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Selection of biomass thermochemical conversion technology in the Netherlands: A best worst method approach

Geerten van de Kaa*, Linda Kamp, Jafar Rezaei

Delft University of Technology, Jaffalaan 5, Delft, 2600 GA, The Netherlands

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A B S T R A C T

This paper studies the technology battle for biomass conversion in the Netherlands. Three types of technologies are currently fighting the battle for standard dominance: combustion, pyrolysis, and gasification. Twelve relevant factors for standard dominance were found: 'financial strength', 'operational supremacy', 'learning orientation', 'technological superiority', 'compatibility', 'flexibility', 'pricing strategy', 'distribution strategy', 'previous installed base', 'regulator', 'effectiveness of the format development process', and 'network of stakeholders'. Applying expert opinions and the Best-Worst Method (BWM), the relative importance (weights) of these factors were calculated. The weights were then used to evaluate and rank the technologies. The results show that biomass gasification has the highest chance of achieving standard dominance and that technological superiority is the most important factor affecting standard success. The weights per factor were explained and theoretical contributions and areas for future research were discussed.

1. Introduction

Biomass has always been a major source of energy for mankind. After the industrial revolution, interest in biomass declined due to heavy exploration and relatively low costs of fossil fuels. However, after the 1970 oil crisis, interest in renewable energy revived (Kamp, 2002), and the use of fossil fuels started to raise many political, economic, and environmental concerns. Interest in renewable energy continued on a small scale in developed areas such as Europe, and in 2000 the European Commission created targets for renewable energy usage (Kamp et al., 2004; van Thuijl and Deurwaarder, 2006). Ever since, the use of renewable energy is becoming more dominant in achieving the change required to address the impact of fuel security and global warming (McKendry, 2002). One of the renewable energy sources and actually the most common, is biomass technology (McKendry, 2002).

Using solid biomass for energy started many centuries ago, since the discovery of fire (Basu, 2013). Biomass is a term for all organic material that stems from plants, including crops, agricultural and forestry residues, organic components of garbage, and algae. In the 20th century, its useful application and the broad diversity of suitable feedstock resulted in increased research and development of technologies to produce power and derive fuels from biomass at an industrial scale (U.S. Department of Energy, 2013). The processes of producing direct power (heat and/or electricity) and deriving liquid/gaseous fuels (in the end also used for power) is called conversion. Conversion can be performed through two major routes: biochemical conversion, by way of fermentation, and thermochemical conversion, by way of direct combustion, gasification or pyrolysis. This paper focuses on thermochemical conversion technologies in the Netherlands, and examines the battle for dominance between three technologies: combustion, pyrolysis, and gasification. It is interesting to compare these technologies due to the common feedstock type of solid, dry biomass. Based on a preliminary research, to date no clearly dominant technology has emerged on the market in the Netherlands.

1.1. Research objectives and contributions

The objective of this research is to determine the factors which affect the success of conversion technologies in the biomass industry in the Netherlands. Van de Kaa et al. (2011) have developed a framework comprising 29 factors for technology success which will be applied in this paper. The framework is based upon the extent

* Corresponding author.
E-mail address: g.vandekaa@tudelft.nl (G. van de Kaa).

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literature on standards battles (Gallagher, 2012; Gallagher and Park, 2002; Schilling, 1998, 2002; Shapiro and Varian, 1999b; Suarez, 2004). The focus in this paper lies on the 23 factors that can be directly influenced by the firm (firm level factors). These factors are grouped under the following four categories, (i) characteristics of the format supporter, (ii) characteristics of the format, (iii) format support strategy, (iv) other stakeholders. The first category, which relates to the strength of the format supporter, consists of four factors: financial strength, brand reputation and credibility, operational supremacy, and learning orientation. The second category, which relates to the elements of the platform that make it technically superior to competing platforms, comprises four factors: technological superiority, compatibility, complementary goods, and flexibility. The third category relates to the strategies of the companies that support the technology and that can be used to win a format battle. These include pricing strategy, appropriability strategy, timing of entry, marketing communications, pre-emption of scare assets, distribution strategy, and commitment. The fourth category consists of factors related to stakeholders other than the group of format supporters, and includes current installed base, previous installed base, a big fish, the regulator, antitrust laws, suppliers, the effectiveness of the format development process, and the network of stakeholders that support the technology.

The framework has been tested for completeness and relevance (Van de Kaa and De Vries, 2015) and has been applied to various contexts to evaluate its applicability and to establish weights for the factors for various empirical contexts (Van de Kaa et al., 2014a; Van de Kaa et al., 2014b; Van de Kaa et al., 2014c). The theoretical contribution of this paper lies in evaluating whether the framework can be applied in the biomass industry and, if so, to assign weights to the factors for this industry. The practical contribution lies in predicting which of the three thermochemical biomass conversion technologies will have the highest chance of achieving success. Since the number of installations for combustion, gasification and pyrolysis are all still small in the Netherlands (25 for combustion, 5 for gasification and 1 for pyrolysis (BTG-BTL, 2016), it can be argued that no clear dominant technology has yet emerged in the market in the Netherlands.

2. Biomass conversion technology in the Netherlands

Globally, the development of renewable energy is becoming more important to address the challenge of clean energy, climate change, and sustainable development (IEA, 2012). In the Netherlands, the use of renewable energy sources, including biomass, has increased over the last decades, and is expected to increase further (Brijder and Dragoman, 2015). The renewable energy target for the Netherlands for 2020 is set at 14%, as agreed upon in the EU Directive Renewable Energy for 2020 (van der Drift, 2013). In 2016, 5.7% of all energy consumed in the Netherlands came from renewable sources, 84% of which was from biomass (Bacovsky et al., 2016). This clearly shows that biomass plays an important role in renewable energy production in the Netherlands.

In the Netherlands, biomass conversion technology for electricity production has been around since 1980, starting with the digestion of manure (Negro, 2007). Later on, thermochemical conversion technology emerged. The technologies serve to convert raw biomass into intermediate products, so that they can be further converted into their respective end products. This technology has a common characteristic of feedstock, in which solid, dry biomass such as woodchips and wood pellets, is used.

Biomass can be directly combusted to produce heat and/or electricity, or can be converted into bio-syngas or bio-oil for indirect heat and/or electricity generation elsewhere. Bio-syngas and bio-oil can also be processed further into biofuels or chemicals, etc.

These applications comprise three thermochemical conversion techniques i.e., direct combustion, gasification, and pyrolysis. These three technologies are presented in Table 1.

We now describe the three technologies in more detail.

2.1. Direct combustion

Combustion is one of the most well-known methods of conversion, and has been around for many centuries, since the discovery of fire (Basu, 2013). The solid feedstock reacts with oxygen at high temperature, producing a flame and smoke. The heat generated by the flame makes the reaction self-sustaining, and the reaction is thereby exothermic (no addition of heat required). The heat is then used to produce steam, which is the main product of this process (Veringa, 2004). The steam drives a steam turbine with attached generator that produces electricity. However, this particular method is not very efficient, sometimes reaching only 10% efficiency (Meng, 2012), but on average achieving 20%–25% efficiency (McKendry, 2002). A disadvantage of the method is the emission of by-products, such as CO, CO_2, NOx, dust and soot.

Combustion technology has been on the market in the Netherlands since 1980. It is the most common biomass power generation method (IRENA, 2012), is commercially available, and can be applied in a wide range of scales, ranging from 1 MW up to 100 MW. Co-firing of biomass with coal in large coal-fired power plants is a relatively easy and cheap manner to increase efficiency and reduce emissions (IRENA, 2012).

2.2. Gasification

In the endothermic process of gasification, solid feedstock is converted into bio syngas by heating it to high temperatures (>700 °C) in an oxygen-starved environment in order to inhibit combustion. The syngas is subsequently used for combustion to provide heat to generate steam as in direct combustion, or to drive a gas turbine for electricity generation. The more energy-dense gaseous fuel (compared to raw biomass) can also be transported and used/stored elsewhere, and is relatively easier than handling raw biomass (Basu, 2013). Overall, gasification produces higher

Table 1
Characteristics of direct combustion, gasification, and pyrolysis.

	Direct combustion	Gasification	Pyrolysis
Energy balance	exothermic	endothermic	endothermic
Main products	steam, heat, electricity	bio syngas, heat, electricity	bio-oil, heat, electricity, biofuel
Energy efficiency	20-25%	40-50%	85-90% (potential)
Commercially available in the Netherlands since	1980	1990	2015 (demonstration plant)
Scale	1 MW - 100 MW	50 kW - 100 MW	2 MW–25 MW
Investment costs/kW	€480/kW - €1040/kW	€1280/kW - € 1840/kW	ca. €4960/kW

Sources: (Veringa, 2004), (McKendry, 2002), (Negro, 2007), (IRENA, 2012), (BTG-BTL, 2017a), (BTG-BTL, 2017b), (Ministerie van Buitenlandse Zaken, 2015), (ETIP-Bioenergy, 2017), (Wright and Brown, 2011) yields for electricity production, especially in low power plants (50 kW–10 MW) and very large power plants (50–100 MW) (Veringa, 2004). A disadvantage of this process is that valves need to be cleaned often due to precipitation of tar (Veringa, 2004).

Gasification has been commercially applied in the Netherlands since 1990 (Negro, 2007). It is relatively efficient (40%–50%; McKendry, 2002) and the produced syngas is highly suitable for further conversion.

2.3. Pyrolysis

Pyrolysis takes place at elevated temperatures in the total absence of oxygen (and sometimes with addition of a catalyst), and converts biomass into gas, liquid, and a solid residue (Basu, 2013; Jayasinghe and Hawboldt, 2012; Meng, 2012). Pyrolysis is the chemical reaction that is the precursor of combustion and gasification, which occurs naturally in the first 2 s. Depending on the temperature and heating rate, the ratio of gas, liquid and solid can be altered. The main product (bigger fraction) is bio-oil, which is obtained at rapid heating rates at a temperature of 450–600 °C. In this endothermic process, large hydrocarbon molecules of biomass are broken down into smaller molecules (Basu, 2013). The bio-oil can be combusted elsewhere, mostly in a co-firing application with another main liquid or gas (fossil) fuel to provide heat and/or electricity. Bio-oil can be further processed into fuel suitable for transportation.

Biomass pyrolysis technology is very new and entered the Dutch market on a commercial scale in 2015. High efficiencies can be reached (85–90%) and the technology is currently applied at relatively small scales, ranging from 2 MW to 25 MW (BTG-BTL, 2017a; ETIP-Bioenergy, 2017). A notable developer of pyrolysis in the Netherlands is the BTG group in Enschede, which opened the world's first pyrolysis plant in 2015 (BTG-BTL, 2017b; Ministerie van Buitenlandse Zaken, 2015).

3. Methodology

Secondary sources were analyzed and interviews were conducted with three experts in the field to determine which of the 23 firm level factors offered by Van de Kaa et al. (2011) are relevant factors for standard dominance for the case of biomass technology selection. Three academics were interviewed: a professor of fluid mechanics at Delft University of Technology (TU Delft), who recently worked on several projects on biomass combustion, a TU Delft professor in the field of thermochemical conversion of biomass, who is an expert in large-scale energy storage, and a post-master student at Eindhoven University of Technology (TU Eindhoven), whose master thesis was on biomass conversion technology. A factor is considered to be relevant if it is mentioned in the literature and/or if at least two of the three interviewees indicated its relevance.

3.1. Ranking factors

After determining the relevant factors, a second round of interviews was conducted with seven experts, among them the three initial interviewees, to rank the importance of each relevant factor. For finding the additional four experts, we used the so-called snowball sampling method. The three experts that were interviewed in the first round of interviews were asked whether they knew other people in industry or academia who had knowledge about the technologies. They directed us towards additional experts in their network. For choosing the experts to interview three selection criteria were applied. First, it was made sure that experts were chosen who have knowledge about each technology but who are not supporting a single technology. Thus, we made sure that the experts were not biased towards a certain technology as this may lead to a bias in the results. Second, the experts should have specific knowledge about the Dutch context since the study focuses on the Netherlands. Third, we made sure that the experts' expertise was complementary as much as possible. Table 2 shows the background and expertise of the interviewees.

A multi-criteria decision-making (MCDM) method called best-worst method (BWM) was used to derive the weight of the factors, to examine which factors play the most important role in the battle for dominance, and finally to predict which of the three thermochemical biomass technologies had the highest chance of achieving success.

An MCDM problem can be simply formulated as a matrix as follows.

$$P = \begin{array}{c} \\ a_1 \\ a_2 \\ \vdots \\ a_m \end{array} \begin{array}{c} \begin{array}{cccc} c_1 & c_2 & \dots & c_n \end{array} \\ \begin{pmatrix} p_{11} & p_{12} & \dots & p_{1n} \\ p_{21} & p_{22} & \dots & p_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ p_{m1} & p_{m2} & \dots & p_{mn} \end{pmatrix} \end{array} \tag{1}$$

where.$\{a_1, a_2, \dots, a_m\}$ is a set of feasible alternatives.$\{c_1, c_2, \dots, c_n\}$ is a set of evaluation/decision criteria, and.p_{ij} is the performance of alternative i with respect to criterion j.

After obtaining the weights, w_j, for all j, the scores p_{ij} are obtained by evaluating technology alternative i with respect to criterion j. As explained in Section 3.1, we derive the scores p_{ij} from a literature review and from interviews with experts. An alternative

Table 2
Interviewee details.

#	Background	Expertise (besides biomass technologies)	Function
1	Academia	Chemical product design: green fuel (biodiesel and quantum dots); carbon capture and bio-based drug delivery; food and consumer goods	Researcher, Delft University of Technology
2	Academia	Process engineering: large scale energy storage, thermochemical biorefinery and renewable energy sources, thermochemical conversion and biorefinery	Professor, Delft University of Technology
3	Academia	Process engineering: feedstock handling problem of biomass	Researcher, Eindhoven University of Technology
4	Academia	Chemical engineering: Process Dynamics and Control and Applied Numerical Mathematics, Process Simulation and Computational Fluid Dynamics	Researcher, Delft University of Technology
5	Industry	Process engineering: natural gas to liquid fuels conversion (namely kerosene, naphtha and Diesel) via the Fischer-Tropsch (FT) reaction;	Process Engineer, AkzoNobel
6	Academia	Chemical engineering: thermodynamics in separation technology area; separation processes, CO2 gas removal from gas processing by chemical absorption; buffering-out effect applied to separate organic solvent from aqueous solutions	Researcher, Delft University of Technology
7	Industry/Academia	Process engineering: Chemicals production from Lignocellulosic Biomass via Fast Pyrolysis, Oxy-fuel Biomass Gasification	Engineer, Shell

can be scored 0, 3, 5, or 7 with respect to a particular criterion: 0: the alternative has no performance with respect to the criterion which is because, for instance, the criterion is not relevant for the alternative in question; 3: the alternative has a poor performance with respect to that criterion; 5: the alternative has a good performance with respect to that criterion; 7: the alternative has an excellent performance with respect to that criterion. The overall scores V_i can be obtained as follows.

$$V_i = \sum_{j=1}^{n} w_j p_{ij} \quad (2)$$

$$\mathrm{w_j} \geq 0, \sum \mathrm{w_j} = 1 \quad (3)$$

The overall scores of all alternatives are compared and the best alternative is the one with the highest overall value.

3.2. BWM

The best-worst method (BWM) is a powerful MCDM method which can be used to find the weights of the criteria. The BWM was developed by Rezaei (2015, 2016), and has been successfully applied in several real-world applications such as supplier segmentation (Rezaei et al., 2015), supplier selection (Gupta and Barua, 2017; Rezaei et al., 2016), evaluating barriers of technological innovation (Gupta and Barua, 2016), evaluating success factors of technological innovation (Ghaffari et al., 2017), evaluating freight bundling configurations (Rezaei et al., 2017), water security management (Chitsaz and Azarnivand, 2016), evaluating external factors affecting sustainability in supply chain management (Ahmad et al., 2017), scientific output evaluation (Salimi, 2017), and efficiency measurement of PhD projects (Salimi and Rezaei, 2016). The salient features of the BWM are: having a very structured pair-wise comparison system, its data efficiency, and producing highly reliable results.

Here we present the five steps of the linear BWM (Rezaei, 2015, 2016):

Step 1

Determining a set of criteria. In this study we have four main criteria: characteristics of the format supporter, characteristics of the format, format support strategy, and other stakeholders, accordingly to the categorization by Van de Kaa et al. (2011).

Step 2

Identifying the best criterion and the worst criterion. The experts decided which factors they thought were the best and the worst during the second round of interviews.

Step 3

Comparing preferences of the best criterion to the other criteria. The preference comes in the score of 1–9 (1: i is equally important to j; 9: i is extremely more important than j). This was also done during the second round of interviews with experts. The result is a Best-to-Others vector:

$$A_B = (a_{B1}, a_{B2}, \cdots, a_{Bn}), \quad (4)$$

where a_{Bj} is the preference of best criterion B to criterion j.

Step 4

Comparing preferences of the other criteria to the worst criterion. The preference comes in the score of 1–9 as explained above. This is also done through the second phase interview with experts. The result is Others-to-Worst vector:

$$A_W = (a_{1W}, a_{2W}, \cdots, a_{nW})^T, \quad (5)$$

where a_{jW} is the preference of criterion j to the Worst criterion W.

Step 5

Solving the following model, the optimal weights are obtained.$\{|w_B - a_{Bj}w_j|\} \leq \xi^L$ for all j.$\{|w_j - a_{jW}w_W|\} \leq \xi^L$ for all j

$$\sum_j w_j = 1 \quad (6)$$

$w_j \geq 0$ for all j.

By solving the problem, we can obtain the optimal weight and ξ^{L*}. ξ^{L*} is an indicator of consistency, where the closer numbers to zero show better consistency.

3.2.1. Deriving the global weights

The factors were clustered into four categories based on Van de Kaa et al.'s framework so that the interviewees first needed to compare four choices. First, the weight of each category was determined by making a pair-wise comparison between categories. These weights are called category weights. Next, pair-wise comparisons were made for the factors within each category to find the local weight of factors. To find the *global weights*, the *category weights* and their associated *local weights* were multiplied.

Initially, interviews with the experts were done to make pair-wise comparisons with the BWM method. We proceeded with the calculations until all the categories and local weights were obtained. Then, two more experts were added to check the convergence of the results. We found that the weights did not change much and did not affect the final ranking. Thus, we concluded that by conducting interviews with seven experts, our data is converging and sufficiently valid.

3.3. Ranking alternatives

To determine how each technology scored on each factor, the relevance of each factor was evaluated based on both secondary and primary sources. The relevance scores ranged from 3 (less relevant), 5 (relevant) to 7 (highly relevant). These relevance scores were then multiplied by the factor weights to determine a score. These scores were then added together to get a final score for each technology.

4. Results

In this section the results of our analysis are presented and analyzed. First, the relevant factors are presented and the consistency ratio is analyzed to examine the reliability of the data. We then analyze the weights of the factors and predict the dominant technology.

12 relevant factors were found in four separate categories. In the category 'characteristics of the format support', 'financial strength', 'operational supremacy', and 'learning orientation' had the highest relevance scores. In the category of 'characteristics of the format', 'technological superiority', 'compatibility', and 'flexibility' scores the highest. In the category 'format support strategy', we found 'pricing strategy' and 'distribution strategy' to be relevant. Finally, in the category 'other stakeholders', 'previous installed base', 'regulator', 'effectiveness of the format development process', and 'network of stakeholders' had the highest relevance score.

The BWM method was used to verify the results on reliability by analyzing the consistency ratio. The results are presented in Table 3.

In Table 2, ξ^{L*} represents the consistency ratio. The numbers shown are the consistency of the scores given by the seven experts. We evaluated the consistency by making a pair-wise comparison within categories (the row categories) and then evaluated the consistency of each pair-wise comparison within each category.

Table 3
Consistency ratio result.

	ξ^{L*} Expert						
	1	2	3	4	5	6	7
Categories	0.0702	0.0650	0.1395	0.0650	0.1088	0.0520	0.0807
Characteristics of the format supporter	0.0571	0.1091	0.0865	0.0571	0.0625	0.0625	0.1563
Characteristics of the format	0.0417	0.1091	0.2347	0.1042	0.0625	0.0417	0.0577
Format support strategy	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Other stakeholders	0.1172	0.0678	0.1842	0.1220	0.0645	0.0650	0,0940

Table 4
Local and average global weights.

Factors	Expert 1	Expert 2	Expert 3	Expert 4	Expert 5	Expert 6	Expert 7	Local average weight	Average global weight
Characteristics of the format supporter	0.2105	0.4715	0.5686	0.2682	0.1156	0.0982	0.1883		**0.2745**
Financial strength	0.0301	0.3086	0.4429	0.1686	0.0145	0.0553	0.1354	0.5159	0.1651
Operational supremacy	0.0481	0.0429	0.0437	0.0383	0.0217	0.0123	0.0118	0.1306	0.0313
Learning orientation	0.1323	0.1200	0.0820	0.0613	0.0795	0.0307	0.0412	0.3535	0.0782
Characteristics of the format	0.5614	0.2683	0.0536	0.1789	0.5850	0.5376	0.0448		**0.3185**
Technological superiority	0.3041	0.1756	0.0038	0.1379	0.4461	0.2912	0.0034	0.4885	0.1946
Compatibility	0.1637	0.0683	0.0394	0.0149	0.0585	0.0896	0.0267	0.3182	0.0659
Flexibility	0.0936	0.0244	0.0104	0.0261	0.0804	0.1568	0.0147	0.1933	0.0580
Format support strategy	0.1579	0.0813	0.1416	0.0813	0.2313	0.2948	0.2825		**0.1815**
Pricing strategy	0.1184	0.0678	0.1275	0.0136	0.2082	0.1965	0.2543	0.7310	0.1409
Distribution strategy	0.0395	0.0136	0.0142	0.0678	0.0231	0.0983	0.0283	0.2690	0.0407
Other stakeholders	0.0702	0.1789	0.2361	0.4715	0.0680	0.0694	0.4843		**0.2255**
Previous installed base	0.0115	0.0879	0.0478	0.0863	0.0190	0.0124	0.0797	0.2376	0.0492
Regulator	0.0153	0.0152	0.1478	0.2875	0.0336	0.0056	0.2731	0.3826	0.1112
Effectiveness of the format development process	0.0376	0.0333	0.0273	0.0288	0.0095	0.0186	0.1062	0.2180	0.0373
Network of stakeholders	0.0059	0.0424	0.0130	0.0690	0.0059	0.0327	0.0253	0.1618	0.0277

Table 5
Ranking of alternatives.

	Combustion		Gasification		Pyrolysis	
	Performancescore	Weighted score[a]	Performancescore	Weighted score	Performancescore	Weighted score
Characteristics of the format supporter						
Financial strength	5	0.83	7	1.16	5	0.83
Operational supremacy	5	0.16	5	0.16	5	0.16
Learning orientation	5	0.39	5	0.39	5	0.39
Characteristics of the format						
Technology superiority	5	0.97	7	1.36	7	1.36
Compatibility	7	0.46	5	0.33	3	0.2
Flexibility	5	0.29	5	0.29	5	0.29
Format support strategy						
Pricing strategy	7	0.99	5	0.7	5	0.7
Distribution strategy	3	0.12	3	0.12	3	0.12
Other stakeholders						
Previous installed base	5	0.25	5	0.25	5	0.25
Regulator	5	0.56	5	0.56	5	0.56
Effectiveness of the format development process	5	0.19	3	0.11	3	0.11
Network of stakeholders	3	0.08	3	0.08	3	0.08
Total		**5.28**		**5.51**		**5.05**

[a] The weighted scores are obtained by multiplying the performance scores by their corresponding weights. For instance for 'financial strength' of 'combustion', the performance score is 5 and the weight of 'financial strength' is 0.1651, so we have 5 × 0.1651 = 0.83.

The result is considered consistent when ξ^{L*} is near zero (Rezaei, 2015, 2016). Looking at Table 3, the categories show good consistency results.

Table 4 presents the weights for the categories and the underlying factors for technology dominance. These weights are based on the average results of the seven experts.

Table 5 presents the results of the final step (raking of alternatives).

5. Discussion

5.1. Interpretation of the weights of the relevant factors

From Table 3 it can be concluded that technological superiority, financial strength, pricing strategy and the regulator are the most important factors. It appears that these factors are also the most important within their categories. In this section, these results are explained.

It can be concluded that 'characteristics of the format' is the most important category of factors for technology dominance (average global weight of 0.3185). Thus, it appears that this is more important than having an installed base or having the strategies to influence that installed base and the resources needed to effectively pursue such strategies. One of the reasons could be that biomass plants are not consumption goods, but are installations which are used to produce and sell electricity, heat and/or fuel. Therefore, it is important to what extent the technology can fulfill its purpose in an effective, efficient, and cost-effective way. Within the 'characteristics of the format' category 'technological superiority' is the most important factor for technology dominance in the biomass industry (average global weight of 0.1946). This is most probably because of the argument given above – the importance of cost-effectiveness and cost-efficiency for the owner of the biomass conversion plant. Prior research into other cases has also emphasized the importance of this factor. For example, in the battle for a multichannel audio sound format, Dolby's AC-3 format was clearly technologically superior whereas the competing MPEG 2 Audio format was technologically in superior partly because it was backwards compatible with MPEG 1 and partly because it was plagued by bugs (Van de Kaa and De Vries, 2015). Another reason why technological superiority is found to be so important in the biomass case could be because biomass conversion technology, especially pyrolysis, is still improving in terms of efficiency.

The second most important factor is financial strength (average global weight of 0.1651). In format wars, financial resources are essential to apply format support strategies such as market campaigns to increase anticipated and expected installed base (Schilling, 2013). This is so important because managing consumer expectations is crucial in network markets (Shapiro and Varian, 1999a). However, for biomass conversion technologies there are no network externalities, because the biomass conversion technology chosen by others does not influence the value that the owner derives from the technology. So why is financial strength then so important? Financial resources are needed for R&D projects, to construct new plants and to improve efficiencies. There is a huge difference between the investment cost of the three technologies (IRENA, 2012). The investment cost for various biomass to power combustion systems varies between €480/kW and €1040/kW, for a biomass gasification plant these costs range between €1280/kW and € 1840/kW, and for a pyrolysis plant, it would involve investment of around €4960/kW (Wright and Brown, 2011). Financial strength overpowers most of the factors as it serves as an enabler of the development.

The third most important factor is pricing strategy (average global weight of 0.1409). In format wars, pricing strategy is often mentioned as a crucial factor for technology dominance. Penetration pricing strategies (Katz and Shapiro, 1985) are used to try to quickly build up an installed base (Katz and Shapiro, 1986). Under the influence of network externalities, the installed base will grow until a dominant position for the format is reached. The factor pricing strategy works differently in the case of biomass. As we discussed above, biomass conversion plants are expensive. Especially the pyrolysis technology comes at a high price and investors may be reluctant to invest in this technology.

The fourth most important factor is the regulator (average global weight of 0.1112). In format wars, regulatory agencies sometimes intervene and enforce a format on the market in which case the format wars ends prematurely (David and Greenstein, 1990). In the case of biomass, the regulator can push a format towards dominance. The regulator has an interest in biomass conversion technology since it could provide energy with less environmental impact (McKendry, 2002; van Thuijl and Deurwaarder, 2006). The regulator can play a role by providing support and consistent policies related to biomass (Negro et al., 2008). Since the Netherlands has a well-established natural gas infrastructure, the Dutch regulator would prefer to achieve the renewable energy target of 14% in 2020 without a major change to the infrastructure. Thus, Dutch regulators may tend to support green gas production by means of gasification more than other biomass conversion options (van der Drift, 2013).

5.2. Technology dominance

From Table 4, it can be concluded that biomass gasification has the highest overall score of 5.51 and thus has the highest chance of becoming the dominant technology in the biomass industry in the Netherlands. Compared to the other technologies, gasification scores the highest on technological superiority and financial strength, and scores adequately on compatibility and pricing strategy.

The results show that gasification and pyrolysis score better (both 1.36) than combustion (0.97) in terms of technology superiority. Indeed, gasification and pyrolysis are generally more efficient and emit less CO_2 than combustion. Gasification scores higher for financial strength. Although it costs twice as much as combustion, it is more efficient, gives more flexibility of end market, and produces lower emissions. Pyrolysis and combustion score the same for financial strength due to an apparent tradeoff with technological performance. Pyrolysis is technologically superior but seven times more expensive than combustion, whereas the latter is less advanced but cheaper. Combustion has the highest score for pricing strategy, because it is a more well-known technology and because it is cheaper. It also scores the highest for compatibility, as it can best be combined with existing coal combustion plants. The co-combustion of biomass waste streams is a cheap way of producing renewable energy that results in a lower product price or, vice versa, lower production costs allowing higher margins (Kwant and van Dijk, 2001). However, gasification is currently also being implemented into co-gasification.

In general, it can also be observed that the other technologies are comparable with respect to their scores, which indicates that the three technologies could continue to co-exist in the Netherlands instead of one technology becoming dominant. This also happens in similar format wars where network effects are apparent, but formats can find niches such as in the various generations of video gaming console platform battles (Gallagher and Park, 2002).

5.3. Comparison with other studies

The question arises how the results compare with other MCDM studies in which renewable energy technologies are compared. Some research has been conducted on which renewable energy technology alternative should be invested in general. For example, recently, Haddad et al. (2017) and Al Garni et al. (2016) find that solar power is best applicable for Algeria and Saudi Arabia respectively while Stojcetovic et al. (2016) find that wind energy is most suited for a company based in Serbia and Štreimikienė et al. (2016) finds that for Lithuania the biomass technology alternative is most suitable. However, these scholars focus on renewable energy technologies in general while our study focuses specifically on the biomass technology and various competing options within this domain. Consequently, these scholars also take other, higher level, factors into account such as social acceptability and political acceptance.

Little research has been conducted on analyzing the three technologies presented in this paper in other regions. One exception is Cutz et al. (2016). However, they evaluate the preference among policymakers for various biomass technologies in Central America. They include a fourth option in their analysis; improved cooking stoves which are used for heat production for cooking, and find that these and combustion technology are the preferred option among policymakers. The reason for this preference is the following. As observed by Cutz et al. (2016) in Central America there is no infrastructure for the biomass value chain so 'simple' technologies using local resources (such as improved cooking stoves and combustion) are preferred. However, in The Netherlands, the infrastructure is mature so this is not a barrier and this could be the reason behind the difference in findings between Cutz et al. (2016) and our paper. Another difference between the paper is that our paper focuses on biomass technologies used for electricity production while the Cutz et al. paper takes a broader focus.

5.4. Theoretical contributions and recommendations for future research

We contribute to the extant literature on format wars by applying the framework of Van de Kaa et al. (2011) to the case of biomass conversion technology in The Netherlands. The framework can be used to assess the importance of factors for technology dominance and to assess which format will have the highest chance of achieving dominance in this case. More specifically, we contribute to the literature by providing further evidence that the process of technology selection can be assessed (Schilling, 2002; Suarez, 2004). We go one step further and show that actual weights can be established for factors for technology dominance in the case of biomass technology, thus building on prior research that provides weights for other cases (Van de Kaa et al., 2014a; Van de Kaa et al., 2014b; Van de Kaa et al., 2014c). Also, this is one of the first times that the best-worst method has been applied, so we have increased evidence for its applicability as a valid MCDM method.

Future research could study other technology battles using the best worst method so that weights for factors for standard dominance can be established in other technological domains. This will add to our understanding of factors for technology success and it will further test the applicability of the BWM method.

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