Technological development of Fast Pyrolysis and Hydrothermal Liquefaction

A combined approach of innovation systems and technological learning to assess future development

Msc thesis Energy Science

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Research partners and context

MSc Energy Science, Utrecht University

This thesis is part of the MSc programme Energy Science that is offered by the Department of Innovation, Environmental, and Energy Sciences at Utrecht University. This master programme provides insight into the production and consumption of energy, the accompanied challenges and the possibilities for a sustainable transition. Technological knowledge as well as energy modelling are key to be able to approach these challenges. This thesis of 30 ECTS is part of MSc programme.

Annotation Sustainable Entrepreneurship & Innovation, Utrecht University

Utrecht University offers the ‘Annotation Sustainable Entrepreneurship & Innovation’. This annotation is given when a student followed the courses ’Technology-related venturing’ and ’Sustainable Entrepreneurship’. Moreover, a research project on a subject related to sustainable entrepreneurship and innovation needs to be performed. This thesis agrees with the requirements of the research project as 1). It concerns newly-developed sustainable production processes to produce renewable jet fuel, 2). This sustainable production processes are new to most firms and this thesis might provide insights into the feasibility for new firms to enter and 3). The thesis exceeds the minimum of 15 ECTS for a research project.

Centre for Energy Policy and Technology, Imperial College

The Centre for Environmental Policy at Imperial College London provides a research interface between science and technology and the economic and policy context in which it is developed and applied. Its focus is on environmental and development issues. This thesis tries to combine energy learning theories with innovation systems, which fits the research that is performed at the Centre for Environmental policy.

Climate-KIC master programme, European Institute of Innovation and Technology

The European Institute of Innovation and Technology (EIT) offers the Climate-KIC MSc programme. This programme is focused on climate entrepreneurship. By studying the latest climate change science, experiencing in which way new technologies can be embedded in new products and services, and by learning to recognize business opportunities for new products and services, this programme educates students to be able to contribute to counteract current climate change. This thesis focuses on production processes of renewable jet fuel to make the aviation sector more sustainable.

RENJET project

The RENJET project develops knowledge and procedures, and tests and pilots, towards the overall goal of a self-sustaining network of regional renewable jet fuel supply chains throughout Europe and beyond. The activities range from selecting and expanding the supply of available feedstocks, conversion steps, support for certification of renewable jet fuel and defining business models. This thesis focuses on assessing the expected future technological development of two production processes to convert biomass into renewable jet fuel. The RENJET project is supported by Climate-KIC.

Executive summary

Current aviation fuel, kerosene, is produced by refining crude oil. The use of this fossil fuel derived kerosene poses three main problems for the aviation industry: price volatility, dependence on a few supply regions and excessive emissions. Therefore, the awareness to find a substitute for crude oil base kerosene is increasing, of which renewable jet fuel (RJF) is considered the most feasible option. A large number of technologies are being developed which are capable of producing RJF. Of those technologies, Hydroprocessed Esters and Fatty Acids (HEFA) currently achieves the lowest production costs, but there is limited availability of sustainable oil feedstocks that are needed for HEFA. Therefore, there is a need to consider technologies which do not require oil feedstocks to enable large scale use of RJF. Criterion to consider other technologies to produce RJF is the production costs. Fast pyrolysis (FP) and hydrothermal liquefaction (HTL) are, based on this criterion, identified as promising technologies.

FP and HTL are both thermochemical conversion technologies that transform diverse lignocellulosic feedstocks or algae into high liquid yields. Both technologies have not been commercialised yet and are currently in demonstration phase. FP and HTL could reach the commercialisation phase, if current technological challenges and current socio-technical barriers can be overcome. This study assesses the current state of the technologies, which results in the identification of the current technological challenges as well. The 'seven functions framework' which is based on the technological innovation system, creates insights into the current socio-technical environment, and hence socio-technical barriers could be identified as well. After the identification of the technological challenges and the socio-technical barriers, an assessment is performed which reveals the chances of overcoming those challenges and barriers. The latter gives insights into the pace towards commercialisation of the technologies that are currently in the demonstration phase.

Furthermore, technologies tend to develop and improve in time. Hence, FP and HTL are likely to experience technological improvements in time, particularly if challenges and barriers may be overcome and the technologies could be commercialised. Frequently, a learning rate is used to describe those learning effects, however, technology-specific learning rates are lacking due to a lack of data of commercialised plants. Therefore, a qualitative approach to create insights into the type of learning effects that may be expected is used. An overview of learning effects mentioned in the literature is established, to be able to assess all possible learning effects. Moreover, an additional framework called 'the learning pathways' is used to gain extra insights into the expected learning effects. Hence, the aim of this study is to assess the chances of overcoming technological challenges and socio-technical barriers, and the learning effects that are expected to play a role throughout the development of FP and HTL.

The incentive to research FP and HTL comes from the aviation industry that needs RJF to become more sustainable. The bio-oil produced by these technologies can, however, be used as petroleum replacements in other markets as well (see Figure I) . The liquids can directly replace petroleum products for heating and electricity purposes and some chemical compounds. The replacement of some other chemicals and transportation fuels requires an additional upgrading step, in which the quality of the bio-oil/biocrude is elevated to the higher requirements of those products. The scope of the research will include all those markets, as they all contribute to the technological development of FP and HTL.

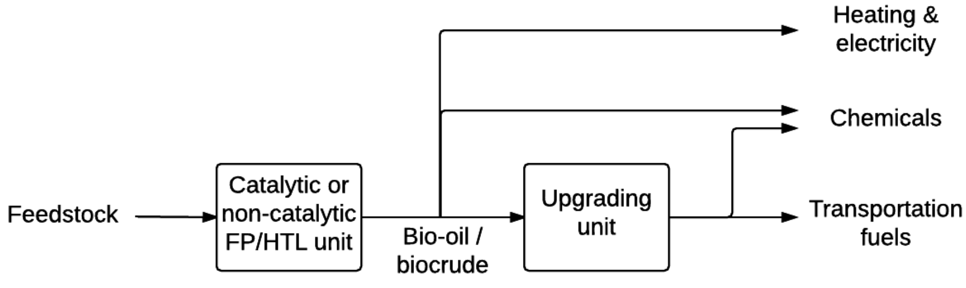

Figure I: graphical overview of applications for FP and HTL liquids (author's own compilation)

The technological challenges for FP and HTL units themselves are well tackled, and the main current challenge is the further scale-up of the technologies. To avoid these scale-up problems, the modular systems approach seems very reasonable and this also fits the distribution of the biomass. The technological challenges for catalysts to be used during the FP/HTL process and upgrading are, however, not yet effectively addressed. Although research is still focussing on the development of novel catalysts, the chance that a novel catalyst is available on the short-term is unlikely. Moreover, additional challenges of adapting the process conditions to the use of catalysts then need to be addressed, making it less likely to be implemented in the short-term. Hence, in order to be able to develop to commercialisation on the shorter-term, emphasis should be given to non-catalytic FP and HTL modular systems. The upgrading also still poses substantial challenges. Although some respondents are optimistic, it is deemed unlikely that the current upgrading processes facing hydrogen challenges, char challenges and catalysts challenges will be able to be implemented on a larger scale soon. The modular system approach is less applicable to upgrading, as hydrogen supply is needed. Hence, there are no current solutions for the upgrading step itself. Therefore, emphasis should be given to co-processing in existing refineries and using the technologies prior to gasification. These options do need more research in order to be implemented though. Moreover, it is likely that a mild upgrading step is needed before co-processing, which poses the upgrading challenges again. However, since this is a mild upgrading step, it might be more reasonable in the shorter term. The upgrading, co-processing and using the liquid prior to gasification, need to be researched more extensively, and are therefore not ready for commercialisation.

Regarding the socio-technical environment, research is mainly performed by universities, and an extensive amount of work have been performed regarding FP and HTL. However, the research tends to focus on similar kind of experiments, and thus a lot of reinvention occurs. Less emphasis has therefore been given to the current technological challenges of catalysts and upgrading options. Mainly small companies and university spinoffs are establishing pilot and demonstration plants. Currently, a few larger scale plants have been erected and the success of those plants are deemed crucial for the further development of FP and HTL. The technologies have suffered from a negative credibility because in the past overestimation and the rapid scale-up without enough experience caused demonstration plants to fail. Hence, the success of current larger scale plants may enhance the credibility again, which might stimulate other companies to enter the market as well. The challenge of entering the market is finding enough funding though, as private funding is not abundant. Moreover, the technologies face competition with other biotechnologies, and those different biotechnologies may compete for second and third generation feedstock as well. Lastly, the products derived by FP and HTL are not (yet) cost competitive to fossil fuel products and therefore face challenges of reaching the market. These challenges are not expected to be overcome without substantial government interference. The commitments being made during the recent COP21 may be the main driver for governments to interfere. Stable long-term policy is needed in terms of 1) setting more incentives/obligations to stimulate the use of the technologies, 2) providing help during the current valley of death in which demonstration plants face enormous difficulties in finding private money and 3) stimulating knowledge diffusion between among actors to enhance technological development. Moreover, the government should take an active role in incentivizing biomass production, creating a clear Europe-wide communication campaign to create acceptance for biotechnologies and dis-incentivize fossil-derived products. One may conclude that if the larger scale plants turn out to be unsuccessful or if the government is reluctant to change its policy, further development towards commercialisation will be very unlikely.

Future technological improvements are indeed expected for FP, HTL and upgrading as well. FP, HTL and upgrading technologies were established by inter-industry-spillovers, and future improvements of the technologies on which FP, HTL and upgrading are based, may again be copied to FP, HTL and upgrading. The learning-by-researching effects have optimized the FP and HTL technologies for the use of biomass and learning-by-failing by means of the Kior case has created valuable lessons for FP as well as for HTL. It can be noted that the user-producer interaction provides few learning effects. This may be explained by the very strict regulations which the bio-oil needs to meet, whereby users may not give extensive inputs for potential improvements of the product or process. Furthermore, agreeing with the expected learning in demonstration and commercial phases identified by the archetypical learning pathway, the learning-by-doing and economies of numbers are expected to play a major role if the technologies would be commercialized. Those learning effects are expected to create efficiency gains, which have a significant impact on the production costs of the liquids derived by FP and HTL. Hence, FP and HTL units gain experience during the demonstration and commercialisation of those units, while simultaneously research on the upgrading and catalysts should be performed. These learning-by-researching effects may increase the quality of the produced oil. During this time, the needed standards for higher value markets may be established as well. Hence, the success of the larger scale plants and changes in current government policy are needed for further development of FP and HTL, which will allow FP and HTL to experience sustained learning effects, while learning-by-researching could promote the quality of the oil with the ultimate goal of reaching higher value markets.

In conclusion, the chances of overcoming technological challenges and socio-technical barriers, rely very much on the success of current larger scale plants and changes in government policy. The main technological improvements for FP and HTL, which will particularly occur if the technologies are commercialised, are expected to be caused by learning-by-doing effects and economies of numbers. Moreover, learning-by-inter-industry-spillovers and learning-by-failing are also expected to enhance incremental technological improvements. Learning-by-researching regarding the upgrading may enhance the quality of the produced products.

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1. Introduction

1.1 Background

Current aviation fuel, kerosene, is produced by refining crude oil (Bauen et al., 2009). The use of this fossil fuel derived kerosene poses three main problems for the aviation industry. First, the volatility in crude oil prices makes the aviation industry vulnerable to fuel price fluctuations (ATAG, 2009; IEA, 2012). Fuel represents approximately 33% of airlines' operating costs and therefore fluctuations in fuel price lead to fluctuating expenses. Secondly, the aviation industry is dependent on a few supply regions, resulting in exposure to possible supply disruptions (Ecofys, 2013; IEA, 2012, 2014). Thirdly, the aviation industry accounts for 2% anthropogenic global CO2 emissions (Ecofys, 2013; ICAO, 2011; IEA, 2012; Owen et al., 2010). As the aviation industry is expected to grow, emissions are expected to increase with an annual rate of 4.5% over the next 20 years if the industry continues the use of kerosene (Ecofys, 2013; ICAO, 2011; IEA, 2012; Owen et al., 2010). Hence, price volatility, kerosene dependency and emission reduction are the main drivers for the aviation industry to find a substitute for crude oil based kerosene.

Several alternative fuels to substitute kerosene are mentioned in literature. Alternative fuels based on a different drivetrain, i.e. solar, hydrogen and fuel cells, are not suitable as short-term solutions (Sandquist & Guell, 2012). A different drivetrain requires adjusted airplanes, causing high investment costs in both airplanes and fuelling infrastructure which forms a barrier to the implementation of those technologies. On the other hand, biomass-based fuel (renewable jet fuel, RJF) is based on the same drivetrain and therefore considered the most feasible option to substitute kerosene (ATAG, 2012; Klein-Marcuschamer et al., 2013; SkyNRG, 2012). By (partly) substituting kerosene, RJF may allow the aviation industry to offset the risks associated with the volatility of oil and fuel prices, reduce the dependency on oil-based kerosene and limit the emissions (Ecofys, 2013; Haq, 2015; IATA, 2013). Since the first commercial flight in 2011, 21 airlines have used RJF in their commercial flights (ATAG, 2015; ICAO, 2015a). Moreover, the Sustainable Aviation Fuel Users Group consists of 28 airlines, that are committed to accelerate the development and commercialisation of RJF (SAFUG, 2016). This proves the willingness of the industry to kick-start the field of RJF (ATAG, 2015).

A large number of technologies are being developed which are capable of producing RJF (Mawhood et al., 2015; Mawhood et al., 2014). Hydroprocessed Esters and Fatty Acids (HEFA), Biomass To Liquids (BTL) by means of Fischer-Tropsch and Direct Synthetic Hydrocarbons Conversion (DSHC) are certified technologies to produce RJF (Ecofys, 2014; ICAO, 2015b). Of those certified technologies, HEFA currently achieves the lowest production costs and as a result most commercial flights used HEFA derived RJF (De Jong et al., 2015). The disadvantage of HEFA is that the technology requires oil feedstocks, and there is a limited availability of sustainable oil feedstocks (De Jong et al., 2015). Despite that this technology achieves the lowest production costs, there is thus a need to consider technologies which do not require oil feedstocks to enable large scale use of RJF.

Criterion to consider other technologies to produce RJF is the production costs. De Jong et al. (2015) looked at the short-term production costs of currently certified technologies and technologies which are expected to be certified by 2020, under the assumption that those technologies would be commercially available. The results show that after HEFA, fast pyrolysis (FP) and hydrothermal liquefaction (HTL) achieve the lowest production costs. Hence, FP and HTL are the most promising technologies to produce RJF after these technologies are certified and commercialized (De Jong et al., 2015). FP and HTL are both thermochemical conversion technologies that transform diverse lignocellulosic feedstocks or algae into petroleum substitutes (Bridgwater, 2012; Brown, 2011; Elliott, 2007).

1.2 Research problem

FP and HTL are identified by De Jong et al. (2015) as promising. However, two assumptions on which this study is based are overly simplified. First, the assumption that the technologies will become commercially available is ambiguous. Both FP and HTL are not commercially employed yet (De Jong et al., 2015). A threat for non-commercial technologies is the ‘valley of death’, which describes the gap between R&D labs and commercialisation and is twofold: technological and commercial (Branscomb & Auerswald, 2001; Markham, 2002). The ´technological valley of death’ means that there is a lack of funding to test, develop and refine a technology (Breakthrough Institute, 2011). The ´commercialisation valley of death´ entails the lack of funding to bring demonstrated technologies towards the commercial production phase. An example of a bio-based technology which ended up in the valley of death is gasification (TKI-BBE, 2015). There has been a lack of finance for large scale gasification plants, resulting in that the technology barely developed since 2008. The valley of death thus creates uncertainty regarding the assumption that the technologies will become commercial.

Secondly, the techno-economic study of De Jong et al. (2015) is based on the current state-of-the-art technologies, without considering future technological improvements. Technologies, however, tend to develop and improve in time (Foster, 1986; Rosenberg, 1994; Grubler, 1998, 2012). A commonly used method to assess technological improvements are learning rates (Junginger et al., 2005; Junginger et al., 2010). Learning rates represent the quantitative relation between cost per unit decrease caused by the technological improvements and the doubling of installed capacity, and are input for energy modelling (Junginger et al., 2005). This method poses two problems when applied to FP and HTL. First, the learning rates are valid from the moment a technology is commercialized, but again, information concerning if and how the technologies will be commercialized is lacking. Secondly, learning rates have to be derived from empirical data, but quantitative historical datasets for non-commercialized technologies are very limited (McDonald & Schrattenholzer, 2001). To my knowledge, two attempts concerning learning rates have been performed. Both studies, performed by Daugaard el al. (2015) and Hayward et al. (2015), used an average energy learning rate of 20% as a result of a lack of historical data. As the use of reliable technology specific learning rates are very important for reliable future cost estimates (McDonald & Schrattenholzer, 2001), the use of the average learning rate of 20% resulted in much uncertainty (Daugaard et al., 2015; Hayward et al., 2015). There are thus no technology specific learning rates for FP and HTL available. Hence, there is currently limited information on which technological improvements may be expected.

1.3 Research aim

This study aims to create more insights into the pace towards commercialisation and the future technological improvements. The question whether FP and HTL will become commercial, depends on the technologies themselves as well as the system in which they develop (Hekkert et al., 2011). Therefore, first the technological development until now, the current technological performance and the current technological challenges are assessed. Secondly, the innovation system in which the technologies develop is described, to include wider socio-technological dynamics (Carlsson & Stankiewicz, 1991). Many innovation systems are namely characterized by some flaws that greatly hamper the development and diffusion of innovations, but also stimulating drivers may be identified (Hekkert et al., 2011). Hereafter, an assessment whether and under which circumstances the technological challenges and the socio-technical barriers could be overcome is performed to include the chances that the technologies will become commercialised.

This study assesses the future technological improvements of FP and HTL as well. The lack of technology-specific learning rates for FP and HTL indicates that a reliable quantitative approach is not available. Therefore, the learning effects that may influence the technological development will qualitatively be described. This results in an assessment which identifies when in the development which learning effects may be expected. Subsequently, the following research question will be answered:

What are the chances of overcoming technological challenges and socio-technical barriers, and which learning effects are expected to play a role throughout the development of FP and HTL?

The incentive to research FP and HTL comes from the aviation industry that needs RJF to become more sustainable. The bio-oil produced by these technologies can be used as a petroleum replacement in other markets as well (Bridgwater, 2012; Venderbosch & Prins, 2010). These markets consist of chemicals, other transportation fuels and heat & electricity applications. The scope of the research will include all those markets, as they all contribute to the technological development of FP and HTL.

1.4 Relevance

This study provides insights in the chances that FP and HTL will become commercial and which learning effects may enhance additional technological improvements. Although the technologies are seen as promising, these expectations of technological development are essential to attract the interest of necessary actors. Governments can, considering these expectations, decide whether to stimulate FP and/or HTL by means of policy or funding. The industry might consider investing in technology development when the technologies are indeed promising (Borup et al., 2006). Expectations may also encourage entrepreneurs to get involved in FP and/or HTL (Jacobsson et al., 2009). The identification of expectations regarding FP and HTL may thus enhance the development of the technologies. This enhancement of FP and HTL will stimulate the positive externalities of reduced oil price volatility, reduced dependency on petroleum based products and reduced emissions in the chemical, transportation and heating & electricity market (EMPYRO, 2016; Jahirul et al., 2012; Mante et al., 2015; US Department of Enrgy, 2015)

1.5 Outline of the thesis

The remainder of this thesis is structured as follows. The FP and HTL section will provide insights into the different variations of pyrolysis and hydrothermal processing, and the demarcation of FP and HTL. The theory section will elaborate on the innovation system approach and the learning effects influencing technological improvements. Moreover, a comprehensive theoretical framework including both theories will be described. The methodology will describe in which way this framework will be assessed, and how the data needed for this study is gathered. Hereafter, the results are described. The thesis continues with a discussion of the used theory and methods, and their implications for this study. All this will lead to the conclusion in which the research question will be answered.

2. Fast pyrolysis and hydrothermal liquefaction

2.1 Pyrolysis

Several variations of pyrolysis exist and in order to define what kind of pyrolysis is included in this study, an overview of the several variations is given. Broadly, there are two main classes of pyrolysis: slow pyrolysis and fast pyrolysis (Yang et al., 2014). The difference between both is the heating rate that is used in the process (Diebold, 2002). Slow pyrolysis is characterised by lower heating rates, resulting in maximizing char yield. On the other hand, fast pyrolysis is heated at rapid rates and thereby maximizes the liquid yields. The achievement of fast heating rates requires high operating temperatures, very short contact times (residence time) and fine particles (Demirbas & Arin, 2002). Besides those two main classes, some variations have been put forward. Very fast pyrolysis is referred to as flash pyrolysis, in which even higher temperatures and shorter residence times as compared to fast pyrolysis are used. The products derived by flash pyrolysis contain a higher oil yield, however, there are still a lot of technological limitations. Therefore, fast pyrolysis has gained popularity in producing liquid yields (Jahirul et al., 2012). Lastly, intermediate pyrolysis has been described, which slightly quicker than slow pyrolysis (Hornung et al., 2011). The heating rate of intermediate pyrolysis is thus significantly lower than in fast pyrolysis, and residence time of intermediate pyrolysis is much longer. The derived products are more evenly distributed between liquid, char and gas as compared to fast pyrolysis. An overview of these most important variations of pyrolysis is given in Table 1. This study focusses on fast pyrolysis to produce liquid yields. Fast pyrolysis can be catalytic, as well as non-catalytic (Bridgwater, 2012), and both are included in this study.

Table 1: schematic overview of pyrolysis variations (author's own compilation)

Process conditions		**Type of pyrolysis**	**Products**		
High	Low	Flash	High	Low	Low
Heating rate	Residence time	**Fast**	Oil yield	Char yield	Gas yield
		Intermediate			
Low	High	Slow	Low	High	High

2.2 Hydrothermal processing

Several variations hydrothermal processing exist as well. Hydrothermal processing is divided into three main classes: hydrothermal carbonisation, hydrothermal liquefaction and hydrothermal gasification (Elliott et al., 2015). Hydrothermal carbonisation occurs at a relatively low temperature and produces mainly char. Higher temperatures allow for hydrothermal liquefaction[4], and this process occurs at subcritical conditions (Jegathese & Farid, 2014; Peterson et al., 2008). HTL results mainly in the production of liquids. At even higher temperatures, gasification reactions dominate, which results in the production of gas (Elliott et al., 2015). The latter happens above the critical point of water (Valdez et al., 2012). An overview of the main classes in given in Figure 1. This study focuses on hydrothermal liquefaction to mainly produce liquids.

[4] Hydrothermal liquefaction is in literature also frequently referred to as direct liquefaction (Elliott et al., 2015) and hydrothermal upgrading (Quitain et al. , 2015).

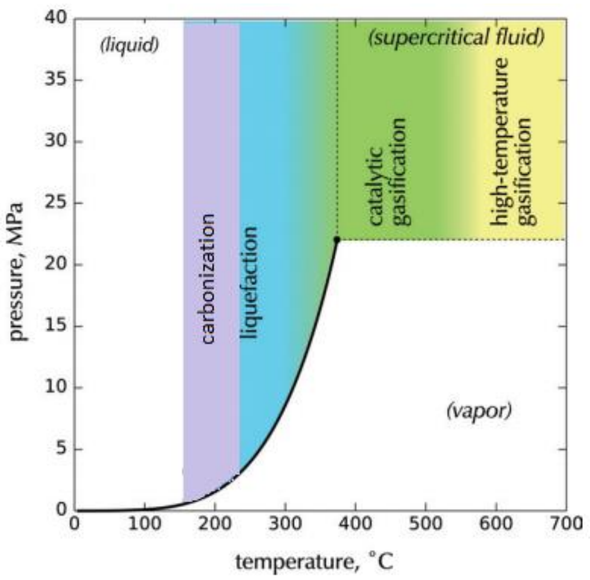


Figure 1: graphical overview of hydrothermal processing variations (based on: Peterson et al. (2008), adjusted to Elliott et al. (2015)

2.3 Difference fast pyrolysis and hydrothermal liquefaction

FP and HTL are both thermochemical conversion technologies that transform diverse lignocellulosic feedstocks or algae into energy dense bio-oil (Bridgwater, 2012; Brown, 2011; Elliott, 2007). However, there are some differences between both technologies as well, and the most important differences are pointed out in Table 2.

Table 2: schematic overview of most important differences between FP and HTL (Demirbas, 2009)

	Fast pyrolysis	**Hydrothermal liquefaction**
Feedstock	Low moisture content	High moisture content
Pressure	Lower	Higher
Oil quality	Lower	Higher

2.4 Applications for fast pyrolysis and hydrothermal liquefaction liquids

FP and HTL are both technologies to maximize liquid products. The liquid product of FP is referred to as bio-oil, and the product of HTL is called biocrude. These liquids are, however, not one on one replacements for all petroleum products. The liquids can directly replace petroleum products for heating and electricity purposes and some chemical compounds. The replacement of some other chemicals and transportation fuels requires an additional upgrading step, in which the quality of the bio-oil/biocrude is elevated to the higher requirements of those products (Bridgwater, 2011; Elliott, 2007). Figure 2 graphically displays the possible applications of bio-oil/biocrude.

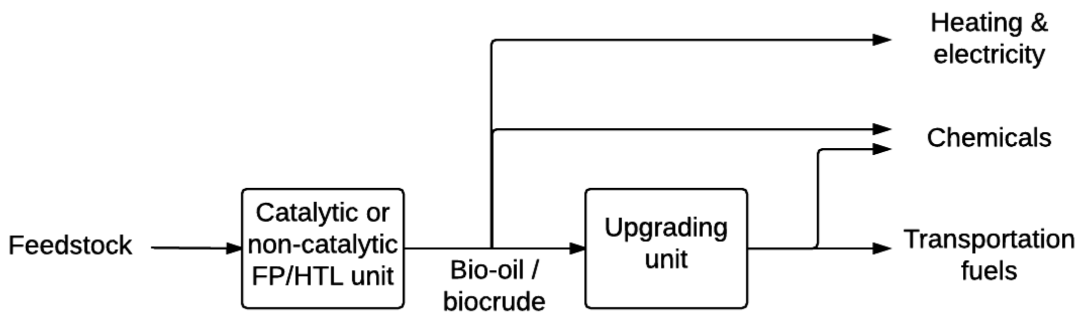


Figure 2: graphical overview of applications for FP and HTL liquids (author's own compilation)

3. Theory

3.1 Technological innovation system

3.1.1 Origin and rationale for the technological innovation system

Innovation models are tools used to understand the mechanisms of commercialising an invention. One of the first innovation models arose after the Second World War and was called the 'Linear model of innovation'. This model considers research as the initiating step and the source of all innovations (Mahdjoubi, 1997; Nelson, 1959). The model starts with basic research, followed by applied research and development, and ends with production and commercialisation. This process from basic research towards commercialisation is seen as a one-way flow.

The model provided policy makers with the belief of a positive relationship between R&D investments and the desired outcome of increased productivity. Contrary to this believe, the emergence of new and important technologies was followed by a reduction of productivity in most OECD countries during the 1970s and 1980s (OECD, 1991). This productivity paradox led to criticism regarding the linear model logic (Schlossstein, 2009; Sharif, 2006) and also scholars started to doubt the model for several reasons. Kline & Rosenberg (1986) wrote that feedback from sales figures, individual users and technological experience at a later stage are underemphasized in the linear model. On the other hand, the role of science is overemphasized in the model as the creator of innovation, while actually the demand of innovation often forces the creation of science. As a result, the scholars developed the 'chain-linked model of innovation'. This new approach sees innovation as a collective activity in which many actors and knowledge feedbacks are included, and recognizes that innovation processes are influenced by their institutional settings and incentive structures, e.g. the market or government policy.

During the late 1980s, these socio-technical insights lead to a consensus among scholars that a systems approach to understand the complex dynamics of innovation is more realistic and more useful to understand the mechanisms of commercialising an invention. Freeman (1987) was the first to define such a system as 'the network of institutions in the public and private sectors whose activities and interaction initiate, import and diffuse new technologies'. Edquist & Johnson (1997) elaborated on this definition, and described that within an innovation system organizations and institutions play an important role. Organizations are formal structures that are consciously created and have an explicit purpose, and are also referred to as actors of the system. Institutions are sets of common habits, norms, routines, established practices, rules or laws that regulate the relations and interactions between individuals, groups and organizations. They are referred to as the rules of the game.

Scholars have elaborated on the concept of an innovation system ever since, and various forms of innovation systems have been put forward. The various innovation systems differ from each other in focus and boundaries of the system (Negro, 2007). The various systems that are described in literature include:

- National systems of innovation, which take a national scale to allow comparison of performance between different countries (Freeman, 1987; Lundvall, 1992)
- Regional systems of innovation, in which the focus lays on a specific region (Cooke et al., 1997)
- Sectoral systems of innovation, where the focus on technological fields is sectoral (Breschi & Malerba, 1997)
- Technological systems of innovation, focussing on a technology (Carlsson & Stankiewicz, 1991)

In order to understand technological change, insights in the dynamics of the innovation system are necessary (Hekkert & Negro, 2009). The scholars identify that the technological innovation system (TIS) allows for mapping these dynamics, contrary to the other forms of innovation systems. The other innovation systems are better suitable for identifying the structure of a system, instead of mapping the dynamics of the system. The TIS therefore is considered the best choice when researching an emerging technological innovation.

3.1.2 The seven functions of technological innovation systems

'The seven functions' is a framework to map the dynamics of the TIS (Hekkert et al., 2007). The framework is frequently used to study the socio-technical drivers and barriers for technological development of emerging energy technologies (e.g. Hekkert et al., 2007; Suurs & Hekkert, 2009; Tigabu et al., 2015; van Alphen et al., 2009). It is expected that the more these system functions are fulfilled, the better the performance of an innovation system will be, resulting in better chances for a successful development and commercialisation of new technologies. The description of each of the seven functions is given in Table 3.

Table 3: description of the seven functions of the technological innovation system (Hekkert et al., 2011; Hekkert & Negro, 2009; Negro, 2007)

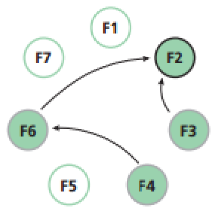
Function number	Function name	Description of function	Indicators of function
F1	Entrepreneurial activities	Entrepreneurs perform the market-oriented experiments necessary to establish technological change. The role of the entrepreneur is therefore to turn new knowledge development, networks and markets into action to generate and make use of business opportunities.	- Existence of New entrants - Existence of diversification activities of incumbents (innovation by incumbents) - Existence of Large scale experimentation
F2	Knowledge development	The development of knowledge is at the heart of any innovation process to enable technological change. Possible sources of new knowledge are R&D, search and experimentation, and imitation, where old and new knowledge is combined in innovative ways.	- Amount of knowledge development - Quality of knowledge development - Fit of knowledge development with knowledge needs
F3	Knowledge diffusion	The knowledge network facilitates the exchange of information among the actors in the innovation system to enable the actors to learn from each other.	- Knowledge exchange between scientists - Knowledge exchange between industrial players - Knowledge exchange between scientists and industry
F4	Guidance of the search	Various technological options exist within an emerging technological field. This function represents the selection process to facilitate a convergence in development. This guidance may take the form of policy targets, as well as through expectations by various actors	- Clear vision development industry (belief in growth potential) - Clear vision technological design - Clear and reliable policy goals
F5	Market formation	New technologies are frequently not able to outpace incumbent technologies. The creation of (niche) markets is therefore necessary to stimulate innovation. Especially in the energy sector this is important, as external costs for fossil fuel-based technologies are often not taken into account.	- Sufficient current market size - Sufficient future market size
F6	Resource mobilization	Material and human factors are necessary for the development of an innovation. These resources are a basic input to all the activities within the innovation system.	- Sufficient human resources - Sufficient financial resources - Sufficient physical resources
F7	Creation of legitimacy	A new technology has to become part of an incumbent regime or has to overthrow it. Established actors often resist this emergence of a new technology.	- Resistance towards new technology

3.1.3 The seven functions during different development phases

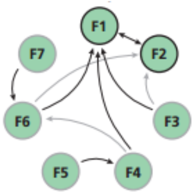
Both the individual fulfilment of each system function and the interaction dynamics among the functions are of importance. Many possible interactions between the seven functions are possible (Hekkert et al., 2007; Negro, 2007). These interactions can be positive, when a sufficient fulfilled function stimulates another function, but may be negative as well when a poorly fulfilled function brings down the other functions. The fulfilment of the functions, as well as their interaction provide therefore insights into the drivers and barriers of the development of a technology. The mostly occurring interaction between functions are elaborated on.

Starting point and pre-development phase

Many possible interactions between the seven functions are possible (Hekkert et al., 2007; Negro, 2007). The number of possible starting points turns out to be much smaller. A common trigger in the field of sustainable technologies is 'guidance of the search' (F4), when societal problems are identified and government goals are set to limit environmental damage. These goals lead to the availability of resources (F6) which consequently leads to knowledge development (F2). During the development towards a working prototype function, those functions together with knowledge diffusion (F3) are the most important functions (Hekkert et al., 2011).



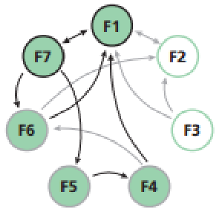
Development phase



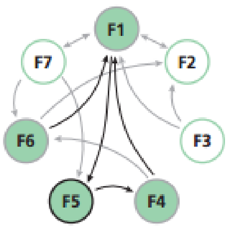
After the working prototype has been established, and a commercial application is looked for, all seven functions play a role and interact. These interacting cycles between functions enlarges the understanding of the dynamics of a system.

Take-off phase

When the first commercial application is found, the fulfilment of the functions plays a role in the market growth towards more commercial applications for the technology. The fulfilment of knowledge development and knowledge diffusion are expected to play a less important role during this phase. The interactions between the other functions start to change compared to the previous phase (Hekkert et al., 2011).



Acceleration phase



When the market is growing, the market will work towards saturation where most commercial applications have been reached. During this phase, the creation of legitimacy is not playing a major role any more, as the new technology already became part of a current regime reaching current or even new markets. The interactions between the functions may change compared to the previous phase (Hekkert et al., 2011).

3.2 Learning effects

3.2.1 Origin and rationale for learning theories

The effect of learning was first observed by Wright (1936) who derived a model to describe the effects of learning concerning the production costs for airframe manufacturing. The model showed that production costs tend to decline at a fixed rate when cumulative production doubles. This observation is now known as the learning rate, which has been widely used to simulate cost reductions that can be expected (Gallagher et al., 2012; Junginger et al., 2005; Junginger et al., 2010). For non-commercial technologies, such as FP and HTL, historical empirical data is unknown. This problem of data availability leads to the fact that it is not possible to empirically determine the progress ratios for the technologies (De Wit et al., 2010)

Instead a qualitative hybrid approach in which insight from engineering studies (scale effects[5], described as scale-dependent learning) and scale-independent learning is elaborated on. This provides insights in the type of learning that may be expected for FP and HTL, and where in the development towards commercialisation those learning effects may occur. To underline, the quantitative amount of cost reductions that may be expected can thus not be determined. The emphasis on different learning effects agrees with Winskel et al. (2014), who developed archetypical learning pathways. In addition, these learning pathways will be used to cross-check the findings of the learning effects.

3.2.2 Scale-independent and scale-dependent learning

Scale-independent learning

Scale-independent learning entails technological improvement that is not related to scale (De Wit et al., 2010). These scale-independent learning effects are seen as the drivers for technological change (Castelnuovo et al., 2005). There are different types of learning that may enhance those scale-independent learning effects.

First, there are two types of learning effects that may be achieved due to internal knowledge creation.

1. **Learning-by-researching**[6] is related to the search for new knowledge that includes basic research and discovery of optimal design characteristics (Cohen & Levinthal, 1989; Gallagher et al., 2012; Kahouli-Brahmi, 2008; Marcucci & Turton, 2012; Yu et al., 2011). Learning-by-researching thus helps to overcome the technological challenges and improves the efficiency of the technology by optimizing the technology units (e.g. reactors) and process conditions of the technology. This learning effect appears from the early stages of the technology, and continues during the entire technological development.
2. **Learning-by-doing**[7] entails that the productivity of a firm increases as the cumulative output for the industry grows (Arrow, 1962). Learning-by-doing implies that repetitive manufacturing tasks leads to the improvement of the production process. Those improvements entail for example labour efficiency increases and small changes in production methods (Bodde, 1976). There are scholars that argue that this type of learning occurs in components of the technology that are not yet mature (Ferioli et al., 2009; Grübler et al., 1999). Hence, learning-by-doing refers to productivity gains internal to the production process, as a result of experience with the production process.

Secondly, the producers and users of the technology may interact with each other. This interaction between producers and users stimulates two other forms of learning:

1. **Learning-by-using** describes the increase in knowledge as a result of subsequent use of a technology by the user of the technology (Rosenberg, 1982). Many potential gains in efficiency can be identified through the experience gained in the use of the product by the consumer (Andersen & Lundvall, 1988;

[5] Scale-up is sometimes referred to as learning-by-scaling, for example by Sahal (1985)

[6] Synonyms for learning-by-researching are learning-by-trying, learning-by-learning, learning-by-searching and learning-by-studying (Garud, 1997; Sagar & van der Zwaan, 2006).

[7] Other scholars also refer to learning-by-operating, learning-by-deployment and learning-by-manufacturing (Liyanage, 2002; MacGillivray et al., 2014; Sagar & van der Zwaan, 2006)

Rosenberg, 1982). This may especially play a role in more complex interacting components or systems, as the outcome of the interaction cannot be precisely predicted by forehand. Learning-by-using therefore helps to determine the optimal performance characteristics of the good and its optimal maintenance. This learning effects inherently appears when the technology has entered the market (Nahuis et al., 2009)

2. **Learning-by-interacting**[8] contains the interactions between producers and users which is, according to Lundvall, (1992), not only driven by price mechanisms, but also by closer interactions involving mutual trust and mutually respected codes of behaviour. By means of cooperation, producers can benefit from insights into user needs and requirements and can adjust their products accordingly. Hence, learning-by-interaction may give rise to process or product innovations, by communicating with the users. Contrary to learning-by-using, learning-by-interacting already occurs when technological opportunities are yet to be identified (Nahuis et al., 2009).

Thirdly, the transfer of knowledge and technologies between different actors may enhance three other types of learning:

1. **Learning-by-imitation**[9] describes that organisations can learn how to construct a technology by imitating the competitor (Sagar & van der Zwaan, 2006). The literature does not suggest a timeframe in the development phase when learning-by-imitation starts. It is assumed that imitation starts during the early development phases, when basic and applied research efforts may be copied by different research groups. When companies enter, it is assumed that also companies try to benchmark their processes to other organisations. Hence, during the entire development of a technology, it is assumed that learning-by-imitation plays a role.
2. **Leaning-by-failing** described on the other hand that organizations can also learn from own and mistakes from other organisations, avoiding making these mistakes whereby learning may be enhanced (Liyanage, 2002). As with learning-by-imitation, a timeframe when this learning effect occurs is not available in the literature. It is however also expected that this learning effect occurs during early as well as later stages of the development.
3. **Learning-from-inter-industry-spillovers** enhances the technology transfer between different industries. These spillovers across technologies can lead to technologically advanced and cost-effective technologies (Azevedo et al., 2013). Other scholars have elaborated on these technologies spillovers, and have introduced 'clusters of technologies' (Seebregts et al., 1999; Smekens et al., 2003). In this view a cluster of technologies is a group of technologies sharing a common essential component. The different technologies, making use of the same essential component, all enhance the learning process of the technologies. These learning effects therefore may start from the beginning of a technology, and may continue during the entire development.

Hence, there is a long list of different types of learning[10] that all influence the technological development. An important issue is that technological knowledge may be accumulated (learning), but it can also be lost (unlearned) (Daugaard et al., 2015; Gallagher et al., 2012). First, knowledge depreciation occurs when knowledge remains tacit (knowledge is not formally written down) and the holders of knowledge leave the university or the firm. It may also be that knowledge is focused in different directions. Secondly, knowledge depreciation may also occur when old knowledge becomes obsolete, and the new learning cannot be proceeded quickly enough.

8 Learning-by-trying is proposed by Fleck (1994), which entails approximately the same as learning-by-interacting

9 Learning-by-copying is used by Sagar & van der Zwaan (2006), which entails approximately the same as learning-by-imitations

10 There are even more learning types, e.g. learning-through implementation (Sagar & van der Zwaan, 2006). This learning type entails for example gaining finance to develop the technology. Those learning types do not directly influence the technology, but may enhance for example learning-by-researching. Therefore, and because the innovation system approach sheds light on socio-technical circumstances, those learning types are not included in this study.

Scale-dependent learning

Scale-dependent learning describes the learning effects related to the increase in scale of the technology (Haldi & Whitcomb, 1967). Two types of scale-up contribute to scale-dependent learning:

1. **Economies of unit size** refers to the increasing capacity of one plant (Wilson, 2012). The scale-up of an individual unit leads to increasing returns to scale, which is a larger increase in output relative to the associated increase in inputs. These increasing return to scale can be explained by an increase of technical efficiency, i.e. a technology works more efficient on larger scale (GEA, 2012). Besides technical efficiency improvement, also capital productivity (spreading fixed costs over higher output volumes) (GEA, 2012) and purchase efficiency (the prices of some inputs are reduced through buying in bulk) (The Economist, 2011) occur. Hence, the increase in scale of one unit may enhance scale-dependent learning effects. The scale-up of individual units starts from the early development of a technology, and may continue through the entire lifetime of a technology.
2. **Economies of numbers** is mostly accomplished by industry scale-up, i.e. the amount of units that have been built increases from the moment the first commercial applications are found, and thus the total volume increases as well. Similar to the increase of an individual unit, fixed costs can be spread over more units (Gallagher et al., 2012) and bulk prices can be established (The Economist, 2011). This type of learning, contrary to scale-up of an individual unit, starts from the commercialisation of a technology.

The way a technology scales up differs per technology. Large centralized energy supply technologies may achieve increasing returns to scale due to the scale-up of the individual unit (Enos, 1962). On the other hand, complex technologies tend to suffer from diseconomies of scale when scaling-up the individual unit (Grubler, 2010). These complex technologies may be better suited to use as smaller-scale technologies and are likely to be characterized by economies of numbers (Gallagher et al., 2012). This is in line with Dahlgren et al. (2013) and Jack (2009), who argue that 'bigger is not always better'. This is especially applicable to biomass technologies, as the economies of scale of larger plants need to compete with the diseconomies of scale of transporting geographically distributed biomass to a central location. Therefore, large numbers of small units are able to compete with large scaled-up facilities, due to learning with the mass production of smaller units, accounting for the same overall capacity (Dahlgren et al., 2013; Jack, 2009).

The scale-independent learning effects, as well as the scale-dependent learning effects are elaborated on. An important notion is that both may influence each other as well, as for example a technology may not scale up in capacity (economies of unit size) when no specific knowledge is available how to scale-up. The scale-up process itself may reveal technological issues which are an input for further learning-by-researching.

3.3 Learning pathways

In addition to the functions of the technological innovation system, and the scale-dependent learning and scale-independent learning approach, a more technology-specific theory is taken into account in this study as well. Winskel et al. (2014) have underlined the lack of cross-over between innovation studies and technology learning. The functions of the innovation system approach, according to the scholars, may fail to capture important differences in socio-technical issues and learning effects of different technologies. The way different technologies may have different degrees of emphasis on different learning types, see section 3.2, is not included in the more general frameworks (Clarke et al., 2006; Kamp et al., 2004; Winskel et al., 2014). Therefore, as a first contribution to linking learning effects and technological innovation systems, Winskel et al. (2014) established a technology-specific framework to include the differences between different types of technologies.

The scholars identified a number of generic issues in energy supply technology innovation systems. Two of these issues are the orientation to radical or incremental innovation, and the organisational and institutional concentration. The radicality of innovation and the organisational distribution entail:

- **The radicality of innovation** influences the learning effects of that innovation. Incremental innovations consist of minor improvements or adjustments to existing technologies (Schoenmakers & Duysters, 2010), whereas radical innovations involve the application of significant new technologies or significant new combinations of technologies (Schoenmakers & Duysters, 2010; Tushman & Nadler, 1986). Stabilising a radical innovation during the RD&D phase often takes longer compared to small incremental innovations (Abernathy & Utterback, 1978; Dosi, 1982). However, during the commercial production phase step-change improvements from radical innovations are emphasized (Abernathy & Clark, 1985).
- **The organisational distribution** in which an innovation is developed influences the learning effects as well (Garud & Karnøe, 2003; Kamp et al., 2004). A distributed environment refers to multiple universities and small enterprises that are involved in the development of an innovation. A concentrated environment consists of large labs and large firms that contribute to an innovation. The latter brings more resources, e.g. financial capital and human capital, which consequently results in a more rapid development. This thought is in line with Chandy & Tellis (2000), who state that small companies tend to have a disadvantage in market, financial and technical capabilities compared to larger incumbent firms. Hence, the development of a technology in a distributed environment may be more sustained over time.

The radicality and the organisational distribution of a technology are thus representative technical and social parameters, and form the Y-axis and X-axis of the learning pathway matrix (see Figure 3). The learning pathway matrix forms a socio-technical landscape which displays the niche origins of energy supply technologies and their learning dynamics over time. Based on numerous case studies that were applied to the learning pathway matrix, archetypal learning pathways for energy supply technologies were established (Winskel et al., 2014). In appendix 1, the different learning pathways in the learning pathway matrix are shown. These archetypal learning pathways may reflect the prospects of different learning pathways for different technology fields, in different societal contexts (Winskel et al., 2014). The archetypal learning pathways identify the learning effects, strengths and weaknesses, both from an innovation system perspective as well as a learning perspective. The derived learning pathways and their characteristics are shown in Table 4.

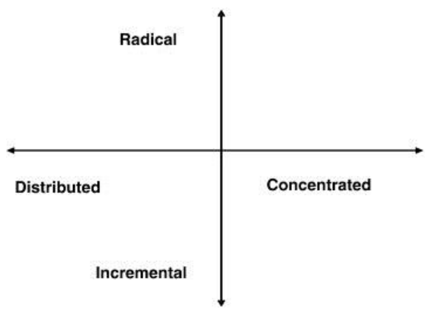


Figure 3: the learning pathway matrix (Winskel et al., 2014)

Table 4: archetypical learning pathways and their learning effects (Winskel et al., 2014)

Learning pathway (with examples)	Typical learning effects	Strengths	Weaknesses
Incremental, early stage (e.g. early onshore wind, marine renewables)	Small firms developing low risk components and systems, possibly pre-existing in other sectors. Learning by adaptation (informal transfer), by experience, by interacting, gradual upscaling.	Can sustain gradual learning over long timescales. Strong feedbacks between developers, users, testers, policymakers and public. Can support high design variety and flexibility, avoiding early 'lock in'.	Long development timescales, so niches are vulnerable to changing wider policy context and/or emergence of rival technologies. Unlikely to rapidly progress radical technologies or step-change improvements.
Incremental, mature stage (e.g. coal and gas fired turbine plant, nuclear fission)	Gradual improvement of more mature technology systems led by incumbent within-regime' organisations (utilities, large equipment manufacturers and affiliated research bodies).	Supported by significant institutional, organisational and financial resources within the regime; builds on established capital assets and knowledge bases.	Emphasis on incremental improvements may offer diminishing returns; may offer an inadequate response to rapidly changing context.
High tech, breakthrough (e.g. advanced nuclear power, jet engines, advanced offshore wind, possibly CCS)	Highly co-ordinated institutionally and concentrated organisationally. Large scale high technology defence/state programmes. Learning by research, and learning by doing/experience within large scale formal RD&D programmes.	Capable of step-change improvements across or within technology fields. Can support and deploy innovations in underpinning/enabling technologies (e.g. IT, materials).	Risk of early-stage failure, 'lock-in' or failure to commercialise over longer term ('picking losers'). May have weak links to wider society, with risk of public backlash. Requires sustained high levels of funding.
High tech, interactive (e.g. advanced marine and bioenergy renewables)	Small-sized high technology publicly funded research groups and private firms operating in highly interactive and fluid networks of suppliers, financiers and customers	Capable of radical/disruptive innovation; likely to be highly responsive to changing context and able to draw on the technical, financial and human resources of a wide network.	Limited core resources, so overall learning may be slow despite potential step changes. Limited resilience to risk and failure, so may tend toward risk averseness or 'start-stop' learning.
High tech, diversification (e.g. solar PV, fuel cells, some bioenergy technologies)	Modular technologies emerging mostly from state-sponsored niches. Emphasis on learning by research for modules and components. For applications, emphasis on learning by experience via small scale trials. Multiple niche markets may exist in parallel.	Small scale, modular systems offer many opportunities for learning by experience in demonstrations and manufacturing. Multiple niche markets offer diversity and flexibility, so learning is more likely to be sustained over time.	High cost modules may be hard to commercialise. State-sponsored niches are vulnerable to changing policies and/or rival technologies. Small scale systems may be 'locked out' by large scale incumbents, and face high balance of system and/or system integration costs.
Transfer and combination (e.g. early CCGTs, possibly CCS)	Combinations of technologies, practices or knowledge from multiple fields or sectors. Learning by formal transfer and adaptation, and also by experience.	Able to 'piggy back' learning investments from other fields and sectors. Novel combinations may enable step change improvements over relatively short timescales.	Transferred technology may be disruptive and difficult to manage in its new context. Incumbents may resist transfer. Adaptation and collaboration challenges/costs (e.g. IP barriers) may be under-appreciated

3.4 Comprehensive model of innovation systems and learning theories in time perspective

3.4.1 Development phases

The technology readiness level (TRL) is a type of measurement system that can be used to assess the maturity level of a particular technology (NASA, 2015). Each technology project is evaluated against the parameters of each technology level and is then assigned a TRL rating based on the projects progress. In total, 9 levels exist of which TRL 1 is the lowest and TRL 9 is the highest. These TRL ratings may be categorized into different development phases (Bioenergy2020+, 2015). These development stages clearly identify when commercialisation occurs, and therefore fit this study that aims to create more insights into the pace towards commercialisation of FP and HTL. An overview of the development phases is given in Table 5.

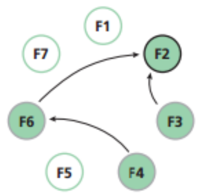
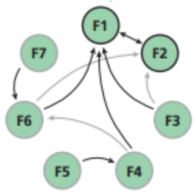
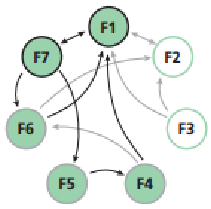
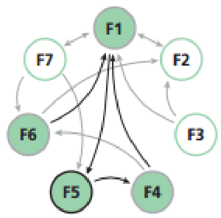
Table 5: the development phases and their parameters{Formatting Citation}

Development phase used in this study	Link to TRL	Parameters per TRL
Research	TRL 1-3	1. basic principles observed 2. technology concept formulated 3. experimental proof of concept
Pilot	TRL 4-5	4. technology validated in lab 5. technology validated in relevant environment (industrially relevant environment in the case of key enabling technologies) In terms of biofuel facilities, this typically means · facility, which does not operate continuously · facility not embedded into an entire material logistic chain; only the feasibility of selected technological steps is demonstrated · the product might not be marketed
Demonstration	TRL 6-7	6. technology demonstrated in relevant environment (industrially relevant environment in the case of key enabling technologies) 7. system prototype demonstration in operational environment In terms of biofuel facilities, this typically means · facility demonstrating the capability of the technology for continuous production (operated mainly continuously) · the facility is covering the entire production process or embedded into an entire material logistic chain · the product is being marketed · facility may not be operated under economic objectives
First-of-a-kind commercial demo	TRL 8	8. system complete and qualified In terms of biofuel facilities, this typically means · facility operated under economic objectives · the product is being marketed
Fully commercial	TRL 9	9. Actual system proven in an operational and competitive environment

3.4.2 Comprehensive model of theories integrated in development phases

The functions of the technological innovation system, the scale-dependent and scale-independent learning effects and the learning pathways are elaborated on. The different theories use different time indications, which makes it less transparent when in the development of a technology the different theories apply. The different theories are therefore classified into the development phases. Hence, a comprehensive model of the theories used in this study per development phase is established. This model is given in Table 6.

Table 6: comprehensive model of theories used in this study per development phase (author's own compilation)

<table>
<tr><th colspan="2"></th><th>Research</th><th>Pilot</th><th>Demonstration</th><th>First-of-a-kind commercial demo</th><th>Fully commercial</th></tr>
<tr><td colspan="2">TIS
(section 3.1)</td><td colspan="2">Pre-development phase

</td><td>Development phase

</td><td>Take-off phase

</td><td>Acceleration phase

</td></tr>
<tr><td rowspan="2">Scale-independent learning (section 3.2)</td><td rowspan="2">Internal Knowledge creation</td><td colspan="5">Learning by-researching</td></tr>
<tr><td colspan="3"></td><td colspan="2">Learning-by-doing</td></tr>
<tr><td rowspan="2">Scale-independent learning (section 3.2)</td><td rowspan="2">User-producer interaction</td><td colspan="3"></td><td colspan="2">Learning-by-using</td></tr>
<tr><td colspan="2"></td><td colspan="3">Learning-by-interacting</td></tr>
<tr><td rowspan="3">Scale-independent learning (section 3.2)</td><td rowspan="3">Knowledge and technology transfer</td><td colspan="5">Learning-by-imitation</td></tr>
<tr><td colspan="5">Learning-by-failing</td></tr>
<tr><td colspan="5">Learning-from-inter-industry-spillovers</td></tr>
<tr><td colspan="2" rowspan="2">Scale-dependent learning (section 3.2)</td><td colspan="5">Economies of unit size</td></tr>
<tr><td colspan="3"></td><td colspan="2">Economies of numbers</td></tr>
<tr><td colspan="2">Learning pathways (section 3.3)</td><td colspan="5">Archetypal learning pathway</td></tr>
</table>

4. Methodology

4.1 Research design

The aim of this research is to assess the chances of overcoming technological challenges and socio-technical barriers, and the learning effects that are expected to play a role throughout the development of FP and HTL. To be able to accomplish this aim, the study was divided into four parts: 1) technological development and current challenges, 2) socio-technical environment and current barriers, 3) overcoming technological challenges and socio-technical barriers, and 4) learning effects throughout the entire development. It is determined that FP is currently in the demonstration phase (PS3, Arup URS Consortium, 2014)[11], the Australian company Licella is leading the development of HTL and is currently in demonstration phase as well[12] and the upgrading technology is in the pilot phase (PS3, Arup URS Consortium, 2014)[13]. Therefore, the first part focused on the technological development until the demonstration phase for FP and HTL, and the pilot phase for upgrading. The state of the art technologies of the current development phase were also elaborated on, and hence the current technological challenges were identified. In the second part, all seven functions of the TIS were expected to play a role in the current development phase of the technologies, and these functions shed light on the current socio-technical barriers. The third part assesses whether these technological challenges and socio-technical barriers are expected to be overcome, which might enable the technologies towards the first-of-a-kind-commercial demo phase. Part 4 assessed the learning effects that have played a role until the current development phase, and elaborated on the expected learning effects if commercialisation could be reached (see figure 4).

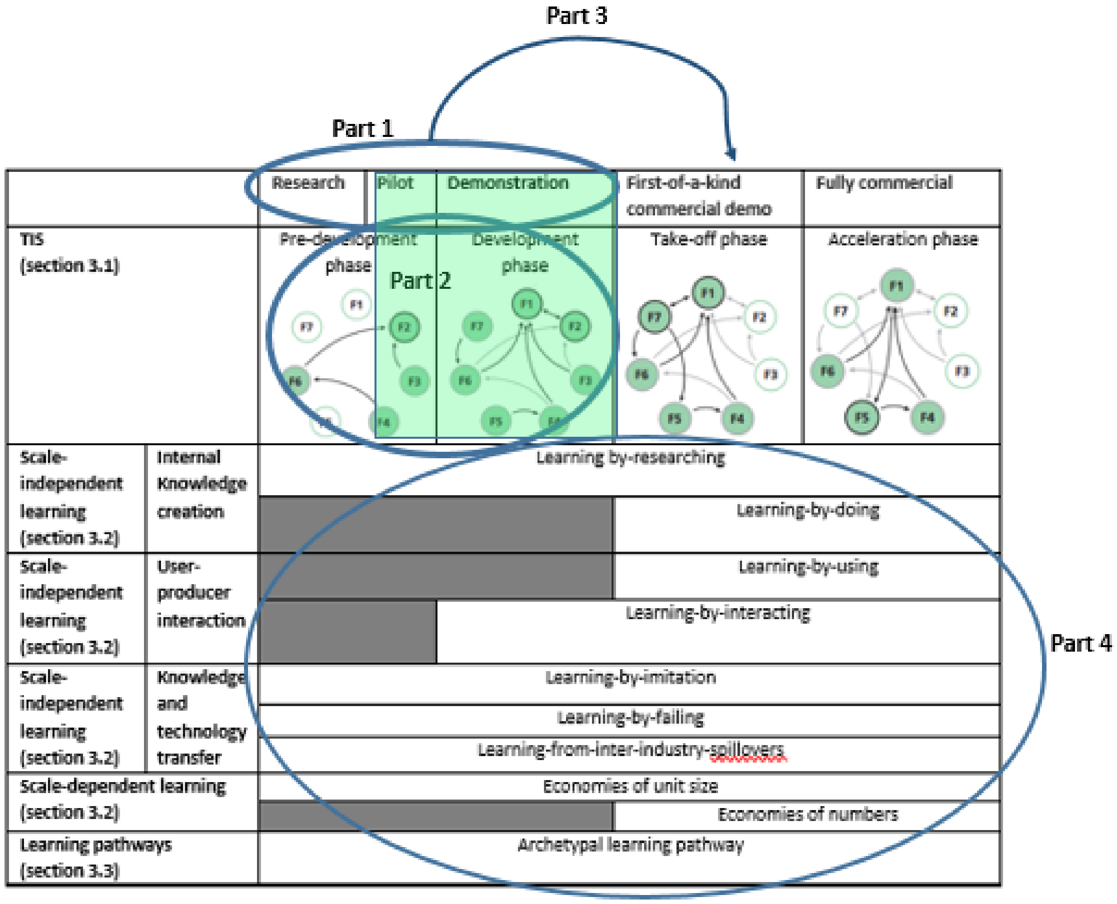


Figure 4: research design of the study (author's own compilation)

[11] These studies determined the Technology Readiness Level (TRL), which are translated to a development phase according to Bioenergy2020+ (2015)
[12] These studies determined the Fuel Readiness Level (FRL), which are translated to a development phase according to Bioenergy2020+ (2015)
[13] This study determined the Technology Readiness Level (TRL), which are translated to a development phase according to Bioenergy2020+ (2015)

4.2 Operationalisation of concepts

4.2.1 Technological development and current challenges

The technological development from the research phase until the demonstration phase was assessed in part 1. First the concept of the origin of the technologies was determined, whereby the rationale to establish the new FP and HTL technologies were elaborated on. Moreover, the establishment of the technologies themselves were elaborated on, which included an assessment on whether the technologies relied on existing technologies or whether the technologies were completely newly developed. The second concept was the research to develop the technologies, which include a description on the amount of research that has been performed and the experiments to scale-up the technologies. The third concept elaborated on the current state of the technologies, which entail the reactor type, the process conditions, the use of catalysts and the scale of the technologies. This third concept, the current state of the technologies, also revealed which technological challenges are still to be overcome. An overview of these concepts to assess part 1, the technological development and current challenges, is given in Figure 5.

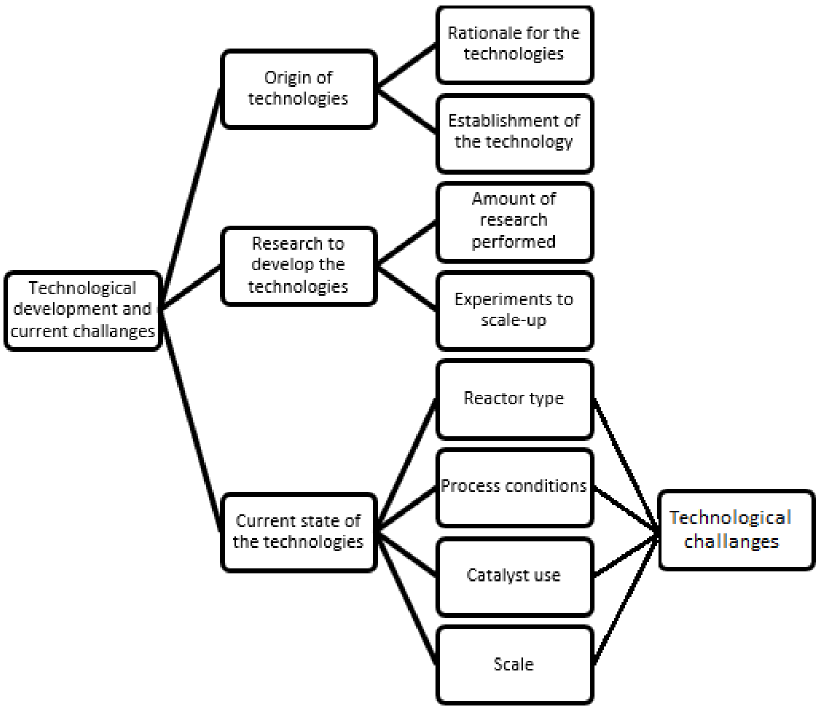


Figure 5: graphical overview of concepts to assess the technological development and current challenges

4.2.2 Socio-technical environment and current barriers

Part 2 consists of the socio-technical environment and current barriers. This environment is described using the seven function framework which is based on the technological innovation system approach (see theory section). The framework is used in different ways in previous studies, according to the preferred outcomes. First of all, the time span of the TIS may differ. For example, Suurs & Hekkert (2009) take a historical approach to identify the formation of a TIS, whereas Kohler et al. (2013) focus on current innovation processes to assess the appropriability of the current TIS. Secondly, the type of data used in the TIS may differ. Negro (2007) takes a more quantitative event approach which can be plotted on a timescale to allow for a historical analysis. On the other hand, Goess et al. (2015) look at the current status quo, and the accompanied drivers and barriers of a TIS for which they use a more qualitative approach based on literature review and interviews. Thirdly, the geographical boundaries in which the TIS is applied, differs per study (Suurs & Hekkert, 2009). Lai et al (2012) set a country specific boundary on China, whereas Bergek et al. (2008) state that TISs are generally global in character. This study used the framework to assess the current global innovation system, which is qualitatively described. Previous studies show that the TIS may indeed be used for this aim, as this is in line with previous studies of Goess et al. (2015) Kohler et al. (2013) and Bergek et al. (2008).

Each function was qualitatively assessed on the indicators of each function, provided in Table 3 in the theory section. This resulted in an elaborated description per indicator of each function, from which the drivers and barriers for further development could be extracted. These drivers and barriers were therefore an indication of the fulfilment of each function. To allow for an overview of the fulfilment of each function, each function was classified in a 5-point scale. The classification is based on the amount of drivers and barriers that are identified within a function, and Table 7 elaborates on the specific scales.

Table 7: overview of the 5-point scale to assess function fulfilment

Scale	Categorized when
	Only drivers within a function, and no indication of barriers
	There were more drivers within a function than barriers
	The amount of drivers within a function was equal to the amount of barriers
	There were more barriers within a function than drivers
	Only barriers within a function, and no indication of drivers

Apart from the assessment of each individual function, the interactions between the functions play a very important role in order to understand the dynamics of the system as described in the theory section (Hekkert & Negro, 2009; Negro, 2007). Therefore, the interactions between the function were assessed as well. These interactions can be negative (i.e. barriers of one function causes a lower fulfilment of another function as well), as well as positive (i.e. drivers of one function causes a better fulfilment of another function). For each function, after the description of the indicators belonging to a function, a graphical overview of the fulfilment of the function (based on Table 7) as well as the interactions of this function was constructed.

4.2.3 Overcoming technological challenges and socio-technical barriers

In part 3, an assessment of chances of overcoming the identified technological challenges and socio-technical barriers was performed. First, the assessment of overcoming technological challenges entailed the description of technological opinions that could be researched and/or implemented to overcome the current challenge. These technological opinions either improve the current technology whereby the challenge will be eliminated, or may pose a differentiation to the technology whereby the challenge will be avoided. After this description, the chances of overcoming a technological barrier per technological option was given which are described in Table 8.

Table 8: classification of chance of overcoming technological challenge (author's own compilation)

Chance of overcoming technological challenge	Categorized when
High	Current knowledge is sufficient for the implementation of the technological option
Medium	Current knowledge is not sufficient for the technological option to be implemented, but

	research emphasises this option and therefore the option may become available on the short term
Low	Current knowledge is not sufficient for the technological option to be implemented and research does not (effectively) assess this option, resulting in that the technological option is not expected to be available in the short term

Secondly, an assessment of overcoming the socio-technical challenges was elaborated on. For each barrier, a possible solution was given, and also the chance of overcoming the barrier was determined. The classification of overcoming socio-technical barriers is given in Table 9.

Table 9: classification of chance of overcoming socio-technical barriers (author's own compilation)

Chance of overcoming socio-technical barrier	Categorized when
High	The barrier can be overcome without substantial changes in the innovation system
Medium	The barrier can be overcome, but government help is needed and there are indications that the government will be helpful
Low	The barrier cannot be overcome without substantial changes in the innovation system, and there is no indication that the government will interfere

4.2.4 Learning effects throughout the entire development

Part 4 focused on which learning effects have played a role during the development, as well as expected learning effects if the technologies could be commercialised. First, each of the learning effects of Table 6 were qualitatively discussed. Hereafter, the learning pathway of the technologies were determined as well. The concept of the learning pathways of Winskel et al. (2014) were approached in a similar way as the scholars constructed the archetypical learning pathways (see theory section). The learning pathway matrix was thus established for the technologies, based on their radicality and the organisational distribution (see figure 3 for the learning pathway matrix). Both radicality and organisation distribution are explained in the theory section, and following Winskel et al. (2014), strict criteria to assess the radicality and the organisation distribution were not used. Instead, radicality and the organisational distribution were qualitatively described and the researcher then transformed this description into a place in the matrix. Hereafter, this matrix was compared to the different matrixes belonging to the different learning pathways (see Appendix 1), to find a matching matrix and hence the archetypical learning pathway was determined.

4.3 Data collection and analysis

4.3.1 Patent analysis – used for part 1

Patents are an appropriate tool to assess technological development for the following reasons (Hall et al., 2001). First, patents are an outcome of the R&D process, contrary to R&D investment which measures innovation input. Secondly, patents are legal documents and assessed by patent examiners, which makes the data reliable and consistent over time. Therefore, patent analysis is chosen as patents are recognized as a rich source of data for the study of invention, innovation and technical change (Hall et al., 2001). In this study, the patents were analysed to explore the establishment of the technologies and the amount of research performed, which are indicators of part 1.

The patents were derived via Espacenet, which is the most comprehensive database of patents consisting of 80 million patents applied for in more than 90 countries. To find the necessary patents, a combination of search terms and the Cooperative Patent Classification (CPC) was used. The CPC is a patent classification system, of which the code Y02P30/20 relates to 'Technologies relating to oil refining and petrochemical industry by means of bio-feedstock'. The code Y02E50/14 relates to '' Technologies for the production of fuel of non-fossil origin by means of bio-pyrolysis''. The search terms, which applies to the title and summary of the patent, ''pyrolysis'', ''liquefaction'', and ''upgrading'' were used. Patents from the period 1970[14]-2015 are included in the research. The derived patents contained some duplicate patents, when one patent was categorized in both CPC classes. Therefore, the dataset was checked for these duplicates, and one of the two patents was deleted to avoid double count. Lastly, patents applied for in the US or Europe are accounted for, as the databases which contain the patent indicators (see following paragraph) focuses on those regions. This may exclude other patents applied for in other regions, however, most FP and HTL work is done in the US and Europe and therefore this is not seen as a large limitation. The following amount of patents were derived:

- 352 FP patents
- 120 HTL patents
- 97 upgrading patents

The analysis of the patents is based on the 'OECD Patent Quality Indicators database, September 2015'. Table 10 shows the indicators out of the database that were used.

Table 10: description of patent quality indicators (Squicciarini et al., 2013)

Indicator	Description	Value	Interpretation value
Originality index	Broadness of the technology fields on which a patent relies	Between 0-1	The higher the indicator, the more different knowledge sources from different technology fields are relied on
Radicalness index	Patent builds upon paradigms that differ from the one it is applied	Between 0-1	The higher the indicator, the more it relies on patents that rely on different technology fields
Patent renewal	The number of times that a patent is renewed	≥0	The higher the patent renewal, the more private value is seen in the patent and thus refers to a more useful patent

The patent analysis compared the average value of the indicators of FP, HTL and upgrading, with the average value of the technology field in which FP, HTL and upgrading are classified. Hence, explorations whether FP, HTL and the upgrading unit are more/less/comparable in originality, radicalness and patent renewal were determined. The average of the indicators of the technology field is given in Table 11.

Table 11: average value of patent indicators in the technology field (Squicciarini et al., 2013)

Indicator	Average value within technology field
Originality index	0.78
Radicalness index	0.40
Patent renewal	8.0

[14] The technologies were taken up in the 1970s, and hence from this moment patents regarding biomass FP, HTL and upgrading were granted

4.3.2 Literature review – used for all parts

The purpose of the literature review is twofold. First, the literature review provided the researcher with a thorough understanding of FP and HTL technologies and their place within the socio-economic context. This resulted in the ability to ask more in-depth questions during the interviews, which will be discussed hereafter. Secondly, the literature review allows for a comparison between what is found in literature and what was said during the interviews.

The literature review consists of peer reviewed articles as well as grey literature. Peer reviewed articles written by academics were found through the use of Google Scholar and Scopus. The grey literature is written by the industry itself, and consists of websites of companies active in FP or HTL, newsletters regarding the technologies (e.g. Pyne for FP and HTL) and reports written by governments or governmental institutes.

4.3.3 Interviews – used for all parts

The introduction already described that a quantitative approach in this study was nearly impossible, as a technology-specific learning rate is lacking due to a lack of data of commercialised plants. Therefore, a qualitative approach was used in this study. Qualitative research offers an in-depth examination of a phenomenon (Bryman, 2008; Patton, 1980). As such, the qualitative approach was beneficial to obtain a holistic view of the current situation and challenges, the chances of overcoming these challenges and the expected future learning effects

The two most common methods of data collection in qualitative research are interviews and focus groups. Focus groups were deemed to be unbeneficial for this study, as 1) the anonymity of the respondents could not be guaranteed, which probably would have led to lower response rates, 2) focus groups may be dominated by one or two participants, possibly leading to less elaborated information, and 3) FP and HTL are employed all over the world, and bringing together respondents from all over the world within one focus group would be impossible due to the time difference. Therefore, interviews were the most appropriate approach to gather qualitative information from a lot of respondents from all over the world.

A semi-structured approach to the interviews was used to combine the advantages of pre-prepared questions with the flexibility to enhance further into an issue when the situation required, since semi-structured interviews allow follow-up questions in order to probe an issue (Babbie, 2005; Flick, 2002). In total, 28 requests were sent to potential FP respondents, 31 requests to potential HTL respondents and 12 requests to potential respondents having knowledge regarding both technologies. As a result, 16 interviews on FP, 8 interviews on HTL and 1 interview on both technologies were conducted in-person, by means of Skype or phone. All respondents are working in Europe, North America or Oceania. There is some skewness in the type of job of respondents, as most respondent are scientists working at universities or institutes. This is a result of that a lot of research is performed at universities and institutes and they are currently the most active actors. The sample may therefore be seen as representative. The consultant group consists out of respondents giving advice on a more techno-economic or market related FP and HTL issues. The industrialists are the respondents from companies trying to develop the technologies with the goal of commercialisation. Table 12 gives an overview of the respondents.

Table 12: overview of interviewed respondents

Reference	Technology	Type	Region
PS1	Catalytic FP	Scientist	North America
PS2	FP	Scientist	Europe
PS3	FP	Scientist	North America
PS4	FP	Scientist	Europe
PS5	FP	Scientist	Europe
PS6	Catalytic FP	Scientist	North America

PS7	Catalytic FP	Scientist	North America
PC1	FP	Consultant	Europe
PC2	Catalytic FP	Consultant	North America
PC3	FP	Consultant	Europe
PC4	FP	Consultant	Europe
PC5	FP	Consultant	Europe
PI1	FP	Industrialist	Europe
PI2	Catalytic FP	Industrialist	Europe
PI3	FP	Industrialist	North America
PI4	FP	Industrialist	Europe
HS1	HTL	Scientist	Europe
HS2	HTL	Scientist	Oceania
HS3	HTL	Scientist	Europe
HS4	HTL	Scientist	North America
HS5	HTL	Scientist	Europe
HS6	HTL	Scientist	North America
HI1	HTL	Industrialist	North America
HI2	HTL	Industrialist	North America
PHS1	FP + HTL	Scientist	Oceania

The interview questions are given in Appendix 2. As the respondents have different backgrounds, not all questions applied to all respondents. Moreover, the interview scheme was slightly changed after some interviews. When data saturation regarding one question was reached, i.e. when it was clear that there had been a consensus regarding a topic also among different types of respondents, this question was not incorporated in following interviews. This allowed for more time and thus a more in-depth conversation during the interviews for questions where consensus between respondents had not been reached. The interviews itself were conducted by phone, Skype or in-person and lasted between 25 and 69 minutes per interview.

A common critic is that a qualitative approach is unsystematic and not rigorous enough to provide reliable results (Bryman, 2008). This study addressed this critic by using NVivo 11 to allow for a systematic analysis of qualitative data by making use of coding. In line with Corbin & Strauss (1990), the coding process consisted of different stages. First, coding was used to categorize the data into different nodes. Hereafter, the nodes that were deemed irrelevant for this study were removed. Second, the nodes were restructured to the theoretical concepts used in this study. Hence, information derived from the interviews was structurally categorized into the theoretical concepts of this study. This consistency in data collection enhanced the reliability of the results. Moreover, as the same set of questions was asked to all respondents, a comparison of the opinions of the different respondents was possible. These opinions were also checked with existing literature, and hence a thorough analysis was done to be able to establish reliable results.

5. Results

5.1 Technological development and current challenges

5.1.1 Origin of the technologies

The process of (slow) pyrolysis has existed for over thousands years (PS3,PS4,PS5), and was mainly used to produce charcoal (PS4). The concept of biomass liquefaction in hot water to produce liquid oil was developed in the 1920s (Zhu et al., 2014). FP and HTL were, however, not taken up until the 1970s when scientists, as a reaction to the oil crisis, looked for opportunities to convert renewable sources into a liquid (PS5; Radlein & Quignard, 2013; Elliott, 2007). They discovered that the liquid yield of pyrolysis increased when using high heating rates, and called this form of pyrolysis ''fast pyrolysis''. Also the concept of HTL was taken up and a biomass HTL process was developed in the 1970s as a reaction to the oil crisis. The shared vision to find an alternative for crude oil is therefore the basis of FP and HTL.

Slow pyrolysis formed the inspiration for fast pyrolysis, however the technologies and process conditions are not comparable (Ronsse et al., 2013). The technologies for the construction of fast pyrolysis find their origin mainly in the petroleum industry (PS2; PS3; PI2). The FP reactor has been used in the petroleum industry since the 1950s (IEA Bioenergy, 2014; San-Miguel, Makibar, & Fernandez-Akarregi, 2012). The first catalysts used for biomass fast pyrolysis originate from the petroleum industry as well (PS1, PS3, PS6, PI2). The technologies on which HTL is based were also mostly existing technologies (HI1). The upgrading technology was again transferred from the petroleum industry (IEA Bioenergy, 2014). The technologies are thus mostly based on inter-industry-spillovers.

The patent characteristics show similar results, and offer extra insights on the inter-industry-spillovers (see Table 13). The originality index refers to the breadth of the technology field on which a patent relies. The derived patents indicate that HTL and the upgrading technology rely on a large number of diverse knowledge sources and/or different technology fields. On the other hand, FP has an average score and thus gathered more of its prior knowledge from the same technology field. This can be explained by the fact that FP technologies originate mainly from the petroleum industry, whereas knowledge regarding HTL and upgrading is mainly acquired from more different technology fields.

Table 13: patent indicators compared to the average of the technology field[15]

	Originality index	Radicalness index
FP	Similar to technologies in same technology field	Higher than technologies in same technology field
HTL	Higher than technologies in same technology field	Higher than technologies in same technology field
Upgrading	Higher than technologies in same technology field	Similar to technologies in same technology field

The radicalness index indicates that FP and HTL patents differ from the predecessors they rely on. This would indicate that those technologies are built upon paradigms that are different from the one to which they are applied to. It is striking that the upgrading technology has an average score regarding the radicalness index and a higher than average score for the originality index, as both indicators are based on backward citations. One explanation might be that upgrading is based on a larger breadth of patents (i.e. more technological fields), but the patents that are cited are mostly used in their own technology field. Figure 6 shows that FP does not cite a lot of patents from different technology fields, but their backward citations do cite patents from different technology fields. HTL relies on patents from different technology fields, and those patents also cite different patents from different technology fields. In conclusion, one might state that FP, HTL and upgrading rely, direct or less direct, on other patents: the technologies are indeed based on technology transfer.

[15] Appendix 3 gives an overview of the values of the patent indicators

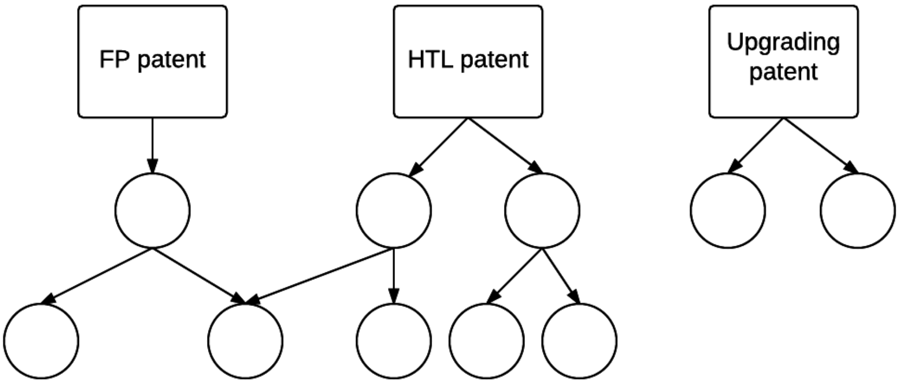


Figure 6: reliance of FP, HTL and upgrading patents on other technology fields

5.1.2 Research to develop the technologies

After the technologies were taken up in the 1970s by scientists, universities and institutes started researching the technologies[16]. Although both FP and HTL find their origin in existing technologies, adjustments to those technologies had to be made to be able to process biomass. During the 1980s, research focused on adapting the reactors and process conditions for the use of biomass to maximize the production of liquids (PS6, Venderbosch & Prins, 2010). During this time, some mainly newly started companies also got involved into FP and HTL, and focused on building pilot plants. Many of those pilot plants however stopped after initial testing for the following reasons (Knight et al., 1983; Maniatis et al., 1993; Radlein & Quignard, 2013; Venderbosch & Prins, 2010; Toor et al., 2011):

- Lack of funding for project
- Lack of a market for bio-oils
- Tax disadvantages
- Legislative limitations
- Technological problems, such as the inability to produce high yields

There were also some research developments in the field of upgrading during the 1980s (Elliott, 2007), but real interest in upgrading the bio-oil for transport fuels arose in the late 1990s (E4Tech, 2009; Jones & Snowden-Swan, 2013; Venderbosch & Prins, 2010). It was discovered that the bio-oil has different physical properties (e.g. oxygen level) as compared to petroleum derived oil, and research regarding improving the quality of bio-oil therefore gained interest (PC1). Research in the field of upgrading is done by universities and institutes as well[17].

Since the 1970s, research regarding maximizing the yield of the technologies and improving the quality of the oil have continued. The interest in both technologies increased over the last decades. Figure 7 shows the total amount of patents which are granted in the bio-pyrolysis patent class, which consists, among other technologies, of FP, HTL and upgrading technologies. The amount of patents has increased exponentially over time, showing an increase of innovative output concerning the technologies[18]. It needs to be stated that the patent renewal of FP, HTL and upgrading is below the average of the technology field. This indicates that after a few years the patents are seen as less useful and are therefore not renewed, as the costs of renewal do not outweigh the benefits of the patents. This indicates that although more and more patents are applied for, a lot of patents which are applied for are commercially less relevant.

[16] based on: Diebold & Scahill (1988), Elliott (2007), Knight et al. (1983), Maniatis et al. (1993), Radlein & Quignard (2013), Sandquist & Guell (2012), Solantausta (2006), Stevens (1994) and Toor et al. (2011)

[17] Based on: Baker & Elliott (1988), Elliott (2007) and Gevert & Otterstedt (1986)

[18] It seems that the amount of patents is decreasing again, however in the database patents that already has been granted are included. Patents can take years before granted, and hence it is expected that there is no actual decrease but there are patents that are still in the application phase

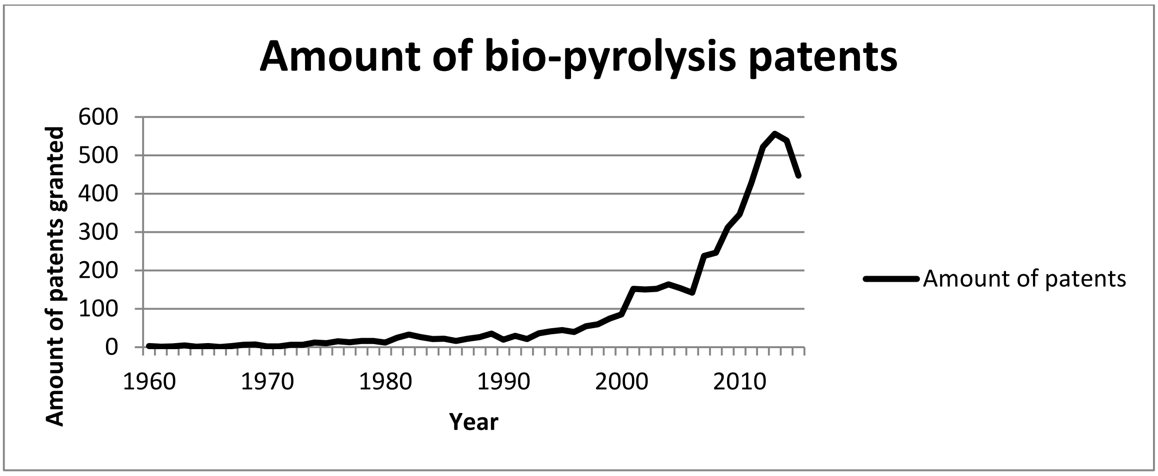


Figure 7: amount of patents in the bio-pyrolysis patent class (including HTL)

5.1.3 Current state of the art of FP

A lot of research is performed and FP has developed to the demonstration phase. The current state of the art FP technology is elaborated on, in which the reactors, process conditions, catalyst use and current scale play an important role. As the technology is not yet fully developed, the current technological challenges are mentioned as well.

Reactors

Reactors are the most researched aspect of fast pyrolysis (Radlein & Quignard, 2013). The most important reactors and their characteristics are listed in Table 14.

Table 14: most important varieties of fast pyrolysis reactors, based on: Brown & Holmgren (2006) and adapted according to Butler et al. (2011) and San-Miguel et al. (2012)

Reactor	Maximum yield (wt%)	Particles in oil	Complexity	Feedstock flexibility	Carrier gas needed	Equipment size	Scale-up
BFB	75	High	Medium	Low	High	Medium	Easy/Medium
CFB	75	High	High	Low	High	Large	Easy
Rotating cone	70	Low	High	High	None	Small	Medium/Hard
Ablative	70/75	Low	High	High	None	Small	Hard
Auger	60/65	Low	Low	High	None	Small	Easy/Medium
Vacuum	55/60	Low	High	Medium	None	Large	Hard

Several reactor types thus exist, however most respondents indicate that a consensus has been established regarding circulating fluidised bed reactor types (CFB)[19] that have been used in the petroleum industry since the 1950s. The respondents prefer this reactor for the following reasons:

- Easy scale-up to high throughputs (PS2;PC5;PI3)
- Build up experience with CFB in the petroleum industry, which may prevent unexpected disadvantages of the reactor and thus only optimization is needed (PS2;PS5;PI2;PI3)
- High liquid yields (PS3) and no char by-product (PS2;PS3).

These arguments agree with IEA Bioenergy (2014) which states that the reactor is robust, scalable and results in a relatively high yield of bio-oil. Companies using a CFB reactor are for example Ensyn and Fortum (Bridgwater, 2012). On the other hand, BTG has built a demonstration plant using the rotating cone reactor, which is according

[19] Also called transporting beds (PS2)

to respondent PS4 also comparable to the reactor used in the petroleum industry. Hence, the CFB reactor is the preferred reactor choice, but also experiments with the petroleum like rotating cone reactor are performed.

Respondent PS6 suggests that the CFB reactor is indeed very scalable, and therefore very suitable for large scale operations. However, there are also experiments performed with small scale distributed conversion fast pyrolysis technologies (1-5 tonnes/day), A technically less complex system like Auger might be preferred for those small scale technologies. This view corresponds with Butler et al. (2011), who argues that certain reactors may be more suitable for particular applications and scales of applications than others.

It is important to note that research efforts have been distributed over the different types of reactors. In Appendix 4, an overview regarding research and industrial activities per reactor type constructed by Bridgwater (2012) is given. It is striking that less research is performed regarding the preferred CFB and rotating cone for larger scale plants, and the auger for smaller scale distributed operations, but yet seem to be the best option. It is striking as well, that although a consensus has been agreed on, there is still research being done concerning the other reactors. The setting of a dominant design, a consensus of technology characteristics, normally stimulates the technology as research can be focussed on those agreed on characteristics. It, however, seems that research still focuses on several technological varieties, whereby the research efforts are distributed.

Process conditions

The process conditions (e.g. temperature, residence time) to maximize the oil yield have been researched extensively as well. Respondents PS5 and PI4 indicate that there was a debate on those conditions, but that they are currently pretty well standardized and understood. Respondent PS5 elaborates by indicating that high yields of liquids are derived in a very narrow temperature window, which is supported by several studies. The essential features of a fast pyrolysis process to produce liquids are indeed: 1) Temperature between 450 and 500 degrees Celsius, 2) Residence times of less than two seconds and 3) Rapid removing of product char and rapid cooling of pyrolysis vapours (Bridgwater, 2012; PS5). This seems to indicate that there are not many research challenges concerning the process conditions in itself.

Catalyst use

The use of catalysts in the FP process has been another focus of research (Radlein & Quignard, 2013). Catalytic fast pyrolysis has some advantages over the non-catalytic process, as the bio-oil produced contains less oxygen and is thus of higher quality (PS3, PS7, PC3). The higher quality bio-oil is easier to upgrade and has a higher energy density (PS3). The respondents hold different opinions as to whether the catalytic process is favourable though. Eleven respondents have a clear opinion about catalytic pyrolysis, of which 2 indicate that it is already a favourable process (it must be noted that this process is still on pilot scale), 7 are in favour of the process but see a lot of challenges before it is worthwhile, and 2 are in favour of not using catalytic pyrolysis. The latter two respondents see too much hurdles which need to be overcome. These research challenges will be described.

The first research challenge regarding catalytic pyrolysis, is the question whether it is best to use catalysts in the same reactor where biomass is being pyrolyzed (in-situ mode) or to have the catalysts in a separate reactor downstream from the pyrolysis reactor (ex-situ mode) (PS2; PS4; PS7). The respondents seemed to have a preference for the ex-situ mode, for the following reasons: 1) The process conditions in the reactor are already intense and finding a catalyst that is able to work properly in those conditions is hard (PS4), 2) In the in-situ mode, the poisons of the biomass are transferred to the catalysts which causes deactivation. Removing the catalysts from the FP step (ex-situ), slows down the deactivation of the catalysts (PS4, PS7, PI2), 3) The ex-situ mode gives the opportunity to tune the process conditions of both reactions (PS7). On the other hand, the second reactor of the ex-situ mode increases the capital and operating costs, and the second reactor may cause further secondary reactions. Respondent PS7 indicates that other organizations may therefore be in favour of the in-situ process. Hence, a consensus regarding the preferred mode is not reached.

The catalysts themselves form a second research challenge. The first catalysts that were used for catalytic fast pyrolysis of biomass, were similar to catalysts used in petroleum refineries (PS1; PS6). Respondent PS6 thinks that those catalysts are preferred, as the costs of those catalysts are not that high, and the catalysts have been proven to work on a small scale as well as very large scale in the petroleum industry. Respondents PS3, PS7 and PI4 see that those petroleum like catalysts are widely used for catalytic fast pyrolysis, however they see good reasons to believe why they are probably not the best catalysts to use. They say that those catalysts are less suitable for the use with biomass, as carbon is depositing on those catalysts (PC2). In this respondent's view, the carbon deposit on the catalyst is negative for the life time of the catalyst, as well for the yield of the oil as the carbon deposits on the catalyst instead of going into the oil. Respondent PS4 is therefore in favour of developing a specific catalyst for biomass catalytic fast pyrolysis. Hence, a consensus regarding the optimal catalyst for the use with biomass is not established (PI2, PI3).

Another consideration is the process conditions of the catalytic FP and the reactors used, especially with in-situ catalytic FP. The process conditions are known for the fast pyrolysis process itself, however, these conditions change when catalysts are used. According to respondent PS1, a common mistake is that people apply catalytic fast pyrolysis under fast pyrolysis conditions. Respondents PS4 and PS7 also state that work has to be done to create a better understanding of the process conditions needed in catalytic fast pyrolysis. Respondent PS1 is even in favour of research on new types of reactors which might fit the catalytic fast pyrolysis process better.

It is notable that catalytic fast pyrolysis has not been proven on a large scale yet. Organizations such as BTG, Ensyn, and Fortum which are currently the most important players producing on demonstration scale, use non-catalytic pyrolysis. The attempt of bringing catalytic fast pyrolysis to a demonstration scale, performed by a company named Kior, failed in 2014 as they scaled up to fast and the conditions were indeed not well understood (respondent PC2). This shows, together with the identified technological challenges, that more research is needed.

Scale of FP

Currently, the maximum scale is around 250 tonnes/day dry biomass input (PS2). It is important to note that the scale-up of the technology does require substantial time (PI1). An example of a company that scaled-up too fast is Kior, that tried to implement a 500 dry tonnes/day catalytic fast pyrolysis process (PS2; PS3; PS6; PS7; PC1; PC2; PI4). The company did not take enough time to gain experience in the laboratory and on intermediate scale, resulting in technological hurdles in the large scale plant. The company jumped a couple of steps in the development cycle by going directly from a bench scale system to a commercial system. This example shows that the intermediate steps are important to explore technological challenges when scaling up.

These technological challenges in scaling up are caused by the endothermic process of fast pyrolysis, i.e. heat needs to be transferred to the process (PS2). All current demonstration activities are based on using the product char to reheat the sand and transfer the reheated sand back into the pyrolysis chamber (CFB and rotating cone reactors). The first problem associated with the sand for heating, is that is causes fatigue in larger scale systems (PI1). The second problem is that the heat transfer between the hot sand, the hot gas and the biomass particles itself is not fully understood to an extent that it is ready to scale-up to very large systems. This is in line with Arup URS Consortium (2014) that states that further improvement of the heat transfer and the control of the heat transfer is needed in order to scale-up.

Overview of current technological challenges

In conclusion, FP is currently quite well understood. The circulating fluidized bed seems to be the preferred reactor choice, with a rotating cone reactor also in the running for large scale facilities. Smaller scale facilities will use less complex reactors such as the Auger reactor. Also the process conditions seem to have researched a lot, and consensus has been reached. The fast pyrolysis process is currently brought to demonstration scale, where it can show its operational reliability. However, there are also still some research challenges that are identified:

- Catalytic fast pyrolysis. Twelve of sixteen respondents have clearly identified a research gap regarding catalytic fast pyrolysis. The respondents see that work needs to be performed in the field of: 1) Improving or adjusting petroleum catalysts for the use in biomass, 2) Developing new catalysts for the use in biomass, 3) Identifying the best catalyst modus (in-situ or ex-situ), 4) Discovering the interplay between process conditions and reactors, and catalysts as they influence each other.
- Scale-up. Current demonstration plants face the problems of fatigue within the system and heat transfer to the biomass. Those problems currently form technological challenges that need to be overcome.

5.1.4 Current state of the art of HTL

Reactors

HTL is a high pressure process, which results in the need for robust reactors for the process (HS6). The two most used reactors are the continuous stirred tank reactor (CSTR) and the plug-flow reactor (PFR) (Mørup et al., 2015). The PFRs are cheap, easy to use on high pressures and produces a uniform product as all feedstock is heated for the same amount of time (HS1). Respondent HI1 states that his company sees the PFR as most promising, as they expect significant cost savings when using that design. The parts needed for a PFR reactor can be purchased, whereas the walls of a CSTR reactor needs to become bigger when scaling up and thus needs customer machining. The other industrialist HI2 indicates that this company also uses components that are already existing. This is in line with literature which state a preference for the PFR when performed on large-scale because they are more economically (Elliott et al., 2015; Pacific Northwest National Laboratory, 2014; Zhu et al., 2014).

The CSTR is more compact compared to the PFR reactor, but has the disadvantage that the feedstock is time wise not equally heated. Hence, some feedstock may be in the reactor for too long and other feedstock for too short. Respondent HS4 believes that the choice of reactor depends on the desired product; the PFR is in favour of a higher reaction order, resulting in a higher oil formation. This respondent therefore thinks that a PFR is preferred when producing biofuel. Respondent HI2 believes that a consensus will be reached due time, but each system is still unique at this point.

In conclusion, there is not a dominant design yet, however consensus concerning the PFR is starting. This would indicate that the research performed should also focus on the PFR. The performed research should focus on the creation of more efficient heat transfer (HS3).

Pumps

An important research challenge has been the pumpability of the wet biomass slurry needed for HTL (HS3, HS4, HS6). Respondent HS4 explains that the pumps have improved significantly during the last 40 years and therefore pumping is more efficient compared to the 1970s. Despite that the pumping has improved, there are still challenges because pumping happens at high temperatures. Respondent HS3 therefore holds the opinion that making pumping more efficient is still a research challenge that needs to be addressed. This is in line with Elliott et al. (2015) who describe that reducing the risk associated with the pumps is needed.

Process conditions within HTL units

The process conditions that have been researched, focus on the effect of process temperature and the residence time of biomass in the reactor (Behrendt et al., 2008; Toor et al., 2011; Xiu & Shahbazi, 2012). Respondents HS1, HI1 and HI2 believe that there is a consensus regarding process conditions of HTL. Respondent HI2 states that ''the operating conditions, in terms of temperature, time and pressure, have been figured out''. This consensus is in contrast with the literature, in which is described that despite the research that has been performed, there is still a low level of scientific understanding of the chemical and physical processes involved (Behrendt et al., 2008; Xiu & Shahbazi, 2012). Hence, one might argue whether the process conditions are really set.

Catalyst use in HTL unit

Research on the effects of different catalysts and the concentration of catalysts has also been performed (Behrendt et al., 2008; Toor et al., 2011; Xiu & Shahbazi, 2012). Respondent HI2 says that it is still an open question whether the use of catalysts is beneficial. Respondents HS4 and HS5 have a stronger opinion and do not see a future in the use of catalysts in the HTL unit. The stability of the catalyst when using biomass (HS4) and the process conditions (HS5) are subjects of concern. They would rather see separate processes which allow for more control on the catalysts, than putting everything in one pot. There seems to be a consensus that the use of catalysts within the HTL unit is not preferred, however, the use of catalysts outside the HTL unit could be an option and needs further research.

Scale

Both industrialists (HI1, HI2) admit that the process of the technology is well understood on a small scale, but that the scale-up to larger scale is uncertain. This is in line with a respondent HS5 who says that there is not enough control of the technology to enable further scale-up. The high pressure and high temperature of HTL make the biomass material stick to the walls of the reactor, hence reducing the diameter of the reactor which influences the needed residence time of the rest of the biomass in the reactor (HS4). A solution for this challenge is yet to be found. Besides the specific scale-up challenges, also the research challenges of pumpability and heat transfer, are not yet properly addressed to a point that the technology is ready to scale-up (HS4, HS5). Hence, there are still technological challenges that need to be researched, before scaling up to bigger plants would be a viable and reliable option.

Overview of current technological challenges

A consensus towards the PFR reactor is starting to arise, and the reactor itself is therefore not considered to be a major research challenge. The process conditions are, according to the respondents, set, but the literature suggests otherwise. A possible explanation could be that the process conditions are understood on a small scale when no catalysts are used, as scaling-up and catalyst use poses problems regarding the process conditions. The following research challenges are identified:

- The currently inefficient heat transfer within the PFR reactor to the biomass
- The pumpability of the biomass slurry to the reactor
- The use of catalysts is questioned as it poses several problems: 1) the stability of the catalysts are an issue, 2) the process conditions when using catalysts are uncertain, 3) the question whether the catalysts should be used inside or outside the reactor may be questioned
- The scale-up of the technology, as the biomass material sticks to the walls of the reactor and the technology can currently not control this issue

5.1.5 Current state of the art of upgrading

Upgrading unit and process conditions

Research regarding upgrading focuses on transforming the bio-oil chemically into products that looks more like petroleum hydrocarbons by reducing the oxygen content and elevating the H/C ratio (Bridgwater, 2011; Elliott, 2007; IEA Bioenergy, 2014). Most research has focused on upgrading FP bio-oil, but due to the similarity of the oils, this research is also valid for HTL (Ramirez et al., 2015). There are three major routes to upgrade fuels: catalytic cracking, high pressure thermal treatment and hydrotreatment (Reyhanitash, 2013), of which hydrotreating and catalytic cracking are seen as the most important ones (IEA Bioenergy, 2014).

The current process development efforts focus for the most part on hydrotreatment (Elliott, 2013). Hydrotreatment/hydrodeoxygeneration (HDO) rejects oxygen as H20 by a two-stage catalytic reaction with hydrogen (Bridgwater, 2012; Elliott & Baker, 1983). Respondent PS7 states that this is currently the best option for deoxygenation of the bio-oil to produce transportation fuels. The respondent does see disadvantages as 1)

The process is very expensive because of the hydrogen requirement, which also has a large impact on the emission life cycle if hydrogen is produced from natural gas, and 2) The catalysts tend to deactivate really rapidly. Respondents PS1, PS4, HS1 and HI2 agree that the current HDO process is way too costly and also IEA Bioenergy (2014) states that the costs of HDO are so prohibitive that their use in industrial application may be very limited. Respondent PS2 therefore has noticed that major players, like UOP/Ensyn, appear to have given up on the HDO process. The respondent underlines that nothing has been said officially, but they appear to have stopped the development work on that.

Catalytic cracking/catalytic decarboxylation (DCO) of bio-oil is inspired by Fluid Catalytic Crackers (FCCs) of the petroleum industry (IEA Bioenergy, 2014; Reyhanitash, 2013). The process is performed without the requirement of hydrogen, and rejects oxygen as CO2 (Bridgwater, 2012). A disadvantage of catalytic cracking is the excessive char formation which results in a low liquid yields and catalyst deactivation (De Miguel Mercader et al., 2011). The resulting liquid product is generally viscous and contains more aromatics (Butler et al., 2011; NREL, 2006). These aromatics, such as benzene, xylene and toluene, are very valuable for the chemical industry.

An additional challenge for algae derived HTL bio-oil is the nitrogen content of the oil (HS2, HS4, HS6). Therefore, more specific research on removing this undesired content by means of catalysts need to be conducted.

Scale

Upgrading experiments are mainly performed in laboratories (NREL, 2011). Experience with larger scale upgrading is limited to modelling the small scale experiments to larger scale experiments, instead of actually performing them (Elliott, 2007). Although this statement was already done in 2007, it still seems a valid statement. In 2011, NREL (2011) described that the scale-up would be a big challenge and much research needs to be done regarding this topic. UOP/Ensyn were involved in the development and scale-up of HDO, but again they appear to have stopped the development work on that. In conclusion, there has been very limited experience with the scaling-up the upgrading technology.

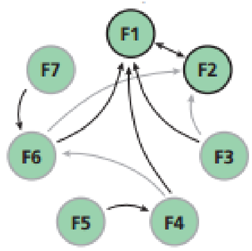
Overview of current technological challenges

Eleven out of the sixteen respondents indicated that upgrading is a topic that needs more research. The specific challenges that need to be overcome are:

- The catalysts used during the upgrading process
- The most cost-effective concentration of hydrogen when applying HDO
- The char formation when applying DCO
- The scale of current upgrading technologies is very limited, and information regarding the scale-up is lacking

5.2 Socio-technical environment and current barriers

Section 5.1 identified that the shared vision to find an alternative for crude oil is the basis of FP and HTL. It may therefore be concluded that the starting point of the new technological innovation system was the 'guidance of the search' function. This lead to resource mobilisation which allowed for the 'knowledge development' of the technologies. This indeed agrees with the starting point and pre-development phase elaborated on in the theory section. In the methodology, it is determined that FP and HTL are currently in the demonstration phase. According to Hekkert et al. (2011), in this phase of the technological innovation system all seven functions are deemed to be important to establish a system in which the technology will be able to further develop.



Function 1: Entrepreneurial experimentation and production

Existence of new entrants

The market-oriented experiments are mostly performed by small companies or university spin-offs (PI1, PI1, PI3). The amount of new entrants in both technologies is however low (PI3, HS4, HS5, HS6). Respondent HI2 explains that building a plant requires high investment costs, which are hard for small companies to acquire. Moreover, the technological problems during scale-up (HS6, HI1, HS5) causes uncertainty (HI1) which hampers new entrants. This is in line with literature, which states that problems during the scale-up causes further development to hamper (Toor et al., 2011). The reliability of potential commercial technologies therefore remains unknown (Xiu & Shahbazi, 2012), which make new entrants reluctant to this shaky business opportunity technology (PI1).

Existence of diversification activities of incumbents

The respondents indicate that the involvement of current oil incumbents is limited. The only oil producing incumbent that was involved in the development of HTL was Shell (López Barreiro et al., 2013; PS4). This incumbent, however, is currently not performing any activities regarding HTL anymore. There are large oil incumbents (e.g. Shell and BP) that occasionally invest in consortia (PS4; PS5). The respondents assume that the incumbents invest because of the opportunity to assess the state of the art of the technologies. Respondents PC3 and PI1 expect that if the technology becomes interesting due to government intervention, public opinion or technological improvements, the oil incumbents will acquire the current small companies involved in the technology. At this moment, there are however no indications that the large oil incumbents are actively diversifying their activities towards FP or HTL.

Existence of large scale experimentation

The experiments on larger scale have just started. FP respondents agree that there are currently three companies that are running demonstration plants on a larger scale (PS5; PI3). Those companies are the EMPYRO project of BTG in The Netherlands (5 tonnes/hour input), the Fortum plant in Finland (10 tonnes/hour) and Ensyn from Canada (3.5 tonnes/hour). This is in line with Ernstig (2015), who identified those three plants as the three largest scale plants running. The HTL technology is currently also implemented in some larger scale plants. Examples are Steeper Energy (60 liter/day), Altaca Energy and Licella which state they have a demonstration plant (Altaca Energy, 2015; Licella, 2015; Steeper Energy, 2015). These projects show that experiments with larger scale plants are practically possible.

Again, because of capital challenges (HI2) and scale-up challenges (HS4; HS5; HS6; HI1), the number of large scale experimentation is limited. This is in line with Girio et al. (2013) who state that a main barrier of the FP technology is the lack of industrial experience. Respondents from the science field as well as the industrial field (PS4, PS5, PI3) do believe that when the above mentioned large scale projects prove to be successful, the credibility of the technology could be restored. Moreover, respondent PS4 and PI2 say that these, although limited, large scale experiments may provide further input for research development to overcome the scale-up challenges. Hence, a limited amount of large scale experimentation exists, but their successfulness will be crucial to restore credibility of these technologies in the future and currently provide the necessary inputs for further R&D regarding the scale-up of the technologies.

Conclusion: drivers, barriers and interactions

Drivers

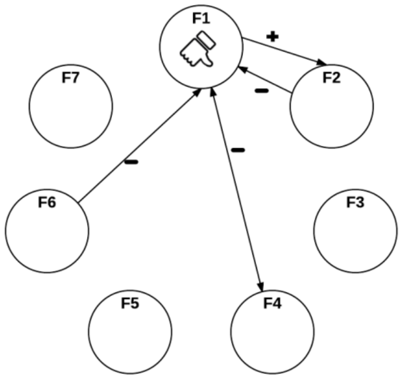
- There large currently some small companies that have developed the technology and reached the demonstration phase.

Barriers

- The new entrants are mainly small companies and university spin-offs, however there is a limited amount of new entrants.
- Amount of large scale experimentation is limited, whereby the industrial experience is lacking.
- Large incumbents are not actively diversifying their activities.

Interactions

- The two-fold negative interaction with guidance of the search (F2): entrepreneurial failures have led to a damaged credibility, which causes reluctance to other entrepreneurs to enter.
- The negative interaction from resource mobilisation (F6): the capital costs needed to build a plant are hard to acquire for the small companies.
- The negative interaction from knowledge development (F2): technological challenges which are not solved during R&D are hampering entrepreneurs to enter the market.
- The positive interaction to knowledge development (F2): the three large-scale plants may provide input for the R&D process to overcome scale-up challenges.



Function 2: Knowledge development

Amount of knowledge development

''Fast pyrolysis has been a great boom for universities, because they can test pyrolysis and write a paper about it'' (PI3). A scientist (PS5) indeed agrees, and indicates that many laboratories have been working on fast pyrolysis. The reason being that the technology is easy to handle in the lab (Mørup et al., 2015). A wealth of information is therefore available. Ramirez et al (2015) and Midgett (2008) agree that FP and HTL have been widely researched to produce oils from biomass. The amount of research on the conversion from biomass to oil is thus extensive.

Quality of knowledge development

The quality of the research performed is however questionable as ''the researchers never get out of the lab'' (PI3). A lot of FP and HTL respondents (PS2, PS5, PS6, PC5, HS2, HS3, HS4, HS5) agree that laboratories are great for understanding fundamentals, testing materials and looking for effects of process conditions, but you can get away with a lot of things when performing R&D on a small laboratory scale. When it comes to real larger units, the technology is more difficult. Respondent HS4 therefore concludes ''the problem is that the results that you can find in the literature are not always valuable''. Xiu & Shahbazi (2012) agrees that most HTL research has been performed using batch reactors.

Respondent PI4 elaborates more on this topic, by indicating that institutes and universities have been working on FP and HTL on a small scale for so long, that they are doing the same tests over and over again while it is already known what works and what does not work. Respondents PS2, HS6 and HI2 indeed agree that past work is not considered or forgotten in the rush to perform new research. ''Universities and institutes are reinventing the wheel'' (PS2). This observation is in line with the literature, as Bridgwater (2012) and Bioenergy Technologies Office (2014) describe that much reinvention is done.

Fit knowledge development with knowledge needs

Part 1 of this study identified that upgrading and the use of catalysts should be an important R&D topic. FP as well as HTL respondents think that these topics are not yet properly addressed, as the small scale experiments do not produce a similar quality bio-oil which makes it hard to consistently research the upgrading process (PC5, HS2, HS5, HS6). As a result, most upgrading research has been based on model as opposed to real bio-oils (Butler et al., 2011).

Most research is performed at universities and institutes by scientists instead of engineers (HI2). These non-engineers are unable to address the current need to make the process more cost-efficient (HI1, HI2). As a result, ''there are a lot of systems that have been developed, but they are way too expensive'' (HI2). The respondent, who did a PhD on HTL before working at a company, adds that the people working at universities or institutes are not worried about the price but are concerned about their grants. The respondent continues by stating that a good research project, does not necessarily translate well into a practical business. Respondent HS3 agrees and says that limited work has been done on making the process more cost efficient.

The lack of focus on cost-effectiveness is not mentioned by the FP respondents. This may be explained because the costs of FP are currently lower compared to the costs of HTL (PS4, HS5). As a result, HTL respondents may be more urged to make the technology more cost-effective, and therefore it is more striking that this issue is not addressed. The observation could, however, also be applicable to FP, as FP research is also performed on universities and institutes by non-engineers who tend to reinvent the wheel. Hence, there might be a possibility that the cost-effectiveness of FP is not properly addressed as well.

Conclusion

Drivers

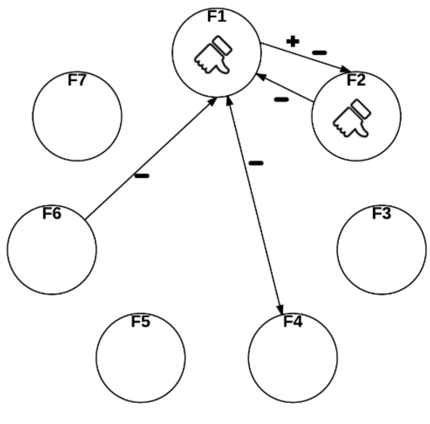
- The amount of research regarding the conversion from biomass to oil is extensive.

Barriers

- The large amount of research is based on small scale experiments, which may limit the usefulness of the results in larger scale plants.
- Reinvention of this small scale research limits the amount of research that is needed in the field of scale-up, upgrading and catalysts.
- Lack of focus on cost-effectiveness by scientists.

Interactions

- The negative interaction from entrepreneurial activities (F1): the limited amount of large scale plants limits the availability of a constant quality produced oil which is needed for research regarding upgrading.
- The negative interaction to entrepreneurial activities (F1): the lack of R&D focused on making the technologies more cost-effective, make the technologies harder to 'leave the lab' and become industrialized.



Function 3: Knowledge diffusion

Knowledge exchange between scientists

The work that is being done by national labs and universities is published, therefore the results of the performed work are well shared (PS7; HS6). Respondent PS3 adds that there are a lot of opportunities to share knowledge, for example in newsletters (Pyne), forums (Pyro) or conferences. These opportunities include FP as well as HTL. The extent to which useful knowledge is shared may be a bit less straightforward. Some research groups use the opportunity to share knowledge as a way to show off over optimistic results in order to gain extra research funding, instead of sharing to enable other research groups to build further on their knowledge (PS6). This might indicate that, as theory described, knowledge depreciation occurs as some knowledge seems to get lost instead of accumulated.

Respondent PS6 indicates that there are also different research groups that focus on their own projects and tend to keep their knowledge to themselves. In his view, it would be more beneficial when several research groups would work together to address technological challenges. This observation is confirmed by FP and HTL literature. Bioenergy Technologies Office (2014) describes that specialized problems are weekly linked to each other. Behrendt et al. (2008) and Toor et al. (2011) indeed identified a lack of cooperation of research activities. The reluctance of research groups to collaborate might hamper the collective learning effects.

Knowledge exchange between industrial players

Respondents being scientists, consultants and also industrial players state that also companies working with FP and HTL try to keep their technology in-house in order to face competition (PS4, PS7, PC5, PI3, PI4, HS4). The best results are therefore being reported by firms using unknown catalysts (PS4, PS7, PC2). This secrecy in technology may hinder the development of the catalysts which are needed to be further developed. On the other hand, respondent PC2 indicates that also companies tend to overestimate their performances in order to gain funding for their company. It is therefore an option that companies using unknown catalysts are not really outperforming public research. There are a few industrial players that have scaled up their technology (see entrepreneurial activities), and respondent PS5 thinks that we can learn a lot from those scaled-up processes. The question is, however, whether this information will be shared.

A well-known collaboration between industrial players is the one between UOP/Honeywell and Ensyn, who together collaborate under the name Envergent. UOP/Honeywell is a multi-national company specialized in process technology and equipment design (Envergent, 2016). Ensyn is an expert on the FP technology. The website states that '' Envergent Technologies brings together two experienced, recognized leaders in their respective fields''. This might indicate that industrial players dare to collaborate and share knowledge, when both industrial players are not directly involved in the same industry as this might reduce the risk of unwanted knowledge spillovers to direct competitors. Direct imitation, learning-by-imitation, which might endanger a company's own position might thereby be avoided.

A great understanding among the respondents is established regarding learning-by-failing. The researcher of this study did not ask any questions about Kior, a very promising industrial player that recently went bankrupt, but all 7 scientists, 2 of the 5 consultants and 1 industrialist active in the FP mentioned the Kior case. These respondents mention the technological issues like char forming and catalysts that Kior was struggling with, issues like changing feedstock prices and an abandoning off taker which changed their economics, and the too quick scale-up without having enough experience on an intermediate scale as reasons for their bankruptcy. This indicates that people currently working with FP are very aware of the failures of Kior, and try to take these into account in order to avoid the same mistakes. Also a HTL respondent, HS5, relates to the Kior bankruptcy, and indicates that HTL can learn from the Kior failures as well.

Knowledge exchange between scientists and industry

Half of the FP industrial respondents (PI2, PI3) admit that knowledge sharing between universities/institutes and companies is lacking as well. This observation is in line with an article of the Bioenergy Technologies Office (2014). The article states that laboratories seem to have a good understanding of the fundamentals, but are not innovative in advancing the commercial state. The industry projects are commercially innovative, but not strong in the fundamentals. The industry is not likely to work with laboratories as the accompanied costs form a barrier.

On the other hand, there have been several consortia bringing together universities, institutes and industrial players (Elliott, 2015; Toor et al., 2011). Examples are the EMPYRO consortium in The Netherlands and the Metso-Fortum-UPM-VTT consortium in Finland. It is notable that these consortia mainly consist of players specialized in different kinds of knowledge. The Metso-Fortum-UPM-VTT consortium consists of a biomass expert (UPM), pyrolysis reactor developer (Metso), expert on derived oil-quality (VTT) and end-user (Fortum) (Fortum, 2009). The EMPYRO consortium consist of a biomass supplier (BKR), biomass drying and storage expert (KAHL), modeller of the process (RRC), engineering party (Stork), steam design system expert (HoSt), research entity regarding the plant performance (BTG), FP plant implementer and exploiter (EMPYRO BV), oil recovery expert (BTG-BTL) and end-user of the surplus heat (AkzoNobel) (EMPYRO, 2016b). Hence, additional bodies of knowledge are brought together.

Conclusion

Drivers

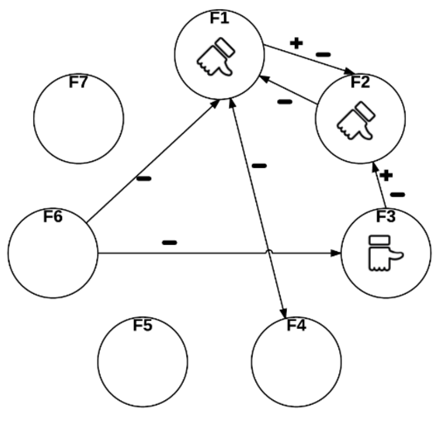
- There are a lot of opportunities for scientists to share their knowledge with other scientists.
- Learning-by-failing by means of the Kior case is very well taken up by people active in the industry and they are aware of the failures and tend to avoid them.
- Industrial collaborations based on additional bodies of knowledge are taking place.
- Consortia in which academics and industrial partners are brought together are taking place with additional bodies of knowledge.

Barriers

- The extent of knowledge sharing among scientists may be limited due to overestimation.
- Different research groups are reluctant to work together on a specific technological issue and there is a lack of coordination between the different research groups.
- There is a reluctance of companies to share their insights, instead overestimation of their results occur.
- Direct collaboration between universities and industrial players is limited.

Interactions

- Positive as well as negative interaction to knowledge development (F2): the knowledge development is stimulated by research on overcoming the technological challenges identified in the Kior case and collaborations based on additional bodies of knowledge might lead to new insights, but specific technological issues are not addressed due to reluctance of working together and a lack of coordination
- Negative interaction from resource mobilisation (F6): the competition for funding grants lead to an overestimation of results and a reluctance to work together on specific technological issues



Function 4: Guidance of the search

Clear vision development industry (belief in growth potential)

Respondent PS4 believes that the COP 21 in Paris has exposed the widely accepted awareness that the unlimited use of fossil fuels is not an option any more, and this awareness is an important driver to shift towards more sustainable options. Products produced by FP and HTL offer sustainability advantages over crude oil substitute products (PS4, PS6, PC2, PC3, PC4, PC5, PI1, PI2, PI3, HS1, HS2, HS3). Biomass is seen as the only form as sustainable carbon, as other technologies, e.g. wind and solar energy, will never be able to replace some necessary carbon products like chemicals and jet fuel (PS4; PI2).

Besides the climate advantages, additional advantages over oil are the security of supply and a possible reduction of price volatility. The industry therefore tends to give more attention to FP and HTL when the oil price is high (HS1, HS4, HS6). A historical example is that the oil crisis in the 1970s created a boom for FP and HTL (Elliott, 2007; IEA Bioenergy, 2014; Toor et al., 2011). In the 1980s, when the oil prices dropped, the interest in the technologies reduced. The reason for that is that the market will always prefer the cheapest option. Currently, the oil prices are low, which reduces the urgency to further develop alternative oil technologies like FP and HTL. With the current oil prices, products derived by FP and HTL are namely higher priced than fossil fuel products which reduces the market attractiveness of the products (all FP respondents, HS1, HS2).

FP and HTL use second and third generation biomass, which offer advantages over the first generation biomass. The first generation biomass, food crops, triggered the food versus fuel discussion which reduced the public acceptance of biomass derived products. The second generation biomass does not directly compete with food (PS4, HI1). Notion is that the discussion regarding land use may still be valid (PS2). This is in line with Cortez et al. (2015) who argue that the main argument against second generation fuels is based on land availability and the protection of global ecosystems. Although algae can make use of unproductive land (Bioenergy Technologies Office, 2015a), water use concerns have been expressed (HI2). Hence, there are still important considerations which should be addressed. A study that compared several studies regarding acceptance regarding bioenergy, states that the public perception regarding bioenergy is still lower as compared to other renewable sources (Halder et al., 2015). The use of the biomass to produce products based on non-food crops is expected to become more accepted, however, currently biomass technologies still tend to have a negative reputation.

Clear vision technological design

There are several technological options to process second generation biomass and those technologies are in competition with each other (PS1, PC5). The race of those biomass processing technologies is expected to be determined by economic and technological factors, i.e. the quality and price of products that can be delivered (PS1)

In the past FP and HTL technologies used lignocellulosic material as a feedstock, and both technologies were therefore in direct competition. In that time, some research projects regarding HTL were stopped due to the better prospects of FP (Behrendt et al., 2008). At this moment the respondents do not see the direct competition as a consensus occurred that the choice of technology depends on the feedstock moisture content. Lignocellulosic material, a relatively dry material, is the preferred feedstock for pyrolysis (PS5, PS6, PS7, HS6, HI2). Respondents PS6 and PS7 add that whenever drying can be done economically, FP is preferred over HTL as FP can be performed at normal pressure which is a cheaper process (HS1). However, when feedstock is wet and the water removal prior to processing is expensive, HTL may be preferred (PS7). The wet biomass can be easily grinded and pumped to create a slurry necessary for HTL (PS5). Hence, when the feedstock is wet, HTL is the preferred technology (PS5, PS6, HS5, HS6, HI2).

There is thus limited competition between FP and HTL, however those technologies are competing with other second generation technologies. The competing technology for HTL is biogas production which also takes wet feedstock (HS5). There is also a trade-off between FP and gasification, and both technologies do not necessarily outshine the other (PS7). Moreover, the literature suggests that biochemical conversion technologies may also be seen as competing technologies. Whereas biochemical conversion technologies first used sugars that triggered the food versus fuel discussions, increasing attention is given on using lignocellulosic material for biochemical technologies (Guo et al., 2015; Limayem & Ricke, 2012). Potential products entail chemicals and fuels, such as renewable gasoline, ethanol and renewable diesel (Bioenergy Technologies Office, 2013) Hence, FP and HTL face competition of biochemical conversion technologies as well.

Worthwhile noting is that FP currently seems to suffer from a negative reputation. Respondent PI3 says: ''when you talk about pyrolysis, people say: oh I have heard that story for 30 years and you are still no further ahead''. Two FP scientists (PS3, PS6) agree and state that this negative reputation is mainly caused by failed companies in the past that were not able to deliver the promised results (e.g. Dynamotive and Kior). The scientists add that there are still a lot of overestimations being published (see knowledge development and diffusion), which may not stimulate the reputational recovery of FP. On the other hand, the reputational recovery of FP may be enhanced by the recently built large-scale demonstration plants may enhance the reputational recovery of FP (PS3, PS4, PS5, PI1, PI3). The proof that bio-oil can be produced on a constant basis may, 1) Accelerate the upgrading process to also bring this bio-oil to higher value products and 2). Stimulate more companies to join the industry. Respondents active in HTL indicate that the same holds for their technology (HS1, HS5).

Clear and reliable policy goals

Debate about potential environmental and societal impacts of using food crops for energy production has led to the interest of governments in biofuels produced from non-food feedstocks (Center for climate and energy solutions, 2010). As a result, in the United States policies that offer subsidies or tax credits for non-food based fuel production and/or use has been established (Center for climate and energy solutions, 2010). Respondent PC5 states that the EU has introduced a maximum of food-based biofuels, and an alternative goal for non-food based biofuels will be introduced. Indeed, the European Commission has set a goal of limiting the share of biofuels from crops grown on agricultural land, and has set a target for advanced biofuels (European Commission, 2016). Hence, governments notice the potential for second-generation biofuels, in which FP and HTL may play a role.

Respondents tend to say that the market stimulation of governments seem to focus more on cheap and established second-generation technologies though (respondent HS3). Governments are currently promoting the incineration of second-generation biomass for heating and electricity purposes (PI1, HS3). (Co-)firing biomasss for heating and electricity purposes is indeed available and very efficient (Creutzig et al., 2015; Guo et al., 2015). Burning biomass stimulated by policy has caused the price for woody feedstocks to rise enormously, resulting in a less favourable business case for FP (PC2, PC5, PI2). Consultant PC2 even states that this was one of the – not the only one – reasons that Kior struggled with their economics. They expected to have a relatively cheap feedstock as pine trees were widely available in Mississippi, but due to UK policy most of those trees were chipped, palletized and shipped to the UK driving up the prices for Kior. The respondents see current second-generation policy therefore as an impediment for their business case to enter the market.

The focus on biomass incineration by politicians may be explained by the lack of knowledge regarding second-generation biomass technologies. Respondents state that politicians are familiar with the combustion technology, but are mostly unaware of new and more advanced technologies like FP and HTL (PS1, PS5, PI2, HS3). Respondents PS5 and HS3 say that they have talked to politicians about their technology, but they state it is hard to transfer the message to politicians that often do not have a technological background.

Industrial respondents from North America indicate that the policies that do exist are non-reliable (PI3, HI2). They state that the vision of the government might change dramatically after elections, as not all political parties have a vision of giving priority to climate change and environmental issues. European industrialists have not mentioned this. Respondent PI2 even disagrees and in the experience of this respondent, policy is reliable. Hence, European policy seems to be stable, but policy in North America may change depending on the elections.

Conclusion

Drivers

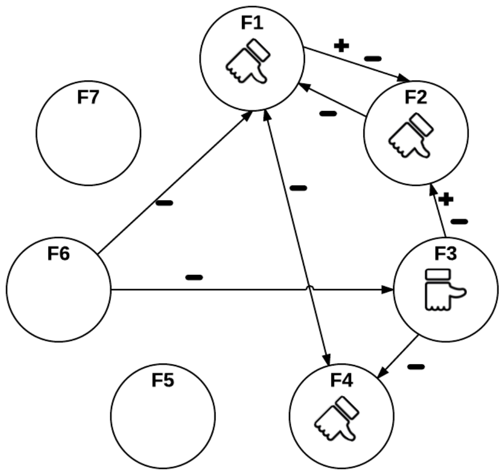
- The industry sees potential for FP and HTL as these technologies use feedstock that offers sustainability advantages, and these feedstocks do not compete with food.
- Governments are aware of the need to stimulate at least second-generation biomass.

Barriers

- Although the second and third generation biomass offer advantages over the first generation of biomass, biomass technologies are still not completely accepted by the public.
- FP and HTL are not the only options for the use of at least second-generation biomass, and competition with other technologies occurs.
- FP and HTL suffer from a negative reputation, and although this might change when the three large scale plants prove to be successful, currently this is a barrier.
- Governments currently stimulate incineration of biomass, due to unfamiliarity with advanced technologies. Incineration is a relatively simple and cheap technology, easy for the politicians to understand, and the market that always focuses on costs might be more willing to accept the incineration.

Interactions

- A negative interaction from knowledge diffusion (F3): due to a lack of knowledge diffusion towards politicians, politicians are unfamiliar with FP and HTL which causes that the current market policy is not enough in favour of FP and HTL.



Function 5: Market formation

Sufficient current market size

The bio-oil produced by the three larger scale FP plants are currently used for heating and electricity purposes (PS5, PI1). Finding off takers for FP oil is hard, but entrepreneurs are working really hard to find those off takers (PI1, PI3). Some respondents think that heating and electricity are indeed a favourable market as more and more countries tend to refuse coals as a source for those purposes and because higher order fuels are hard to produce (PS3, PS5, PS7, PI3). The current bio-oil is also ready for the use of heating and electricity purposes, as bio-oil standards for these purposes have been established (PS5, PS7, PI3). This is in line with the literature, which suggests that a set of standards has recently been approved by ASTM[20] (IEA Bioenergy, 2014). These standards qualify pyrolysis oils as burner fuels and they provide benchmark-type minimum requirements upon which applications and trading of bio-oils can be based. Further standardization efforts regarding heating and electricity purposes have been performed by the EU CEN (European Commission, 2013). These standards will ensure better similarities between bio-oil, which is necessary to overcome market challenges. For HTL, standards are an area

[20] ASTM International is one of the largest voluntary standards developing organizations in the world. The organisation is a not-for-profit organization that provides a forum for the development and publication of international voluntary consensus standards for materials, products, systems and services. The organisation develops technical documents that are the basis of manufacturing, management, procurement, codes and regulations for dozens of industry sectors, among others for the oil industry (ASTM, 2016).

where more work is needed (HI1, HI2). There is also no indication that current biocrude derived by HTL is being used as heating and electricity fuels.

Some respondents are less in favour of the heating and electricity purposes. Those respondents notice that heat and power are more widely available and other forms of producing heat and electricity might be cheaper. According to those respondents, it makes more sense to use biomass as a valuable sustainable carbon source (PS2, PS4, PS6, PC5, HI1). The heating and electricity is currently however the only option due to a lack of economic applications, and the knowledge gap regarding upgrading to higher value products (IEA Bioenergy, 2014; Venderbosch & Prins, 2010). Therefore, at the moment, the bio-oil should be used to substitute fossil fuels in heat and power production as a temporary market to gain experience and to be able to further develop the upgrading process which can then be used to produce higher value products in the future (PS3, PS4 PI1, PI4).

Sufficient future market size

The higher value markets are seen as potentially attractive markets for both FP and HTL. There are however some respondents (HS2, HS6) who think the market formation may be influenced by the feedstock being used. Lignocellulosic material, processed by FP, contains a lot of chemicals and aromatic compounds. On the other hand, when using algae for HTL, the transportation market is a more logical choice.
There are two possibilities of producing chemicals. The first one is creating new chemical building blocks (PS4, PI2). These new building blocks may have new properties and new applications, which cannot be derived out of crude oil. The disadvantage of this approach is that there is no existing market yet (PI2). The second opportunity is producing chemical building blocks that have the same properties as the existing chemicals. Respondents PS3, PS5, PC1 and PI2 believe that the chemical market would be a good application to make use of the aromatic compound of bio-oil. This is in line with the literature, that states that the production of chemicals would be a very interesting market and may help to develop and enhance the economic viability of the upgrading (Butler et al., 2011; IEA Bioenergy, 2014; Venderbosch & Prins, 2010)

Currently there is a company, Red Arrow, active in the chemical market which serves primarily chemicals for the use in the food industry. The company has existed for several decades and is successful, however the market is quite small so the company has saturated the whole market (PS6). Annellotech and Bio-BTX, both FP, are both aiming to enter the BTX market and they show promising results of a cost competitive price when the oil price is 45-65 dollars/barrel. Licella uses HTL to produce a range of biochemicals, and they also claim to have promising results. It needs to be noted that these prospects look promising, but it is not yet proven on a large scale.

Transportation fuels may be used in several transportation sectors, such as ships, trucks and buses (Elliott, 2007). In the United States, the army may create an initial niche market for the transportation market. The army, which is one of the largest single users of transportation fuels in the United States, is looking at alternative fuels that are not subject to price and supply volatility (PS6, PC2). People from the United States air force were also involved in the Kior project. This shows that the army might be an interesting niche market to gain experience.

The marine sector would be an interesting transportation market, according to respondent PS4 and PC4. This sector has to deal with harbour emission guidelines and has less stringent rules regarding the specifications of the fuels. Respondent PS4 adds that the market is also willing to accept the fuel, as Maersk has signed a memorandum of understanding with Progression Industry – a university spin-off – to buy 50.000 tonnes of fuel if Progression Industry is able to develop the fuel. Moreover, the same respondent adds that the specification of marine fuel is less stringent than for other transportation fuels, and thus might be easier to reach.

The respondents hold different opinions as to whether the aviation market would be favourable. Respondent PI2 sees potential, as this type of transport is not expected to be electrified soon. This respondent actually targets the chemical market, but sees opportunities for using the residue bio-oil for RJF purposes. Respondents PS2, PS7 and PC3 see the stringent specifications for RJF as a barrier. The airlines have said to be more than willing to use the fuel, however they will not be willing to pay extra for the fuel (PI3). This market may thus be attractive, although not the easiest to each.

The respondents indicate that more work needs to be done regarding standards to be able to reach the above described higher value markets. These more elaborated standards are needed to create a wider application for bio-oil (PS4, PS5, PI3).

Conclusion

Drivers

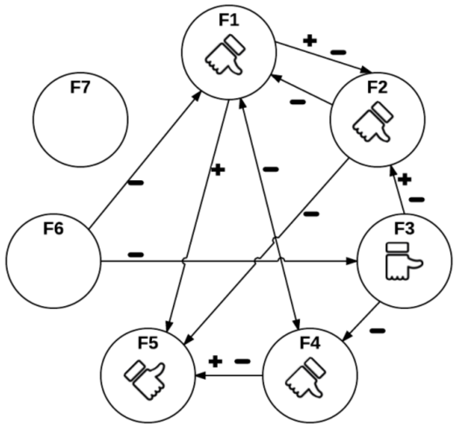
- Creation of the (temporary) market of heating and electricity, which is hard to reach but proven that it can be done.
- Standard for the heat and electricity markets are established.
- Future market is very large and the industry is experimenting to reach those markets.

Barriers

- Standards will need to be established to be able to enter future markets.
- The derived products of FP and HTL are not cost-competitive with current fossil fuels.

Interactions

- Positive interaction from entrepreneurial activities (F1): entrepreneurs that are currently producing some bio-oil are actively involved in finding off takers and creating a market.
- Positive as well as negative interaction from guidance of the search (F4): the possible advantages of less volatile oil prices and supply give rise to the military niche market, but the unawareness of politicians leads to that the market is currently not enough stimulated by governmental incentives.
- Negative interaction from knowledge development (F2): the immaturity of the upgrading technology leads to the inability to reach higher value markets.



Function 6: Resource mobilisation

Sufficient human resources

The amount of people skilled in FP and HTL is not abundant (PS5, PI3, HS6). Respondent PI3 elaborates by saying that FP went through a real drop in popularity in the 1990s-2000s. As a result, according to this respondent, ''we miss a generation of scientists and engineers who are skilled to move things forward''. The respondents do imply that this shortage of skilled people is changing the other way around, as more people start to become active in the industry. At this moment however, the amount of human resources may not be seen as sufficient.

Sufficient financial resources

Respondents from all regions suggest that public funding is available (PS3, PS5, PS6, PI3). This public funding on FP and HTL is mostly directed towards research and development projects on the technologies itself, and the upgrading part (Bioenergy Technologies Office, 2014; Breakthrough Institute, 2011; Bridgwater & Peacocke, 2000; Elliott, 2015; Meier et al., 2013; NREL, 2011; Qi et al., 2007). The dates of previous sources indicate that this public funding has been around for quite a while and is caused by the direction of the search towards alternative oil technologies. According to the literature, the funding does not focus on establishing larger scale projects. The respondents indicate that public funding is spent on research and development, but on subsidizing demonstration plants as well (PI2, PI3). The demonstration plants can be publicly subsidized up to 50% of the plants, according to a European as well as a Canadian respondent (PI2, PI3). However, 50% of the capital still need to be funded by private parties.

Private funding is partly done by current oil incumbents. As described in Function 1: Entrepreneurial experimentation and production, those incumbent companies tend to invest in research consortia to assess the start of the art of the technologies. There are however no indications that those companies invest in the smaller companies to establish a scaled-up plant. Therefore, FP and HTL companies rely on investors to gain the needed private funding (HS6). Investors are looking for quick returns on their investments (PC2, HS3, HI2). However, FP and HTL are not fully developed yet, which make it a risky and long-term investment for the investor (PS6, PC4, HS5, HI5). Hence, gaining private funding for demonstration projects is really hard (PI1, PI2, HS1, HS5, HS6). This gap in funding impedes the possible scaled-up projects. This in in line with the literature, in which is stated that there are problems with finding capital for the establishment of larger scale plants (Ramirez et al., 2015; Toor et al., 2011; Venderbosch & Prins, 2010).

Sufficient physical resources

The physical resources needed for FP and HTL, the biomass feedstock, differ per technology. Therefore, a distinction will be made between lignocellulosic (preferred for FP) and wet feedstock (preferred for HTL). Regarding lignocellulosic material, a consensus among the respondents is formed that a lot of wood based material is available in the Nordic European countries, the United States and Canada (PS4, PS7, PC2, PI3, PI4). The large forest dieback in the US (PS4) and the trend of using less trees by the paper and pulp industry (PC2) create additional opportunities for feedstock supply. However, the transport of those feedstocks may pose substantial challenges. Transporting lignocellulosic material means that, if not dried before transportation, 50% of water and 25% of oxygen is transported. Hence, a lot of non-carbon sources are transported as well, increasing the costs of transporting. This is in line with theory, which states that several challenges exist for the sourcing, transportation and utilization of biomass feedstock into bio-oil (IEA Bioenergy, 2014).

Moreover, in other parts of the world, the limited available land resources and the sustainability issue will form an issue regarding the feedstock supply (PS2, PC2, PC3). As a result, increasing international trade of woody biomass is occurring. This trade may pose several challenges to the advantages of bio-oil described in the introduction. First, there are several regions identified that are rely on the import of biomass as local availability is not abundant (Matzenberger et al., 2015). Hence, one might question the advantage of security of supply, when some regions are still dependent the import of feedstock. Secondly, as section 5.2 showed, the trade stimulates increasing prices and thus might disrupt the advantage of the more stable price level of bio-oil. Thirdly, the trade of biomass might reduce the sustainability of the value chain as the transport is emitting (Rosillo-Calle, 2016).

There is an interest for algae as a wet feedstock source for HTL. The growth of algae is however still a challenge (HS2), which is confirmed by the FP respondents PS1 and PS7 who indeed think that the large scale supply of algae might be real challenge. Respondent PS5 adds that, in comparison with the more distributed and available lignocellulosic material, algae are less distributed. The challenge of algae supply is the reason that one of the HTL industrialist currently uses lignocellulosic material as a feedstock. The respondent admits that algae would be a better feedstock, but in the absence of an indication that it will be available any time soon in large quantities, the company focuses on lignocellulosic material. Hence, the feedstock availability for HTL is a real barrier.

Conclusion

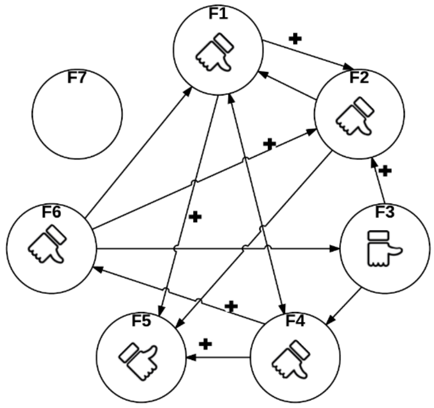
Drivers

- Public funding is available.

- Feedstocks are in some parts of the world available.

Barriers

- Shortage of FP and HTL skilled labour.
- Private funding is lacking, because FP and HTL projects do not create revenues on a short term.
- Feedstock is in some parts of the world not abundant, and transporting the feedstock causes challenges
- The increasing international trade of woody biomass may reduce the proposed advantages of FP and HTL



Interactions

- A positive as well as a negative interaction towards knowledge development (F2): public funding for FP and HTL R&D is available, but a shortage of skilled labour may be a hinder the development of new knowledge
- A positive interaction from guidance of the search (F4): the awareness that alternative oil technologies need to be developed, has led to the availability of public funding

Function 7: Creation of legitimacy

Resistance towards new technology

None of the respondents have indicated an active resistance against FP or HTL. The respondents did indicate that the incumbent regime has multiple advantages over FP and HTL. The established oil industry has a very efficient logistic system (PC4), is performed on a scale two magnitudes higher than current FP technologies (PS6, PC2) and currently is cheaper than FP and HTL products (all respondents). Moreover, current policy tends to enlarge the competition based on price in favour of crude oil products. Respondent PS2 states that the current crude oil price of 30 dollars/barrel is unreal and that a politic free crude oil price would cost around 100 dollars/barrel. Respondent PS4 agrees and mentions that fossil fuels are heavily subsidized, even more than biomass sources. In an industry where sustainability advantages are not offering a competitive advantage, as the market solely looks at the cheapest option, heavily subsidized fossil fuels make it very hard for bio-oil to enter.

The respondents give no indication that the current crude oil industry is actively thwarting FP or HTL, however, maybe for the reason being that the incumbents do not see an urgent threat of the technologies. The other reason might be that when FP and/or HTL will become interesting, the incumbents are likely to acquire the small companies which are currently involved in the technology (PC3, PI1). Therefore, the small companies developing FP and HTL will not be direct competition for the incumbent actors.

Conclusion

Drivers

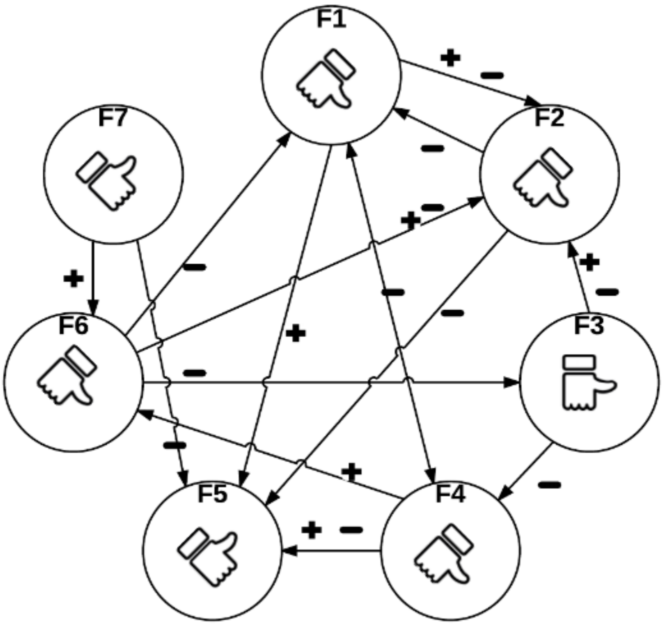
- No active resistance noted from the oil incumbents is identified.
- The oil incumbents do see FP and HTL as potentially interesting, and therefore assess the state-of-the-art of the technologies.

Barriers

- The subsidized incumbent oil industry has accumulated their experience and advantages towards very efficient processes.

Interactions

- Positive interaction to resource mobilisation (F6): incumbents invest in consortia to assess the state of the start of the technology, raising the financial resources
- Negative interaction to market formation (F5): the cheaper prized crude oil products may hinder the market development of FP and HTL products



5.3 Overcoming technological challenges and socio-technical barriers

5.3.1 Chances of overcoming current technological challenges

The main technological challenges, as identified in part 1, are catalysts for the use in the FP/HTL units, the upgrading process of both technologies and the scale-up of the technologies. Therefore, the structure of this section is as follows: first technological improvements regarding processes within the FP/HTL unit will be assessed, i.e. among others the use of catalysts. Hereafter, the technological improvements regarding upgrading are described. And lastly, proposed solution to the scale-up challenges will be addressed. The possible improvements for the technological challenges are based on the respondents.

FP/HTL unit challenges

Possible improvement 1: Process conditions

The process conditions of FP are, as described in the past development, set and well understood. There are therefore no technological challenges to be overcome, but there are some opportunities for cost reductions that are identified. Respondent PS7 indicates that slight changes in the process conditions, e.g. slightly elevated pressures, can cause cost reduction due to a reduction in CAPEX associated with vessel sizing. Respondent PS4 indicates that some slight pressure change may cause cost reductions as well.

Regarding HTL, research is being performed to slightly lower the pressure (HS6). Currently, very robust reactors built with expensive materials are needed because HTL is a high pressure system. A slightly lower pressure might reduce the CAPEX as a result of less expensive materials. There are also some efficiency improvements expected in the heat transfer (HS4, HI1). Respondent HI2 even elaborates that the respondent's company already has been able to partly optimize the heat transfer, indicating that indeed improvements are possible.

Catalysts challenges

Possible improvement 1: New catalysts

Respondents PS6 and PS7 give a timescale in which they expect catalysts will be available. Respondent PS6 says that in his lab an experiment on pilot scale with novel catalysts shows good results. The respondent therefore thinks that within 2-5 years this catalytic process will be available, although the respondent adds that the community has been saying that for the last 20 years. Respondent PS7 takes a more conservative view and says that it will take at least 5 years for improvement in catalysts before they will be implemented.

One may conclude that from the current state of not being able to effectively use catalysts, towards using catalysts within 5 years may be overestimated. Extensive and more research is needed on a small scale, as well as on intermediate scale to prevent that catalytic FP/HTL is scaled-up to fast like Kior did.

Upgrading challenges

Possible improvement 1: upgrading as a co-process in existing petroleum refineries

An alternative for upgrading bio-oil in plants specifically developed and erected to process bio-oil, is co-processing in existing petroleum infrastructure (PS4, PS7, HS3, HS5). This is potentially a very attractive way to convert bio-oil into end-products because:

- The derived products meet current standards, e.g. transportation fuels
- The capital costs for upgrading bio-oils are high, and co-processing would reduce those costs (IEA Bioenergy, 2014; Pacific Northwest National Laboratory, 2009; Radlein & Quignard, 2013).
- Co-processing allows for the reduction of needed facilities to produce hydrogen and thus hydrogen costs (HS5).
- The advantages of economy of scale and experience in a conventional refinery (Bridgwater, 2012).

The bio-oil insertion is most likely to occur at the refinery's hydroprocessing (hydrotreatment and hydrocracking) or fluid catalytic cracking reactors (FCCs) (IEA Bioenergy, 2014). FCCs can handle hydrotreated bio-oil up to 20% without the need of hydrogen, and results in lower value end products such as marine fuels. On the other hand, hydroprocessing requires more deoxygenated bio-oil (max 3-5% oxygen) and is designed to produce higher grade diesel and jet fuel. Prior to the insertion, a mild hydrotreatment step is thus still necessary. There are opportunities arising to upgrade refinery-ready intermediates in existing refineries (IEA Bioenergy, 2014). First, at least in the US, refinery utilization is expected to decrease over the next decade (Energy Information Administration, 2009). Secondly, it is projected that for the next decades refineries will be producing less gasoline and more diesel and jet fuels (IEA Bioenergy, 2014). This shift means that petroleum refineries will shift from FCC units towards hydrocracking units (Energy Information Administration, 2015). Those FCC units, which can handle quite an amount of bio-oil, may be used to co-process bio-oil to produce for example marine fuel.

According to PS4 and PI1, research regarding co-processing is performed. In Europe, a large consortium called Biocoup consisting out of universities, small companies and large oil incumbents is established to research co-processing. In the United States, Petrobras has established a partnership with institutes and other companies (UOP, Chevron Technologies and NREL (Ensyn, 2015)) to perform research regarding co-processing. Respondent PC2 thinks that a pilot can be undertaken in 5 years.

The refineries' view regarding co-processing is very important, as they may counteract to this change. Respondents see opportunities as well as bottlenecks here. Respondent PI4, currently working at a company that produces FP oil, states that refining companies have asked for FP oil as a feedstock for the refinery. This indicates that some refineries are interested, which might be explained by the renewable fuel standard in the US and the EU RED in Europe. These standards are introduced in Europe and the US by the government, where a certain percentage of the end product of transportation fuel should be biofuel (PI4, HI2). As there is money attached to this legislation, this might encourage refineries to accept the bio-oil.

There are also two bottlenecks for refineries in order for them to accept the bio-oil. First, respondent HI2 says that the respondent's company talked to a refinery about their view, and the refinery seems very scared of the oxygen and contaminants that may deactivate the catalysts. The oxygen in bio-oil can create catalytic coking in their pipes. Respondent PS4 agrees and states that the bio-oil should therefore indeed be deoxygenated to an extent that is acceptable for refineries. Secondly, the higher priced bio-oil as compared to crude oil forms a barrier, even when taking into account the money that is involved with the renewable fuel standard (PS1, PS4, HS5, HI2). Respondent PS1 puts forward the idea of convincing policy makers instead of refinery owners, as the policy makers can set a more stringent target or increase the money involved to the renewable fuel standard. Moreover, standards need to be developed in order to bring this option available (PS1).

Possible improvement 2: avoid upgrading to using bio-oil as an input for gasification

Two FP respondents state that FP prior to gasification is technically attractive (PS2, PS5), as gasification of an ash free liquid is much easier, efficient and reliable than gasification of solid biomass (PS2). Respondents PS2 and PS5 see potential for FP as an intermediate process, to produce energy-dense oils which can be fed to gasifiers to produce for example transportation fuels. The quality of the FP oil plays a less important role, whereby the bio-oil does need to be upgraded prior to the gasification. Moreover, because the quality of the bio-oil is less important, lower valued feedstocks can be used. This process in being performed on a pilot scale in Germany (bioliq process, PS5). Hence, according to the respondents PS2 and PS5, when more experience is gained, this option might be beneficial to produce fuels while avoiding upgrading. On the other hand, TKI-BBE (2015) identified that gasification has been in the valley of death for years. At this moment, it is already challenging to find funding for either FP, HTL or gasification, whereby finding funding for two emerging technologies at the same time would be even more challenging. Therefore, one might conclude that this is not a viable option yet, however the technical attractiveness and the current research activities might enhance the credibility of this option, whereby it might also become more viable.

Scale-up challenges

Possible improvement 1: modular systems in a hub and spoke model

The current maximum scale for a FP unit is 250 tonnes/day (PS2). Despite the current problems associated with scale-up, respondents PS5, PS6 and PC2 still think that in time a scale around the 1000 tonnes/day would be reachable. Respondent PS5 explains this by making the comparison with the pulp and paper industries, which also handle several thousands of tonnes of biomass per day. The scale-up to large plants is thus expected to be possible by some respondents. The actual future scale will, however, depend on the availability of biomass and the transport of it (PS1, PS3, PS4, PS6, PS7, PC1, PC2, PI1, PI4, HI1, HI2). Most respondents are therefore not in favour of very large plants, as the transport cost of biomass could cause diseconomies of scale (PS2, PS4, PC1, PI1) and the existence of a large plant with low throughput also causes diseconomies of scale as well (PC1). Rather, the respondents aim at plants of 300-400 tonnes/day to control for the transportation costs.

Respondents PS2, PC3 and PI1 see potential for modular systems. Respondent PS2 describes that the economies of scale for somewhat smaller modular units are not much different from building single bigger units. The modular systems do offer advantages of improved reliability and improved availability. Practically, this implies that if you prefer not to run at full capacity, or have a problem with feed or blockage, you do not have to shut down the entire plant, but some modules can still run. Hence, it provides better availability of the system and lower risks in the operation. This is in line with Vural Gursel et al. (2014), who also state that modular plants can achieve capacity adaptation. These respondents also underline that those plants can be built in a shorter time, enhancing a faster time-to-market.

Another recent trend of pyrolysis providers is to focus on small scale, mobile pyrolysis technologies of 1-5 ton/day (IEA Bioenergy, 2014). These small FP technologies produce bio-oils, which can be transported to and processed at a large central facility. Small scale, distributed pyrolysis facilities will have lower feedstock transportation costs, but require relatively higher capital costs and transportation of bio-oil to a central refinery (Bioenergy Technologies Office, 2014).

The HTL respondents also agree on the modular systems approach. Respondents HS3 and HS4 believe that scaling-up of HTL will consist of a lot of parallel running reactors. Respondent HS3 states that the maximum scale per reactor will be around 10-100 tonnes/hour. The reason for this modular approach is the foreseen problems with heat transfer and pumping. Small scale mobile HTL technologies, which are currently emphasized in the FP, are not an option for HTL. The high pressure and high temperature HTL reactors make the technology dangerous and thus unsuitable for mobile units (HS4). Hence, the modular approach seems most suitable for HTL.

However, there are no real scale-up solutions available for the upgrading unit. Due to the transport and logistic challenges that come along with biomass, there is a lot of interest in hub-and-spoke-systems which allow for modular FP/HTL systems (PS1, PS5, PC1, PC2, HI1, HI2). Those spokes could either be FP or HTL units, where after the produced bio-oil can be more economically transported to a central hydrotreating facility (hub). The transport could be performed using trucks or pipelines (HS3). The second option is that the spokes can be just drying facilities, which also enables a more economic transport towards a hub consisting of the FP/HTL facility together with a hydrotreater (PC2). This system requires a large scale upgrading plant. Respondents PS1, PS4, HS1 and HI2 state that the current HDO process is way too costly. Respondents PC5 and HS3 think that the upgrading unit should therefore indeed be scaled-up to a large scale to allow economies of scale to reduce the costs. Respondent PS6 states that when the upgrading process can run in the laboratory under commercially relevant conditions, the step to a commercial scale is fairly straightforward. This respondent believes that within 2-5 years the upgrading step will be optimized and used by the industry.

One may ask the question whether this optimistic view regarding upgrading is realistic. The upgrading has always been put on the back burner, even today because of the limited availability of bio-oil. The underlying thought of going straight to a commercial scale is the experience with HDO comparable technologies in the petroleum industry. It took the FP industry almost 35 years to erect some demonstration scale plants, based on technologies that already existed. Optimizing and scaling up of the upgrading technology may therefore not be reached in 5 years. Respondent PI1 indeed agrees that it will take at least 5 years before the process can be used on commercial scale. The industry should be very careful about spreading those optimistic views regarding upgrading, as the guidance of the search function has suffered from negative views that may have hindered the development in the past. Setting expectations which are realistically not able to reach, will again reduce the credibility of the technology in a moment where the momentum of the technologies is enhancing.

Chances of overcoming technological barriers

Part 1 described that the FP and HTL technologies are currently quite well understood. There are still possibilities to make the technologies more efficient, e.g. slight changes in process conditions, heat transfer and pumpability for HTL, but the current technologies work on their current scale. To avoid further scale-up problems, the modular systems approach seems very reasonable and this also fits the distribution of the biomass. Although research is still focussing on the development of novel catalysts, the chance that a novel catalyst is available on the short-term is unlikely. Moreover, additional challenges of adapting the process conditions to the use of catalysts then need to be addressed, making it less likely to be implemented in the short-term. Hence, in order to be able to develop to commercialisation on the shorter-term, emphasis should be given to non-catalytic FP and HTL modular systems.

The upgrading, however, still poses substantial challenges. Although some respondents are optimistic, it is deemed unlikely that the current upgrading processes facing hydrogen challenges, char challenges and catalysts challenges will be able to be implemented on a larger scale soon. The modular system approach is less applicable to upgrading, as hydrogen supply is needed. Hence, there are no current solutions for the upgrading step itself. This might also be the reason that UOP/Ensyn appear to have given up on the HDO process. Therefore, emphasis should be given to co-processing in existing refineries and using the technologies prior to gasification. These options do need more research in order to be implemented though. Moreover, it is likely that a mild upgrading step is needed before co-processing, which poses the upgrading challenges again. However, since this is a mild upgrading step, it might be more reasonable in the shorter term. The upgrading, as well as the proposed solutions need to be researched more extensively, and are therefore not ready for commercialisation. An overview of the chances of overcoming the technological barriers is given in Table 15.

Table 15: chances of overcoming technological barriers

Technological challenge	Possible solution	Chance of overcoming challenge based on current knowledge
Catalysts	New catalysts	Low
Upgrading	Co-process in existing refineries, prior to gasification	Medium
Scale-up challenges FP, HTL	Modular systems	High
Scale-up challenges upgrading	Easy scale-up from lab to commercialisation	Low

5.3.2 Chances of overcoming current socio-technical barriers

The seven function framework showed that there is no function which is completely built up by drivers, or completely built up by barriers. Inherently, within every function there are some barriers that need to be overcome. Overcoming these barriers is important to sustain and further develop the socio-technological system in which FP and HTL develop. Therefore, in Table 16, the barriers of every function are elaborated on whether the respondents expect that this barrier might change in the future and under which circumstances. The chance of success of overcoming the barriers is also elaborated on

Table 16: chances of overcoming socio-technical barriers

Function	Socio-technical barrier	Possible solution	Chance of overcoming barrier within current system
1: entrepreneurial activities	The new entrants are mainly small companies and university spin-offs, however there is a limited amount of new entrants	If the larger scale FP/HTL plants prove to be reliable → negative reputation of guidance of the search will be countered → new entrants having restored faith enter the market	High
	Amount of large scale experimentation is limited, whereby the industrial experience is lacking	Building on the previous change, if new entrants enter the market → more larger scale facilities → more industrial experience	High
	Large incumbents are not actively diversifying their activities	If policy in the guidance of the search would provide incentives/obligations, and when the technologies have developed up to a point they are commercial, large incumbents will buy smaller companies active in the field to have access to FP/HTL knowledge and experience	Medium
2: Knowledge development	The large amount of research is based on small scale experiments, which may limit the applicability in larger scale plants.	Experience in larger scale plants is not expected to come from scientists, but from entrepreneurs.	High
	Reinvention of this small scale research limits the amount of research that is needed in the field of scale-up, upgrading and catalysts.	Again, if new entrants having restored faith will enter the market → a constant quality oil can be delivered, and the restored faith will incentivize the higher value market possibilities → research on upgrading and catalysts will increase	High
	Lack of focus on cost-effectiveness by scientists	Improving the cost-effectiveness is not expected to be solved by scientists, rather here is a role for entrepreneurs	High
3: Knowledge diffusion	The extent of knowledge sharing among scientists may be limited due to overestimation	The underlying reason for overestimation is gaining funding, this incentive will not change without intervention.	Low
	The reluctance of different research groups to work together on a specific technological issue and a lack of coordination between the different studies of different research groups	The current FP/HTL situation can be compared with the biochemical situation of 20 years ago, which faced the same barrier. In the biochemical industry, governments enhanced the collaboration between research groups by means of shared funding → collaborations focused on specific technological challenges established → guidance of the search can via resource mobilisation establish collaborations	Medium
	Reluctance of companies to share their insights and overestimation of their results	This situation can be compared with the power plant situation. In the power plant industry, the first plants were based on secrecy → information was not shared outside the companies → in time this vanished, and currently there	Low

		are few secrets and the technologies are commonly known. The same is expected for FP and HTL.	
	Direct collaboration between universities and industrial players is limited	No indications from respondents that this might change.	Low
4: Guidance of the search	FP and HTL not the only options for the use of second-generation biomass, and competition with other technologies occur	The technologies that will diversify on feedstock and/or become the most price competitive will be likely to win. In meantime, policies are expected to capture all possible at least second-generation feedstock technologies, by means of broad policy targets (which is the comparable to the current situation)	Low
	FP and HTL suffer from a negative reputation	If the larger scale FP/HTL plants prove to be reliable → negative reputation of guidance of the search will be countered	High
	Governments currently stimulate incineration of biomass, with might have to do with the unfamiliarity with advanced technologies. This is a relatively simple and cheap technology, easier for the politicians to understand, and the market that always focuses prices might be more willing to accept the incineration	Scientists state they are and will promote FP and HTL at governments → awareness regarding more advanced possibilities may incentivize policy to use biomass for more advanced technologies, and other technologies (e.g. wind, sun) for electricity purposes → enhance guidance of the search towards advanced technologies such as FP and HTL.	Medium
5: Market formation	Standards will need to be established to be able to enter future markets	Work is already being done regarding this topic → standards are expected	High
	The derived products of FP and HTL are not cost-competitive with current fossil fuels	The products of FP and HTL are unlikely to become cost-competitive in the short term. They are expected to become more competitive tough. Incentives and/or obligations can help the wider market entry of FP and HTL.	Medium
6: Resource mobilisation	Shortage of FP and HTL skilled labour	FP and HTL seem to create more momentum compared to some years ago → more people are getting skilled now	High
	Private funding is lacking, because FP and HTL projects do not create revenues on a short term	No changes expected in demonstration phase. When the technologies are commercially proven → private funding might become available	Low
	Amount of feedstock available and the transport of that feedstock is a challenge	Residue streams from sawmills, the pulp and paper industry, the agricultural sector, the food industry and current biorefineries can be used → larger availability and lower value feedstock. Another option is the use of end of life plastic as a feedstock for FP → plastics 1) are low cost as the plastics would otherwise go to landfill, 2) do not contain any oxygen, and 3) do not contain any water → larger availability,	High

		lower value feedstock, and easier to process[21]	
	The increasing international trade of woody biomass may reduce the proposed advantages of FP and HTL	Guidelines and certification regarding the trade of biomass is needed to ensure that the proposed advantages of biomass will sustain	Medium
7. Creation of legitimacy	The subsidized incumbent oil industry has accumulated their experience and advantages towards very efficient processes	No changes expected	Low

Again, it must be noted that the analysis whether the chances of success are based on the current socio-technical system. The technology needs to enable this change as well, e.g. when the current demonstration plants do not prove to be reliable, the guidance of the search will not be enhanced. However, within the current system, it is deemed a possible change.

The expected changes almost all relate to entrepreneurial experimentation and guidance of the search. The successfulness of the larger scale plants that are currently established seem to be crucial in the success of the innovation system which is based on dynamic interactions. The following important cycles are expected by the respondents if the larger scale plants are successful:

- If the plants prove to be successful (F1) → negative reputation of guidance of the search will be countered (F4) → new entrants belief in entering the market enhancing the amount of industrial activities (F1) → larger amount of constant quality oil is available for the research on upgrading (F2)
- If plants prove to be successful (F1) → negative reputation of guidance of the search will be countered (F4) → incentives/obligations can help the wider market entry of FP and HTL (F5) → Incumbents will see the opportunity or obligation to enter the market (F1), which are companies that have more financial capabilities (F6) compared to the current small companies

Hence, it may be concluded that the development of the innovation system is very dependent on 1) The success of entrepreneurial activities, and 2) The reaction of the governments as incentives/obligations are needed. These two functions will be in interaction with the other functions, that might bring the whole innovation system forward.

A crucial barrier that is not expected to be overcome within the current system, is the lack of funding during the demonstration phase. Respondents PI2, PI3 and PI4 suggest that the government should become more active in this demonstration phase, but do not have the expectation that this will happen. They mention the several options for governments to help during this phase: 1) building demonstration plants by the government which can be used by entrepreneurs to test their technology, 2) increasing the current 50% subsidies to a higher level, which makes entrepreneurs less dependent on private parties, 3) the government could take a role similar to venture capitalists. Their view is in agreement with the literature that evaluated and analysed innovation policy in the energy sector. This literature argues that there is indeed a tendency of underinvestment by private parties, which may be seen as a failure that should incentivise the government (Jaffe et al., 2005). The government should therefore play an important role in this 'valley of death' phase (Grubler & Wilson, 2013; Jaffe et al., 2005; Norberg-Bohm, 2000; Weyant, 2011). Goldenberg & Johansson (2004) state that direct support for demonstration projects, tax incentives, low-cost or guaranteed loans and/or temporary price guarantees for energy products of demonstration projects are effective during the demonstration phase. Hence, the government may implement multiple policy interventions that can be used to help bridging the valley of death.

[21] Respondent PC2 admits that one might question the sustainability of this feedstock as plastics are made out of crude oil, but adds that this potential feedstock would otherwise go to landfill.

Other important barriers occur during the research phase, and entail that the uncoordinated research focus and the lack of knowledge sharing between different actors hold back the technological development. Section 5.1.3 revealed that although good reactors have been established and a consensus regarding the type of reactors are set, a lot of research is still being performed with exotic reactors. This could be explained by created insights from section 5.2, which explained that research proposals which have a great chance of getting funding are sometimes more preferred than research proposals addressing actual research challenges. The funding structure of research which causes a lot of reinvention, might also cause a lot of exotic research, distracting the focus of the real urgent problems of catalysts and upgrading. Moreover, the different actors are reluctant to share their knowledge and collaborate on urgent challenges. This is in line with Vandermeulen et al. (2012) who performed a study regarding the biobased economy in general. The scholars found that cooperation in terms of R&D is very limited. It is not expected that actors involved in the technology will be willing to change this situation by themselves, because of their own competitive edge. Therefore, governments should intervene. It is already elaborated on that governments may enhance the collaboration between research groups by means of shared funding. Moreover, Jaffe et al. (2005) state that there the model of subsidizing research to public-private partnerships have proven to be working. Hence, the collaboration among scientists, and between scientists and the industry can and should be stimulated by the government.

In conclusion, if the large scale plants prove to be reliable, this will enhance the innovation system. However, substantial government help is needed in terms of 1) setting more incentives/obligations to stimulate the use of the technologies, 2) providing help during the current valley of death in which demonstration plants face enormous difficulties in finding private money and 3) stimulating knowledge diffusion between different actors to enhance technological development. Lovio & Kivimaa (2012) performed a study on emerging biofuel field and conclude that a stable policy framework is key to success. Burns et al. (2016) add that a stable policy gives private investors confidence to invest in the bioeconomy. Also Vandermeulen et al. (2012) emphasize the importance of a stable policy. One might conclude that without stable long-term government help, very important socio-technical barriers are not expected to be overcome, which makes the development towards commercialisation nearly impossible.

5.4 Learning effects throughout the entire development

5.4.1 Scale-dependent and scale-independent learning effects

Learning-by-researching

Currently, the amount of research performed is extensive. However, the research is mainly performed using small scale experiments and a lot of reinvention is done regarding FP and HTL. This indicates that knowledge is 'unlearned', which hampers further learning-by-researching effects. If the recognition that those technologies do not need extensive research any more is established, research focus can be given to more urgent issues. These issues include the development of catalysts and the adjustments of process conditions when using catalysts, upgrading processes facing hydrogen challenges, char challenges and catalysts challenges, and alternative upgrading processes such as co-processing. It is expected that if FP and HTL will become commercially employed, the amount of constant quality oil will increase which will facilitate the research of those current research challenges. It must be noted, that the future learning-by-researching effects are not expected to benefit the technology in the short-term, but will enhance the quality of the oil in the long term. Contrary to most learning effects, those learning-by-researching effects will not decrease the costs of the technologies, but the costs of the produced product will increase. The result of higher quality bio-oil will on the other hand also be more valuable, which may make it beneficial. Hence, learning-by-researching effects have increased the efficiency of FP and HTL by improving the technology units and process conditions, and in the future learning-by-researching effects may increase the quality of the produced products.

Learning-by-doing

The learning-by-doing effects are, as the technologies are not commercialized, not abundantly established yet. If commercialized, repetitive manufacturing tasks leads to improvement of the production process by for example small changes in the production methods. These learning effects are indeed expected by respondents PI1 and HI2. Also respondent HI1 thinks that knowhow and experience with the technologies will optimize the current processes. Respondent HI2 gives the example of heat transfer, which is currently established, but with increasing experience, the heat transfer may become more efficient. Respondent PI4 expects efficiency gains as well, as there are currently only a couple of plants running in the world which have paid initial trails and modifications. When the technologies will be standardized and more mature, the efficiency will increase according to the respondent. It must be noted that the learning-by-doing effects will first entail the FP and HTL technologies, as upgrading first needs more learning-by-researching before it could be commercially employed. Hence, improvements of current FP and HTL processes are expected.

Learning-by-using

Learning-by-using effects also occur from the moment a first-of-a-kind commercial demo is established. Learning effects regarding this type of learning may be expected more in terms of logistics. According to the theory, potential gains in efficiency can especially be identified in more complex interacting systems. In the case the bio-oil derived by FP and HTL, for example more experience with the storage will occur (PI1). However, the respondents did not see many opportunities for further technological improvements based on this learning type.

Learning-by-interacting

Learning-by-interacting starts from the demonstration phase and entails the interaction between producers and users, to provide insights to producers regarding the user needs and requirements. The user needs and requirements for FP and HTL products are/will be strictly defined by means of standards. The current bio-oil is also ready for the use of heating and electricity purposes, as bio-oil standards for these purposes have been established (PS5, PS7, PI3). Producers of the bio-oil know what those standards contain, and indeed need to adapt the bio-oil to those standards. Currently, the standards for higher value markets have not been established, however the requirements of current petroleum based products are known and the producers of bio-oil can anticipate on that in order what to expect. There is thus not much slack in those requirements, and that is also not expected in the future. Learning-by-interacting may, besides end users, also occur with existing petroleum refineries when co-processing is strived for. However, one may expect that standards for bio-oil that can be used for co-processing will be established as well. Therefore, although learning-by-interacting occurs because the bio-oil has to meet the standards, many technological improvements because of new user insights are not expected.

Learning-by-imitation

This learning effect is assumed to start from the beginning of the development, continuing throughout all development phases. Currently, all actors try to keep valuable insight into the technology in-house, which makes it almost impossible for others to copy the processes. Therefore, the learning effect does not play a role in the development of the technology yet. However, the technological innovation system revealed that although most actors currently rely on secrecy, it is expected that in the future less secrets regarding the technologies will remain. This provides potential for learning-by-imitation, where new entrants in the field may copy existing technologies, and current players in the field can benchmark their process to others. This information will thereby enhance learning-by-imitation. It must be noted that one may expect that secrecy will diminish only in the very long term when the technology is completely standardized and embedded within the current energy system. Therefore, this learning effect will eventually play a role, but may be less important in the near future.

Learning-by-failing

A great understanding among the respondents is established regarding learning-by-failing. The researcher of this study did not ask any questions about Kior, a very promising industrial player that recently went bankrupt, but all 7 scientists, 2 of the 5 consultants and 1 industrialist active in the FP mentioned the Kior case. These respondents mention the technological issues like char forming and catalysts that Kior was struggling with, issues like changing feedstock prices, an abandoning off taker which changed their economics, and the too quick scale-up without having enough experience on an intermediate scale as reasons for their bankruptcy. This indicates that people currently working with FP are very aware of the failures of Kior, and try to take these into account in order to avoid the same mistakes. Also a HTL respondent, HS5, relates to the Kior bankruptcy, and indicates that HTL can learn from the Kior failures as well. Hence, learning-by-failing effects have played a major role in order to develop the technology and prevent previous mistakes. It is also expected that those lessons will play a role in the future, as for example the belief of not scaling up too fast is still enhanced. Possible future failures are expected to have this same effect again, although future failures might reduce the credibility as well which is a negative effect.

Learning-from-inter-industry-spillovers

The technologies for the construction of FP, HTL and upgrading find their origin mainly from inter-industry-spillovers, as elaborated on in section 5.1. The patent analysis confirmed that the technologies are based on technologies of other technology fields. Respondent PHS1 performed research on FP and HTL and talked to technology developers regarding learning effects of those technologies. The respondent, based on the technology developers, concluded that for FP and HTL, around 75% of the components of the technologies are already known technology, e.g. the reactor. Those inter-industry-spillovers have thus played an important role of establishing FP and HTL in the past, but also future improvements may be expected by inter-industry-spillovers. In line with the theory of Seebregts et al. (1999) and Smekens et al. (2003), when improvements occur in technologies of other industries on which FP and HTL are based, those improvements may be copied to the FP and HTL technologies as well. Hence, learning-from-inter-industry-spillovers have played a major role, and smaller incremental improvements may be enhanced in the future as well.

Economies of unit size

The FP and HTL technologies have scaled up to their current size, and it is expected that a more modular approach will be chosen based on the current scale. Upgrading, on the other hand, is currently still on a small scale as there are too much technological challenges to be overcome before the technology is ready to increase in scale. Hence, for FP and HTL economies of unit size may not further be expected. However, economies of unit size for the upgrading unit may be expected. Respondents PC5 and HS3 believe that the scale-up of the upgrading unit will indeed allow for efficiency gains. However, as elaborated on in section 5.4.1, the scale-up of the upgrading unit may be expected in the far future. In the near future, no economies of unit size effects may therefore be expected.

Economies of numbers

It can be concluded that it is most likely that FP and HTL will be modular systems. Respondents PS4, PC3, PC5, HS5 and HI2 foresee the biggest efficiency improvements through economies of scale. Respondent HS2 and HS3 state that the economies of numbers allow for bulk purchases of equipment. The modular plants have according to the literature specific positive and negative scaling (and broader) effects:

- The economies of scale will indeed be enhanced by economies of numbers (Grubler & Wilson, 2013).
- The indirect costs of engineering and construction expenses are expected to be lower because of standardization and pre-manufacturing (Vural Gursel et al., 2014).
- Fast improvement in delivery costs due to improved supply logistics (Daugaard et al., 2015).
- Small-scale plants need more manual intervention per unit capacity (Daugaard et al., 2015).

The future modules are thus expected to benefit extensively from economies of numbers.

5.4.2 Learning pathway

The shared vision (concentrated on the X-axis) to find an alternative for crude oil is the basis of FP and HTL. After the establishment of this vision, mainly multiple universities and small companies (distributed on the X-axis) and some larger companies (e.g. Shell, concentrated on X-axis) started to develop FP and HTL technologies which are mostly copied from the petroleum industry. Hence, as distributed as well as concentrated efforts are made, the FP and HTL technologies are set in between distributed and concentrated on the X-axis. As FP and HTL involve the application of combining several technologies in a new environment, e.g. biomass value chains need to be set up which are different to current value chains, the technologies may be seen as radical on the Y-axis. Currently, multiple application possibilities are arising and also multiple ways to reach those applications are emerging. Those multiple ways to reach the different applications differ in organisational distribution and radicality. The hub & spoke approach and the biorefinery are based on the newly set up biomass value chain and use the newly combined technologies, and may therefore be seen as radical. Co-processing in existing petroleum plants may be seen as less radical, as this option makes use of current infrastructure. Moreover, biorefineries and co-processing in the petroleum infrastructure are large concentrated activities, whereas the hub & spoke approach contains distributed plants. This is graphically displayed in Figure 8. It should be noted that even more ways to use FP and HTL exist, for example prior to gasification. This matrix, however, already gives enough information for a comparison with the archetypal learning pathways of Winskel et al. (2014).

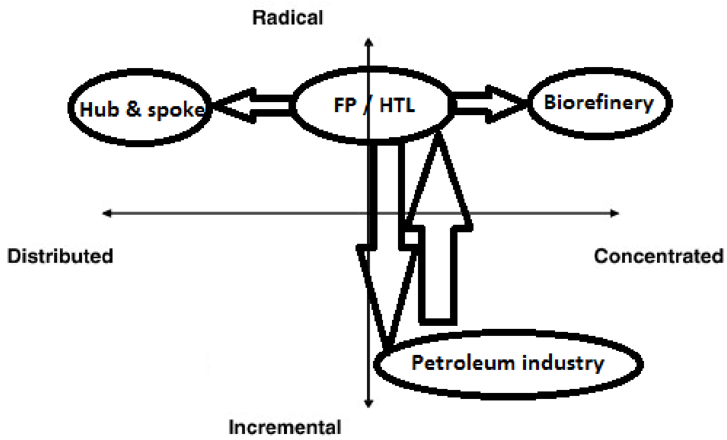


Figure 8: the learning pathway matrix for FP and HTL technologies

When the matrix of Figure 8 is compared to the archetypal learning pathways given in Appendix 1, one can conclude that FP and HTL may be characterized as 'the diversification pathway'. This pathway is established by a more heterogeneous socio-technical pathway of production and application (Winskel et al., 2014). The learning pathway is characterized by modular technologies, with great emphasis for learning by research for modules and components. For applications, emphasis is on learning by experience via small scale trials. Multiple niche markets may exist in parallel. This indeed fits the characteristics of FP and HTL. The learning effects in the socio-technical context are:

- Small scale modular systems offer many opportunities for learning by experience in demonstrations and manufacturing
- Multiple niche markets offer diversity and flexibility, so learning is likely to be sustained over time
- The high cost modules may be hard to commercialise
- The niches are vulnerable to changing policies and/or rival technologies
- Small scale systems may be locked out by large scale incumbents, and face high system integration costs

5.4.3 Overview of most important learning effects

Section 5.4.1 and 5.4.2 provided insights in the learning effects that have played a role and are expected to play a role in the future. Table 17 gives an overview of which learning effects are expected to play a role during the future development of FP and HTL. Again, it must be noted that some of those learning effects may only be achieved if the technologies reach the first-of-a-kind commercial demo and the fully commercial phase. The user-producer interaction is expected to provide few learning effects. This may be explained by the very strict regulations which the bio-oil needs to meet, whereby users may not give extensive inputs for potential improvements of the product or process. Furthermore, agreeing with the expected learning in demonstration and commercial phases identified by the archetypical learning pathway, the learning-by-doing and economies of numbers are expected to play a major role if the technologies will be commercialized. Furthermore, the learning effects of learning-by-researching, learning-by-failing and learning-from-inter-industry-spillovers are expected to continue to play a role. Note is that learning is expected to sustain over time.

Table 17: overview of expected learning effects for FP and HTL

<table>
<tr><th colspan="2"></th><th>Research</th><th>Pilot</th><th>Demonstration</th><th>First-of-a-kind commercial demo</th><th>Fully commercial</th><th>Learning effects is expected to play a role</th></tr>
<tr><td rowspan="2">Scale-independent learning (section 3.2)</td><td rowspan="2">Internal Knowledge creation</td><td colspan="5">Learning by-researching</td><td>Yes</td></tr>
<tr><td colspan="3"></td><td colspan="2">Learning-by-doing</td><td>Yes</td></tr>
<tr><td rowspan="2">Scale-independent learning (section 3.2)</td><td rowspan="2">User-producer interaction</td><td colspan="3"></td><td colspan="2">Learning-by-using</td><td>No</td></tr>
<tr><td colspan="2"></td><td colspan="3">Learning-by-interacting</td><td>No</td></tr>
<tr><td rowspan="3">Scale-independent learning (section 3.2)</td><td rowspan="3">Knowledge and technology transfer</td><td colspan="5">Learning-by-imitation</td><td>No</td></tr>
<tr><td colspan="5">Learning-by-failing</td><td>Yes</td></tr>
<tr><td colspan="5">Learning-from-inter-industry-spillovers</td><td>Yes</td></tr>
<tr><td colspan="2" rowspan="2">Scale-dependent learning (section 3.2)</td><td colspan="5">Economies of unit size</td><td>No</td></tr>
<tr><td colspan="3"></td><td colspan="2">Economies of numbers</td><td>Yes</td></tr>
</table>

6. Discussion

6.1 Methodological considerations

Interview respondents

The interviews allowed for an in-depth examination of the current situation and challenges, the chances of commercialisation and the expected future learning effects. However, there are also some considerations to take into account. More people in the HTL field were approached with the enquiry for an interview, but the number of respondents is skewed towards fast pyrolysis. As a result, the researcher gained more information regarding FP and this technology might therefore be overrepresented as compared to HTL.

Furthermore, further research could include additional respondent groups to create additional insights into the socio-technical environment of FP and HTL. These additional respondent groups are:

- Government respondents. The government is identified as a key factor to overcome important socio-technical challenges. Respondents involved in this study state that policy makers in governments are unfamiliar with FP and HTL, and hence current policies do not always benefit the development of FP and HTL. It would be interesting to discover whether this statement is valid, or whether another underlying reason can be identified for the somewhat ineffectiveness of government policy. Another underlying reason could be the involvement of different government departments. Multiple departments, e.g. department of energy, department of agriculture, department of transportation, are involved in FP and HTL (Bioenergy Technologies Office, 2015b). These different departments face a lack of coordination to introduce policy instruments (Soderhold et al., 2014). Besides different departments, different policy levels, e.g. the EU, national levels and local levels, play a role in the development (Vandermeulen et al., 2012). Hence, the lack of coordination among different government departments, and the difficulties of involvement of different policy levels may also be an important factor of somewhat ineffective governmental policy.
- Incumbent oil companies. Respondents stated that, besides the current reluctance towards co-processing bio-oil containing a too high oxygen content, there is not much resistance towards the development of FP and HTL. On the other hand, an exploratory study of Smink et al. (2013) got preliminary results that oil incumbents see biofuels as disrupting to their fossil fuel operations. As a result, incumbents are in regular contact with governments providing arguments why blending biofuels and fossil fuels are disadvantageous. An elaboration of those preliminary results could provide insights in the exact role that oil incumbents play.
- Asian respondents. In this study, respondents from North America, Oceania and Europe are included. Recent literature, however, shows that there could be much potential for implementing the FP and HTL technologies in Asia for the following reasons: 1) the prevalence of bioenergy and biopharmaceuticals in Asia has grown significantly and is set to rise over the next decades (Kang et al., 2015; Lee, 2015), 2) Asian governments are interested in the development of a bioeconomy and much policy and targets are being implemented (Kumar et al., 2015; Mofijur et al., 2015), 3) a lot of potential feedstock is available as for example rice straws offer major amounts of agricultural residues as lignocellulosic feedstocks (Singh et al., 2015), food waste generated in Asian countries is expected to rise in the upcoming years (Karmee, 2016) and there is an extensive experience in algae growth in Asian countries (Song et al., 2015). Hence, among others, FP and especially HTL have gained significant interest to be used in Asian countries such as Malaysia (Awalludin et al., 2015). Although it is not expected that the technological challenges and learning effects would change when taking into account Asian respondents, the socio-technical situation might slightly change.

Patent analysis

The patent analysis should be seen as explorative and additional research may provide additional insights to the preliminary results. First, it is identified that FP, HTL and upgrading rely heavily on patents of other technology fields. Improvements in the technologies on which FP, HTL and upgrading rely, could also be copied to FP, HTL and upgrading. Patent analysis to provide insights in the exact technologies on which FP, HTL and upgrading rely, offers a more comprehensive view of expected learning-by-inter-industry-spillovers. Secondly, this study identified that the patent renewal is low, which could be explained by 1) the value of the patents is low, whereby the cost of renewal is not worth it, or 2) the small companies involved in the technologies do not have the financial resources to sustain a patent. Additional patent analysis could provide insights in which patents from which patent owners are poorly renewed.

Moreover, a recent patent boom for patents in the bio-pyrolysis class has been observed. It is easy to dedicate all of those patents to an increased research effort, which will be partly the case, but it is important to note that also other influences might play a role. Due to increasing ’fuzzy boundaries’ and ’patent trolls’, the number of invalid patents have increased over time (Bessen & Meurer, 2007). The increasing number of patents observed might be partly explained by this phenomenon as well.

Operationalisation of technological innovation system

Drivers and barriers were identified for each function of the seven function framework. After the identification of those drivers and barriers belonging to each function, the functions were classified into a 5-point scale to give an overview of the current situation. This classification is performed based on the amount of drivers and barriers per function (see Table 7). The relative importance of each individual driver or barrier is hereby not taken into account, e.g. one might argue that as the funding needed to establish demonstration plants is very limited, the whole ’resource mobilisation’ function is very negative. However, drivers were also identified for the ’resource mobilisation’ function, and therefore this function is not classified in the lowest scale. Taking into account the relative importance could therefore slightly change the overview of the current situation. Although this could be seen as a limitation, it does not influence later results as the rest of this study focuses primarily on overcoming the socio-technical barriers themselves.

6.2 Theoretical considerations

The seven functions framework

The seven functions framework is used in this study to sketch the socio-technical environment, and to identify the socio-technical challenges. Critics state that the framework focuses on technology-specific change. They argue that strategic transformation of broader systems is not included in the framework (Markard & Truffer, 2008; Meelen & Farla, 2013; Weber & Rohracher, 2012). Recent work has therefore focused on combining the TIS with the Multi-Level Perspective (MLP) to include a wider perspective. For this study, the seven function approach is deemed to be sufficient, as this study indeed takes a technology-specific focus, which aims to assess potential technological development and related learning effects. Moreover, Lovio & Kivimaa (2012) performed a study in which they compared outcomes of MLP studies and TIS studies in the biofuel field. The scholars conclude that although the two approaches differ theoretically, the empirical findings are not significantly different. Therefore, the exclusion of the MLP in this study is justified.

An important difference between the seven functions framework and learning theories is identified during the application of both theories in this study. Hekkert et al. (2011) state that from the ’take-off phase’, i.e. from the first-of-a-kind-commercial-demo phase, the knowledge development (F2) and knowledge diffusion (F3) do not play a significant role any more. This is in contrast with Gallagher et al. (2012) and Yu et al. (2011) who argue that learning-by-researching will still play an important role during these phases. Moreover, learning-by-doing effects start to arise during these phases (Arrow, 1962). The latter view is also in line with the results of this study which state that for example learning-by-researching and learning-by-doing will play an important role in the first-of-a-kind-commercial demo phase and the fully commercial phase. Moreover, this study also emphasised the role of learning-by-failing and learning-by-inter-industry-spillovers during these phases. The view of the seven functions framework that knowledge development and knowledge diffusion do not play an important role during the take-off phase and the acceleration phase, may therefore be seen as an understatement. Hence, an addition to the seven functions can be made, that also during the take-off phase and the acceleration phase, knowledge development and knowledge diffusion continue to keep playing an important role.

Scale-dependent and scale-independent learning effects

This study acknowledged that using a non-technology specific learning rate would pose a lot of uncertainty to the results. Therefore, an alternative approach to assess learning effects if the technology will be commercialized was set up. This alternative approach consists of different learning effects divided in scale-dependent learning and scale-independent learning. In this study, an overview of the different learning effects in time perspective has been established. This establishment was necessary as, to my knowledge, such an overview was lacking in the literature. This study therefore contributes by offering this overview on which other studies may rely. It must be noted, that during the establishment of this overview, it was striking that a lot of scholars use different learning effects for the same phenomenon. In this study, footnotes were applied when this situation occurred, to secure the clarity of the overview of the learning effects. To secure this clarity in other studies as well, it is proposed to straighten the learning effects for the same phenomenon.

While establishing the overview of the learning effects in time perspective, it was noted that no time perspective could be found for learning-by-imitation and learning-by-failing. In the theory section, it was assumed that those learning effects start from the research phase and continue the entire development of the technology. This study confirmed that learning-by-failing has played a role by means of the Kior case. Substantial learning-by-imitation effects have not been discovered so far. The reason being that the extreme secrecy in the field makes it almost impossible for others to copy processes. Further research may shed light on when learning-by-failing and learning-by-imitation precisely play a role, as it is expected that secrecy plays a role in almost all emerging technologies, and hence, may only play a role in later development phases.

Furthermore, this study revealed that the learning effects belonging to user-producer interaction, learning-by-using and learning-by-interacting, did not play an important role. The needs and requirements of users are set by standards and regulations, and there is not much slack in those requirements. The producers just need to produce products that meet the standards. Hence, in very strictly regulated technology fields, it may be expected that learning-by-using and learning-by-interacting are non-important learning effects.

The comprehensive model suggests, based on literature, that learning-by-doing and economies of numbers play a role in the first-of-a-commercial-demo phase and the fully commercial phase. The learning pathway, on the other hand, emphasises that small scale modular systems may offer many learning opportunities during demonstration and wider manufacturing. Hence, the framework suggests that these learning effects already start in the demonstration phase, as compared to the suggested first-of-a-commercial-demo phase. One explanation could be that the 'diversification learning pathway' enhances that learning should be sustained over time, and hence relatively more time is spent in the demonstration phase as compared to the other learning pathways. Therefore, the experience in the demonstration phase might already trigger for example learning-by-doing effects. This difference between the learning effects and the learning pathways underlines that the classification of learning effects per development phase in the comprehensive model is advantageous for the overview of the effects, however the development phases are not a strict dividing line between the learning effects and some slight overlap may occur.

Lastly, an observed limitation of learning theories is the lack of focus regarding the quality of the produced product. In current literature, learning effects mostly describe efficiency gains and thus potential costs reductions. In this study, learning-by-researching will very likely cause an increase in costs when catalysts and upgrading technologies will be applied. However, the quality of the produced products and hence the value of the products increases as well. This observation is in line with Thompson (2001) who also identified that learning may, besides efficiency and cost reductions, also enhance quality. It is also well known that a technology or product may become competitive by means of lowering costs as well as differentiation, i.e. performance improvement (Porter, 1985). A way to incorporate the measure of performance is not yet addressed, but this study has underlined the importance of assessing quality improvements besides taking an inward-view on efficiency and thus costs.

Learning pathways

To the best knowledge of the author, this study is the first attempt to practically use the learning pathways framework. The 'diversification learning pathway' is derived for the technologies, which is characterised by learning-by-research for modules and components (i.e. upgrading and catalysts) and learning during small scale trials in the demonstration and commercialisation phase (learning-by-doing). When the learning effects described by the learning pathway are compared with the scale-dependent and scale-independent learning effects, several differences may be identified.

- The learning pathways provide a timeframe of sustained learning, which is hard to establish using more traditional learning theories. The latter can be seen as a benefit of the learning pathway framework.
- The framework did not capture the learning-by-inter-industry-spillovers, which are applicable to FP and HTL.
- The role of learning-by-failing is underemphasized as compared to the identified scale-independent learning effects
- A large consideration is that Blyth et al. (2014) state that modular technologies indeed can benefit from mass installation and economies of scale, but state that those benefits are rapidly achieved. This is in contrast with the expected sustained learning of the learning pathway. This may be explained by Blyth et al. (2014) focusing more on the scale-dependent learning effects, whereas scale-independent learning may be more sustained. Hence, the framework of Winskel et al. (2014) focusses mainly on scale-independent learning effects. Scale-dependent learning effects, however, also play a very important role and the learning pathways could therefore be complemented with more technology specific scale-dependent learning effects.

In conclusion, currently the learning pathway may be used as a quick overview of learning effects for a particular technology, offering the general learning effects of that technology. However, if one would want to gain in-depth insights in learning effects of a particular technology, another approach may be more suitable. In that case, the overview of different learning effects established in this study may be assessed by means of interviews.

6.3 Practical considerations

Learning effects leading to cost reductions

Learning effects enhance technological improvement, which inherently leads to diminishing costs. An article of Hayward et al. (2015) analysed among others the sensitivity of different parameters on the costs of FP and HTL produced liquids. This analysis shows that the highest impacts can be made by:

- Improving the conversion efficiencies. Even small improvements here can have a significant impact.
- Experience by the labour employed at the units
- Biomass costs, including harvesting and transport

The expected learning effects tend to focus on learning-by-doing and economies of numbers. Hence, especially the learning-by-doing effects seem to be very important, as improving the conversion efficiencies may have a large impact on cost reductions. Again, it should be noted that the learning-by-doing effects have not been started yet, but this may offer opportunities for the future if FP and HTL would be commercialised.

An addition to the possible scale-dependent learning effects can be made, based on a benchmark with smaller petroleum based companies. The Economist (2011) states that purchasing in bulk may significantly enhance the scale-dependent learning effects. Smaller companies operating in the petroleum industry, therefore tend to collaborate regarding the purchase of needed materials. This collaboration allows economies of scale for smaller companies, without the need of scaling up. Hence, FP and HTL companies can collaboratively purchase materials to gain efficiency and save money.

Government intervention

A very recent article of Hartmann & Sam (2016) states that 'we have entered an era of more affordable oil that is likely to last for the foreseeable future'. These lower prices are the result of the oil business being disrupted. In the past, it took 5 to 10 years to explore, develop and bring production of a new oil field to the market. However, current shale oil producers can ramp up production within a few months. These shale oil and gas producers are currently acting as quasi-swing producers. Hence, if the price of oil goes up, the shale oil and gas producers can counteract this rising price within a few months rather than years. These expected low crude oil prices may have an influence on government intervention in the following ways:

- According to the respondents in section 5.2, subsidies are currently more in favour of the fossil fuels than the bioenergy alternatives. The new arising opportunity is that net oil importing nations can save a lot of money on importing crude oil and petroleum products, whereby governments may be able to reduce petroleum subsidies and increase its excise duty on petrol and diesel (Hartmann & Sam, 2016).
- Hartmann & Sam (2016) also assessed the influence of the consistently affordable oil on renewable energy. They conclude that renewable energy sources, such as solar and onshore wind, which have experienced cost reductions and are more competitive, will continue to exist. For other technologies, such as FP and HTL, the future lays completely in the commitments being made during the recent COP21. Hence, the urge to reduce emissions should stimulate governments to enhance policy interventions. However, due to the fact that governments were historically less enthusiastic to invest in FP and HTL when the oil price was low (Chemical Weekly, 2015), the question is really whether this will be realistic.

Recently, a big study regarding the biochemical conversion technologies was performed for the European Commission (E4tech et al., 2015). Technological challenges for biochemical conversion technologies are insufficiently being addressed by R&D, and contain among others improving efficiency, increasing yields, and enhance process integration along the whole value chain. The socio-technical barriers entail the demand side policy, public perception, investment & financing and feedstock. Hence, the technological challenges as well as the socio-technical barriers are very similar to the FP and HTL situation. Moreover, although biochemical technologies are being commercialized, there is still a clear valley of death for those technologies (E4tech et al., 2015). As a result, most projects are either in the pilot phase or the first-of-a-kind-demonstration phase, and very few projects are being demonstrated. The study for the European Commission concludes with potential policy improvements for biochemical technologies, which are due to the similarities of the situation also deemed to be applicable for FP and HTL. Those improvements include 1) longer-term stability of mandates, 2) setting biomass use between fuels and chemicals on a level playing field, 3) incentivizing biomass production, 4) creating a clear Europe-wide communication campaign, 5) dis-incentivizing fossil-derived products, 6) improving access to capital and loan guarantees and 7) simplifying available funding mechanisms. Again, those policy improvements are very similar to the ones described in this study, and besides the second possible policy improvement, all were mentioned in this study. Hence, a lot of policy improvements needs to be implemented to create a more favourable socio-technical environment which may stimulate FP and HTL towards commercialisation. However, as the oil price is expected to stay low and the incentives for government intervention are thus mainly based on emission reduction, one might rethink whether governments would be willing to implement all those incentives.

7. Conclusion

The aim of this study is to assess the chances of overcoming technological challenges and socio-technical barriers, and the learning effects that are expected to play a role throughout the development of FP and HTL. FP and HTL are not yet controlled to an extent that the technologies can scale-up easily, and therefore the modular system approach seems to be a reasonable option. The technological challenges for upgrading processes and catalysts are, however, not expected to be overcome on the short-term and extensive research is needed to address those challenges. Overcoming current socio-technical challenges relies heavily on the success of current established larger scale plants, and government intervention. The success of current established plants may increase the credibility of the technologies, which would cause positive interaction with other functions in the innovation system, bringing the whole system forward. Substantial stable long-term government help is needed in terms of 1) setting more incentives/obligations to stimulate the use of the technologies, 2) providing help during the current valley of death in which demonstration plants face enormous difficulties in finding private money and 3) stimulating knowledge diffusion between among actors to enhance technological development. Moreover, the government should take an active role in incentivizing biomass production, creating a clear Europe-wide communication campaign to create acceptance for biotechnologies and dis-incentivize fossil-derived products. One may conclude that if the larger scale plants turn out to be unsuccessful or if the government is reluctant to change its policy, further development towards commercialisation will be very unlikely.

FP, HTL and upgrading technologies were established by inter-industry-spillovers, and future improvements of the technologies on which FP, HTL and upgrading are based, may again be copied to FP, HTL and upgrading. The learning-by-researching effects have optimized the FP and HTL technologies for the use of biomass and learning-by-failing by means of the Kior case has created valuable lessons for FP as well as for HTL. It can be noted that the user-producer interaction provides few learning effects. This may be explained by the very strict regulations which the bio-oil needs to meet, whereby users may not give extensive inputs for potential improvements of the product or process. Furthermore, agreeing with the expected learning in demonstration and commercial phases identified by the archetypical learning pathway, the learning-by-doing and economies of numbers are expected to play a major role if the technologies would be commercialized. Those learning effects are expected to create efficiency gains, which have a significant impact on the production costs of the liquids derived by FP and HTL. Hence, FP and HTL units gain experience during the demonstration and commercialisation of those units, while simultaneously research on the upgrading and catalysts should be performed. These learning-by-researching effects may increase the quality of the produced oil. During this time, the needed standards for higher value markets may be established as well. Hence, the success of the larger scale plants and changes in current government policy are needed for further development of FP and HTL, which will allow FP and HTL to experience sustained learning effects, while learning-by-researching could promote the quality of the oil with the ultimate goal of reaching higher value markets.

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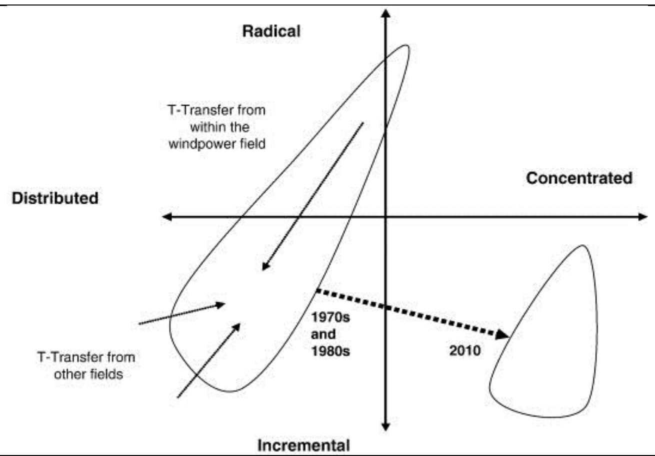
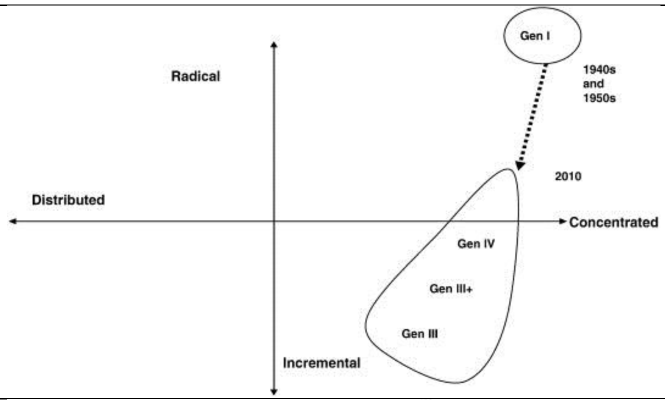
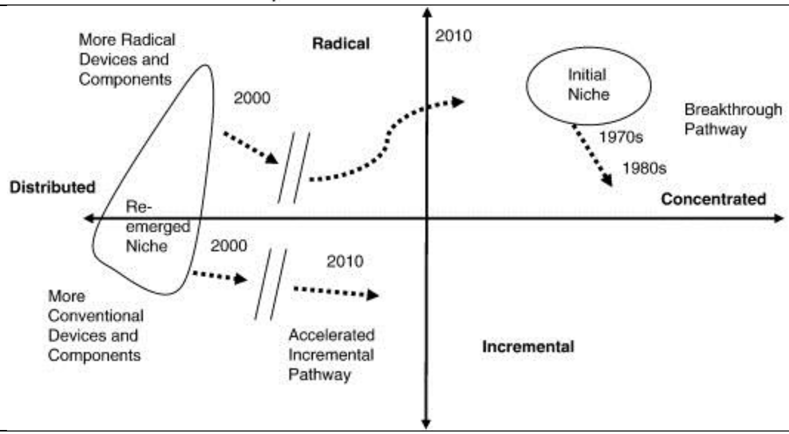
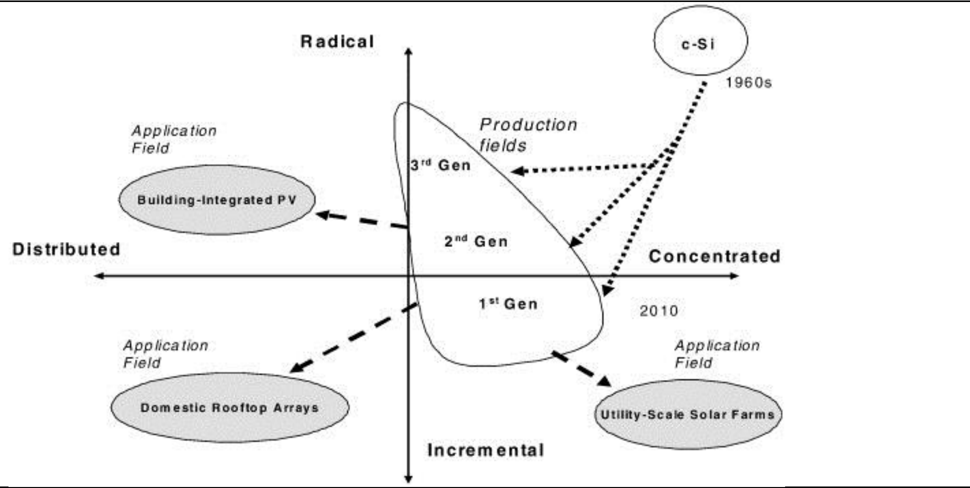
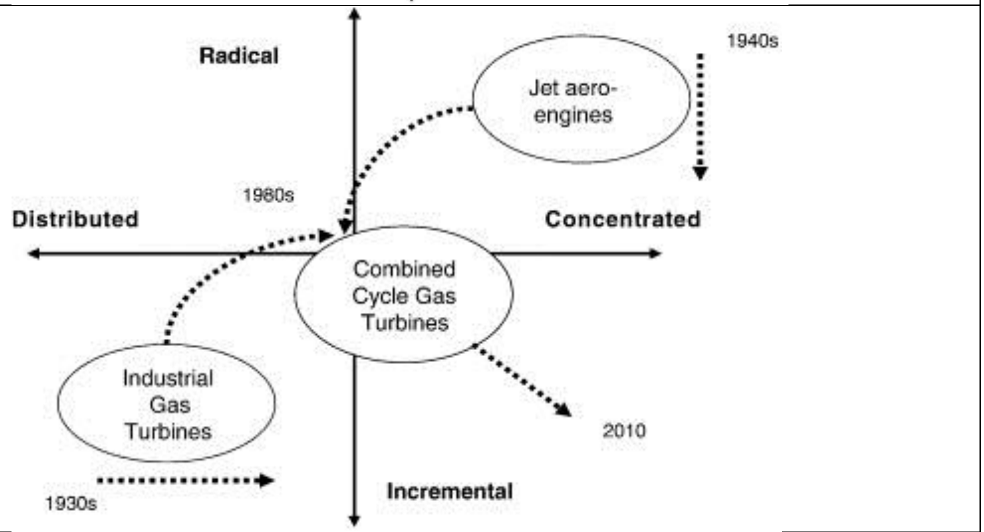
Appendix 1: Learning pathways

The learning pathways of Winskel et al. (2014) were established using historical cases of energy supply technologies. The historical cases were applied to the learning pathway matrix and those are shown in this appendix.

<table>
<tr><th>Learning pathway (with examples)</th><th>Learning pathway matrix</th></tr>
<tr><td>Incremental, early stage (e.g. early onshore wind, marine renewables)</td><td>
</td></tr>
<tr><td>Incremental, mature stage (e.g. coal and gas fired turbine plant, nuclear fission)</td><td>No pathway matrix available. This is not seen as a problem, as FP and HTL are not commercialized yet and are thus not in the mature stage.</td></tr>
<tr><td>High tech, breakthrough (e.g. advanced nuclear power, jet engines, advanced offshore wind, possibly CCS)</td><td>
</td></tr>
<tr><td>High tech, interactive (e.g. advanced marine and bioenergy renewables)</td><td>
</td></tr>
</table>

<table>
<tr>
<td>High tech, diversification (e.g. solar PV, fuel cells, some bioenergy technologies)</td>
<td>
</td>
</tr>
<tr>
<td>Transfer and combination (e.g. early CCGTs, possibly CCS)</td>
<td>
</td>
</tr>
</table>

Appendix 2: Interview questions

This Appendix gives the standard list of questions that were used during the interviews. It should be noted that not all questions applied to every respondent, depending on their background. Moreover, some questions were not asked any more after data saturation regarding that question was reached. This allowed for more time and thus a more in-depth conversation during the interviews for questions where consensus between respondents had not been reached. Lastly, this appendix gives an overview of the stand list of questions. The semi-structured approach allowed to follow up questions when required.

FP/HTL technology

- The technology has existed for quite a long time, and was really taken up in the 1970s. How would you describe the development from 1970 until now?
- Several reactors exist, do you consider it a good thing that there are several design or should we push towards one standard design?
- To what extent are the process conditions (e.g. residence time, temperature) understood?
- How do you see the use of catalysts in the technology?
- In which way will the technology scale-up?
- What do you consider a maximum scale for the technology?
- What are the current research challenges and to what extend have they been addressed?
- What are the main differences and similarities between FP and HTL?
- What are the main competing technologies?

Upgrading technology

- What are the main research gaps for upgrading the bio-oil?
- Several ways to perform upgrading exist. What do you consider the most favorable upgrading process?
- Do you consider the upgrading technology ready for scale-up?

Socio-economic environment

- What kind of organizations are involved in the development of the technology?
- To what extend do they different actors involved in the technology share their knowledge with each other?
- What parties are investing in the technology, and is this sufficient?
- How do you see the role of the government in the development of the technology?
- What lobby activities exist and what is your opinion regarding those activities?
- What do you consider the most favorable market to reach?
- In which way do the current standards stimulate or hamper the technology?
- To what extent fits the technology within the current infrastructure?

Technological improvements

- Which technological improvements do you expect?
- What is needed to bring the technology to a commercial scale?
- Do you expect cost reductions and where would they come from?
- What are the biggest drivers for future development?
- What are the biggest bottlenecks for future development?

Appendix 3: Patent analysis

The appendix of the patent analysis shows the average patent score regarding the generality index, the originality index, the radicalness index and the patent renewal. This average patent score is given for FP, HTL, upgrading and the technology field of those technologies.

		Generality index	Originality index	Radicalness index	Patent renewal
FP	EU	0,552311	0,800901	0,490438	5,235294
	VS	0,705897	-	0,64121	-
HTL	EU	0,585073	0,85991	0,582556	4,857143
	VS	0,666887	-	0,658894	-
Upgrading	EU	0,494952	0,87134	0,421461	5,5
	VS	0,612083	-	0,590067	-
Technology field	Average EU	0,42	0,78	0,4	8

Appendix 4: Research activities regarding reactor types

Appendix 4 shows the overview created by (Bridgwater, 2012). This overview contains most of the known recent and current activities in FP arranged by reactor type and maximum known throughput.

Fast pyrolysis	**Industrial**	**Units built**	**Max size kg/h**	**Research**	**Max size kg/h**
Fluid bed (BFB)	Agritherm Canada	2	200	Adelaide U Australia	1
	Biomass Engineering Ltd UK	1	200	Aston U. UK	5
	Dynamotive Canada	4	8000	Cirad France	2
	RTI Canada	5	20	Curtin U Australia	2
				ECN NL	1
				East China U. Science and Technology Shanghai China	nk
				Gent U. Belgium	0,3
				Guangzou Inst China	10
				Harbin Institute of Technology	nk
				Iowa State U. USA	6
				Monash U. Australia	1
				NREL USA	10
				PNNL USA	1
				Shandong U. Technology	nk
				Shanghai JiaoTong U	1
				Shenyang U. China	1
				South East U. China	1
				Texas A&M U. USA	42
				TNO Netherlands	10
				U. Basque Country Spain	nk
				U. Campinas Brazil	100
				U. Maine USA	0,1
				U. Melbourne Australia	0,1
				U. Naples Italy	1
				U. Science and Technology of China	650
				U. Seoul Korea	nk
				U. Twente Netherlands	1
				U. Western Ontario Canada	nk
				U. Zaragoza Spain	nk
				USDA ARS ERRC USA	1
				Virginia Tech. U. USA	0,1
				VTT Finland	1
				vTI Germany	6
				Zhejiang U. China	3
				Zhengzhou U. China	2
Spouted fluid bed	Ikerlan Spain	1	10	Anhui U. of Science & Technology China	5
				U. Basque Country Spain	nk
Transported bed & CFB	Ensyn Canada	8	4000	CPERI Greece	1
	Metso/UPM Finland	1	400	Guangzhou Inst. Energy Conversion China	nk
				U. Birmingham UK	nk

				U. Nottingham UK	nk
				VTT Finland	20
Rotating cone	BTG Netherlands	4	2000	BTG Netherlands	10
Integral catalytic pyrolysis	BioEcon Netherlands + Kior USA	nk	nk	Battelle Columbus USA	1
				PNNL USA	1
				Technical U. of Munich	nk
				U. Massachusetts–Amhurst USA	nk
				Virginia Tech. U. USA	3?
Vortex				TNO Netherlands	30
Centrifuge reactor				Technical U. Denmark	nk
Ablative	PyTec Germany	2	250	Aston U. UK	20
				Institute of Engineering Thermophysics Ukraine	15
				Latvian State Institute Latvia	0,15
				Technical U. Denmark	1,5
Augur or Screw	Abritech Canada	4	2083	Auburn U. USA	1
	Lurgi LR Germany	1	500	KIT (FZK) Germany	500
	Renewable Oil Intl USA	4	200	Mississippi State U. USA	2
				Michigan State U. USA	0,5
				Texas A&M U. USA	30
Radiative-Convective				CNRS – Nancy U. France	nk
Entrained flow				Dalian U. of Technology China	nk
				Institute for Wood Chemistry Latvia	nk
				Shandong University of Technology	0,05
Microwave	Carbonscape New Zealand & UK	nk	nk	Chinese Academy of Sciences Dalian 116023 P. R. China	nk
	Bioenergy 2020 + gmbh Austria	1	nk	National Inst. Advanced Industrial Sci. & Technol. Japan	<0.1
				Shandong U. China	<0.1
				Technical U. Vienna Austria	nk
				U. Malaysia Sarawak	<0.1
				U. Minnesota USA	10
				U. Mississippi	nk
				U. Nottingham UK and China	nk
				U. York UK	nk
				Washington State U.-Tricities USA	<1
Moving bed and fixed bed	Anhui Yineng Bio-energy Ltd. China	3	600	Anadolu University Turkey	nk
				U. Autònoma de Barcelona Spain	nk
				U. Science & Technology of China	~0.5
Ceramic ball downflow				Shandong University of Technology China	110
Unspecified				U. Kentucky USA	nk
				U. Texas USA	nk
				Technical U. Compiegne France	nk
Vacuum	Pyrovac Canada	1	3500	None known	