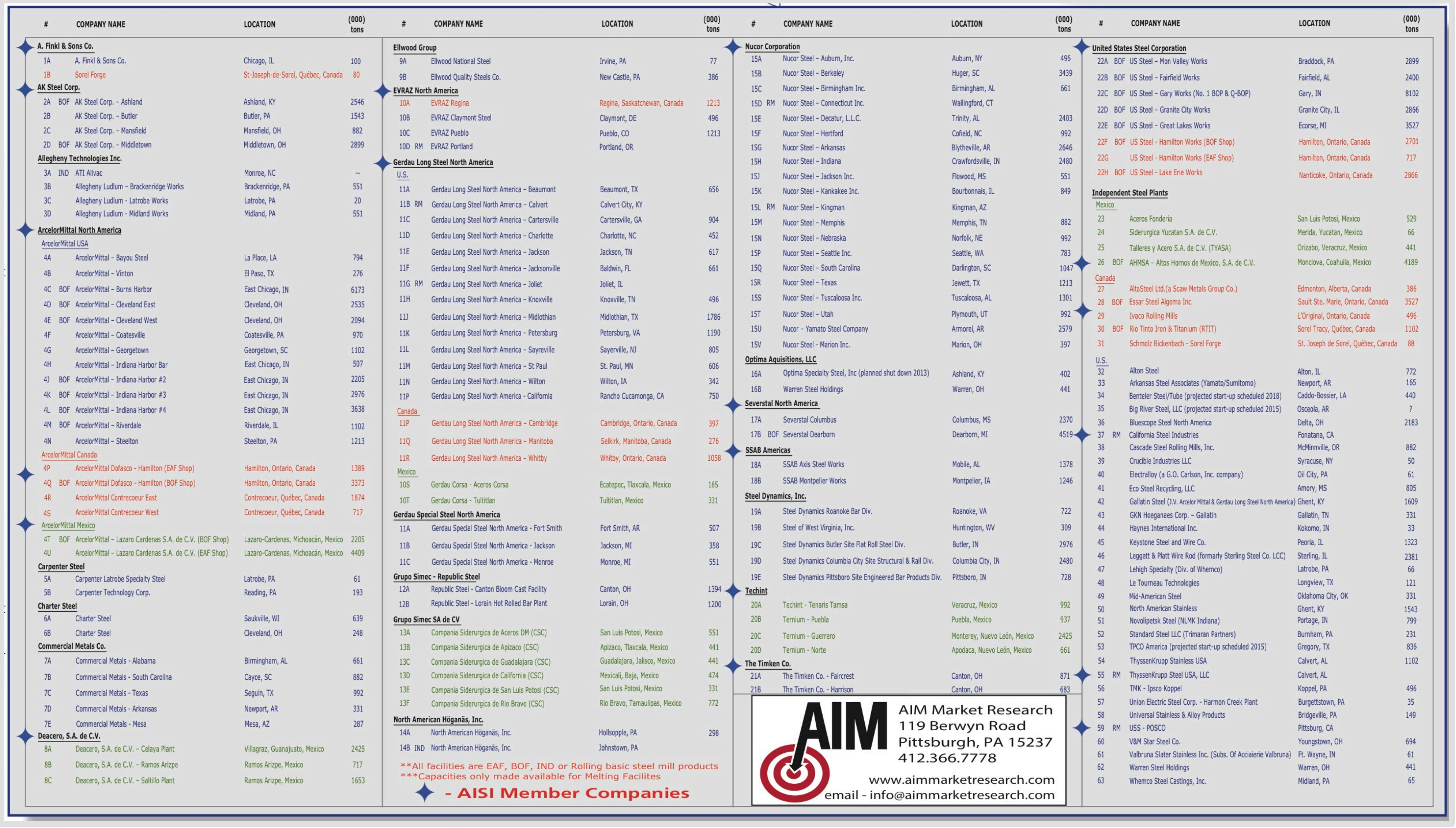


Figure 55: Steel producers of North America (including U.S.) – part 1 (AISI, 2015b)



#		COMPANY NAME	LOCATION	(000) tons
✦		**A. Finkl & Sons Co.**		
1A		A. Finkl & Sons Co.	Chicago, IL	100
1B		Sorel Forge	St-Joseph-de-Sorel, Québec, Canada	80
✦		**AK Steel Corp.**		
2A	BOF	AK Steel Corp. – Ashland	Ashland, KY	2546
2B		AK Steel Corp. – Butler	Butler, PA	1543
2C		AK Steel Corp. – Mansfield	Mansfield, OH	882
2D	BOF	AK Steel Corp. – Middletown	Middletown, OH	2899
		Allegheny Technologies Inc.		
3A	IND	ATI Allvac	Monroe, NC	--
3B		Allegheny Ludlum – Brackenridge Works	Brackenridge, PA	551
3C		Allegheny Ludlum - Latrobe Works	Latrobe, PA	20
3D		Allegheny Ludlum - Midland Works	Midland, PA	551
✦		**ArcelorMittal North America**		
		ArcelorMittal USA		
4A		ArcelorMittal – Bayou Steel	La Place, LA	794
4B		ArcelorMittal – Vinton	El Paso, TX	276
4C	BOF	ArcelorMittal – Burns Harbor	East Chicago, IN	6173
4D	BOF	ArcelorMittal – Cleveland East	Cleveland, OH	2535
4E	BOF	ArcelorMittal – Cleveland West	Cleveland, OH	2094
4F		ArcelorMittal – Coatesville	Coatesville, PA	970
4G		ArcelorMittal – Georgetown	Georgetown, SC	1102
4H		ArcelorMittal – Indiana Harbor Bar	East Chicago, IN	507
4J	BOF	ArcelorMittal – Indiana Harbor #2	East Chicago, IN	2205
4K	BOF	ArcelorMittal – Indiana Harbor #3	East Chicago, IN	2976
4L	BOF	ArcelorMittal – Indiana Harbor #4	East Chicago, IN	3638
4M	BOF	ArcelorMittal – Riverdale	Riverdale, IL	1102
4N		ArcelorMittal – Steelton	Steelton, PA	1213
		ArcelorMittal Canada		
✦ 4P		ArcelorMittal Dofasco - Hamilton (EAF Shop)	Hamilton, Ontario, Canada	1389
4Q	BOF	ArcelorMittal Dofasco - Hamilton (BOF Shop)	Hamilton, Ontario, Canada	3373
4R		ArcelorMittal Contrecoeur East	Contrecoeur, Québec, Canada	1874
4S		ArcelorMittal Contrecoeur West	Contrecoeur, Québec, Canada	717
✦		ArcelorMittal Mexico		
4T	BOF	ArcelorMittal – Lazaro Cardenas S.A. de C.V. (BOF Shop)	Lazaro-Cardenas, Michoacán, Mexico	2205
4U		ArcelorMittal – Lazaro Cardenas S.A. de C.V. (EAF Shop)	Lazaro-Cardenas, Michoacán, Mexico	4409
		Carpenter Steel		
5A		Carpenter Latrobe Specialty Steel	Latrobe, PA	61
5B		Carpenter Technology Corp.	Reading, PA	193
		Charter Steel		
6A		Charter Steel	Saukville, WI	639
6B		Charter Steel	Cleveland, OH	248
		Commercial Metals Co.		
7A		Commercial Metals - Alabama	Birmingham, AL	661
7B		Commercial Metals - South Carolina	Cayce, SC	882
7C		Commercial Metals - Texas	Seguin, TX	992
7D		Commercial Metals - Arkansas	Newport, AR	331
7E		Commercial Metals - Mesa	Mesa, AZ	287
✦		**Deacero, S.A. de C.V.**		
8A		Deacero, S.A. de C.V. – Celaya Plant	Villagraz, Guanajuato, Mexico	2425
8B		Deacero, S.A. de C.V. – Ramos Arizpe	Ramos Arizpe, Mexico	717
8C		Deacero, S.A. de C.V. – Saltillo Plant	Ramos Arizpe, Mexico	1653
		Ellwood Group		
9A		Ellwood National Steel	Irvine, PA	77
9B		Ellwood Quality Steels Co.	New Castle, PA	386
✦		**EVRAZ North America**		
10A		EVRAZ Regina	Regina, Saskatchewan, Canada	1213
10B		EVRAZ Claymont Steel	Claymont, DE	496
10C		EVRAZ Pueblo	Pueblo, CO	1213
10D	RM	EVRAZ Portland	Portland, OR	
✦		**Gerdau Long Steel North America**		
		U.S.		
11A		Gerdau Long Steel North America – Beaumont	Beaumont, TX	656
11B	RM	Gerdau Long Steel North America – Calvert	Calvert City, KY	
11C		Gerdau Long Steel North America – Cartersville	Cartersville, GA	904
11D		Gerdau Long Steel North America – Charlotte	Charlotte, NC	452
11E		Gerdau Long Steel North America – Jackson	Jackson, TN	617
11F		Gerdau Long Steel North America – Jacksonville	Baldwin, FL	661
11G	RM	Gerdau Long Steel North America – Joliet	Joliet, IL	
11H		Gerdau Long Steel North America – Knoxville	Knoxville, TN	496
11J		Gerdau Long Steel North America – Midlothian	Midlothian, TX	1786
11K		Gerdau Long Steel North America – Petersburg	Petersburg, VA	1190
11L		Gerdau Long Steel North America – Sayreville	Sayerville, NJ	805
11M		Gerdau Long Steel North America – St Paul	St. Paul, MN	606
11N		Gerdau Long Steel North America – Wilton	Wilton, IA	342
11P		Gerdau Long Steel North America - California	Rancho Cucamonga, CA	750
		Canada		
11P		Gerdau Long Steel North America – Cambridge	Cambridge, Ontario, Canada	397
11Q		Gerdau Long Steel North America – Manitoba	Selkirk, Manitoba, Canada	276
11R		Gerdau Long Steel North America – Whitby	Whitby, Ontario, Canada	1058
		Mexico		
10S		Gerdau Corsa - Aceros Corsa	Ecatepec, Tlaxcala, Mexico	165
10T		Gerdau Corsa - Tultitlan	Tultitlan, Mexico	331
		Gerdau Special Steel North America		
11A		Gerdau Special Steel North America - Fort Smith	Fort Smith, AR	507
11B		Gerdau Special Steel North America - Jackson	Jackson, MI	358
11C		Gerdau Special Steel North America - Monroe	Monroe, MI	551
		Grupo Simec - Republic Steel		
12A		Republic Steel - Canton Bloom Cast Facility	Canton, OH	1394
12B		Republic Steel - Lorain Hot Rolled Bar Plant	Lorain, OH	1200
		Grupo Simec SA de CV		
13A		Compania Siderurgica de Aceros DM (CSC)	San Luis Potosi, Mexico	551
13B		Compania Siderurgica de Apizaco (CSC)	Apizaco, Tlaxcala, Mexico	441
13C		Compania Siderurgica de Guadalajara (CSC)	Guadalajara, Jalisco, Mexico	441
13D		Compania Siderurgica de California (CSC)	Mexicali, Baja, Mexico	474
13E		Compania Siderurgica de San Luis Potosi (CSC)	San Luis Potosi, Mexico	331
13F		Compania Siderurgica de Rio Bravo (CSC)	Rio Bravo, Tamaulipas, Mexico	772
		North American Höganäs, Inc.		
14A		North American Höganäs, Inc.	Hollsopple, PA	298
14B	IND	North American Höganäs, Inc.	Johnstown, PA	
✦		**Nucor Corporation**		
15A		Nucor Steel – Auburn, Inc.	Auburn, NY	496
15B		Nucor Steel – Berkeley	Huger, SC	3439
15C		Nucor Steel – Birmingham Inc.	Birmingham, AL	661
15D	RM	Nucor Steel – Connecticut Inc.	Wallingford, CT	
15E		Nucor Steel – Decatur, L.L.C.	Trinity, AL	2403
15F		Nucor Steel – Hertford	Cofield, NC	992
15G		Nucor Steel – Arkansas	Blytheville, AR	2646
15H		Nucor Steel – Indiana	Crawfordsville, IN	2480
15J		Nucor Steel – Jackson Inc.	Flowood, MS	551
15K		Nucor Steel – Kankakee Inc.	Bourbonnais, IL	849
15L	RM	Nucor Steel – Kingman	Kingman, AZ	
15M		Nucor Steel – Memphis	Memphis, TN	882
15N		Nucor Steel – Nebraska	Norfolk, NE	992
15P		Nucor Steel – Seattle Inc.	Seattle, WA	783
15Q		Nucor Steel – South Carolina	Darlington, SC	1047
15R		Nucor Steel – Texas	Jewett, TX	1213
15S		Nucor Steel – Tuscaloosa Inc.	Tuscaloosa, AL	1301
15T		Nucor Steel – Utah	Plymouth, UT	992
15U		Nucor – Yamato Steel Company	Armorel, AR	2579
15V		Nucor Steel - Marion Inc.	Marion, OH	397
		Optima Aquisitions, LLC		
16A		Optima Specialty Steel, Inc (planned shut down 2013)	Ashland, KY	402
16B		Warren Steel Holdings	Warren, OH	441
✦		**Severstal North America**		
17A		Severstal Columbus	Columbus, MS	2370
17B	BOF	Severstal Dearborn	Dearborn, MI	4519
✦		**SSAB Americas**		
18A		SSAB Axis Steel Works	Mobile, AL	1378
18B		SSAB Montpelier Works	Montpelier, IA	1246
		Steel Dynamics, Inc.		
19A		Steel Dynamics Roanoke Bar Div.	Roanoke, VA	722
19B		Steel of West Virginia, Inc.	Huntington, WV	309
19C		Steel Dynamics Butler Site Flat Roll Steel Div.	Butler, IN	2976
19D		Steel Dynamics Columbia City Site Structural & Rail Div.	Columbia City, IN	2480
19E		Steel Dynamics Pittsboro Site Engineered Bar Products Div.	Pittsboro, IN	728
✦		**Techint**		
20A		Techint - Tenaris Tamsa	Veracruz, Mexico	992
20B		Ternium - Puebla	Puebla, Mexico	937
20C		Ternium - Guerrero	Monterey, Nuevo León, Mexico	2425
20D		Ternium - Norte	Apodaca, Nuevo León, Mexico	661
✦		**The Timken Co.**		
21A		The Timken Co. - Faircrest	Canton, OH	871
21B		The Timken Co. - Harrison	Canton, OH	683
✦		**United States Steel Corporation**		
22A	BOF	US Steel – Mon Valley Works	Braddock, PA	2899
22B	BOF	US Steel – Fairfield Works	Fairfield, AL	2400
22C	BOF	US Steel – Gary Works (No. 1 BOP & Q-BOP)	Gary, IN	8102
22D	BOF	US Steel – Granite City Works	Granite City, IL	2866
22E	BOF	US Steel – Great Lakes Works	Ecorse, MI	3527
22F	BOF	US Steel - Hamilton Works (BOF Shop)	Hamilton, Ontario, Canada	2701
22G		US Steel - Hamilton Works (EAF Shop)	Hamilton, Ontario, Canada	717
22H	BOF	US Steel - Lake Erie Works	Nanticoke, Ontario, Canada	2866
		Independent Steel Plants		
		Mexico		
23		Aceros Fonderia	San Luis Potosi, Mexico	529
24		Siderurgica Yucatan S.A. de C.V.	Merida, Yucatan, Mexico	66
25		Talleres y Acero S.A. de C.V. (TYASA)	Orizabo, Veracruz, Mexico	441
✦ 26	BOF	AHMSA – Altos Hornos de Mexico, S.A. de C.V.	Monclova, Coahuila, Mexico	4189
		Canada		
27		AltaSteel Ltd.(a Scaw Metals Group Co.)	Edmonton, Alberta, Canada	386
28	BOF	Essar Steel Algoma Inc.	Sault Ste. Marie, Ontario, Canada	3527
✦ 29		Ivaco Rolling Mills	L'Original, Ontario, Canada	496
30	BOF	Rio Tinto Iron & Titanium (RTIT)	Sorel Tracy, Québec, Canada	1102
31		Schmolz Bickenbach - Sorel Forge	St. Joseph de Sorel, Québec, Canada	88
		U.S.		
32		Alton Steel	Alton, IL	772
33		Arkansas Steel Associates (Yamato/Sumitomo)	Newport, AR	165
34		Benteler Steel/Tube (projected start-up scheduled 2018)	Caddo-Bossier, LA	440
35		Big River Steel, LLC (projected start-up scheduled 2015)	Osceola, AR	?
36		Bluescope Steel North America	Delta, OH	2183
✦ 37	RM	California Steel Industries	Fonatana, CA	
38		Cascade Steel Rolling Mills, Inc.	McMinnville, OR	882
39		Crucible Industries LLC	Syracuse, NY	50
40		Electralloy (a G.O. Carlson, Inc. company)	Oil City, PA	61
41		Eco Steel Recycling, LLC	Amory, MS	805
42		Gallatin Steel (J.V. Arcelor Mittal & Gerdau Long Steel North America)	Ghent, KY	1609
43		GKN Hoeganaes Corp. – Gallatin	Gallatin, TN	331
44		Haynes International Inc.	Kokomo, IN	33
45		Keystone Steel and Wire Co.	Peoria, IL	1323
46		Leggett & Platt Wire Rod (formarly Sterling Steel Co. LCC)	Sterling, IL	2381
47		Lehigh Specialty (Div. of Whemco)	Latrobe, PA	66
48		Le Tourneau Technologies	Longview, TX	121
49		Mid-American Steel	Oklahoma City, OK	331
50		North American Stainless	Ghent, KY	1543
51		Novolipetsk Steel (NLMK Indiana)	Portage, IN	799
52		Standard Steel LLC (Trimaran Partners)	Burnham, PA	231
53		TPCO America (projected start-up scheduled 2015)	Gregory, TX	836
54		ThyssenKrupp Stainless USA	Calvert, AL	1102
✦ 55	RM	ThyssenKrupp Steel USA, LLC	Calvert, AL	
56		TMK - Ipsco Koppel	Koppel, PA	496
57		Union Electric Steel Corp. - Harmon Creek Plant	Burgettstown, PA	35
58		Universal Stainless & Alloy Products	Bridgeville, PA	149
✦ 59	RM	USS - POSCO	Pittsburg, CA	
60		V&M Star Steel Co.	Youngstown, OH	694
61		Valbruna Slater Stainless Inc. (Subs. Of Acciaierie Valbruna)	Ft. Wayne, IN	61
62		Warren Steel Holdings	Warren, OH	441
63		Whemco Steel Castings, Inc.	Midland, PA	65

**All facilities are EAF, BOF, IND or Rolling basic steel mill products
***Capacities only made available for Melting Facilites

✦ - AISI Member Companies

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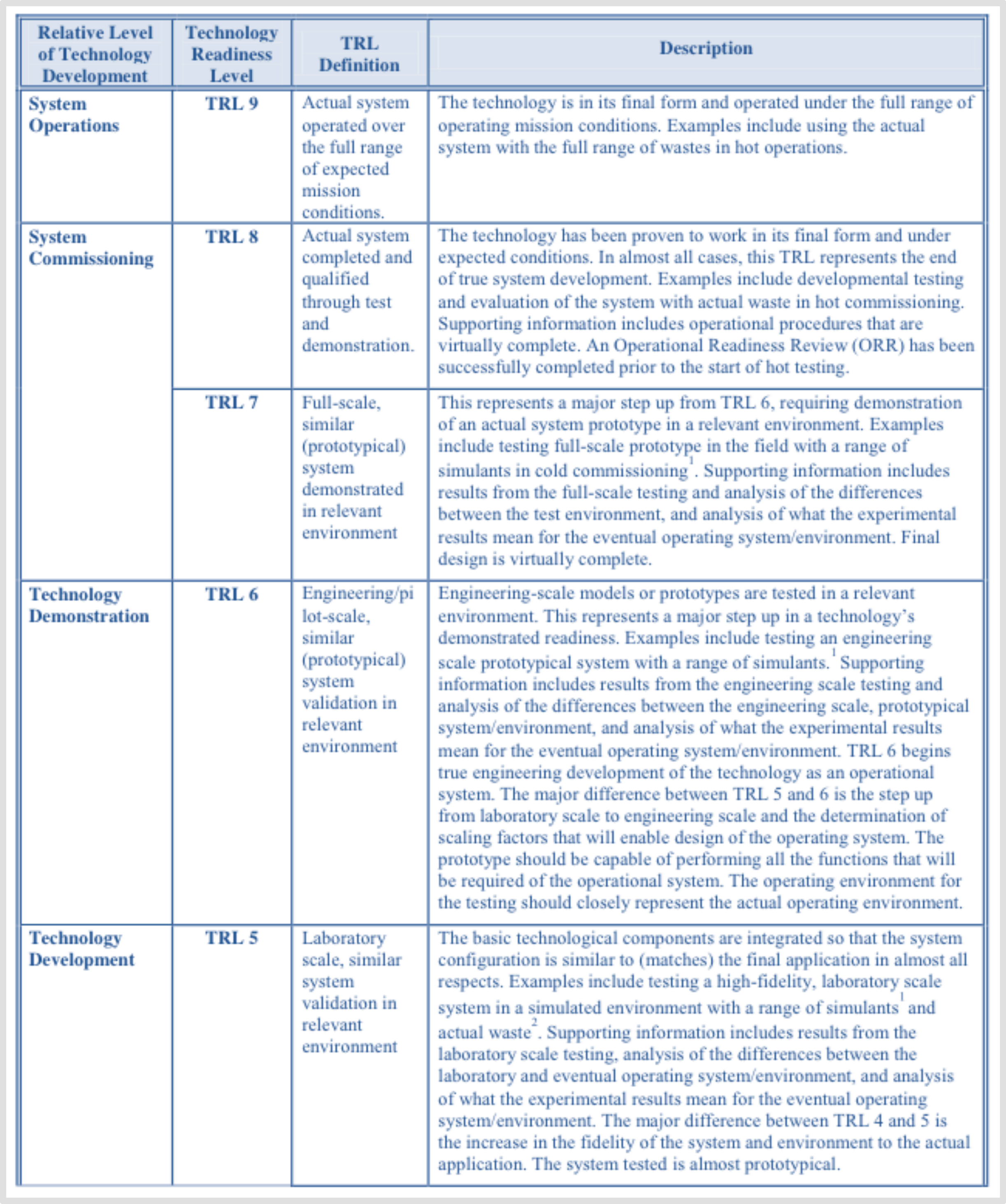
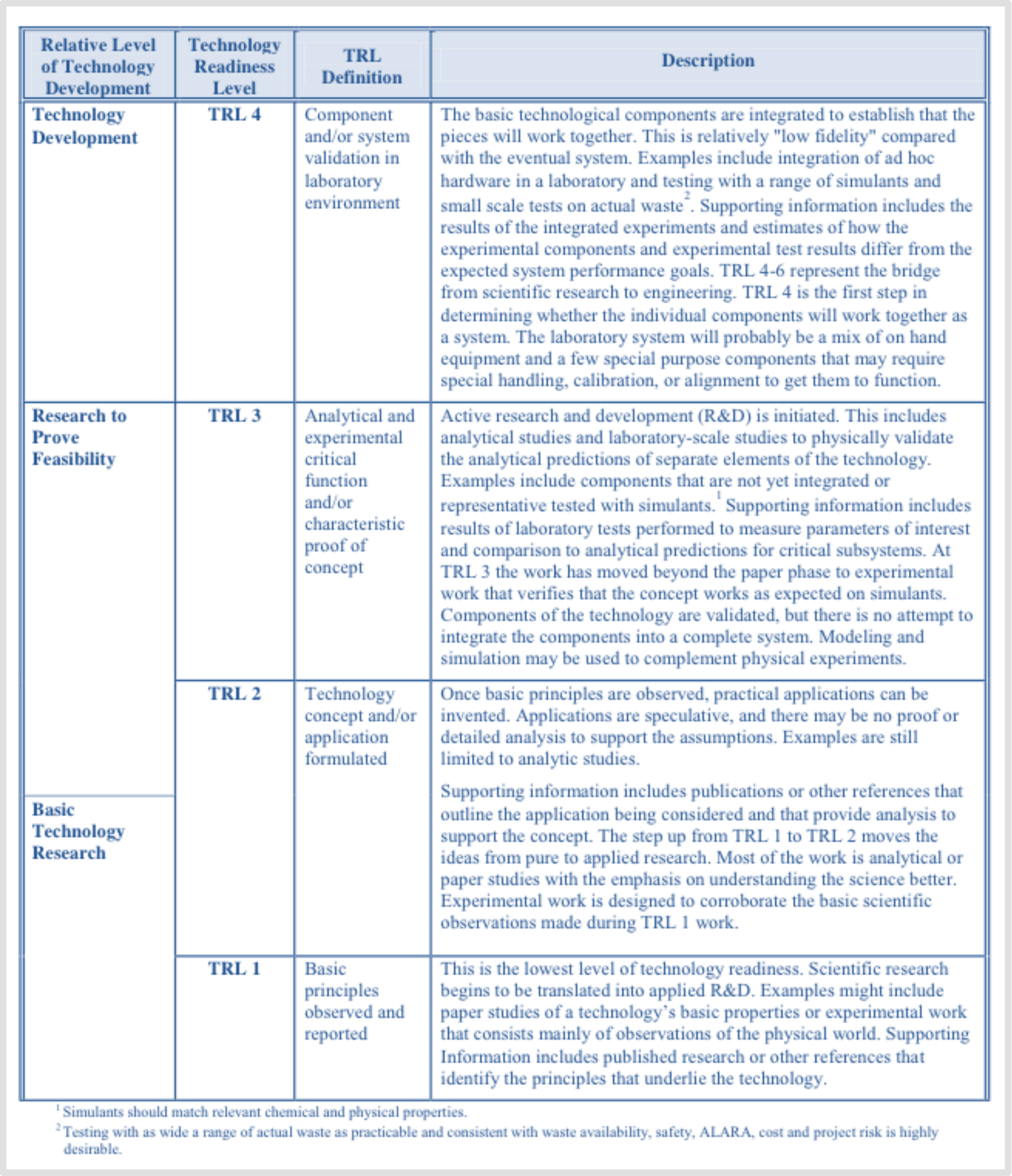
Figure 55: Steel producers of North America (including U.S.) – part 2 (AISI, 2015b)

APPENDIX B3 – TECHNOLOGY READINESS LEVELS



Relative Level of Technology Development	Technology Readiness Level	TRL Definition	Description
System Operations	**TRL 9**	Actual system operated over the full range of expected mission conditions.	The technology is in its final form and operated under the full range of operating mission conditions. Examples include using the actual system with the full range of wastes in hot operations.
System Commissioning	**TRL 8**	Actual system completed and qualified through test and demonstration.	The technology has been proven to work in its final form and under expected conditions. In almost all cases, this TRL represents the end of true system development. Examples include developmental testing and evaluation of the system with actual waste in hot commissioning. Supporting information includes operational procedures that are virtually complete. An Operational Readiness Review (ORR) has been successfully completed prior to the start of hot testing.
	TRL 7	Full-scale, similar (prototypical) system demonstrated in relevant environment	This represents a major step up from TRL 6, requiring demonstration of an actual system prototype in a relevant environment. Examples include testing full-scale prototype in the field with a range of simulants in cold commissioning[1]. Supporting information includes results from the full-scale testing and analysis of the differences between the test environment, and analysis of what the experimental results mean for the eventual operating system/environment. Final design is virtually complete.
Technology Demonstration	**TRL 6**	Engineering/pilot-scale, similar (prototypical) system validation in relevant environment	Engineering-scale models or prototypes are tested in a relevant environment. This represents a major step up in a technology's demonstrated readiness. Examples include testing an engineering scale prototypical system with a range of simulants.[1] Supporting information includes results from the engineering scale testing and analysis of the differences between the engineering scale, prototypical system/environment, and analysis of what the experimental results mean for the eventual operating system/environment. TRL 6 begins true engineering development of the technology as an operational system. The major difference between TRL 5 and 6 is the step up from laboratory scale to engineering scale and the determination of scaling factors that will enable design of the operating system. The prototype should be capable of performing all the functions that will be required of the operational system. The operating environment for the testing should closely represent the actual operating environment.
Technology Development	**TRL 5**	Laboratory scale, similar system validation in relevant environment	The basic technological components are integrated so that the system configuration is similar to (matches) the final application in almost all respects. Examples include testing a high-fidelity, laboratory scale system in a simulated environment with a range of simulants[1] and actual waste[2]. Supporting information includes results from the laboratory scale testing, analysis of the differences between the laboratory and eventual operating system/environment, and analysis of what the experimental results mean for the eventual operating system/environment. The major difference between TRL 4 and 5 is the increase in the fidelity of the system and environment to the actual application. The system tested is almost prototypical.

Table 1: Technology Readiness Levels – part 1 (source DOE (2011))



Relative Level of Technology Development	Technology Readiness Level	TRL Definition	Description
Technology Development	**TRL 4**	Component and/or system validation in laboratory environment	The basic technological components are integrated to establish that the pieces will work together. This is relatively "low fidelity" compared with the eventual system. Examples include integration of ad hoc hardware in a laboratory and testing with a range of simulants and small scale tests on actual waste[2]. Supporting information includes the results of the integrated experiments and estimates of how the experimental components and experimental test results differ from the expected system performance goals. TRL 4-6 represent the bridge from scientific research to engineering. TRL 4 is the first step in determining whether the individual components will work together as a system. The laboratory system will probably be a mix of on hand equipment and a few special purpose components that may require special handling, calibration, or alignment to get them to function.
Research to Prove Feasibility	**TRL 3**	Analytical and experimental critical function and/or characteristic proof of concept	Active research and development (R&D) is initiated. This includes analytical studies and laboratory-scale studies to physically validate the analytical predictions of separate elements of the technology. Examples include components that are not yet integrated or representative tested with simulants.[1] Supporting information includes results of laboratory tests performed to measure parameters of interest and comparison to analytical predictions for critical subsystems. At TRL 3 the work has moved beyond the paper phase to experimental work that verifies that the concept works as expected on simulants. Components of the technology are validated, but there is no attempt to integrate the components into a complete system. Modeling and simulation may be used to complement physical experiments.
Basic Technology Research	**TRL 2**	Technology concept and/or application formulated	Once basic principles are observed, practical applications can be invented. Applications are speculative, and there may be no proof or detailed analysis to support the assumptions. Examples are still limited to analytic studies. Supporting information includes publications or other references that outline the application being considered and that provide analysis to support the concept. The step up from TRL 1 to TRL 2 moves the ideas from pure to applied research. Most of the work is analytical or paper studies with the emphasis on understanding the science better. Experimental work is designed to corroborate the basic scientific observations made during TRL 1 work.
	TRL 1	Basic principles observed and reported	This is the lowest level of technology readiness. Scientific research begins to be translated into applied R&D. Examples might include paper studies of a technology's basic properties or experimental work that consists mainly of observations of the physical world. Supporting Information includes published research or other references that identify the principles that underlie the technology.

[1] Simulants should match relevant chemical and physical properties.

[2] Testing with as wide a range of actual waste as practicable and consistent with waste availability, safety, ALARA, cost and project risk is highly desirable.

Table 2: Technology Readiness Levels – part 2 (source DOE (2011))

APPENDIX C1 – WORKSHOP RESULTS

Facilitators: Quirine Dechesne, Rhodri Owen-Jones
Note taker: Jort Rupert
Duration: 5 hours

Participants: Eric de Coninck (ArcelorMittal), Hans Wiltink (De Gemeynt/ISPT), Arzu Feta (TATA Steel), Burkard Schlange (Shell), Simon Spoelstra (ECN), Nick Hubbers (Eneco), Gerard Jägers (TATA Steel), Erik Saat (Entrepreneur), Margot Weijnen (TU Delft), Derk Straathof (Eneco), Emiel Sanders (Shell), Eric Puik (Shell), Oscar Kraan (Shell/TU Delft/Leiden University).

Introduction

Firstly, Wim Thomas, who is part of the Scenarios team for over twelve years and an experienced scenario practitioner, gave an introduction to how Shell uses scenarios. Secondly, an introducing presentation was given by Quirine Dechesne to explain the scenario method that was used during the workshop. During the workshop the scenario steps that were based on the theory by Schwartz (1991) were followed.

Step 1: Identify focal issue or decision

Method: the focal question was set in advance to the workshop by the author of the thesis. The question was defined somewhat broader than the research question in order to prevent a tunnel view and to leave the scenario creativity during the workshop evolve. The focal question was: How will the U.S. steel producers change their energy use between now and 2050?

Step 2 & 3: Key forces in the local environment & driving forces

Method: Step 2 and 3 where combined in the workshop due to time constraints. Gerard Jägers and Eric de Coninck where asked to provide a presentation about the steel industry and to answer the question: what are, according to you, the drivers of the steel industry and the change in energy use between now and 2050? From this presentation a number of drivers came forward. In addition, the participants where asked to identify drivers themselves on forms that where given to them. Subsequently, after the presentations a plenary discussion took place to add the drivers that were missing according to the other participants. After the identification of drivers, clustering the drivers according to overarching theme shortened the list of drivers. The identified drivers where captured on magnetic hexagons (see figure 56). By doing this, the drivers could be clustered by moving the hexagons around on the magnetic board. This resulted in a list of six key drivers that captured the smaller drivers in one key driver.

Figure 56: Hexagons with drivers

Figure 57: Polarising the drivers in the workshop

Step 4 & step 5: Rank by importance and uncertainty & selecting scenario logics

Method: The group was split up in two, so the following actions where conducted in twofold. Firstly, the identified key drivers where tested on their degree of uncertainty and degree of impact. The key drivers to search for where those with the highest uncertainty and biggest impact, called the critical uncertainties. In addition, the identified critical uncertainties where polarised along axes; a sliding scale was created for each of the critical uncertainties (see figure 57). For example for the price of supply the polarised scale could be identified as low and high. If a group felt that the name of the key driver needed adjustments this was possible. After the development of separate axes the axes could be tested in different sets to create a traditional x/y-axes plane to see what four scenarios came out of the various sets. The goal was to find a set of axes that resulted in scenarios with the following features: plausible, recognisable from signals in the present, include 'good' and 'bad' aspects, internally consistent, challenging, consequential, and memorable. After testing a couple of axes, each group chose their best set of axes. Thereafter a plenary discussion followed to decide upon the decision for the final set of axes.

Result: In both the groups the discussions resulted in different outcomes. However, in general can be stated that the drivers price of supply (feedstock), global demand, and environmental policy came out as critical uncertainties, whereas the drivers role of recycling, technology deployment, and location of supply where identified to be a little less critical and uncertain. After testing various sets of axes in both groups, and a plenary discussion for the final choice the following set was chosen: price of supply (feedstock, and in particular iron) (high/low) and environmental policy (continued/more stringent), resulting in the following scenarios:

- Scenario A: continued environmental policy and high iron prices
- Scenario B: more stringent environmental policy and high iron prices
- Scenario C: continued environmental policy and low iron prices
- Scenario D: more stringent environmental policy and low iron prices

Step 6: Fleshing out the scenarios

Method: the group was again split up in two. In the chosen set of axes four scenarios had to be 'fleshed out'. Each group got the task to deepen two of the four scenarios, so that in the end all four scenarios were touched upon. The question 'What will the world look like in this scenario in 2050?' was addressed. Following the STEEP method, for every theme a moment was taken to think about. For example, what technologies are used in this scenario?

Result: for each scenario a list of bullet points with characteristics was created. For example for the scenario with continued environmental policy with a low iron price the following characteristics where identified:

- Higher margins, increased production as more producers move
- Downside rise from policy change
- More investment in capacity
- Steel production becomes lazy, leading to lower margins over time
- Higher emissions

The development of the set of axes and the four scenarios with a number of characteristics formed the basis and a platform to continue the research. After the scenario workshop each of the four scenarios were checked again for to check to what degree they complied with the features of a 'good' scenario: plausible, recognisable from signals in the present, include 'good' and 'bad' aspects, internally consistent, challenging consequential, and memorable. Scenario B and C were found to be more in compliance with these features than scenario A and D. Also, considering the aim of the research - the fuel change to electricity and hydrogen –, which is specifically related to the technology, the various scenario pathways should preferably lead to different outcomes in technologies in use. Based on these two reasons there was chosen to continue with scenario B and C.

Figure 59: Fleshing out the scenarios in the workshop

The scenarios where further flashed out after the scenario workshop by the author in order to go into more depth. Also step 7 (implications) and step 8 (selection of leading indicators and signposts) where done afterwards.

APPENDIX C2 – DRIVERS WITH IMPLEMENTATION

Key driver category	Driver	Included in qualitative scenario?	Line of reasoning	Implemen-table in WEM?	Explanation
Price of iron ores	Price of iron ores	Yes	This is a critical uncertainty, and is part of the scenario hypotheses. QB high, WR high.	No	Price of non energy feedstock is not included. However the storylines that follow from the price of iron and those storylines are implementable
	Location of scrap	No	This is difficult to say. Could argue with WR more scrap available in general.	No	Non-feedstock steel inputs are not included in the model.
	Availability and price of scrap	Yes	More steel results in more scrap. QB low availability, high price, WR high availability, low price	No	Non-feedstock steel inputs are not included in the model.
Technology deployment	Availability of incremental innovation technologies	No	Research only analysed radical changing technologies	Yes	To have more realistic calculations this needs to be taken into account in WEM. Included in the energy service efficiency calculation. Although incremental innovations are not the main focus of the research, hence it is assumed that the incremental innovation per year 0.1% is.
	Availability of radical innovation technologies	Yes	Technologies under R&D in U.S. and Europe. Strict climate policy leads to more radical innovation. QB high, WR low	Yes	Included in the energy service efficiency calculation. It is assumed that certain technologies become available in defined years
	Availability of R&D funding	Yes	Strict climate policy makers provide more funding. QB high, WR low.	No	However this can be reflected in the availability of innovative technologies. Assumed is that when there is more availability of funding for R&D, technologies become slightly earlier commercially available.
	Energy efficiency improvement	Yes	More radical technologies results in higher efficiency. QB high, WR low	Yes	This is included in the energy service efficiency calculations
	Availability of capital	Yes	Lower iron price results in higher profit margin, and thus more money available. QB low, WR high.	No	However this can be reflected in the availability of innovative technologies. Assumed is that when there is more availability of funding for R&D, technologies become slightly earlier commercially available.
	Intermittency of renewables	Yes	Stricter climate policy leads to higher need to solve intermittency problem. QB partly solved, WR not solved	Yes	It can be included in the supply potential of RES, which is set higher if intermittency problem is significantly addressed, resulting in increased availability of RES
	Maturity of new technology	No	Future maturity is uncertain but likely that stricter climate policy leads to faster maturity.	No	However, it is partly reflected in the availability of a new technology together with the yearly incremental improvements of 0,1%.
	Lifetime of stock/turnover	Yes	Stricter climate policy pushes old and dirty technology out of market. QB high, WR low	Yes	This is included with producer legacy churn rate. The higher the % of churn, the shorter the lifetime and the faster technologies need to be replaced.
	CCS cost/availability	Yes	CCS will become available in both scenarios. With stricter policy measures CCS is more deployed thus cheaper. QB low, WR high	Yes	With the input 'CCS costs' (standard scenario inputs). Data set with higher or lower CCS costs can serve as input.
	Government support for new technologies	Yes	Strict environmental policy makers support more. QB high, WR low	Yes	Support for a technology, and hence certain use of fuel types, can be reflected with the fuel convenience factor. Utility is increased for a fuel type because of support.
Environmental policy	CO2 policy (e.g. price)	Yes	Stricter climate policy results in higher CO2 tax. QB high, WR low	Yes	Reflected in the input 'CO2 price' (standard scenario inputs). Data set with higher or lower CO2 prices can serve as input.
	EU ETS progress	No	Out of scope of research	No	The model only looks at the U.S., and not at dynamics between countries.
	Amount of CO2 emissions	Yes	Stricter climate policy leads to less CO2 emissions. QB low, WR high	No	This driver can be seen as a driver that indirectly effects other drivers such as development of environmental policy measures. It is difficult to model this as it is a cause and effect of other drivers.
	CCS cost/availability	Yes	CCS will become available in both scenarios. With stricter policy measures CCS is more deployed thus cheaper. QB low, WR high	Yes	With the input' CCS costs' (standard scenario inputs). Data set with higher or lower CCS costs can serve as input.
	Government support for new technologies	Yes	Strict environmental policy makers support more. QB high, WR low	Yes	Support for a technology, and hence certain use of fuel types, can be reflected with the fuel convenience factor. Utility is increased for a fuel type because of support.
	Public pressure	No	Not specific enough	No	Difficult to quantify. Indirect driver for other defined drivers (e.g. policy)
	Availability of R&D funding	Yes	Strict climate policy makers provide more funding. QB high, WR low.	No	However this can be reflected in the availability of innovative technologies. Assumed is that when there is more availability of funding for R&D, technologies become slightly earlier commercially available.
	Mandatory fuel policy	Yes	Strict climate policy leads to more fuel policy. QB high, WR low	Yes	This can be reflected in the fuel convenience factor. A minus factor leads to a lower utility for a fuel.
	All energy prices	Yes	Varies per energy type, but in general QB high, WR low	Yes	With the end-user inputs 'source prices', 'natural gas prices',' coal prices' (standard scenario inputs). Data set with higher or lower prices can serve as inputs.
	Level of decarbonisation	Yes	Strict climate policy leads to more decarbonisation. QB high, WR low	No	This driver can be seen as a driver that indirectly affects other drivers such as development of environmental policy measures. It is difficult to model this as it is a cause and effect of other drivers.
(Global) demand	(Global) steel demand	Yes	Only national steel demand addressed. Stringent policy constraints steel use. QB low, WR high	Yes	Steel demand is reflected in the variable energy service (tonnes of steel per capita). A higher tonnes of steel per capita means higher steel demand. This in included in the historical data, and for the scenarios it is automatically calculated in the model with the energy service efficiency and total final consumption. It can be influenced with energy ladder parameter inputs
	Economic growth	Yes	Stringent policy constraints economic growth. QB low, WR high	Yes	Reflected in the GDP parameter
	Consumer demand for quality	Yes	Stringent policy leads to demand for light weight and quality products. QB quality, WR quantity	No	No differentiation between types of steel is made.
	Steel substitution with other material	Yes	High steel price leads to more substitution. QB high, WR low	No	But this is reflected in the steel demand
	Urbanization and growth in population	Yes	Strict climate policy hinders growht. QB low, WR low.	No/yes	Growth in population is reflected in input ' GDP' (standard scenario input). Urbanization can be indirectly reflected in steel demand
	Standardization	No	Unclear for the scenarios	No	Difficult to quantify the effect on the steel industry
	Ramp-up of production outside U.S.	Yes	China and India have effect in both scenarios. More if steel price high. QB more WR less	No	The model only looks at the U.S. Can be indirectly included through steel demand.
	Consumption per capita	Yes	Stringent policy constraints steel use. QB low, WR high	Yes	This is the variable energy service (tonnes of steel per capita). A higher tonnes of steel per capita means higher steel demand. This

	Consumer behaviour	Yes	With strict climate policy more sustainability. QB, sustainable QR less sustainable	No	But can be partly reflected in steel demand
	De-materialization	Yes	With strict climate policy more. QB, high WR low	No	But can be partly reflected in steel demand
Location of supply	Energy prices	Yes	Varies per energy type, but in general QB high, WR low	Yes	With the end-user inputs 'source prices', 'natural gas prices',' coal prices' (standard scenario inputs). Data set with higher or lower prices can serve as inputs.
	New entry by companies in developing economies	Yes	Higher market profit more new entry. QB low, WR high	No	The model only looks at the U.S. Can be indirectly included through steel demand.
	Availability of shale gas	Yes	In both scenarios available, but in WR more deployed. QB low, WR high	Yes	With the end-user input 'natural gas prices'. Data set with higher or lower prices serve as inputs.
	Raw material price	Yes	Varies per energy type, but in general QB high, WR low	Yes/no	Energy fuel raw material with the end-user input 'source prices' and 'coal prices'. Non-energy fuel prices are not included.
	Coal price	Yes	Stringent climate policy high coal price. QB high, WR low	Yes	With the end-user input 'coal prices' (standard scenario inputs). Data set with higher or lower prices can serve as inputs.

Table 10: Drivers in the WEM

APPENDIX C3 – TECHNOLOGY MIX ASSUMPTIONS

The share of each of the technologies, or in other words the technology mix, that is in use per year varies for both scenarios. Below the assumptions that are done to create the graphs are shown. These assumptions follow the scenario storylines.

QUARTERBACK TECHNOLOGY MIX

Technology A:
- 2014-2019 0,5% decrease
- 2020-2050 1% decrease

Technology B:
- 2014-2019 0,5% increase
- 2020 – 2029 0% change
- 2030 – 2039 0,5% increase
- 2040 – 2050 0,5% decrease

Technology C:
- 2040- 2050: 0,5% increase

Technology D:
- 2020-2029 1% increase
- 2030-2039 0,5% increase

WIDE RECEIVER TECHNOLOGY MIX

Technology A
- 2014-2029 0,1% decrease
- 2029 – 2039 0,5% increase
- 2039 – 2050 0,5 decrease

Technology B
- 2014-2019 0,1% increase
- 2019-2029 0% change
- 2029 – 2039 1% decrease
- 2039 – 2050 0,5% decrease

Technology C
- 2039 – 2050 0,1 % increase in first year and then constant

Technology D
- 2019-2029 0,1% increase
- 2029 – 2039 0,5% increase
- 2039 – 2050 0,1% increase

APPENDIX D1 – WEM STRUCTURE

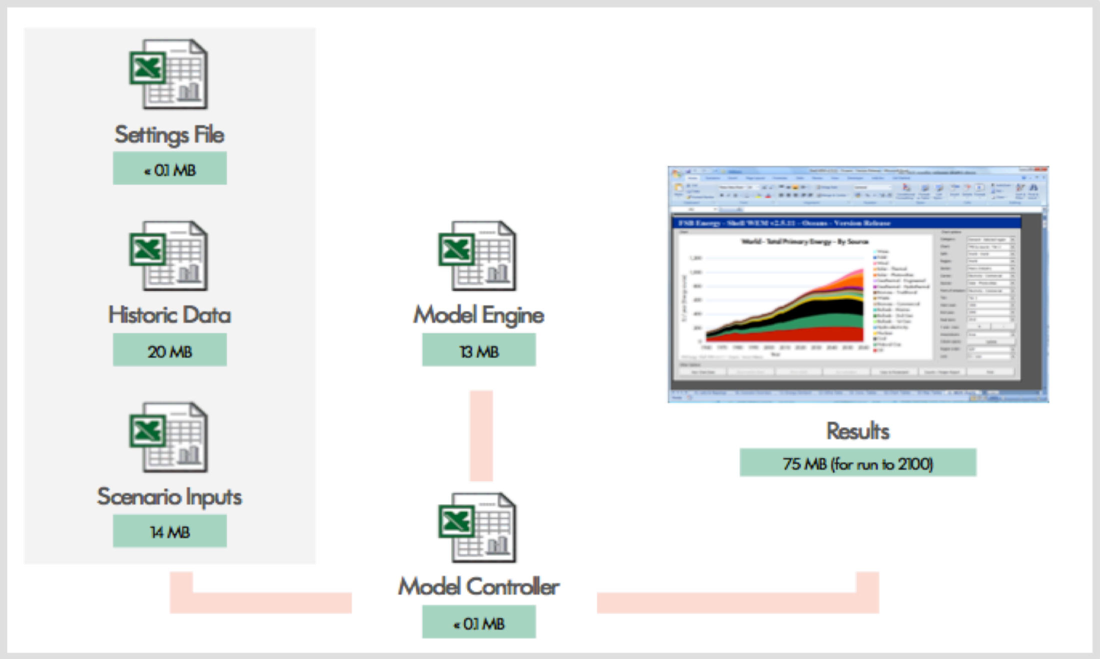


Figure 60: WEM model set-up

Figure 61: WEM segmentation

APPENDIX D2 – WEM HISTORICAL DATA ADJUSTMENTS

The historical data includes data about TPE and TFC from the International Energy Agency (IEA) of all sectors built in the model.

1. ADJUSTMENT OF TOTAL FINAL CONSUMPTION DATA

Firstly, for the TFC the historical data of U.S. heavy industry is changed to the TFC for the U.S. steel industry only, in order to make it possible to model the scenarios at steel industry level. For this Shell internal data from the IEA was used.

2. ADJUSTMENT OF HISTORICAL ESE DATA

Secondly, with regard to the ESE, historical data about the ESE is calculated in the model, by means of dividing the TFC by the Energy Service (historically data in the model). However, the historical data and scenario inputs did not match with new calculated energy service efficiency, because the historical ESE is based on total heavy industry, which is simplified by the average of three heavy industries, including steel, aluminium and cement, by the Shell modellers. To match the historical ESE data with the scenario ESE data, the historical data was adjusted and specified for the steel industry. This was done by taking the steel industry values from 2014, and from this point the historical data is adjusted backwards, by taking the percentage increase from the historical data between 2013 and 2014. Subsequently the steel industry value from 2014 is taken and divided by the percentage increase to calculate the year 2013. This is continued back until the year 1960. To give an example:

Increase = year 2/ year 1. E.g. 0,000098 (2014)/ 0,00097 (2013) = 1,007013, which means 0,7% increase of the ESE.

APPENDIX D3 – WEM PARAMETERS

Parameter	Function
Energy Ladder Inputs	
Population	Affects aggregate demand in Energy Ladder
GDP	Principle driver of aggregate demand
Exchanges rates	Used to normalise USD prices
Energy service efficiency	The end-users' efficiency in using energy carriers, or efficiency trend assumptions for end-use technology
Energy source prices	Assumption on future price movements of all primary energy sources - Calibrated by end-user in price-balancing
Energy source taxes	Taxes and subsidies on energy sources. Principally used for subsidies on renewable sources
Natural gas prices	Simulates the different levels of natural gas price which varies by geographical market. Affect the energy choice through the utility function
Coal prices	Simulates the different levels of coal price which varies by geographical market. Affect the energy choice through the utility function
Energy source taxes (CO_2 price)	Apply CO_2 taxes at the primary energy level
CO_2 scope	Determines which sectors experience a CO2 price
CCS costs	The costs of applying CCS in each sector
CCS efficiency hit	The drop in production efficiency as a result of applying CCS
CCS – percentage CO_2 captured	The percentage of CO2 captured by the CCS installation
Energy carrier conversion cost	Cost of supply curves for renewables, and capital cost trends for other source-to-carrier pathways such as GTL
Energy carrier taxes	Taxes on electricity, gasoline, etc. (keep the terminology consistent, so if you've talked about energy carriers up until now, then keep referring to them as such)
Energy carrier taxes – pass through coefficients	Degree of insulation of end-users to price changes, through changes to subsidies
Energy carrier taxes – pass through phase out	Date and rate of phase out of any accumulated pass through subsidies
Energy Ladder parameters	Sets of price and income parameters, by country and income band
Choice inputs	
End-use churn	Annual turnover rate of equipment (cars, steel mills, heating systems) in end-use sectors
End-use price parameters	A calibrated value that acts as a coefficient for the price parameter in the multi-nomial logit choice function
End-use investment parameters	A calibrated value that acts as a coefficient for the investment parameter in the multinomial logit choice function
End-use fuel convenience	Fuel convenience factor, calibrated on recent history, reflecting preferences by the end-user for particular energy carriers. Factor that affects the energy choice through the utility function
End-use capital cost trends	Trends in costs of end-use energy equipment
End-use CCS percentage of stock	Percentage of end-user stock that has CCS applied
Plug-in hybrids available	Introduction date for plug-in hybrids
Hydrogen vehicles available	Introduction date for hydrogen fuel cell vehicles
Producer churn	Annual turnover rate of capital stock (power stations, refineries, biofuel factories) for energy industry
Producer – Price parameters	A calibrated value that acts as a coefficient for the price parameter in the multi-nomial logit choice function
Producer – Investment parameters	A calibrated value that acts as a coefficient for the investment parameter in the multinomial logit choice function
Producer – fuel convenience	Fuel convenience factor, calibrated on recent history, reflecting preferences by the producer for particular energy sources. Factor that affects the energy choice through the utility function
Producer – CCS percentage of stock	Percentage of producer stock that has CCS applied
Producer - Second-generation biofuels available	Introduction date for 2nd gen (i.e. cellulosic ethanol)
Producer - Technology - Geothermal engineered	Introduction date for geothermal engineered (i.e. geothermal sites that can produce electricity)
Producer – Solid hydrocarbon fuel from oil	Function that determines the amount of pet coke coming from oil throughput in refineries
Producer – Gaseous hydrocarbon fuel from oil	Function that determines the amount of LPG coming from oil throughput in refineries
Producer – Gas to liquid production	Assumptions on future gas to liquid production capacity
Producer – Coal to liquid production	Assumptions on future coal to liquid production capacity
Producer - Waste - Percentage to energy	Calculated function that sets the split between those countries that have a preference for burning waste in energy, and those that prefer to recycle waste.

Producer - Waste - split per carrier	Sets the amount of waste than can be absorbed in the different energy carriers
Producer - Biofuels	Enables blend wall limits to be put in place for liquid hydrocarbon fuel
Producer - Load factors	Load factors for all forms of electricity generation
Producer - Production efficiency	Improvements in conversion efficiency or reduction of losses from distribution or the energy sector
Commercial biomass split	Controls the amount of biomass used for biogas and that used as commercial biomass
Supply	
Supply potential - Conventional oil	Supply potential of an energy source set a constraint with regard to the maximum amount of energy supplied per year for that energy source, reflecting the availability of primary energy sources
Supply potential - Unconventional oil	
Supply potential - Conventional gas	
Supply potential - Unconventional gas	
Supply potential - Coal	
Supply potential - Nuclear	
Supply potential - Hydro	
Supply potential - Biofuels	
Supply potential - Geothermal Hydrothermal	
Supply potential - Geothermal Engineered	
Supply potential - Solar PV central	
Supply potential - Solar PV decentral	
Supply potential - Solar thermal central	
Supply potential - Solar thermal decentral	
Supply potential - Wind	
Supply potential - Tidel	
Supply potential - Wave	
Demand potential - Electricity - natural gas	Sets limits to growth of gas or coal in electricity as a result of announced country energy policies
Demand potential - Electricity - coal	

Table 11: Parameters included in the WEM

APPENDIX D4 – STANDARD SCENARIO INPUTS

Standard scenario inputs settings	Wide receiver (oceans)	Explanation	Quarterback (mountains)	Explanation	Inputs (standard data sets/manually adjusted)
Ladder					
UN population	Hybrid case		Hybrid case		Standard data sets
GDP	Tight squeeze without environmental feedback	Higher GDP growth	Stretched loose with middle income trap	Lower GDP growth	Standard data sets
Energy Service Efficiency	Stretched loose - Moderate ESE	Manual calculations, adjusted for steel industry specifically	Tight squeeze - Highest ESE	Manual calculations, adjusted for steel industry specifically	Manually adjusted
Source prices	Stretched loose	Lower prices	Tight squeeze	Higher prices	Standard data sets
Source taxes	Base case		Base case		Standard data sets
Natural gas prices	BBC15		BBC15		Standard data sets
Coal prices	BBC14		BBC14		Standard data sets
CO2 price	Scramble	Slow increase, same pace as today	Blueprint	Faster increase	Standard data sets
CO2 scope	Industry sectors, developing countries late		Industry sectors, developing countries late		Standard data sets
CCS costs	Base case		Base case		Standard data sets
CCS efficiency hit	15 per cent		15 per cent		Standard data sets
CCS - percentage CO2 captured	85 per cent		85 per cent		Standard data sets
Carrier price conversion - default cost increase	Base case		Base case		Standard data sets
Carrier taxes	Base case		Base case		Standard data sets
Carrier taxes - pass through coefficients	World Bank		World Bank		Standard data sets
Carrier taxes - pass through phase out	From 2010, Non-MRH countries quicker		From 2010, Non-MRH countries quicker		Standard data sets
Ladder - scenario inputs	Base - Import corrected	S-curve ends higher (higher steel use/capita)	Stretched Loose - Mountains - Compact cities + world is plastic	S-curve ends lower (lower steel use/capita)	Standard data sets
Choice					
End-use - Legacy churn rates	Natural base churn	Lower legacy churn rate	Natural base churn	Higher legacy churn rate	Standard data sets
End-use - Price parameters	History, but industrial users less sensitive		History, but industrial users less sensitive		Standard data sets
End-use - Investment parameters	History, but private users less sensitive		History, but private users less sensitive		Standard data sets
End-use - Fuel convenience	Mountains	Manually adjusted	Oceans	Manually adjusted	Manually adjusted
End-use - Capital cost trends	Zero end use capital cost trends		Zero end use capital cost trends		Standard data sets
End-use - CCS percentage of stock	Scramble 2010	Lower percentage of stock	Blueprints 2010	Higher percentage of stock	Standard data sets
End-use - Technology - Plug-in hybrids	Set A		Set A		Standard data sets
End-use - Technology - hydrogen	Set A		Set A		Standard data sets
Producer - Legacy churn rates	Oceans reaction	Lower legacy churn rate	High coal churn	Higher legacy churn rate	Standard data sets
Producer - Price parameters	History, typical		History, typical		Standard data sets
Producer - Investment parameters	History, typical		History, typical		Standard data sets
Producer - Fuel convenience	Mountains	Similar to a mountains world	Oceans	Similar to an oceans world	Standard data sets
Producer - CCS percentage of stock	Scramble 2010	Lower percentage of stock	Blueprints 2010	Higher percentage of stock	Standard data sets
Producer - Technology - 2nd gen biofuels	Set A		Set A		Standard data sets
Producer - Technology - Geothermal engineered	From 2051	Less innovation	From 2031	More innovation	Standard data sets
Producer - SHCF from oil	Default downstream view		Default downstream view		Standard data sets
Producer - GHCF from oil	Default downstream view		Default downstream view		Standard data sets
Producer - GTL production	BBC14		BBC14		Standard data sets
Producer - CTL production	BBC14		BBC14		Standard data sets
Producer - Waste - Percentage to energy	Promote waste to energy	Focus on energy	Promote recycling, leaving less waste for energy	Focus on recycling	Standard data sets

Producer - Waste - Percentage to energy	Promote waste to energy	Focus on energy	Promote recycling, leaving less waste for energy	Focus on recycling	Standard data sets
Producer - Waste - split per carrier	Base values		Base values		Standard data sets
Producer - Biofuels	Base values		Base values		Standard data sets
Producer - Load factors	Base values		Base values		Standard data sets
Producer - Production efficiency	Slow improvement		Slow improvement		Standard data sets
Commercial biomass split	Gasified biomass promoted		Gasified biomass promoted		Standard data sets
Supply					
Supply potential - Conventional oil	Streched loose - raw	Similar to oceans	Tight squeeze - demand adjusted	Similar to mountains	Standard data sets
Supply potential - Unconventional oil	BBC12		BBC12		Standard data sets
Supply potential - Conventional gas	Streched loose - demand adjusted	Similar to oceans	Tight squeeze - demand adjusted	Similar to mountains	Standard data sets
Supply potential - Unconventional gas	BBC12		BBC12		Standard data sets
Supply potential - Coal	Tight squeeze - Oceans	Similar to oceans	Stretched loose - Mountains	Similar to mountains	Standard data sets
Supply potential - Nuclear	BBC15		BBC15		Standard data sets
Supply potential - Hydro	Ecofys 2012	Normal hydro	High case Brazil	Much hydro	Standard data sets
Supply potential - Biofuels	Ecofys 2009		Ecofys 2009		Standard data sets
Supply potential - Geothermal Hydrothermal	WEM v2 - country targets - high		WEM v2 - country targets - high		Standard data sets
Supply potential - Geothermal Engineered	Ecofys 2012 - Base		Ecofys 2012 - Base		Standard data sets
Supply potential - Solar PV central	Ecofys 2012 - Base	Base share of Solar pv supply	Ecofys 2012 - High	High share of Solar PV supply	Standard data sets
Supply potential - Solar PV decentral	Ecofys 2012 - Roofs + facades	Lot of distributed solar (no need for governmental support)	Ecofys 2012 - Roofs only	Less of distributed solar	Standard data sets
Supply potential - Solar thermal central	Ecofys 2012 - Base	Base share of solar thermal	Ecofys 2012 - High	Higher share of solar thermal central	Standard data sets
Supply potential - Solar thermal decentral	Ecofys 2012		Ecofys 2012		Standard data sets
Supply potential - Wind	Ecofys 2012 - Base	Base share of wind (less governmental support)	Ecofys 2012 - High	High share of wind (governmental support)	Standard data sets
Supply potential - Tidel	Set A		Set A		Standard data sets
Supply potential - Wave	Set A		Set A		Standard data sets
Demand potential - electricity - natural gas	Oceans		Oceans		Standard data sets
Demand potential - electricity - coal	Oceans		Oceans		Standard data sets
Supply potential - Solar thermal central	Ecofys 2012 - Base	Base share of solar thermal	Ecofys 2012 - High	Higher share of solar thermal central	Standard data sets
Supply potential - Solar thermal decentral	Ecofys 2012		Ecofys 2012		Standard data sets
Supply potential - Wind	Ecofys 2012 - Base	Base share of wind (less governmental support)	Ecofys 2012 - High	High share of wind (governmental support)	Standard data sets
Supply potential - Tidel	Set A		Set A		Standard data sets
Supply potential - Wave	Set A		Set A		Standard data sets
Demand potential - electricity - natural gas	Oceans		Oceans		Standard data sets
Demand potential - electricity - coal	Oceans		Oceans		Standard data sets

Table 12: Scenario inputs with built-in data sets

In the WEM many inputs are named after one of the Shell scenarios (Mountains versus Oceans), (Scramble versus Blueprint) or called Tight Squeeze versus Stretched Loose. These are just names, and for this research the data is analysed and the best suitable set is chosen.

APPENDIX D5 – ENERGY SERVICE EFFICIENCY ASSUMPTIONS

Seven data sets for the seven energy carriers from 2014 to 2050 had to be created. This was conducted based on the following assumptions:

Technology A – Integrated route

The following assumptions account:

- The incremental improvement is 0,1% per year

Technology B – EAF route

The following assumptions account:

- Incremental improvement is 0,1% per year

Technology C – Radical innovations with focus on electricity

This technology representation includes the innovations MOE and electrolysis (ULCOWIN). In the technologies a larger percentage of the total energy comes from electricity. It is unknown yet what technology will be the 'winner', and therefore for the calculation a combination of both is used. The following assumptions account:

- Both technologies are introduced in the year 2040.
- Incremental improvement is 0,1% per year (if there is no radical innovation that year).
- With the introduction of a new technology the average fuel mix changes from that year onwards accordingly. In this case there is a transition of 20% natural gas to electricity.
- The technologies are more efficient so less energy is used. The energy use of MOE is 12,6 GJ/tonne of steel, for ULCOWIN applies 15-20 GJ/tonne of steel. The two combined (with best value for ULCOWIN): 12,6 GJ + 15 GJ = 13,8 GJ/tonne of steel.
- For the innovations around 2040 the efficiencies were smoothened out over a number of years with linear interpolation.

Technology D – Other radical innovations

This technology representation includes the innovations TGR, PHS, HIsarna, and HFS. It is unknown yet what technology will be the 'winner', and therefore for the calculation a combination of all is used. The following assumptions account:

- The technologies become available in the following years: TGR in 2020, PHS and HIsarna in 2030, HFS in 2040.
- Incremental improvement is 0,1% per year (if there is no radical innovation that year).
- With the introduction of a new technology the average fuel mix changes from that year onwards.

Furthermore, a fuel switch is assumed in some technologies:

- Top gas recycling: less coal use because there is less coke necessary.
- PHS: coal use instead of coke; the coke making step is skipped. Energy use is 11,5 GJ/tonne of steel.
- HIsarna: less coal use, small increase of use of hydrogen, natural gas and biomass. The technology has 20% energy efficiency improvement of today, which is 0,8*17,6 GJ = 14,08 GJ/tonne of steel.
- HFS: more use of hydrogen and natural gas.

If you combine this to averages:

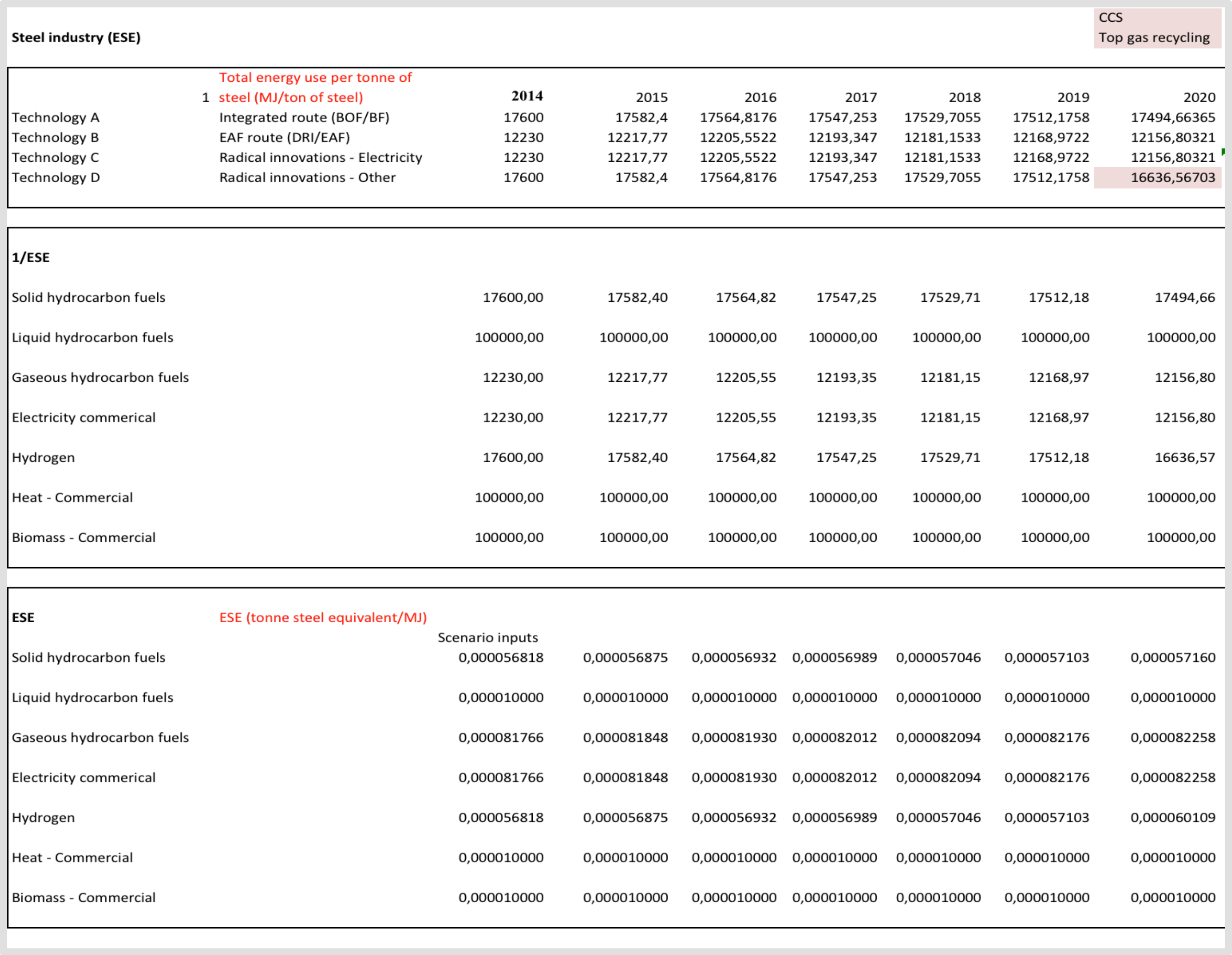
- From year 2015 to 2020: no technology available.
- From year 2020 to 2030:
  - TGR available → less coal use (10% reduction, distributed over other fuels except for liquid hydrocarbon fuels), assume 5% decrease in total energy consumption compared to year 2019.
- From year 2030 to 2040: TGR, PSH, HIsarna available → less coal use, small increase use of hydrogen, natural gas and biomass. Taking the average total energy use: 11,5 GJ/tonne of steel (PHS) + 14,08 GJ/tonne of steel (HIsarna) + 16,6 GJ/tonne of steel (TGR)/3 = 13,88 GJ/tonne of steel.
- From year 2040 to 2050: TGR, PSH, HIsarna, HFS available → less coal use, somewhat higher increase use of hydrogen, natural gas and biomass. Taking the average total energy use: 0,75

(75%)*13,88 GJ/tonne of steel + 0,25 (25%)* 12,06 GJ/tonne of steel (HFS) = 13,425 GJ/tonne of steel. The fuel mix changes to: 15% less coal, and 5% increase in hydrogen, natural gas and biomass.

With these assumptions the efficiency of each technology pathway per year could be defined (see upper square in figure XXX (note: figure shows only beginning of data sets). In the figure is shown that for example in 2020 CCS and top gas recycling are introduced, which leads to another average efficiency for technology D.

In the next square the carriers are linked to one technology pathway. For example, solid hydrocarbon fuels are used a lot in the integrated route (technology A), and thus gets the carrier the efficiency of this technology. Again, it needs to be stressed that big assumptions are made here.

Finally, the ESE is calculated by dividing 1 by the numbers in the second squared box. This results in seven data sets with approximated the amount of steel equivalent to one MJ of carrier.



Steel industry (ESE)									CCS Top gas recycling
	1	Total energy use per tonne of steel (MJ/ton of steel)	**2014**	2015	2016	2017	2018	2019	2020
Technology A		Integrated route (BOF/BF)	17600	17582,4	17564,8176	17547,253	17529,7055	17512,1758	17494,66365
Technology B		EAF route (DRI/EAF)	12230	12217,77	12205,5522	12193,347	12181,1533	12168,9722	12156,80321
Technology C		Radical innovations - Electricity	12230	12217,77	12205,5522	12193,347	12181,1533	12168,9722	12156,80321
Technology D		Radical innovations - Other	17600	17582,4	17564,8176	17547,253	17529,7055	17512,1758	16636,56703

1/ESE							
Solid hydrocarbon fuels	17600,00	17582,40	17564,82	17547,25	17529,71	17512,18	17494,66
Liquid hydrocarbon fuels	100000,00	100000,00	100000,00	100000,00	100000,00	100000,00	100000,00
Gaseous hydrocarbon fuels	12230,00	12217,77	12205,55	12193,35	12181,15	12168,97	12156,80
Electricity commerical	12230,00	12217,77	12205,55	12193,35	12181,15	12168,97	12156,80
Hydrogen	17600,00	17582,40	17564,82	17547,25	17529,71	17512,18	16636,57
Heat - Commercial	100000,00	100000,00	100000,00	100000,00	100000,00	100000,00	100000,00
Biomass - Commercial	100000,00	100000,00	100000,00	100000,00	100000,00	100000,00	100000,00

ESE	ESE (tonne steel equivalent/MJ)							
		Scenario inputs						
Solid hydrocarbon fuels		0,000056818	0,000056875	0,000056932	0,000056989	0,000057046	0,000057103	0,000057160
Liquid hydrocarbon fuels		0,000010000	0,000010000	0,000010000	0,000010000	0,000010000	0,000010000	0,000010000
Gaseous hydrocarbon fuels		0,000081766	0,000081848	0,000081930	0,000082012	0,000082094	0,000082176	0,000082258
Electricity commerical		0,000081766	0,000081848	0,000081930	0,000082012	0,000082094	0,000082176	0,000082258
Hydrogen		0,000056818	0,000056875	0,000056932	0,000056989	0,000057046	0,000057103	0,000060109
Heat - Commercial		0,000010000	0,000010000	0,000010000	0,000010000	0,000010000	0,000010000	0,000010000
Biomass - Commercial		0,000010000	0,000010000	0,000010000	0,000010000	0,000010000	0,000010000	0,000010000

Figure 62: ESE data calculations (shows only first part of data sets)

APPENDIX D6 – CHOICE – FUEL CONVENIENCE FACTOR

Adjustments for Quarterback:

Hydrogen

Timeline	Old values	New values
Start values (2020)	-7	-2.0
Mid values (2060)	-7	0.5

The new values are higher due to the environmental policy measures advocating for hydrogen use.

Biomass – commercial

Timeline	Old values	New values
Start values (2020)	-2	-4
Mid values (2060)	-3	-5

Unrealistic amounts of biomass were shown in results, so value had to be decreased.

Solid hydrocarbon fuels

Timeline	Old values	New values
Start values (2020)	-1.50	-1
Mid values (2060)	-3.00	-3

The new values are low due to the environmental policy measures counteracting the use of oil. Also almost no oil is consumed in the steel industry so the pre-implemented value was too high.

The fuel convenience factor values of other carriers do not require adjustments since the original base values in the model match the scenario storylines.

Adjustments for Wide Receiver:

Solid hydrocarbon fuels

Timeline	Old values	New values
Start values (2020)	0	-0.5
Mid values (2060)	-2	-2

The new values are low due to the environmental policy measures counteracting the use of oil. Also almost no oil is consumed in the steel industry so the pre-implemented value was too high.

Gaseous hydrocarbon fuels

Timeline	Old values	New values
Start values (2020)	-1	0.0
Mid values (2060)	1	1

Shale gas is significantly deployed so convenience factor is increased.

Electricity commercial

Timeline	Old values	New values
Start values (2020)	1	1.5
Mid values (2060)	1	1.5

The old values were too low for this scenario, as even in Wide Receiver relatively much electricity is used in the EAF.

The other fuel convenience factor values do not require adjustments since the original base values in the model match the scenario storylines.

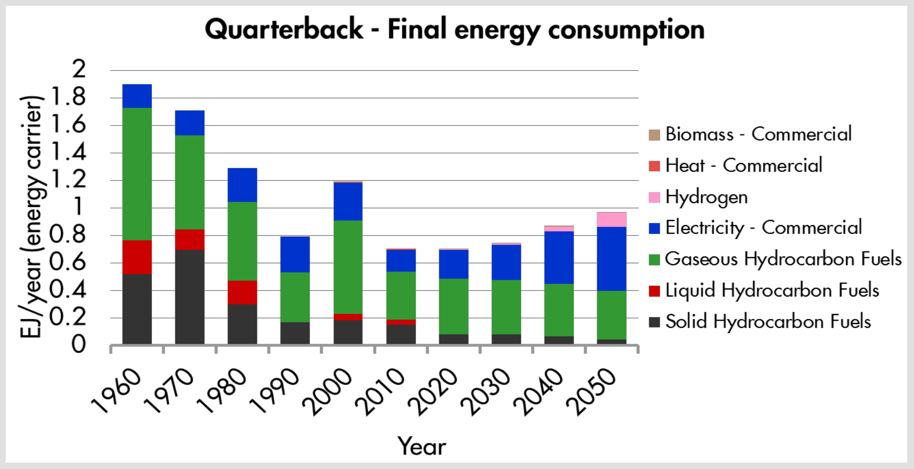


Figure 63: Final energy consumption by the U.S. steel industry – WEM results

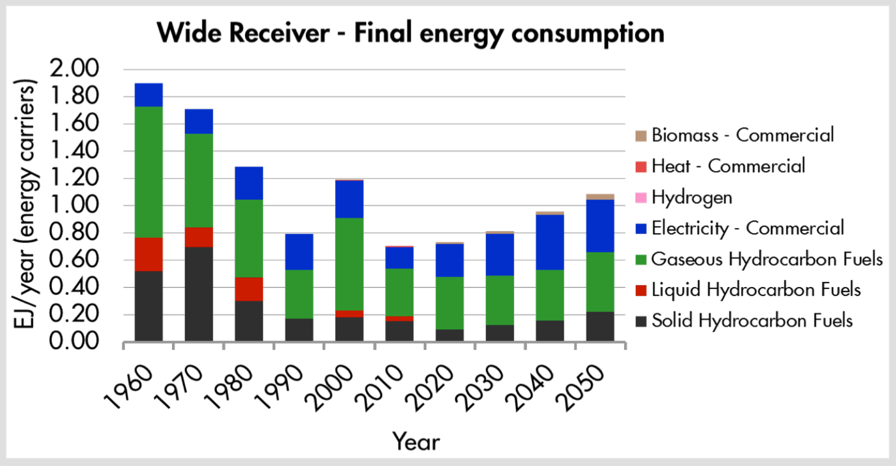


Figure 64: Final energy consumption by the U.S. steel industry – WEM results

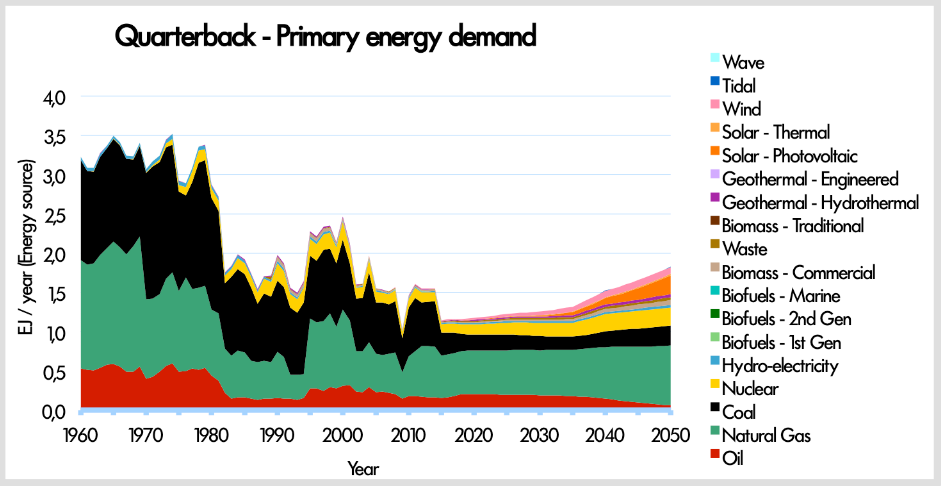


Figure 65: Total primary energy demand from the U.S. steel industry

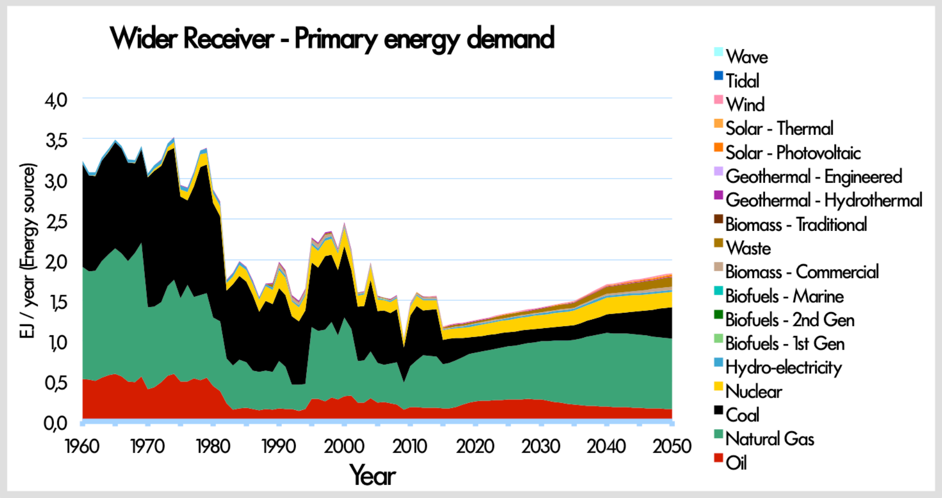


Figure 66: Total primary energy production for the U.S. steel industry – WEM results

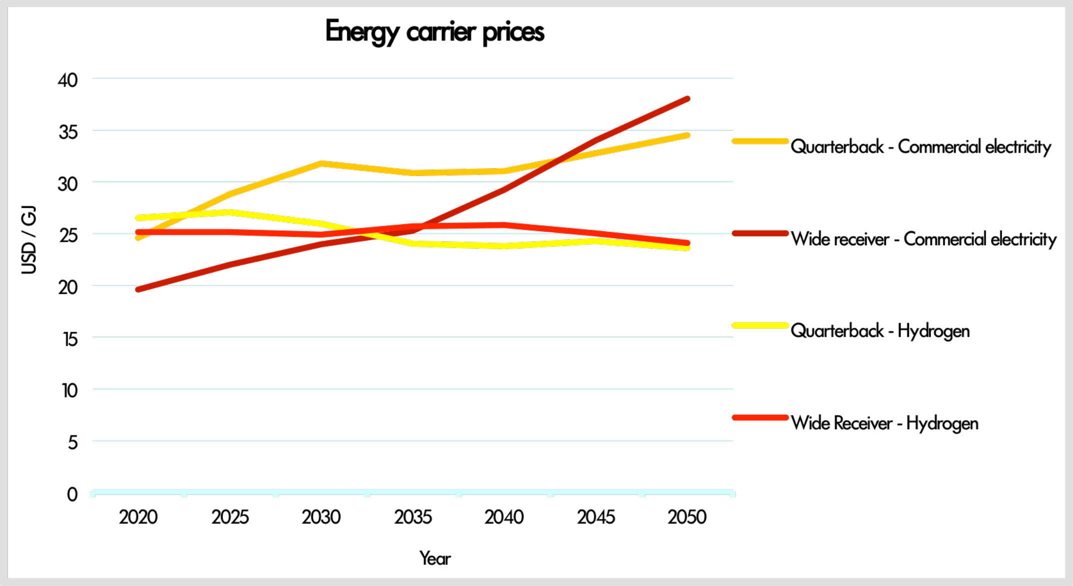


Figure 67: Energy carrier prices of both scenarios – WEM results

APPENDIX D8 – STEEL INDUSTRY WEM FRAMEWORK

	Price of iron		Technological availability									
Parameter	Price of iron ores	Availability and price of scrap	Availability of incremental innovation technologies	Availability of radical innovation technologies	Availability of R&D funding	Energy efficiency improvement	Availability of capital	Intermittency of renewables	Maturity of new technology	Lifetime of stock/turnover	CCS cost/availability	Government support for new technologies
Energy Ladder Inputs	🟥	🟥	🟩	🟩	🟥	🟩	🟥	🟥	🟥	🟥	🟩	🟥
Population												
GDP												
Exchanges rates												
Energy service efficiency			🟩	🟩	⬛	🟩	⬛		⬛			⬛
Energy source prices												
Energy source taxes												
Natural gas prices		⬛										
Coal prices	⬛											
Energy source taxes (CO_2 price)												
CO_2 scope											🟩	
CCS costs											🟩	
CCS efficiency hit											🟩	
CCS – percentage CO_2 captured												
Energy carrier conversion cost												
Energy carrier taxes												
Energy carrier taxes – pass through coefficients												
Energy carrier taxes – pass through phase out												
Energy Ladder parameters												
Choice inputs	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟩	🟩	🟩
End-use churn					⬛		⬛		⬛	🟩		⬛
End-use price parameters												
End-use investment parameters												
End-use fuel convenience								⬛				🟩
End-use capital cost trends												
End-use CCS percentage of stock											🟩	
Plug-in hybrids available												
Hydrogen vehicles available												
Producer churn												
Producer – Price parameters												
Producer – Investment parameters												
Producer – Fuel convenience												
Producer – CCS percentage of stock											🟩	
Producer - Second-generation biofuels available												
Producer - Technology - Geothermal engineered												
Producer – Solid hydrocarbon or gaseous hydrocarbon fuel from oil												
Producer – Coal or gas to liquid production												
Producer - Waste - Percentage to energy												
Producer - Waste - split per carrier												
Producer - Biofuels												
Producer - Load factors												
Producer - Production efficiency												
Commercial biomass split												
Supply	🟥	🟥	🟥	🟥	🟥	🟥	🟥	⬛	🟥	🟥	🟥	🟥
Supply potential - Conventional oil, unconventional oil, conventional gas, unconventional gas, coal, nuclear, hydro, biofuels, geothermal (hydrothermal/engineered, solar PV (central/decentral), solar thermal (central/decentral), wind, tidel, wave								⬛				
Demand potential - electricity - natural gas or coal												

Figure 68: Steel industry WEM framework – part 1

	Environmental policy							
Parameter	CO2 policy (e.g. price)	Amount of CO2 emissions	CCS cost/availability	Government support for new technologies	Availability of R&D funding	Mandatory fuel policy	All energy prices	Level of decarbonisation
Energy Ladder Inputs	🟩	🟥	🟩	🟥	🟥	🟩	🟩	🟥
Population								
GDP								
Exchanges rates								
Energy service efficiency				⬛	⬛			
Energy source prices							🟩	
Energy source taxes						🟩		
Natural gas prices							🟩	
Coal prices							🟩	
Energy source taxes (CO_2 price)	🟩							
CO_2 scope			🟩					
CCS costs			🟩					
CCS efficiency hit			🟩					
CCS – percentage CO_2 captured								
Energy carrier conversion cost								
Energy carrier taxes						🟩		
Energy carrier taxes – pass through coefficients						🟩		
Energy carrier taxes – pass through phase out						🟩		
Energy Ladder parameters								
Choice inputs	🟥	🟥	🟥	🟩	🟥	🟩	🟥	🟥
End-use churn				⬛	⬛			
End-use price parameters								
End-use investment parameters								
End-use fuel convenience				🟩		🟩		
End-use capital cost trends								
End-use CCS percentage of stock			🟩					
Plug-in hybrids available								
Hydrogen vehicles available								
Producer churn								
Producer – Price parameters								
Producer – Investment parameters								
Producer – Fuel convenience								
Producer – CCS percentage of stock								
Producer - Second-generation biofuels available								
Producer - Technology - Geothermal engineered								
Producer – Solid hydrocarbon or gaseous hydrocarbon fuel from oil								
Producer – Coal or gas to liquid production								
Producer - Waste - Percentage to energy								
Producer - Waste - split per carrier								
Producer - Biofuels								
Producer - Load factors								
Producer - Production efficiency								
Commercial biomass split								
Supply	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
Supply potential - Conventional oil, unconventional oil, conventional gas, unconventional gas, coal, nuclear, hydro, biofuels, geothermal (hydrothermal/engineered, solar PV (central/decentral), solar thermal (central/decentral), wind, tidel, wave								
Demand potential - electricity - natural gas or coal								

Figure 68: Steel industry WEM framework – part 2

	(Globa) demand										Location of supply				
Parameter	(Global) steel demand	Economic growth	Consumer demand for quality	Steel substitution with other material	Urbanization and growth in population	Standardization	Ramp-up of production outside U.S.	Consumption per capita	Consumer behaviour	De-materialization	All energy prices	New entry by companies in developing economies	Availability of shale gas	Raw material price	Coal price
Energy Ladder Inputs	🟩	🟩	🟥	🟥	🟩	🟥	🟥	🟩	🟥	🟥	🟩	🟥	🟩	🟥	🟩
Population					🟩										
GDP		🟩													
Exchanges rates															
Energy service efficiency															
Energy source prices											🟩			⬛	
Energy source taxes															
Natural gas prices											🟩		🟩		
Coal prices											🟩				🟩
Energy source taxes (CO_2 price)															
CO_2 scope															
CCS costs															
CCS efficiency hit															
CCS – percentage CO_2 captured															
Energy carrier conversion cost															
Energy carrier taxes															
Energy carrier taxes – pass through coefficients															
Energy carrier taxes – pass through phase out															
Energy Ladder parameters	🟩			⬛	⬛			🟩							
Choice inputs	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
End-use churn															
End-use price parameters															
End-use investment parameters															
End-use fuel convenience															
End-use capital cost trends															
End-use CCS percentage of stock															
Plug-in hybrids available															
Hydrogen vehicles available															
Producer churn															
Producer – Price parameters															
Producer – Investment parameters															
Producer – Fuel convenience															
Producer – CCS percentage of stock															
Producer - Second-generation biofuels available															
Producer - Technology - Geothermal engineered															
Producer – Solid hydrocarbon or gaseous hydrocarbon fuel from oil															
Producer – Coal or gas to liquid production															
Producer - Waste - Percentage to energy															
Producer - Waste - split per carrier															
Producer - Biofuels															
Producer - Load factors															
Producer - Production efficiency															
Commercial biomass split															
Supply	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
Supply potential - Conventional oil, unconventional oil, conventional gas, unconventional gas, coal, nuclear, hydro, biofuels, geothermal (hydrothermal/engineered, solar PV (central/decentral), solar thermal (central/decentral), wind, tidel, wave															
Demand potential - electricity - natural gas or coal															

Figure 68: Steel industry WEM framework – part 3

APPENDIX D9 – GENERALIZATION OF DRIVERS TO HEAVY INDUSTRY

Driver U.S. steel industry	Driver generalized to heavy industry	Implementable
Price of iron ores	Price of non-energy feedstock	⬛
Availability and price of scrap	Price of non-energy feedstock	⬛
Availability of incremental innovation technologies	Availability of incremental innovation technologies	🟩
Availability of radical innovation technologies	Availability of radical innovation technologies	🟩
Availability of R&D funding	Availability of R&D funding	⬛
Energy efficiency improvement	Energy efficiency improvement	🟩
Availability of capital	Availability of capital	⬛
Intermittency of renewables	Intermittency of renewables	🟩
Maturity of new technology	Maturity of new technology	⬛
Lifetime of stock/turnover	Lifetime of stock/turnover	🟩
CCS cost/availability	CCS cost/availability	🟩
Government support for new technologies	Government support for new technologies	🟩
CO2 policy (e.g. price)	CO2 policy (e.g. price)	🟩
Amount of CO2 emissions	Amount of CO2 emissions	🟥
Mandatory fuel policy	Mandatory fuel policy	🟩
All energy prices	All energy prices	🟩
Level of decarbonisation	Level of decarbonisation	🟥
(Global) steel demand	(Global) demand for product	🟩
Economic growth	Economic growth	🟩
Consumer demand for quality	Consumer demand for quality	🟥
Steel substitution with other material	Product substitution with other material	🟥
Urbanization	Urbanization	🟥
Growth in population	Growth in population	🟩
Standardization	Standardization	🟥
Ramp-up of production outside U.S.	Ramp-up of production outside country of origin	🟥
Consumption per capita	Consumption per capita	🟩
Consumer behaviour	Consumer behaviour	🟥
De-materialization	De-materialization	🟥
New entry by companies in developing economies	New entry by companies in developing economies	🟥
Availability of shale gas	Availability of shale gas	🟩
Raw material price	Non-energy feedstock	⬛
Coal price	Coal price	🟩

Table 13: Generalization of steel industry drivers to heavy industry drivers