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Role of bioenergy in the future cities
Deliverable 3.1.3

Sustainable Bioenergy
Solutions for Tomorrow

Cleen Oy
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Name of the report: Role of bioenergy in the future cities

Key words: clustering, bioenergy technologies, sustainability criteria, urban energy system, energy storage

Summary

Deliverable 3.1.1 focused on energy systems and the role of bioenergy in five Finnish and five German case cities. To assess the role of bioenergy in other cities and to search for potential new markets in which the successful practices from the case cities can be transferred, case cities need to be generalized. To achieve this generalization, there were three objectives for this study. The main objective was to cluster the case cities representing a group of similar cities by using general and energy-specific characteristics. The second objective was to identify and describe the bioenergy technologies that are assumed to have importance in urban environments, and assess the factors affecting the potential of different bioenergy concepts in future cities. The third objective was to select sustainability criteria to assess sustainable urban energy systems. For the Finnish city clusters, the generalization resulted in four clusters and four clustering characteristics. It can be concluded that particularly two clusters can be useful in searching new Finnish markets for transferring successful urban practices. For the German cities, seven characteristics were included in the clustering. It can be concluded that particularly three clusters can be useful in searching new German markets for transferring successful urban practices. Due to similar population distributions in Germany and Europe, it could further be argued that, to a certain extent, the German city clusters could provide a decent basis for assessing the adaptability of the successful practices found in the German case cities to a large number of European cities with similar population numbers. Overall, it could be argued that the city clusters can be used as a screening tool in planning future urban energy and bioenergy systems prior to more detailed assessments. One example for successful urban practices transferable to other urban markets within the same city cluster is the technologies used for bioenergy production. Assessing the suitability of bioenergy technologies in different city clusters requires analysis of the technologies and comparison of the technology requirements to city conditions. To provide a basis for further technology analyses, ten bioenergy technologies that are assumed to have importance in urban environments were described in this report. The maturity of the technologies described varies greatly, and in the short term, technologies in the commercial and early commercial development stage are expected to be important in urban bioenergy systems. However, the technologies which are currently in an early development stage may also be implemented in the case cities, for instance as demonstration plants, due to reputational reasons. The role of bioenergy is, among others, dependent on the biomass availability in the city and surrounding area. Waste materials are a significant city-internal feedstock for energy production and thus have potential in future urban environments. Bioenergy may also have an important role in increasing the flexibility of renewable energy systems. Moreover, based on sustainability criteria and selection requirements identified in literature, a set of sustainability criteria was selected using a series of sorting steps and a scoring process. The process resulted in a final set of seven environmental, economic, technical and social criteria, which can be useful for the further development of the clustering tool.

Tampere, October 2014

Contents

1 Introduction

Deliverable 3.1.1 focused on energy systems and the role of bioenergy in five Finnish and five German case cities. Among others, energy and climate strategies of the case cities were described and analyzed in the report. Furthermore, an effort was made to identify common development trends and find forerunner concepts among the chosen case cities. The objective of deliverable 3.1.2 was to evaluate feedstock potential especially for energy, but also for nutrient and material, recovery in integrated urban biomaterial management system.

The present report mainly builds on the findings from deliverable 3.1.1. In this report, the case cities are generalized to assess the role of bioenergy in other cities, which in turn facilitates the search for potential new markets to where the successful practices from the case cities can be transferred. To achieve this generalization, there were three objectives for this study. The main objective was to cluster the case cities representing a group of similar cities by using general and energy-specific characteristics. The second objective was to identify and describe the bioenergy technologies that are assumed to have importance in urban environments, and assess the factors affecting the potential of different bioenergy concepts in future cities. Bioenergy technologies are one example for successful urban practices that can be transferred from one city to other urban markets within the same city cluster. The last objective was to select sustainability criteria to assess sustainable urban energy systems. In general, selecting appropriate sustainability criteria is crucial to assess the sustainability of a project, development or case study because this choice can influence the results of an assessment significantly.

The structure of this report mirrors the objectives of the study starting with section 1 focusing on city clustering. First, clustering characteristics are discussed, followed by the clustering of the case cities, before the use of the city clusters as a screening tool for new markets and successful practices is explained. To provide a basis for further technology analyses, the bioenergy technologies that are assumed to have importance in urban environments are briefly described in section 2. Moreover, the potential of different bioenergy concepts is described in section 3. In section 4, the selection of sustainability criteria is outlined.

2 City clustering

So far the analysis of the urban energy systems has focused on analysing the energy systems in case cities. Deliverable 3.1.1 focused on energy systems and the role of bioenergy in five Finnish and five German case cities. It was noticed that although all case cities were aiming to increase their bioenergy use, in most of the cities bioenergy had only a supportive role. In two of the case cities bioenergy was, however, noticed to have a more important role. Furthermore, the used and planned bioenergy measures varied between the cities, transport biofuels and biomass-based heat and CHP production being among the most popular measures.

To enable applying the information obtained from the case cities in assessing the role of bioenergy in other cities, case cities need to be generalized. Case cities can be clustered to represent a group of similar cities. When assessing the role of bioenergy in the cities, clustering is based on city characteristics describing for instance the energy infrastructure and biomass availability. Clustering can be used to search for potential new markets, where the successful practices from the case cities can be transferred. For instance, it can be used to find other cities, where bioenergy can potentially have an important role in energy production.

This section presents the city clustering procedure. In section 2.1, the clustering characteristics are first discussed. In section 2.2, the clustering-relevant characteristics of the case cities are presented and summarized to form the city clusters. In section 2.3, the use of the city clusters as a screening tool for new markets and successful practices is explained.

2.1 Clustering characteristics

The characteristics relevant for the city clustering can be divided in general and energy-specific characteristics. General characteristics are population, population density, population growth, and climate zone. Each of the characteristics can be used to divide cities in different groups or clusters. For example, cities can be classified based on their population number as global cities, metropolises, and large, mid-large, mid-small, and other cities. The population number classification is shown in Table 2.1. Furthermore, the classifications based on population density, population growth, and climate zone are shown in Table 2.2, Table 2.3 and Table 2.4, respectively.

Table 2.1: Population number classification

Population class	Population number
Global city	> 2 000 000
Metropolis	1 000 000 – 2 000 000
Large city	500 000 – 1 000 000
Mid-large city	250 000 – 500 000
Mid-small city	150 000 – 250 000
Small city	10 000 – 150 000
Others	< 10 000

Table 2.2: Population density classification

Population density class	Population density [$1/km^2$]
Very high	> 3000
High	2000–3000
Medium	1000–2000
Low	500–1000
Very low	< 500

Table 2.3: Population growth classification

Population growth class	Population growth [%]
High growth	> 10
Medium growth	5–10
Modest growth	0–5
Modest decline	-(0–5)
Medium decline	-(5–10)
High decline	< -10

Table 2.4: Climate zone classification

Climate zone	*Description*
Oceanic	Mild, no dry season, warm summers
Humid continental	Severe winters, no dry season, warm summers
Subarctic	Severe winters, no dry season, cool summers

Energy-specific characteristics focus on cities´ greenhouse gas (GHG) emission reduction targets, current energy infrastructure, and biomass availability. GHG emission reduction targets can be identified from the energy strategies of the cities, and the classification is shown in Table 2.5. Current energy infrastructure is described by district heating network length and density, and the proportion of CHP in electricity production. The classifications of these characteristics are shown in Table 2.6 and Table 2.7, respectively. Furthermore, the estimations of the availability of agriculture and forest biomasses are based on the land used for agriculture and forestry, respectively. The estimations are based on the total agriculture and forestry land without considering which proportion of the land could actually be used in biomass cultivation for energy production. The classification for biomass availability is shown in Table 2.8.

Table 2.5: GHG emission reduction target classification

GHG emission reduction target class	GHG emission reduction target [%]
Very high	> 40
High	30–40
Medium	20–30
Low	10–20
Very low	< 10

Table 2.6: District heating network length and density classification

District heating network	
Length	
Length class	***Length [km]***
Very high	> 2000
High	1000–2000
Medium	500–1000
Low	200–500
Very low	< 200
Density	
Density class	***Density [km/km^2]***
Very high	> 2.5
High	2.0–2.5
Medium	1.5–2.0
Low	0.5–1.0
Very low	< 0.5

Table 2.7: CHP proportion classification

CHP proportion classification	Proportion of CHP in electricity production capacity [%]
Very high	> 90
High	80–90
Medium	50–80
Low	< 50

Table 2.8: Biomass availability classification

Biomass availability class	Land used for agriculture or forestry [ha]
Very high	> 50 000
High	10 000–50 000
Medium	5 000–10 000
Low	1 000–5 000
Very low	< 1 000

Depending on the aims set for the clustering, different characteristics can be chosen. The characteristics presented in this section were chosen to enable estimating the potential role of bioenergy in different cities. The clustering principle can, however, be applied also outside of the bioenergy sector, by selecting suitable characteristics which meet the aims set for the clustering. For instance, new urban markets for solar panels could be searched by clustering cities based on characteristics such as solar irradiance, price of electricity, and emission reduction targets.

2.2 Clustering of case cities

Earlier within the BEST project, five Finnish and five German cities were selected as case cities to represent urban energy systems in Finland and Germany. When selecting the case cities, cities with high population number and forerunner energy strategies were prioritized. Furthermore, geographical and size diversification was considered. The cities selected were Espoo, Tampere, Turku, Joensuu, and Vaasa and Berlin, Hamburg, Munich, Wuppertal, and Freiburg im Breisgau. The selected case cities, their energy infrastructure and energy strategies, and bioenergy use and plans were presented in Deliverable 3.1.1.

As shown in Table 2.1, cities can be divided in several size groups by their population number. Figure 2.1 shows how German cities are distributed in the largest 5 size groups. From the case cities selected, Berlin is a global city and Hamburg and Munich metropolises. Wuppertal is a mid-large city and Freiburg im Breisgau a mid-small city. However, there is no case city representing large cities with a population number between 500 000–1 000 000. Therefore, a new case city was selected to represent this population category. Given the focus on geographical distribution and forerunner energy strategies, Dresden was chosen for closer examination.

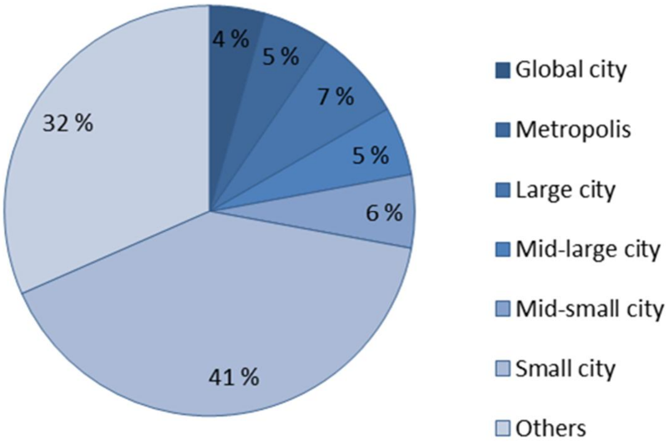

Figure 2.1: Population distribution in Germany (Destatis 2011)

Furthermore, studying the energy systems and energy strategies of Wuppertal revealed that it is a follower, not a forerunner city. Furthermore, the information available concerning Wuppertal´s energy systems and strategies was found to be limited. Therefore, Wuppertal was decided to be replaced by another city. Wuppertal is located in the Ruhr region, which is the largest urban agglomeration in Germany. The region is very densely populated and has a population of circa 5 million, which means it is the fifth largest urban area in Europe (Regionalverband Ruhr 2014). It could be argued that the urban agglomeration of polycentric nature in the Ruhr region, and even more so in the Rhine-Ruhr metropolitan region, which is the largest metropolitan region in Germany with circa 11.5 million inhabitants (Metropole Ruhr 2010), can be regarded as a megacity – the only city of this kind in Germany. Thereby Wuppertal was decided to be replaced by another city in the Ruhr region. Furthermore, a city in the same population category was searched. Finally, Gelsenkirchen was chosen for closer examination.

In the following subsections, the clustering-relevant characteristics of the case cities are described, and they are summarized to describe the city clusters. First, the five Finnish cities are described and the city clusters based on the Finnish case cities are formed. Then the same clustering procedure is applied to the six German case cities.

The proportion of CHP in electricity production was estimated by the electrical capacities of the power plants located in each city. For German cities, only power plants with an electrical capacity higher than 10 MW were taken into consideration. It is to be noted that this approach results in CHP proportions that may remarkably differ from the proportion of electricity produced by CHP in total electricity consumption. Biomass availability was estimated separately for agriculture and forest biomass by the land area used in forestry and agriculture. For the Finnish cities, only provincial information was available. Hence, the land area suitable for biomass production was estimated by proportioning it to the total area of the city and the province. This estimation may give overrated land areas available for energy crop cultivation, because in truth, the proportion of the land used in agriculture and forestry is smaller in the cities than in the surrounding area. Moreover, the competition for biomass for other uses, such as food production, needs to be considered. Thereby the estimation based on total agriculture and forest areas only provides an indication of maximal theoretical land area available for biomass production.

2.2.1 Finnish case cities

In this section, the five Finnish case cities – Espoo, Tampere, Turku, Joensuu and Vaasa – are briefly described. Then, city clusters are formed based on these cities, and the applicability of the city clusters is discussed.

2.2.1.1 Espoo

Espoo is the only mid-large city in Finland. It has a population of 253 950, which represents 4.7 % of the population of Finland (Väestörekisterikeskus 2012). The population density in Espoo is 813 1/km^2 (Väestörekisterikeskus 2012; Maanmittauslaitos 2013), and the estimated population growth until 2020 11.7 % (Tilastokeskus 2012). Espoo is located on the southern coast of Finland. According to the Köppen climate classification, Espoo's climate can be regarded as humid continental, which means it is humid with severe winters, no dry season, and warm summers (Chen and Chen 2013; Chen H. 2014).

Espoo has a target of reducing its GHG emissions by 28 % from the level of 1990 until 2020 (Covenant of Mayors 2011). The length of the district heating network in Espoo is 789.5 km, and the density 2.53 km/km^2 (Energiateollisuus ry 2012; Maanmittauslaitos 2013). 100 % of the capacity of electricity production in Espoo is based on CHP (HSY 2012, Fortum 2014). The estimated land areas used in agriculture and forestry are 6 200 (Maanmittauslaitos 2013; Maataloustilastot 2014) and 16 100 ha (Maanmittauslaitos 2013; Metla 2014), respectively.

2.2.1.2 Tampere

Tampere is one of the three mid-small cities in Finland. Its population, 215 529, represents 4.0 % of the Finnish population, whereas all mid-small cities represent 11.1 % of the population (Väestörekisterikeskus 2012). The population density of Tampere is 411 1/km^2 (Väestörekisterikeskus 2012; Maanmittauslaitos 2013), and the population is estimated to increase by 6.7 % until 2020 (Tilastokeskus 2012). Tampere is located in south-western Finland. According to the Köppen climate classification, Tampere has a borderline humid continental climate/subarctic climate, which means severe winters, no dry season, and warm to cool summers (Chen and Chen 2013; Chen H. 2014).

Tampere aims to reduce its GHG emissions by 30 % from 1990 to 2030 (Tampereen kaupungin ilmastostrategia 2010). The length of the district heating network in Tampere is 504.1 km, and the density 0.96 km/km^2 (Energiateollisuus ry 2012; Maanmittauslaitos 2013). 96 % of the electricity production capacity in Tampere is based on CHP (Tampereen Sähkölaitos 2013). The land areas used for agriculture and forestry are estimated as 6 800 (Maanmittauslaitos 2013; Maataloustilastot 2014) and 17 600 ha (Maanmittauslaitos 2013; Metla 2014), respectively.

2.2.1.3 Turku

Turku is a mid-small city with a population of 178 564, which represents 3.3 % of the population in Finland (Väestörekisterikeskus 2012). In Turku, there are on average 727 inhabitants per km^2 (Väestörekisterikeskus 2012; Maanmittauslaitos 2013), and the population growth until 2020 is estimated to be 3.8 % (Tilastokeskus 2012). Turku is located on the south-west coast of Finland. According to the Köppen climate classification, Turku’s climate can be regarded as humid continental, which means it is humid with a severe winter, no dry season and a warm summer (Chen and Chen 2013; Chen H. 2014).

The GHG emission reduction target in Turku is 20 % from the 1990 level until 2020. The district heating network is 351.3 km long and its density is 1.43 km/km^2. The electricity is mainly produced in neighboring municipality Naantali by a coal CHP plant with an electrical capacity of 290 MW (Energiavirasto 2014). The areas used for agriculture and forestry are estimated to be 6800 (Maanmittauslaitos 2013; Maataloustilastot 2014) and 26 300 ha (Maanmittauslaitos 2013; Metla 2014), respectively.

2.2.1.4 Joensuu

Joensuu is a small city with a population of 73 697. The population of Joensuu represents 1.4 % of the Finnish population, whereas all small cities represent 54.4 % of the population. (Väestörekisterikeskus 2012) The population density in Joensuu is 31 1/km^2 (Väestörekisterikeskus 2012; Maanmittauslaitos 2013). The population is estimated to increase by 3.2 % until 2020 (Tilastokeskus 2012). Joensuu is located in eastern Finland. According to the Köppen climate classification, Joensuu’s climate can be regarded as subarctic, which means severe winters, no dry season, and cool summers (Chen and Chen 2013; Chen H. 2014).

Together with the neighboring municipalities Kontiolahti, Liperi, Outokumpu, and Polvijärvi, Joensuu aims to reduce the GHG emissions by 16 % from 2005 level until 2020 (Joensuun seutu 2009). 97 % of the electrical capacity in Joensuu is based on CHP production (Energiavirasto 2014). The length of the district heating network in Joensuu is 198 km, and its density is 0.08 km/km^2 (Energiateollisuus ry 2012; Maanmittauslaitos 2013). The estimated land areas used in agriculture and forestry are 11 400 (Maanmittauslaitos 2013; Maataloustilastot 2014) and 194 400 ha (Maanmittauslaitos 2013; Metla 2014), respectively.

2.2.1.5 Vaasa

Vaasa is a small city with a population of 60 267, which represents 1.1 % of the population in Finland (Väestörekisterikeskus 2012). Vaasa has a population density of 165 1/km^2

(Väestörekisterikeskus 2012; Maanmittauslaitos 2013), and its population growth until 2020 is estimated to be 7.2 % (Tilastokeskus 2012). Vaasa is located on the west coast of Finland. According to the Köppen climate classification, Vaasa's climate can be regarded as subarctic, with severe winters, no dry season, and cool summers (Chen and Chen 2013; Chen H. 2014).

Vaasa has published no numerical targets for GHG reduction. Second phase of the energy and climate program has been started in 2014, and concrete action plan will be created (Vaasa 2014). The district heating network in Vaasa is 211.1 km long and has a density of 0.58 km/km^2 (Energiateollisuus ry 2012; Maanmittauslaitos 2013). 97 % of the capacity of the electricity production in Vaasa is based on CHP (Pohjolan Voima 2014; Westenergy 2014). The land areas used in agriculture and forestry are estimated as 9 100 (Maanmittauslaitos 2013; Maataloustilastot 2014) and 23 600 ha (Maanmittauslaitos 2013; Metla 2014), respectively.

2.2.1.6 Clustering of the Finnish case cities

The general characteristics of the Finnish case cities are summarized in Table 2.9. It shows that none of the Finnish case cities belongs to the three largest city size groups classified in Table 2.1. Furthermore, the population density in all the case cities is either low or very low. The population of all the cities is growing, but the growth rate varies. Moreover, all Finnish cities have either a humid continental or subarctic climate.

Table 2.9: General characteristics of Finnish case cities

	Espoo	**Tampere**	**Turku**	**Joensuu**	**Vaasa**
Population	253 950 Mid-large city	215 529 Mid-small city	178 564 Mid-small city	73 697 Small city	60 267 Small city
Population density *[1/km^2]*	809 Low	411 Very low	727 Low	31 Very low	165 Very low
Population growth *[%]*	11.7 High	6.7 Medium	3.8 Modest	3.2 Modest	7.2 Medium
Climate zone	Humid continental	Humid continental/ subarctic	Humid continental	Subarctic	Subarctic

Energy-specific characteristics of the Finnish case cities are summarized in Table 2.10. It shows that the GHG emission reduction targets in the Finnish case cities are very similar, varying from low to medium. Furthermore, the district heating network length and density are relatively low in all Finnish case cities with the exception of Espoo, where the density of the district heating network is very high. In contrast, the proportion of CHP in electricity production is very high in the Finnish case cities. The biomass availability is also estimated rather similar in the case cities. An exception to this is Joensuu, where the availability of both agriculture and forest biomass is estimated to be remarkably higher than in other case cities.

Table 2.10: Energy-specific characteristics of Finnish case cities

	Espoo	**Tampere**	**Turku**	**Joensuu**	**Vaasa**
GHG emission reduction target					
[%]	28	30	20	16	-[1]
	Medium	Medium	Low	Low	-
District heating network					
Length					
[km]	789.5	504.1	351.3	198	211.1
	Medium	Medium	Low	Very low	Low
Density					
[km/km^2]	2.53	0.96	1.43	0.08	0.58
	Very high	Low	Low	Very low	Low
Proportion of CHP in electricity production					
[%]	100	96	≈100[2]	97	97
	Very high	Very high	Very high	Very high	Very high
Biomass availability					
Agriculture biomass					
[ha]	6 200	6 800	6 800	11 400	9 100
	Medium	Medium	Medium	High	Medium
Forest biomass					
[ha]	16 100	17 600	26 300	194 400	23 600
	High	High	High	Very high	High

[1] Energy- and climate strategy under development

[2] Electricity mainly produced in neighboring municipality Naantali by 290 MW$_e$ CHP plant

In Table 2.11, the general and energy-specific characteristics are summarized to form city pre-clusters. Each city pre-cluster is based on one case city. The characteristics that are the same or very similar for all case cities were left out because they do not assist in differentiating city clusters to assess the role of bioenergy in those city clusters. For the Finnish case cities, those characteristics are population density, climate zone, GHG emission reduction targets, characteristics describing the CHP production, and the district heating network length.

Table 2.11: City pre-clusters based on Finnish case cities

	Pre-cluster 1	**Pre-cluster 2**	**Pre-cluster 3**	**Pre-cluster 4**	**Pre-cluster 5**
Population					
	Mid-large city	Mid-small city	Mid-small city	Small city	Small city
Population growth					
	High	Medium	Modest	Modest	Medium
District heating network density					
	Very high	Low	Low	Very low	Low
Biomass availability					
Agriculture biomass					
	Medium	Medium	Medium	High	Medium
Forest biomass					
	High	High	High	Very high	High

It can be seen that the differences between the city pre-clusters in Table 2.11 are in general very small. The only difference between pre-cluster 2 and pre-cluster 3 is the population growth that in pre-cluster 2 is medium and in pre-cluster 3 modest. Hence, pre-clusters 2 and 3 were combined to form one city cluster. Each of the other pre-clusters was chosen to represent one city cluster. As the availability of both agriculture and forest biomass was noticed to follow the same trend, they were combined as general biomass availability. The city clusters formed are shown in Table 2.12.

Table 2.12: Finnish city clusters

	Cluster 1	**Cluster 2**	**Cluster 3**	**Cluster 4**
Population				
	Mid-large city	Mid-small city	Small city	Small city
Population growth				
	High	Modest-medium	Modest	Medium
District heating network				
Density	Very high	Low	Very low	Low
Biomass availability				
	High	High	Very high	High

Cluster 1 represents mid-large cities with high population growth. As the majority of the Finnish cities belong to smaller size groups, cluster 1 is rather useless in searching new markets for transferring successful practices. Similarly only very few cities belong to cluster 2, which represents mid-sized Finnish cities with average characteristics. Based on the population number, clusters 3 and 4 represent a significantly larger number of cities. These two city clusters are distinguished by the biomass availability. Cluster 3 represents small cities with very high biomass availability. Numerous cities especially in northern and eastern part of Finland belong to this cluster. As Joensuu, the city on which the cluster is based, is a forerunner city in bioenergy, studying the biomass availability in cities of the same size group may reveal other cities in which the role of bioenergy is or has potential to be significant. Furthermore, cluster 4 represents small cities with average characteristics. Therefore, the cities belonging to this cluster are potential markets for the energy and bioenergy practices found successful in Vaasa, which was the ideal for the city cluster.

2.2.2 German case cities

In this section, the six German case cities – Berlin, Hamburg, Munich, Dresden, Gelsenkirchen, and Freiburg im Breisgau – are briefly described. Then, city clusters are formed based on these cities, and the applicability of the city clusters is discussed.

2.2.2.1 Berlin

Berlin is the only global city in Germany. Its population, 3 501 872, represents 4.3 % of the population in Germany. The population density is 3 927 1/km^2 (Destatis 2011), and the estimated population growth until 2020 is 5.6 % (Destatis. 2012; Senatsverwaltung für Stadtentwicklung und Umwelt. 2012). Berlin is located in the north-east of Germany. According to the Köppen climate classification, Berlin’s climate can be regarded as oceanic, which means it is mild with warm summers and no dry season (Chen and Chen 2013; Chen H. 2014).

Berlin aims to reduce its GHG emissions by 40 % until 2020 (Suck et al. 2011). The district heating network in Berlin is 1 750 km long and has a density of 1.95 km/km^2 (Destatis 2011; Suck et al. 2011; Vattenfall 2014). The proportion of CHP in electrical capacity is estimated as 98 % (Bundesnetzagentur 2014). Land used in agriculture and forestry are 3 951 and 16 349 ha, respectively (Amt für Statistik Berlin-Brandenburg 2012).

2.2.2.2 Hamburg

Hamburg is one of the three metropolises in Germany, and has a population of 1 798 836, which represents 2.2 % of the German population. All metropolises represent 5.2 % of the population. (Destatis 2011) The population density in Hamburg is 2 382 1/km^2 (Destatis 2011), and the estimated population growth until 2020 is 2.4 % (Destatis. 2012; Statistische Amt für Hamburg und Schleswig Holstein 2010). Hamburg is located in the north-west of Germany. According to the Köppen climate classification, Hamburg’s climate can be regarded as oceanic, which means it is mild with warm summers and no dry season (Chen and Chen 2013; Chen H. 2014).

Hamburg has a target of reducing GHG emissions by 40 % until 2020 (Behörde für Stadtentwicklung und Umwelt Hamburg 2012). The length and density of the district heating network in Hamburg are 770 km and 1.02 km/km^2, respectively (Destatis 2011; Vattenfall 2014). The percentage of CHP in the electricity production capacity is estimated as 94 % (Bundesnetzagentur 2014). Land areas used in agriculture and forestry are 18 559 and 4 807 ha, respectively (Statistisches Amt für Hamburg und Schleswig-Holstein 2014).

2.2.2.3 Munich

Munich is a metropolis with a population of 1 378 176. Its population represents 1.7 % of the population in Germany, while all three metropolises represent 5.2 % of the population (Destatis 2011). The population density per km^2 is 4 436 (Destatis 2011) and the estimated population growth until 2020 10.1 % (Destatis 2012; Landeshauptstadt München 2011). The city is located in the south-east of Germany. According to the Köppen climate classification, Munich has a borderline oceanic/humid continental climate, which means a mild climate with severe winters, no dry season, and warm summers (Chen and Chen 2013; Chen H. 2014).

The GHG emission reduction target of Munich is 50 % by 2030 (Karg et al. 2013). The length and density of the district heating network are 800 km and 2.57 km/km^2, respectively (Destatis 2011; Stadtwerke München 2014). The proportion of electricity production capacity based on CHP is estimated to be 89 %. The estimated agricultural land area is 5 186 ha and the estimated forestry land area is 1 480 ha (Bayerisches Landesamt für Statistik und Datenverarbeitung 2013).

2.2.2.4 Dresden

Dresden is a large city with a population of 529 781. The population of Dresden represents 0.68 % of the German population, whereas all ten large cities represent 7.10 % of the population. The population density in Dresden is 1 614 1/km^2. (Destatis 2011) The population in Dresden is estimated to increase by 4.6 % by 2020 (Destatis. 2012; Landeshauptstadt Dresden 2013a). Dresden is located in the eastern part of Germany. According to the Köppen climate classification, Dresden's climate can be regarded as oceanic, which means it is mild with warm summers and no dry season (Chen and Chen 2013; Chen H. 2014).

The GHG emission reduction target in Dresden is 40 % by 2030 compared to the 2005 level (Landeshauptstadt Dresden 2013b). The length and density of the district heating network are 519 km and 1.58 km/km^2, respectively (Destatis 2011; Drewag Netz GmbH 2011). Dresden has only one power plant with an electrical capacity over 10 MW, and as the power plant is a natural gas fired CHP plant (Bundesnetzagentur 2014), the estimated CHP proportion of the electrical capacity is 100 %. The estimated agricultural land area is 10 767 ha and the estimated forestry land area is 7 345 ha (Statistisches Landesamt Freistaat Sachsen 2013).

2.2.2.5 Gelsenkirchen

Gelsenkirchen is a mid-large city with 256 652 inhabitants. Its population represents 0.32 % of Germany´s population, while all 14 mid-large cities represent 5.41 % of the population. The population density in Gelsenkirchen is 2 446 per km^2. (Destatis 2011) The population decline between 2011 and 2020 is estimated to be 4.2 % (Destatis. 2012; Landesbetrieb Information und Technik Nordrhein-Westfalen 2012). Gelsenkirchen is located in the state of North Rhine-Westphalia in western Germany. It is in the northern part of densely populated Ruhr region, which is the largest urban agglomeration in Germany. According to the Köppen climate classification, Gelsenkirchen's climate can be regarded as oceanic, which means it is mild with warm summers and no dry season (Chen and Chen 2013; Chen H. 2014).

The GHG emission reduction target in Gelsenkirchen is 40 % by 2020 (Stadt Gelsenkirchen 2011). The estimated length of the district heating network in Gelsenkirchen, Essen and Bottrop is 632 km (Steag Fernwärme GmbH 2012). In proportion to the city areas of the three cities, the length of the district heating network in Gelsenkirchen is 158 km, and the density 1.52 km/km^2 (Landesbetrieb Information und Technik Nordrhein-Westfalen 2013; Steag Fernwärme GmbH 2012). 68 % of the electrical capacity is estimated to be based on CHP production (Bundesnetzagentur 2014). 901 and 1 400 ha of land are used in agriculture and forestry, respectively (Stadt Gelsenkirchen 2011; Gelsendienste 2005).

2.2.2.6 Freiburg im Bresigau

Freiburg im Bresigau is a mid-small city and has 229 144 inhabitants, which represents 0.29 % of the population in Germany. All 52 mid-small cities represent 5.80 % of the population. The population density in Freiburg im Breisgau is 1 497. (Destatis 2011). The population is estimated to increase by 0.2 % by 2020 (Destatis 2012; Statistisches Landesamt Baden-Württemberg. 2013).The city is located in the south-west of Germany. According to the Köppen climate classification, Freiburg's climate can be regarded as oceanic, which means it is mild with warm summers and no dry season (Chen and Chen 2013; Chen H. 2014).

Based on scenario ”Optimales Klimaschutz-Umfeld", the GHG emission reduction target in Freiburg im Breisgau is 29 % by 2020 (Timpe et al. 2007). No numerical data about Freiburg's district heating network could not be obtained. District heating is promoted by obligating buildings in some areas to be connected to the local district heating network. However, exceptions can be allowed to passive houses and houses with individual wood pellet heating systems (Timpe et al. 2007). Electricity production capacity is estimated to be 62 % based on CHP production (Bundesnetzagentur 2014). The agriculture and forestry land use is 3 614 and 6 560 ha, respectively (Statistisches Landesamt Baden-Württemberg. 2012).

2.2.2.7 Clustering of the German case cities

The general characteristics of the six German cities are summarized in Table 2.13. It shows that the case cities represent the five largest size groups classified in Table 2.1. The population density in the cities varies from medium in Dresden and Freiburg im Breisgau to very high in Berlin and Munich. The variation in population growth is even higher: Gelsenkirchen has a modest population decline, whereas the population growth in Munich is high. The climate zone, however, is very similar in all of the case cities.

Table 2.13: General characteristics of German cities

	Berlin	**Hamburg**	**Munich**	**Dresden**	**Gelsen-kirchen**	**Freiburg im Breisgau**
Population						
	3 501 872 Global city	1 798 836 Metropolis	1 378 176 Metropolis	529 781 Large city	256 652 Mid-large city	229 144 Mid-small city
Population density						
[1/km^2]	3 927 Very high	2 382 High	4 436 Very high	1 614 Medium	2 446 High	1 497 Medium
Population growth						
[%]	5.6 Medium growth	2.4 Modest growth	10.1 High growth	4.6 Modest growth	-4.2 Modest decline	0.2 Modest decline
Climate zone						
	Oceanic	Oceanic	Oceanic/ humid continental	Oceanic	Oceanic	Oceanic

Energy-specific characteristics of the German case cities are represented in Table 2.14. It shows that most of the German cities have high or very high GHG emission reduction targets. Only the GHG emission reduction target in Freiburg im Breisgau is medium, but when considering its reputation as the ‘Green city of Germany’, it can be assumed that the level of GHG emitted from the city is already on a relatively low level and further GHG reductions can be considered hard to achieve. Furthermore, the length of the district heating network is mostly higher than in the Finnish case cities, which is due to the bigger scale of the German case cities. When the length of the district heating network is proportioned to the city area, the variation is higher. The estimated density of the district heating network in Hamburg is low, whereas in Munich it is high. The district heating density is higher in the German cities than in the Finnish cities, because of the Finnish cities’ lower population densities. There is a lack of data regarding the proportions of the German case city populations connected to district heating networks, but it can be assumed that generally a higher proportion of the population is connected to district heating networks in the Finnish case cities. This assumption is based on the information that Dresden’s central district heating network, to which about half of Dresden’s homes are connected, is considered as one of the biggest in Germany (Landeshauptstadt

Dresden 2013c), whereas the lowest district heating network population coverage of the Finnish case cities is 57 % (Energiateollisuus ry 2013). Furthermore, the proportion of CHP in electricity production capacity is in most cities lower than in the Finnish case cities. Also in Berlin, Munich, and Hamburg the majority of the power plants producing electricity are based on CHP. Moreover, the biomass availability is lower than in the Finnish case cities, and the variety is higher. In Gelsenkirchen the availability of agriculture and forest biomass is very low and low, respectively, while in Dresden the availability of agriculture and forest biomass is high and medium, respectively. This can be explained by the different locations of the two cities. Gelsenkirchen is located in the northern part of the densely populated Ruhr region, which is the largest urban agglomeration in Germany, whereas Dresden is not close to other bigger cities.

Table 2.14: Energy-specific characteristics of German cities

	Berlin	**Hamburg**	**Munich**	**Dresden**	**Gelsenkirchen**	**Freiburg im Breisgau**
GHG emission reduction target						
[%]	40	40	47	40	40	29
	High	High	Very high	High	High	Medium
District heating network						
Length						
[km]	1 750	770	800	519	158	-[1]
	High	Medium	Medium	Medium	Very low	-
Density						
[km/km^2]	1.96	1.02	2.57	1.58	1.52	-[2]
	High	Low	Very high	High	High	-
Proportion of CHP in electrical capacity						
[%]	98	94	89	100	68	62
	Very high	Very high	High	Very high	Medium	Medium
Biomass availability						
Agriculture biomass						
[ha]	3 951	18 559	5 186	10 767	901	3 614
	Low	High	Medium	High	Very low	Low
Forest biomass						
[ha]	16 349	4 807	1 480	7 345	1 400	6 560
	High	Low	Low	Medium	Low	Medium

[1] No data could be obtained

[2] No data could be obtained

Alike in the clustering of the Finnish case cities, it can be noticed that the climate zone is very similar in all of the case cities and can thus be left out because this characteristic does not assist in differentiating city clusters to assess the role of bioenergy. However, other characteristics are varying more between the case cities and are therefore included in the clustering. Furthermore, it can be argued that unlike the Finnish case cities, all the German case cities have unique characteristic combinations. Each of the case cities was therefore chosen to represent one city cluster. The German city clusters are presented in Table 2.15.

Table 2.15: German city clusters

	Cluster 1	Cluster 2	Cluster 3	Cluster 4	Cluster 5	Cluster 6
Population	Global city	Metropolis	Metropolis	Large city	Mid-large city	Mid-small city
Population density	Very high	High	Very high	Medium	High	Medium
Population growth	Medium growth	Modest growth	High growth	Modest growth	Modest decline	Modest decline
GHG emission reduction target	High	High	Very high	High	High	Medium
District heating network						
Length	High	Medium	Medium	Medium	Very low	-
Density	High	Low	Very high	High	High	-
Proportion of CHP in electrical capacity	Very high	Very high	High	Very high	Medium	Medium
Biomass availability						
Agriculture biomass	Low	High	Medium	High	Very low	Low
Forest biomass	High	Low	Low	Medium	Low	Medium

Cluster 1 represents global cities with a very high population density and a medium population growth. As there is only one global city in Germany, cluster 1 is fairly useless in searching new markets for transferring successful practices. Similarly, both clusters 2 and 3 represent metropolises, although there are only three metropolises in Germany. Despite the first three clusters' limitations in searching new markets for transferring successful practices in Germany, these clusters can be considered useful on a European scale when considering the similarities between German and European cities in terms of population distribution (section 2.3). Clusters

4 to 6 represent a significantly larger number of cities in Germany and Europe. The cities in these clusters have in common a medium or high population density and relatively little changes in their population sizes are predicted. With the exception of cluster 6, it can be noticed that the GHG emission reduction targets are very ambitious in all clusters. Important to consider in this connection is the starting level, as higher GHG emission reduction targets can be considered more difficult to achieve when the level of GHG emitted from the city is already on a relatively low level. Naturally, there is a positive correlation between the lengths of the district heating networks and the city sizes. District heating network densities are generally high across the city clusters, with the exception of cluster 2. In that regard, particularly the difference between clusters 2 and 3, which both cover metropolises, is remarkable. This difference in district heating network densities can be explained by cluster 2’s lower population density. A difference between clusters 1–4 and clusters 5–6 can be observed when comparing the proportion of CHP in electrical capacity. In general, this proportion is higher in the larger cities (clusters 1–4). Important distinctions between the clusters can be made with respect to the availabilities of agricultural and forestry biomasses. It could be argued that these availabilities are highly location-dependent. For instance, both biomass availabilities are low for cluster 5, which represents a mid-large city located in the highly populated Ruhr region. A number of cities in the Ruhr region and other highly populated regions belong to this cluster or cluster 6, which characteristics are mostly similar to those in cluster 5. In general, it can be worth a consideration to assess which of the other 64 same-sized German cities could be potential new markets for the energy and bioenergy practices found successful in Gelsenkirchen and Freiburg im Breisgau, which were the ideals for the city clusters. Similarly, the other nine German cities potentially belonging to cluster 4 could be assessed. Particularly cities in this cluster which have similar biomass availabilities as Dresden (ideal for the city cluster 4) could be interesting for transferring the city’s successful energy and bioenergy practices.

2.3 Clustering tool

The main principle of the city clustering is that it generalizes the case cities to represent groups of similar cities to transfer successful sustainable urban practices. It could be argued that the city clusters can be used as a screening tool in planning future urban energy and bioenergy systems prior to more detailed assessments. The screening tool can be used in two different ways. Firstly, it can be used to create a shortlist of potentially suitable cities to where a successful practice from one (case) city could be transferred. This enables, for example, energy companies to find new urban markets for their products. Secondly, it can be used to create a shortlist of successful practices that have potential in a certain city. This approach can be useful for example for city decision-makers while searching for new energy solutions for their city. The shortlists produced by the screening tool based on city clusters are, naturally, not giving direct answer of the suitability of the practices in individual cities but provide basis for further analysis of transferring urban practices.

The population distribution in Germany was shown in Figure 2.1. Figure 2.2 shows the population distribution of the five largest city size groups in Germany and Europe. It can be seen that the percentages of the population living in those city groups are remarkably similar in Germany and Europe. As the five biggest city size groups presented in Figure 2.2 cover 500 European cities, it could be argued that the city clusters formed for German cities provide a good basis for assessing the adaptability of the successful practices found in the German case cities to a large number of European cities with similar population numbers. Naturally, the population number is only one factor used in dividing the cities in different clusters, and also other city characteristics need to be taken into account. In this connection, it should be noted that the different characteristics can be seen as “filter” or “query” parameters for the screening, and the size of a created shortlist will depend on the number of characteristics considered for the screening.

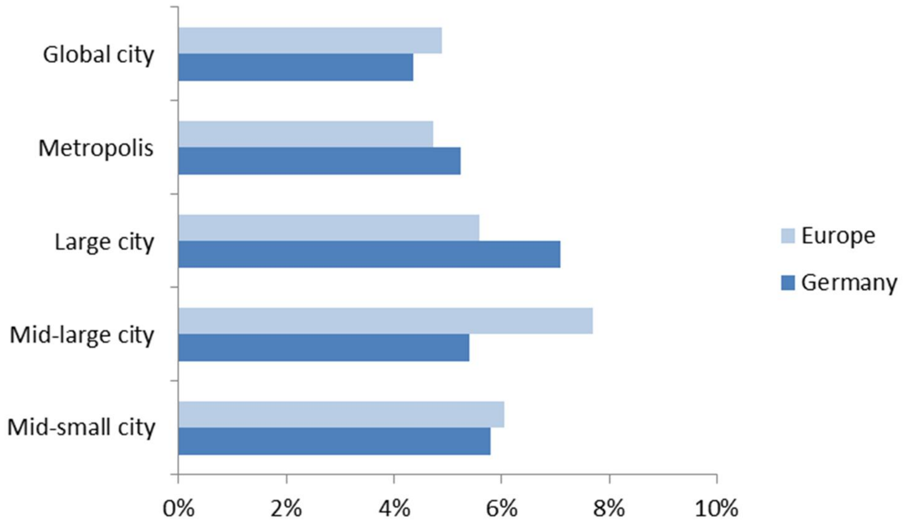

Figure 2.2: Population distribution in Europe and Germany (vom Hove 2010; Destatis 2011)

One example for successful urban practices that can be transferred from one city to other urban markets is the technologies used for bioenergy production. The factors affecting the suitability of a bioenergy technology are for instance type of biomass available, type of product needed (for instance heat, electricity, or transportation fuel), scale of the planned or desired bioenergy production, and requirements set by the city energy system, for example need for balancing the fluctuations in renewable energy production. Assessing the suitability of bioenergy technologies in different city clusters requires analysis of the technologies and comparison of the technology requirements to city conditions. To provide a basis for further technology analyses, the bioenergy technologies that are assumed to have importance in urban environments are briefly described in the next section.

3 Bioenergy technologies

Many of the case cities discussed in this report aim to increase their bioenergy production. For most of the cities no concrete and detailed plans, such as decisions of bioenergy technologies, are, however, announced in the scenarios strategies published. Most popular bioenergy technologies mentioned in cities´ strategies were transport biofuels and biomass-based heat and CHP production. Moreover, biogas, bio liquids, and energy production and heat recovery from waste materials were mentioned in the strategies.

The aim of the clustering presented in the previous section is to transfer successful urban practices to new market areas. Bioenergy technologies are a good example of these practices. If one city successfully applies one technology in bioenergy production, it can be assumed to be suitable also for other similar cities, that is, cities within the same city cluster. On the other hand, the suitability of a bioenergy technology can be assessed in one city cluster, instead of assessing its suitability separately for each city. Naturally, also city level assessments are needed, but clustering can be used to screen the cities, where a particular technology has most potential. To assess the suitability of technologies for urban bioenergy production, information of both the technologies and the city characteristics are needed. City characteristics were discussed in the previous section. Depending on the desired specificity, more characteristics may be needed for the technology assessment.

There are numerous bioenergy technologies. Figure 3.1 shows a simplified schematic of different biofeedstock conversion routes and products. Some biomass conversion technologies convert biomass directly to electricity or heat, whereas other technologies can be used to convert biomass for instance to transport biofuels or gaseous biofuel. Moreover, some biomass upgrading processes can be directly combined with energy production, which complicates the division of the conversion technologies to ones used for energy production and biomass upgrading. For instance, gasification, that converts solid biomass into gaseous biofuel, can be combined with steam and gas turbines in integrated gasification combined cycle (IGCC) for power and possibly also heat production.

In general, technologies suitable for converting bioenergy in electricity and heat can be classified either as thermochemical or biochemical conversion processes. In this section, bioenergy technologies, that are assumed to have most potential in future urban environments, are presented. Thermochemical conversion technologies presented are combustion, co-combustion, gasification, pyrolysis, torrefaction, pelletization, and waste-to-energy technologies. From biochemical conversion technologies, anaerobic digestion is discussed. Furthermore, liquid biofuel production is presented.

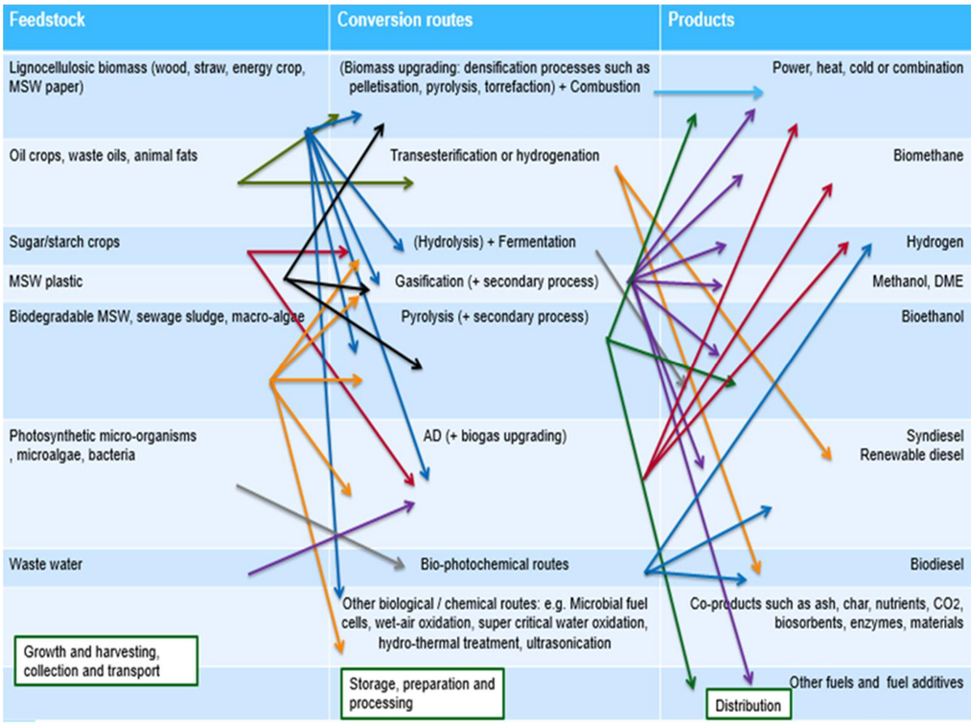

Figure 3.1: Conversion routes and products for bioenergy (adapted from IEA Bioenergy 2009)

In addition, combined heat and power (CHP) technology has an important role in energy production especially in urban areas, where both electricity and heat are required throughout the year. It will, however, be discussed later in section 4.4 together with other bioenergy concepts that are expected to have potential in urban energy systems.

3.1 Combustion

Direct combustion is the first method used for converting biomass into energy, and it is still widely used in many areas. Direct combustion is most commonly used in small-scale applications such as wood-fired fireplaces and pellet stoves. Biomass can also be used as a fuel in large-scale applications for the production of electricity and heat (Basu 2013, p. 353–373).

The combustion properties of biomass significantly differ from those of fossil fuels, which hinders the fuel replacement in power plants. Especially high volatile content and quality variations set biomass apart from fossil fuels. (Hyppänen & Raiko 2002) There are numerous types of biomass, including virgin wood, agricultural and food residues, energy crops, and industrial slurries. Compared to agricultural crops, woody biomass is generally more suitable for combustion as well as for other thermal conversion processes. (Helynen et al. 2009, p.165–170) For example, agricultural crops typically contain more alkali metals, which leads to enhanced deposit formation and thus to corrosion (Antunes & Lopes de Oliveira 2013).

Grate combustion is the most conventional combustion technology for solid fuels. Grate-fired boilers are, however, generally seen to have low efficiencies and emissions. Using biomass as fuel also induces new problems. For example, combusting biomass with high Cl content is likely lead to severe problems with deposit formation and corrosion (Yin et al. 2008).

Fluidized bed boilers are suitable for lower quality fuels and fuels with quality variations and are thus one of the most potential technologies for biomass combustion (Hyppänen & Raiko 2002 p. 490). In addition, fluidized bed boilers provide low emissions of NO_x and incombustible materials, inexpensive desulfurization, uniform temperature distribution, efficient heat transfer between the bed and heat exchange surfaces, large solid-gas exchange area, and stable combustion at low temperatures (Hyppänen & Raiko 2002, p. 490; Khan et al. 2011). Combusting biomass, however, results in various problems also in fluidized bed boilers, such as erosion in the boiler due to high velocities of solid particles and defluidisation problems as a consequence of bed material agglomeration. Furthermore, the high dust content of flue gases and the need for efficient separation of gases and solids are problematic (Khan et al. 2011).

3.2 Co-combustion

As stated earlier, the properties of biomass, such as quality variations and high volatile content, complicates the combustion of biomass. Furthermore, biomass combustion tends to cause surface corrosion. These problems can be reduced by co-combusting biomass with fossil fuels. In addition, co-combustion can be applied in existing fossil fuel fired power plants, which decreases the investment costs. Also the power generation costs are low compared to other bioenergy production options, and co-combustion can be applied also when the available biomass feedstock is limited. Due to the great number, large-scale applicability and mature development state of coal fired power plants, the co-combustion of coal and biomass is of special interest.

Despite the advantages, co-combustion reduces the thermal efficiency of the power plant. The efficiency reduction is proportional to the mass percentage of biomass in the fuel. Moreover, the different properties of biomass and fossil fuels result in challenges in for instance fuel storage and grinding. The differences can be reduced by torrefaction that changes the partial structure of biomass making it more similar to coal. For example storage and grinding characteristics are enhanced, and quality variations evened. Torrefaction is discussed in more detail in section 3.5.

Co-combustion can be direct, indirect, or parallel. In direct co-combustion, both fuels are fed directly into the same boiler after common or separate preparation processes. Direct co-combustion is simple and low-cost process and is therefore the most commonly used co-combustion method. It is, however, suitable for only low biomass-to-coal ratios. Too high biomass proportions lead to for instance corrosion, slagging, and fouling. Also these problems can be diminished by using torrefied biomass.

In indirect co-combustion, solid biomass is first gasified and then the product gas is combusted in the same furnace with the fossil fuel. Indirect co-combustion is thus also known as gasification co-combustion. It is applicable to a wide range of fuels. Furthermore, the alkali compounds from the biomass can be removed before combustion, which leads to less fouling and corrosion problems.

In parallel co-combustion, biomass and fossil fuel are combusted in separate boilers. The biomass boiler produces low-grade steam that is then used in the steam cycle replacing the steam from the main boiler. Separate boilers increase the reliability of the plant and mitigate the corrosion and fouling problems. The investment costs are, however high compared to other co-combustion methods (Basu 2013, p. 353-373).

3.3 Gasification

In gasification, solid or liquid biomass is converted into gaseous fuel and chemicals. The main components of the produced syngas are H_2, CO, CH_4, and CO_2. Gasification is closely related to combustion, but its main principle is remarkably different. In combustion, the chemical bonds in the feedstock are broken to release energy, whereas in gasification energy is packed in the chemical bonds. Gasification adds hydrogen to the fuel and removes carbon, resulting in a product gas with high H/C ratio.

Typical biomass gasification process begins with lowering the moisture content of biomass to 10–20 % to increase the heating value. After drying, large hydrocarbon molecules are broken into smaller molecules by pyrolysis or degradation. Actual gasification consists of chemical reactions among the hydrocarbons and gases in the reactor. Gasification of char is the most important gasification reaction. Due to the higher porosity and reactivity of biomass char, the reaction behavior in biomass gasification differs from that in coal gasification.

Gasification process takes place in a gasification medium that reacts with hydrocarbons and solid carbon rearranging them into gases with low molecular weight, such as CO_2 and H_2. The composition and the heating value of the product gas depend on the gasification medium used. Oxygen, steam, and air are the most commonly used mediums (Basu 2013, p. 199-248).

The main gasifier types in biomass gasification are fixed bed, fluidized bed and entrained flow gasifiers. Due to the low tar formation, flluidized bed reactors are especially suitable for gasification. The advantages of fixed bed and entrained flow gasifiers are their simplicity and reliability and the suitability for small-scale gasification of wet biomass. However, entrained flow gasifiers are used for biomass only when biomass is co-gasified with coal (Kurkela & Jahkonen 2002, p. 567-572; Wang et al. 2008).

Gasification can be applied to the production of power and heat, hydrogen, liquid and gaseous fuels such as Fischer-Tropsch liquids or synthetic natural gas, and chemicals. The syngas from biomass gasification can be used in conventional combustion systems, and it reduces ash-related problems and other typical problems caused by biomass firing. In co-combustion it also enables using higher biomass percentages. The power generation by steam turbine has, however, a limited efficiency, and therefore other methods for syngas utilization are of high interest. High quality syngas can be used as a fuel also in engines and gas turbines. Integrated gasification combined cycle (IGCC) combines gasification with both gas and steam turbines. The syngas is first combusted in gas turbine to produce electricity. The hot gas turbine exhaust gases are then used to generate steam that is expanded in a steam turbine for additional power or heat generation. The efficiency of the IGCC cycle is higher than that of conventional condensing plants and the flue gas emissions are lower. Most of the IGCC research has focused on coal-based gasification, but IGCC is stated to have potential also in biomass gasification, especially in CHP production. (Wang et al. 2008; Kurkela & Jahkonen 2002, p. 568–581) So far, IGCC has been tested in pilot plants and industrial-scale demonstrations. Especially the process economics has to be improved before IGCC can be fully competitive in commercial scale (Sahraei et al. 2014).

In integrated gasification fuel cell cycle (IGFC), the gasification syngas is used for energy production in a fuel cell. This requires syngas purification to remove components causing fouling. In fuel cells, electricity is generated directly from the chemical energy of the fuel. Also heat can be recovered from the process. The most significant advantages of fuel cell technology are low or zero emissions, integration capability to other systems and flexible operation (Naraharisetti et al. 2014).

3.4 Pyrolysis

Pyrolysis is a thermochemical conversion process where complex hydrocarbon molecules are decomposed into smaller and simpler molecules. It can be used to produce bio-oils or biochar from biomass. Pyrolysis differs from gasification as it does not involve chemical reactions with an external medium. Instead, it forms essential gasification pre-steps.

In pyrolysis biomass is rapidly heated to a so-called pyrolysis temperature, which typically varies between 300 and 650 °C. The process is carried out in the absence of oxygen and produces condensable gases and solid char. The condensable gases may decompose further into char, liquid product, and non-condensable gases such as CO, CO_2, H_2, or CH_4. While also the char and the gases can be utilized, the liquid is usually the main product of the process. This bio-oil consists of hydrocarbons, oxygen, and up to 20 % water.

There are several pyrolysis variations. In traditional, fast pyrolysis, the heating time is shorter than the characteristic pyrolysis reaction time, and bio-oil and gas are the primary products. Fast pyrolysis can be further divided into flash and ultrarapid pyrolysis. Slow pyrolysis, where the heating time is longer than the characteristic pyrolysis reaction time, is mainly used for char production. Depending on the temperature used, it is known as torrefaction or carbonization.

Usually the term pyrolysis is used only for the production of liquid, and torrefaction is thus discussed separately in section 3.5.

The main parameters in pyrolysis are heating rate, final temperature, and gas residence time. The relation between liquid, gas, and char production can be affected by varying these parameters. Furthermore, the size of biomass particles affects the heating rate and therefore also the yield composition (Basu 2013 p.147-176).

3.5 Torrefaction

As mentioned in section 3.4, torrefaction is actually one type of pyrolysis. It takes place in lower temperatures and with slower heating rate than actual pyrolysis and aims to increase the yield of the solid product. In torrefaction, the carbon content of the biomass is increased whereas the oxygen and hydrogen contents are decreased. This increases the energy density of the biomass. In general, torrefaction alters the structure and properties of biomass closer to those of coal, which simplifies its combustion. Furthermore, it makes biomass more suitable for pelletization and as a feedstock in chemical industry.

Torrefaction reduces both the mass and density of biomass. In addition, the size of particles decreases, the variation of particle sizes reduces and the particle structure becomes more brittle and less fibrous. The changes in particle structure simplify grinding and pulverization, but on the other hand, storage of torrefied biomass contains a risk of fire and explosion. The moisture content of biomass decreases by about 90% during torrefaction. Torrefied biomass is also hydrophobic, which improves its storage properties (Basu 2013 p. 87-145).

3.6 Pelletization

In pelletization, biomass is dried and compressed under high pressure into cylindrical pieces with high energy density. The fuel produced is uniform and stable and produces less dust than untreated fuel. Pellets also have significantly smaller volume than untreated biomass. (Uslu et al. 2008) Wood is the most suitable feedstock for pellet production, and its advantages include higher efficiency, cleaner burning, easier operation, easier fuel storage. Furthermore, pellets can be produced from other agricultural and forest biomass, such as straw, sawdust, and animal waste (Sultana & Kumar 2012, Pa et al. 2013).

In the pelletization process biomass is first dried and grinded. Then it is pelletized under high pressure, and finally cooled. Typically, the thermal and net efficiencies of the pelletizing process are approximately 94 and 87 %, respectively. The moisture content is decreased from around 10–15 % to 5–10 %, and the net caloric heating value of the end product is approximately 16–18 MJ/kg (Uslu et al. 2008).

In Europe, pelletization is most widely used in Finland and Sweden (Uslu et al. 2008). Pellets are most commonly used to replace firewood in district and residential heating but can also be burned in large-scale power plants (Sultana & Kumar 2012). Moreover, the minimization of the energy consumption of the pellet production by integrating it with other processes, such as CHP plants, pulp mills, and sawmills, has been investigated (Song et al. 2011).

3.7 Waste-to-energy technologies

Waste is an important biomass source in urban environments. Urban waste flows consist of industrial waste and waste produced by households and services. Industrial waste is always city-specific, and in addition often treated by the industrial sector. Therefore it is reasonable to concentrate discussing the utilization of municipal solid waste (MSW), which is the solid waste that is produced by households and commercial establishments and is collected by or on behalf of the municipalities (EEA 2013, p. 7–9).

The main components of MSW are carbon, oxygen, hydrogen, nitrogen, sulfur, moisture and ashes. It is a heterogeneous fuel with heating value in a range of 8–12 MJ/kg and varying moisture content. In industrialized countries, approximately 400 kg of waste per person per year is produced, and the seasonal variations are negligible (Qiu et al. 2009).

Waste incineration is the most traditional waste-to-energy technology. It is applicable to a wide range of different wastes. Incineration can be used for both mixed and pretreated MSW. However, waste incineration residues contain both hazardous materials and valuable resources such as various metals. Out flows of waste incinerators include bottom ash and air pollution control residues. Before the modern emission regulations and cleaning technologies waste incineration plants have caused serious environmental problems, and the public opinion is thus relatively antagonist (Brunner & Hwong-Wen 2009).

Many waste-based fuels are also suitable for co-combustion in existing fluidized bed boilers. In addition, gasification and pyrolysis can be used to generate energy from waste materials. The advantages of gasification over conventional waste incineration include lower emissions of dioxin, furans, and NO_x, and lower operation that results in reduced amount of volatilized heavy metals and alkalis. If the pretreatment steps are also included, gasification, however, often has lower efficiency than traditional waste incineration. It is also stated that wider use of waste gasification requires inter alia development of better and cheaper gas cleaning systems, higher electricity conversion rate (Arena 2012, Arafat 2013).

3.8 Anaerobic digestion

Anaerobic digestion (AD) is biological degradation process where anaerobic micro-organisms digest organic matter in the absence of oxygen. It is used for the production of biogas and reduction of organic matter such as biowaste. The most typical feedstock for AD is liquid waste such as wastewater, but the process is also suitable for the treatment of solid biomass such as municipal solid waste. (Mata-Alvarez 2003) The main components of produced biogas are methane and carbon dioxide, and the methane content varies between 55 and 80 % (Nizami et al. 2013).

The degradation process can be divided into four steps. In the first three subprocesses – hydrolysis, acidification, and acetogenesis – the macromolecules are stepwise converted into acetic acids, CO_2, and H_2. This is known as acid fermentation. In the last phase, methanogenesis, the products of the acid fermentation are converted further into CO_2 and CH_4. In an anaerobic digester, all four above-described process steps occur simultaneously, and the concentrations of intermediate products are low. Hydrolysis is usually the rate-determining step (van Haandel & van der Lubbe 2007, p. 377–380).

Anaerobic digestion can be either natural or controlled process. There are several alternative types of anaerobic digesters and the optimal design depends inter alia on the substrate type, scale of the plant and operational parameters (Nizami et al. 2013). In urban environments, anaerobic digestion is most commonly applied at wastewater treatment plants for the production of biogas.

3.9 Liquid biofuel production

The most common liquid biofuels are bioethanol and biodiesel. Depending on the feedstock used, liquid biofuels are divided to first or second generation biofuels. First generation biofuels are produced from feedstock eligible for food production, whereas second generation biofuels are produced from non-food biomass.

Traditionally bioethanol has been produced from sucrose containing or starchy feedstocks by hydrolysis and fermentation. Possible feedstocks include sugar crops, wheat, and corn. Second generation bioethanol can be produced lignocellulosic biomass. The structure of lignocellulosic biomass is more complex than that of traditional feedstock, which increases the need for pretreatment and thus production costs. Due to the availability and low cost of the feedstock, lignocellulosic biomass is, however, expected to become the main feedstock for bioethanol production (Cardona & Sánchez 2007).

Bioethanol can be used as a transport fuel or in fuel cells to produce heat and power. When used as a transport fuel, bioethanol is typically mixed with gasoline. Blends with less than 10 % of bioethanol can be used in normal gasoline engines. Flexible fuel vehicles can use blends with up to 85 % bioethanol share (Viinikainen et al. 2009, p.133-134).

Biodiesel can be produced from fats and oils of both vegetable and animal origin. First generation biodiesels are produced by transesterification and consist mostly of fatty acid methyl esters (FAME). Second generation biodiesels are produces by hydrogenation, and are thus called hydrotreated vegetable oils (HVO) (Fangrui & Mildford 1999).

The properties of biodiesel are similar to fossil-based diesel, and it can thus be used to replace conventional diesel in transportation (Abbaszaadeh et al. 2012). Biodiesel is non-toxic, almost sulphurless, and non-aromatic and it can contribute to remarkable emission reductions. Biodiesel reduces CO emissions by approximately 20 %, HC emissions by 30 %, particulate matter emissions by 40 % and soot emissions by 50 %. However, the NO_x emissions increase by 10–15 %, but the increase can be neglected by injection timing (Canakci et al. 2008).

4 Bioenergy in urban energy systems

Bioenergy has several advantages. Alike other renewable energies, it is often considered as carbon-neutral, and it decreases the dependency on fossil fuels. Furthermore, bioenergy has potential to improve the security of the energy supply. The energy production by most renewable energy sources varies greatly depending on the conditions. For instance, solar energy production requires sunny weather, and wind energy can only be produced at suitable wind velocities. Moreover, energy production and need are often occurring non-simultaneously. This may detrimentally decrease both the security of energy supply and grid stability. Bioenergy enables flexible power generation to balance the fluctuations of other renewable energy sources and thus secure renewable energy supply systems. Flexible energy production can be realized by biomass or biofuel storage. The increased storage needs and reduced full-load hours will increase the cost of bioenergy, but also the price obtained from bioenergy will increase as it is sold during peak loads (Szarka et al. 2013).

In general, there are several options for implementing the energy storage, as presented in Figure 3.1. Electrical energy can be directly stored for example in capacitors, but these energy storage method is very limited in both storage duration and capacity. Moreover, energy can be stored in flywheels that are suitable for short-term, small capacity energy storage. Batteries enable medium-term (up to 10 h) energy storage but have, however, low energy and power density and lifetime. Compressed air reservoirs (CAES) are suitable for slightly longer time and higher capacity energy storage, up to 100 h and slightly over 1 GWh. However, there are currently only two CAES energy storage systems in operation. Pumped storage hydroelectric power plants (PHS) have a slightly higher storage capacity, and are generally used for storing electricity from several hours to several days. The overall capacity of pumped storage is, however, limited by geographical factors and environmental conditions.

Currently, energy reserves are provided by storing fossil fuels such as oil, coal, and natural gas. This enables storing energy worth of several month´s consumption. Also, for renewable based energy systems, storage in secondary energy carriers is, with current technologies, the only viable option for long-term and high capacity energy storage. Different hydrogen and carbon-based fuels are the most typical secondary energy carriers. In Figure 3.1, secondary energy carriers are presented as hydrogen (H_2) and methane (CH_4). These two gases can be produced from various renewable energy sources, such as bioenergy, and thus used to balance the production and demand fluctuations in the system. (Specht et al. 2011)

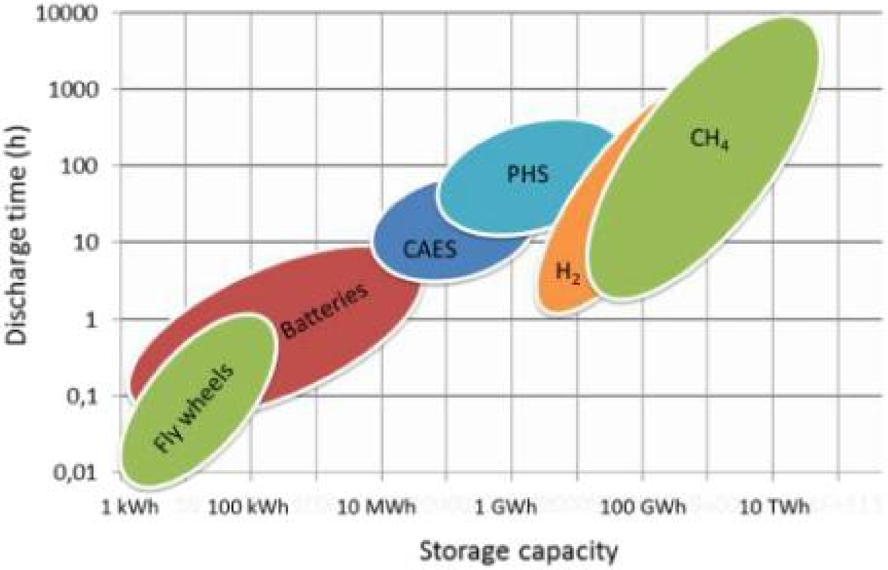

Figure 4.1: *Discharge time and storage capacity of various energy storage systems (Persson et al. 2014)*

Currently the energy reserves are provided by storing fossil fuels such as oil, coal, and natural gas. This enables storing energy worth of several month´s consumption. Also in renewable based energy systems, storage in secondary energy carriers is with current technologies the only viable option for long-term and high capacity energy storage. Different hydrogen and carbon-based fuels are the most typical secondary energy carriers. In Figure 3.1, secondary energy carriers are presented as hydrogen (H_2) and methane (CH_4). These two gases can be produced from various renewable energy sources, such as bioenergy, and thus used to balance the production and demand fluctuations in the system. (Specht et al. 2011)

The following sections present promising technologies for implementing the bioenergy based energy storage in gas fuels. In the power-to-gas technology surplus electricity during high production or low demand is used to produce hydrogen or methane gases that can be stored and used for electricity production during peak demand or low production. Smart gas grids have potential in storing and distributing these gases in existing natural gas infrastructure. (Persson et al. 2014) Furthermore, biorefineries provide another option to balance the instabilities in energy production and consumption by flexible production of both bioenergy and other bioproducts.

Moreover, combined heat and power (CHP) is discussed in this section. CHP is very convenient for urban energy production, because both electricity and warm water are needed in the cities throughout the year. CHP has higher efficiency than separate power and heat productions, and hence enables more efficient use of limited biomass resources.

4.1 Power-to-gas

In power-to-gas technology, surplus electricity during low demand or high production is converted to gas, that can be stored and used for electricity production during high demand or low production. Electricity is converted to hydrogen by electrolysis. Hydrogen can also be converted to methane by catalytic or biological conversion. The distribution and end use of hydrogen and methane is discussed in more detail in the section 4.2.

In electrolysis, an electrical energy input is used to split water molecules into hydrogen and oxygen. Water molecules have a stable structure, and hence the energy needed to decompose a water molecule is relatively high. Large-scale hydrogen production by water electrolysis is therefore expensive, and currently only around 4–5 % of the global hydrogen production is done by water electrolysis.

In the electrolysis process, two electrodes are set in water. When direct current is passed in the water through the electrodes, oxygen is produced at the positive electrode, anode, while the negative electrode, cathode, produces hydrogen. The overall electrolysis reaction is

$$H_2O(l) \rightarrow H_2(g) + \frac{1}{2}O_2(g)\,. \tag{4.1}$$

Commercial electrolyzers commonly have efficiencies of 55–75 %. (IEA 2007)

The conversion of hydrogen into methane can be conducted either as catalytic or biological process. In catalytic methanation, hydrogen is combined with carbon dioxide or carbon monoxide as described by

$$4H_2(g) + CO_2(g) \rightarrow CH_4(g) + 2H_2O(g) \tag{4.2}$$

and

$$3H_2(g) + CO(g) \rightarrow CH_4(g) + H_2O(g)\,. \tag{4.3}$$

Furthermore, catalytic methanation can be used to produce hydrogen from carbon monoxide and water as described by

$$H_2O(g) + CO(g) \rightarrow CO_2(g) + H_2(g)\,. \tag{4.4}$$

The methanation reactions are catalyzed by metal catalyst such as nickel or ruthenium. They are exothermic reactions favored by low temperatures and high pressures, and have overall energy conversion efficiency of 80 %. (Kopyscinski et al. 2010) The methanation reaction described by Equation 4.2 is also known as the Sabatier reaction, and has been widely investigated since its discovery in 1902 (Brooks et al. 2007).

In biological methanation, the same micro-organisms that contribute to the methane-forming step in biogas production are used. The metabolic methanation reactions occur naturally in the presence of specialized micro-organisms. Methanogenic archaea use hydrogen and carbon dioxide for the metabolism, and simultaneously produces methane. The conditions in the biological methanation are very similar to those in biogas production. The reactions start already at ambient pressure and temperatures from 35 °C. (Strauch et al. 2014)

When applying power-to-gas in renewable energy systems, the source of the carbon dioxide used in the methanation has to be taken into account. The use of fossil or renewable carbon dioxide from power plant exhaust gases requires the use of carbon capture methods, which results in a high carbon dioxide price. Furthermore, carbon can be extracted for instance from air or waste gases. However, biogas plants may offer a remarkably cheaper source of carbon dioxide, as biogas contains up to 50 % of carbon dioxide (Bensmann et al. 2014). Hence, applying the power-to-gas concept in a biogas facility has great potential. In a biogas plant, there are several ways for gas production. For instance, hydrogen can be added in-situ to biogas reactor to increase biogas production. In this method, an additional gas upgrading is required before injecting the gas into the gas grid. Furthermore, hydrogen and biogas can be added in a biological or catalytic methanation unit. In this case, no traditional gas upgrading is needed. Gas upgrading before gas grid injection is unnecessary also if hydrogen and clean carbon dioxide from biogas upgrading process are added to the biological or catalytic methanation unit to produce methane. On the contrary, electricity, as well as heat, can be produced directly from biogas, or biogas can be upgraded to biomethane, injected to the grid, and used for off-site energy production.

In addition to technical feasibility, wide-spread use of power-to-gas technology and other energy storing methods in balancing the fluctuations of renewable energy production require economic motivation. Currently the feed-in tariffs guarantee the same price for the renewable based electricity independent of if it is produced during electricity shortage or when surplus electricity is available. As additional energy conversion steps always decrease the overall efficiency and thus the cost of the electricity, the current situation does not motivate for balancing the energy production. To achieve stable, renewable energy systems, the fluctuations in the electricity price based on production fluctuations have to be transferred to the total income got from renewable electricity. (Persson et al. 2014)

4.2 Smart gas grids

Hydrogen produced from surplus electricity can be used in energy production in both transport and stationary systems. In transport applications, hydrogen is most typically converted in energy in fuel cells. Also internal combustion engines can be used. In stationary power generation, thermal cycles and fuel cells are applied. (Conte et al. 2009)

The use of hydrogen as energy carrier also requires the storage and distribution of hydrogen. The hydrogen storage is challenging. Hydrogen has very low gas density, and the storage as gas therefore requires large storage volumes and pressures. Furthermore, the storage as liquid requires cryogenic temperatures due to the low boiling point of hydrogen. In addition to the storage as gas or liquid, the storage as metal hydrides is used. Also the gas adsorption storage is possible. (Lanz et al. 2001) Due to the low volumetric density, also the distribution is rather energy-intensive and expensive (IEA 2007). Furthermore, the existing hydrogen infrastructure is still rather insignificant (Persson et al. 2014).

On the contrary, the distribution systems of natural gas are widely spread and its end use technologies mature (Persson et al. 2014). Natural gas consists of approximately 85–95 % of methane (Demirbas 2010, p. 57). The Siberian natural gas used in Finland has even higher methane content, approximately 98 % (Suomen kaasuyhdistys 2014). Hence, methane can in principal be treated as natural gas. Methane produced from surplus renewable electricity can thus be injected into existing natural gas grid, which enables the energy storage as gas in the grid. Moreover, natural gas grids are combined with additional gas storages to enable seasonal natural gas storage. These underground storages could also be used for shorter-term storage for the gas produced from surplus electricity. Naturally, the storage capacity of the gas grid and the attached underground storages is limited, and can only be used to store a limited amount of renewably produced gas. If the scale of power-to-gas technology exceeds the capacity of the gas grid, either additional gas storages need to be connected in the grid, or other storage methods considered. Furthermore, suitable underground storage sites may compete with the storage of carbon dioxide extracted in carbon capture processes for instance from power plant flue gases. (Persson et al. 2014)

4.3 Biorefineries

A biorefinery is a facility that enables producing multiple bioproducts. It is comparable to petroleum refineries, where petroleum is refined to different fuels and other products. The advantage of the biorefinery concept is that it enables flexible production and maximizing the value of the products. For instance, biorefinery can produce more electricity during electricity shortage, when also the price for electricity is high. When no electricity is needed, other bioproducts are favored. Furthermore, the production of low-volume but high-value chemical products becomes more profitable, when they can be produced together with other products.

Like petroleum refineries, biorefineries have two basic types of products. Firstly, the biomass can be converted to energy and fuels, such as electricity and heat, bioethanol, biodiesel, biogas, and hydrogen. Second, different chemicals and biomaterials can be produced. Biopolymers are one example of the possible biomaterial products. Currently polymers, for instance plastics, are produced from petroleum, but both limited petroleum resources and environmental concerns have driven for polymer from renewable resources (PFRR). There are three basic types of biopolymers: natural polymers, for instance cellulose; synthetic polymers from natural monomers, such as thermoplastic; and polymers from microbial fermentation, for example polyhydroxybutyrate (PHB). Like the properties of petroleum-based polymers, also those of biopolymers can be improved by blending and composite formation. (Rojas 2014)

4.4 Combined heat and power (CHP)

Combined heat and power (CHP) technologies are based on simultaneous production of both heat and power. Electricity is in most cases the primary product of a CHP plant, but whereas the heat in non-CHP power plants is wasted, in CHP plants it is utilized for instance for district heating purposes. The electrical efficiency of a CHP plant is lower than in a power plant used only for electricity production, but the overall efficiency is higher than the if both electricity and heat would be produced separately.

CHP production is a good alternative for cities, where both electricity and warm water are needed throughout the year. As heat cannot be transferred over long distances, CHP production often results in rather small, decentralized electricity production units instead of large centralized units (Green & Perry 2008). In addition to cities, CHP plants are common in energy-intensive industry, such as paper and steel industry, where the refining processes require both electricity and heat.

The energy production in the majority of the CHP plants is based on conventional thermal power devices such as steam and gas turbines, piston engines, and internal combustion engines. There are alternatives for the conventional thermal power devices, such as Stirling engine and fuel cells, but these technologies have only a minor role in current CHP plants. Many of these alternative technologies are still in the research and development stage, which also explains their minor role. In general, CHP processes can be based either on combustion or gasification. Technologies based on combustion are steam turbine, piston steam engine, organic Rankine cycle (ORC), Stirling engine, and hot-air turbine. In this processes, the energy of the hot flue gases is used to evaporate water or organic fluid or heat air. (Liu & Boukhanouf 2014) Steam turbine is one of the most common technologies in commercial large scale CHP plants (Tobiasen et al. 2012, p. 11758–11767). In smaller units steam turbines are, however, less efficient for example due to the lower temperatures (Sipilä et al. 2005; Frigo et al. 2014). In small applications, for example when CHP is used to produce electricity and heat for only one neighbourhood, other CHP technologies, so-called micro-CHP technologies, are more suitable. For instance piston steam engines can operate with low volume flows and low heat input temperatures and achieve overall efficiencies up to 87 %. Piston steam engine technology is, however, still in the research and development stage. (Ferrara et al. 2013) Organic Rankine cycle (ORC) is similar to conventional steam turbine process, but instead of water it uses an organic fluid, for example cooling agent or hydrocarbon. These fluids have lower boiling point than water and ORC cycle can thus use lower temperature waste heat than conventional steam turbine process. (Tchanche et al. 2011) The ORC process is on early commercial stage (Konttinen 2011). There are CHP plants with 100–1500 kW electrical capacity using thermal oil, and efficiencies up to 82 % have been achieved (Tchanche et al. 2011). Stirling engine technology for CHP is on pilot scale (Konttinen 2011). Stirling engines can achieve efficiencies up to 87 %, and can use several fuels (Liu & Boukhanouf 2014). Challenges related to Stirling engines are the requirements for tight cylinder, efficient heat transfer from combustion chamber to the medium, and high combustion chamber temperature without scorification of the heat exchanger (BIOS 2014). Hot air gas turbine (HGT) is a gas turbine, where combustion chamber has been replaced by a high temperature heat exchanger. HGT can increase the efficiency of a solid biomass fuelled power plant by 15–30 %. The main problems with HGT are high temperature requirements, ash sintering, slagging and fouling, material problems in heat exchanger, and required large heat exchanger areas (Gaderer et al. 2010).

Large-scale CHP processes based on gasification are indirect co-combustion and integrated gasification combined cycle (IGCC) technology. Indirect co-combustion was discussed in section 3.2 and IGCC in section 3.3. In smaller scale, internal combustion engines and fuel cells can be used. The use of internal combustion engines is, however, hindered by the low efficiencies and high emissions. (Liu & Boukhanouf 2014) From fuel cells, high temperature fuel cells, that is, molten carbonate fuel cell (MCFC) and solid oxide fuel cell (SOFC), are suitable for CHP production. Besides electricity, MCFC fuel cell produces water and heat. The products of SOFC fuel cell are electricity, water, carbon dioxide, and remainders from fuel and air. The fuel and air remainders can be used for heat and steam production. In CHP production, fuel cells can achieve overall efficiencies up to 90 % (Hsieh et al. 2012).

In the literature, CHP power and heat production is considered as one of the most potential future energy production methods (Kohl et al. 2013; Keirstead et al. 2012). CHP production is one of the most favored bioenergy measures also in the national and municipal strategies analyzed in deliverable 3.1.1. Although the feedstock of CHP plants is in most cases not described in the strategies, the targets of increasing renewable energy production give to assume that CHP production would be at least partially biomass-fired. Moreover, integration of biomass upgrading processes with CHP plants is considered to have great potential (Kohl et al. 2013).

5 Potential of bioenergy technologies

There are several aspects affecting the potential of the bioenergy technologies. First, the feedstock requirements of the technologies are different. As self-sufficiency in feedstock supply for energy production was noticed to be a common aim for the case cities, the role of bioenergy is strongly dependent on the biomass availability in the city and surrounding area. The amount of waste per capita is approximately same in all cities, but otherwise the biomass availability varies greatly. Some cities have own biomass production, some are surrounded by forest and agricultural areas with large biomass production potential whereas other cities have significantly less biomass available within a reasonable radius. Thus, there are cities that have more potential for biomass-fired energy production, whereas in some cities for example co-

combustion of biomass with fossil fuels is a more realistic option. In addition to the amount of biomass available, also the type and quality of the biomass affect the technologies suitable for bioenergy production.

Furthermore, the energy demand in the city affects the selection of the bioenergy technologies. Again, the scale of the production is essential, but also the type of the energy product differs between the technologies. It has been estimated that by 2050 7.5 % of the world´s electricity demand and 15 % of the heat demand could be covered by bioenergy (IEA 2012). Furthermore, biomass can also be converted into transport fuels. According to the estimations, biofuels could provide 27 % of all transport fuels by 2050 (IEA 2011).

Moreover, some bioenergy technologies can be used to provide base load energy (Diesendorf 2007), and they could thus replace current base load power plants. For instance in Finland the current base load energy production is mostly based on fossil fuels, nuclear energy, and hydropower (Energiateollisuus ry 2015). Especially replacing the coal-fired power plants by biomass-fired energy production would propitiously affect the carbon dioxide balance. However, replacing the nuclear energy by bioenergy would increase the carbon dioxide emissions, although the carbon dioxide balance would remain unaffected. The opinions of nuclear energy are, however, very contradictory, and thereby replacing also the nuclear power by bioenergy may be beneficial. Furthermore, bioenergy has potential to increase the flexibility of renewable energy production. Currently the peak load production is often based on natural gas, diesel, or pumped storage hydroenergy (Platts 2015). Hydropower is, however, able to answer only to a limited share of the peak load demand; globally around 19 % of the hydropower is already in use, whereas in some countries the percentage goes up to 60 % (IEA 2010). Replacing the fossil peak load energy sources with bioenergy would increase the share of renewables and enhance the carbon dioxide balance. As discussed in section 4, energy storage may have an extremely important role in the future energy systems, if the use of intermittent renewable energy sources increases as predicted.

In addition to the other effects mentioned, also the development stage of the technologies affects their potential in urban energy production especially in the near future. The maturity of technologies described above varies greatly. The development stage of bioenergy technologies can be divided into commercial, early commercial, demonstration, and research and development (R&D) stage. The technologies in early development stages, that is, in R&D or demonstration stage, will most likely not be fully commercial in the near future. In short term, technologies in the commercial and early commercial development stage are expected to be important in urban bioenergy systems. However, based on the study of the Finnish and German case cities, many cities have a will to gain reputation as forerunners for modern low-carbon technologies. Therefore, also the technologies which are in an early development stage may be implemented in the case cities for instance as demonstration plants. (Miettinen 2014)

Table 5.1 compares a few bioenergy technologies presented in earlier sections considering the aspects described above. It shows that despite anaerobic digestion, in principle all the selected technologies are suitable for converting all three biomass types, that is, forest and agricultural biomass, and waste, into energy products. Combustion of agricultural biomass is more complicated than the combustion of woody biomass due to the chemical properties of agricultural biomass, for instance its potassium and chlorine content that may lead to corrosive salt depositions and boiler performance problems. However, technical innovations and further understanding of non-wood biomass quality are potentially enabling wider energy use of non-wood biomass. (REAP 2015) Furthermore, waste combustion, that is, waste incineration, is one of the most common methods for municipal solid waste disposal (Lai et al. 2011). One of the advantages of gasification is its high flexibility in converting different types of biomass into energy products, and in principle all types of biomass can be used as raw material (Heidenreich & Foscolo 2015). There are several technologies used for liquid biofuel production that can thus also use all three types of biomass as raw material (Nigam & Singh 2011). Furthermore, power-to-gas and CHP technology can be implemented by many different bioenergy technologies, and are therefore also able to use different biomass types. However, due to the high content of lignin and crystalline cellulose in woody biomass, anaerobic digestion is suitable for processing it only after raw material pretreatment. Without pretreatment, only 40–50 % of the biomass can be converted into gas. (Ahring et al. 2015) Furthermore, all technologies presented in Table 5.1 except liquid biofuel production are able to produce electricity and heat. In principle, also liquid biofuels can also be used for power and heat production, but as this use is very marginal compared to the use as transport fuel, it is left out of the consideration. In addition to liquid biofuels, also the gas derived from biomass can be refined into transport fuel (Heidenberg & Foscolo 2015).

In addition to the primary energy products, all technologies based on combustion of solid biomass, that is, combustion, co-combustion, and CHP, produce combustion residues such as ash and soot. Ash from biomass combustion is rich of nutrients; for instance wood ash contains nearly all nutrients needed for plant growth (Moilanen et al. 2013). Ash has been used to fertilize agricultural lands, for instance by slash-burning cultivation. Moreover, its nutrients could be salvaged by industrial fertilizer production. (Hogue & Inglett 2012) Also the digestate formed in anaerobic digestion contains a significant amount of nutrients, and could thus be used for fertilizer production (Owamah et al. 2014). In gasification, chemicals, solid char, and tars are produced aside with the gaseous fuel. The reaction products strongly depend on the conditions used. The solid products usually contain over 75 % of carbon, and can thus be directly used for industrial purposes. The gaseous product typically includes hydrogen, carbon monoxide, carbon dioxide, methane, water, and other hydrocarbons, such as acetylene, ethylene, benzene, toluene and xylene. Furthermore, ammonia may be produced. (Balat et al. 2009) Depending on the product composition, they may be used for instance as fertilizer or for plastic manufacturing. The production of FAME-type biodiesels produces glycerine, whereas the by-products in the hydrotreating process are propane and hydrocarbons, such as gasoline and liquefied petroleum gas. Several possible uses for the glycerine product have been investigated, such as converting into more valuable products, for example propylene glycol (Dasari et al. 2005; Alhanash et al. 2008), acetol (Chiu et al. 2006), or hydrogen (Cortright et al. 2002); composting (Malhotra 2007) or increasing the biogas production in anaerobic digestion (Holm-Nielsen et al. 2008; DeFrain et al. 2004); or animal-feeding (Cerrate et al. 2006; Lammers et al. 2008). Furthermore, propane can be used for example as vehicle fuel or for heating purposes (NPGA 2001). The use of other hydrocarbons depends on the type of hydrocarbons produced, but the possible uses are in general similar for most hydrocarbons, including uses for transport and heating.

An advantage of bioenergy over the majority of renewable energies is that it enables flexible energy production. Already the possibility to store the biomass feedstock brings flexibility to the energy production, and thus all bioenergy technologies could in principle be used for peak load energy production. The technologies that produce gaseous fuel, that is, gasification and anaerobic digestion, have especial flexibility as the gas produced can be directly converted to energy or stored and used during energy shortage. However, the storage of solid biomass has some advantages over the storage in gaseous form, such as low energy losses. (Szarka et al. 2013) Furthemore, the principle of the power-to-gas technology is to increase the flexibility of energy production by converting electricity into gas during oversupply of electricity. The gas can be stored and then used for energy production during shortage. Moreover, also liquid biofuels can be relatively easily stored.

From the technologies discussed, only combustion, direct co-combustion, and CHP are on fully commercial development stage. Parallel co-combustion is on early commercial and indirect co-combustion on demonstration state. From liquid biofuel production, the production of first-generation biofuels is on commercial and the production of second-generation biofuels on early commercial stage. Furthermore, gasification and anaerobic digestion are on early commercial development stage. (Miettinen 2014) The technologies applied in power-to-gas systems have different maturity stages. For instance, alkaline fuel cells and chemical methanation are on commercial development stage, whereas PEM fuel cells and biological methanation are less mature (Grond et al. 2013). The power-to-gas technology itself has been demonstrated in several pilot-scale plants (Gahleitner 2013).

Table 5.1: Comparison of bioenergy technologies and concepts

	Feedstock			**Product**				Energy storage	Development stage
	Forest biomass	Agri-culture biomass	Waste	Electricity	Heat	Transport fuel	Other bio-product		
Combustion/co-combustion	x[1]	x	x	x	x	-[2]	Combustion residues	x	Commercial/ early commercial/ demonstration
Gasification	x	x	x	x	x	x	Chemicals, char, tar	x	Early commercial
Anaerobic digestion	-	x	x	x	x	x	Digestate	x	Early commercial
Liquid biofuel production	x	x	x	-	-	x	Glycerine/ Propane, hydro-carbons	x	(Early) commercial
Power-to-gas	x	x	x	x	x	x	-	x	Demonstration
CHP	x	x	x	x	x	-	Combustion residues	x	Commercial

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[1] Suitable
[2] Not suitable

Altogether, it can be concluded that in general, most technologies are suitable for processing all biomass types. However, there are differences in the suitability of different types of the biomass for some bioenergy technologies. Furthermore, most of the technologies can be used to produce electricity and heat. In case of transport biofuels are desired, the number of suitable technologies is, naturally, lower. The by-products of the bioenergy production can, however, be an important factor while assessing the feasibility of the technologies in the future. If the by-products can be efficiently exploited, it may significantly increase the feasibility of bioenergy production. Moreover, it is likely that in the future biorefineries will become more important and the production of bioenergy and other bioproducts will be more connected.

6 Sustainability criteria

In this section, it is outlined how sustainability criteria can be selected. Sustainability criteria and requirements to review and select them are discussed and summarized. Based on that, a process was carried out to review and select sustainability criteria to assess sustainable urban energy systems.

The selected sustainability criteria can be useful in the future. Then, urban stakeholders can be involved to confirm/further develop the sustainability criteria based on which different successful (bio)energy systems/practices in cities could be assessed using decision-making techniques. For the clustering tool, the selected sustainability criteria can also be useful when identifying factors affecting the suitability of a bioenergy technology (section 2.3).

In principle, sustainability criteria can provide an overview of the whole energy system (including interlinkages and trade-offs among various aspects of sustainable development) and long-term implications of current decisions and behaviors (Vera and Langlois 2007). Sustainability criteria reflect issues of concern of stakeholders and can be used to measure and communicate the sustainability of projects or progress on sustainable development (Sheppard and Meitner 2005; Vera and Langlois 2007; Lattimore et al. 2009; Buytaert et al. 2011). Sustainable development can be described as a continuous improvement process to meet the needs of the present without negative impacts on the ability of next generations to meet their own needs (World Commission on Environment and Development 1987). Environmental protection, economic development and social development at local, regional, national and global levels are commonly described as the overlapping and mutually reinforcing pillars in the sustainable development concept (e.g. United Nations 2002; Bell and Morse 2003).

Selecting appropriate sustainability criteria is crucial to assess the sustainability of a project, development or case study because this choice can influence the results of an assessment significantly (e.g. Rovere et al. 2010). Also, the high complexity level of an issue (e.g. the natural environment) demands the need of appropriate criteria (Olsthoorn et al. 2001). In other words, selection of appropriate criteria (ideally by stakeholders) is crucial for assessing a project, development or case study. In the sustainability context, however, it is emphasized that this selection becomes a, “delicate process of translation from socio–environmental agreements to specific observed properties of a complex system” (Shmelev and Rodríguez-Labajos 2009) (p. 2562), and that the chosen criteria are the result of the social and political framework at a particular period in history (Munda 2004). For that reason, no clear consensus amongst bioenergy experts and other stakeholders exists on which sustainability criteria are critical for sustainable bioenergy generation (McCormick and Kåberger 2007; Buchholz et al. 2009). Although there are tools such as life-cycle assessment (LCA) (e.g. Clift 2014) focusing on environmental impacts, other criteria (e.g. social, economic and technical criteria) also have to be considered when assessing the sustainability of bioenergy systems (Evans et al. 2008). The lack of consensus on appropriate sustainability criteria critical for a decision-making situation (e.g. in the bioenergy context) or a sustainability assessment implies a need for processes to select appropriate criteria which can be used for specific decision-making situations or sustainability assessments (e.g. Starkl and Brunner 2004). Therefore, sustainability criteria and requirements to review and select them are identified and synthesized in this section, whereby the process used is based on similar previous similar efforts (e.g. Sheppard and Meitner 2005; Gilmour et al. 2007; Graymore et al. 2009; Kowalski et al. 2009).

6.1 Sustainability criteria from literature

Employing sustainability criteria for decision-making or sustainability assessments has been addressed extensively in scientific literature and other publications covering the sustainability assessment field in general and the energy and bioenergy fields in particular. It can be observed that sustainability criteria are either grouped into the broad categories: environmental, economic and social (e.g. Singh et al. 2008b; Lattimore et al. 2009), or an additional forth category (technical) is common to evaluate energy systems or scenarios in particular (e.g. Ashley et al. 2008; Rovere et al. 2010). These four categories were also considered in the work presented in this report.

In this section, environmental, economic, technical and social sustainability criteria are mainly identified and synthesized, whereby environmental criteria are focused on. Then, the identified sustainability criteria can be reviewed and selected (section 6.3) based on review and selection requirements (section 6.2).

To define environmental criteria for an environmental performance assessment (as part of a sustainability assessment), an LCA approach can be of assistance. LCA is defined as, “a systematic tool for identifying and evaluating the environmental aspects of products and services from extraction of resource inputs to the eventual disposal of the product or its waste” (International Organization for Standardization 2006a and 2006b). A full LCA takes a ‘cradle-to-grave’ assessment approach, and the complete supply chain of energy and materials required to provide a product or service, including transportation steps, is considered. This can include~~:~~ extraction, material purification, manufacturing process(es), use and disposal or recycling. In the bioenergy context, Elghali et al. (2007), for instance, used a broad system boundary (including foreground and background components[3]) to assess different technologies (processes: cultivation of bioenergy crops, harvesting, transport, storage, use of the biomass (including pre-treatment (e.g. drying of biofuels etc.)), disposal of residues and processes related to any ancillary inputs (e.g. agrochemicals, transport fuels and equipment use))[4].

For LCA, two approaches have been developed to aggregate burdens/interventions into impact categories – one approach uses mid-point impacts, while the other approach uses end-point impacts. For the longer established approach, mid-point impacts, which work with specific physico-chemical effects, are used. For the other approach developed to aggregate burdens/interventions into impact categories, end-point impacts, which address areas of social and economic concern (e.g. human health), are used (Clift 2014). Although it is clear that following the latter approach introduces further uncertainties, it could be argued that using end-point impact categories can offer a way to present information that is more intelligible and accessible to all stakeholders and decision-makers (particularly policy makers, the lay public and stakeholders from different backgrounds) than using mid-point impact categories (Clift 2014). Also, when using the end-point approach, the number of impact categories can be reduced, which, for instance, facilitates formal decision-making processes (e.g. multi-criteria analysis (MCA)) processes (Clift 2014). It should be noted that the two different approaches for classification are not incompatible (Clift 2014). For the work presented in this report, predominantly end-point impacts were considered in the process to select environmental criteria (section 6.3).

A limitation of using an LCA approach is its focus on assessing environmental performance. In assessing energy systems, economic, social and technical aspects decisions also have to be considered to make sustainable decisions. In literature covering the sustainability assessment field in general and the energy and bioenergy fields in particular, also a wide range of economic, technical and social criteria can be found. These criteria are listed and grouped in Table 6.1. Also, the sources in which they have been mentioned are illustrated in that table.

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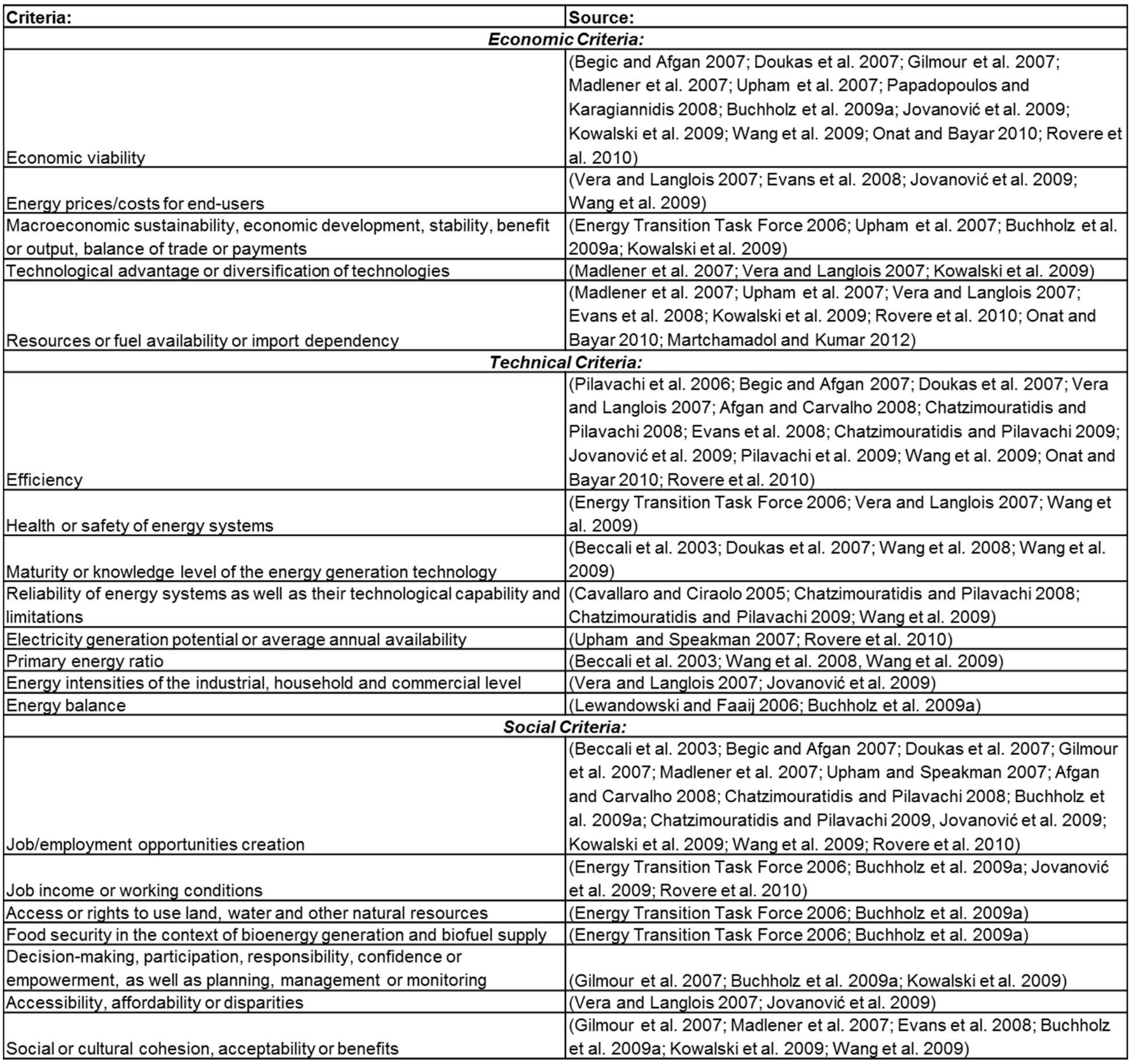
[3] Foreground components are affected directly by decisions. Background components are avoided impacts (e.g. impacts of a coal power plant as a power generation substitute) and processes that interact with the foreground by supplying or receiving material or energy (e.g. production of ancillary inputs and equipment) (Elghali et al. 2007).

[4] Note: In 2010, the European Commission presented a report on sustainability requirements for the use of solid biomass and biogas in electricity, heating and cooling (EU Commission 2010) which provides a common GHG calculation methodology (LCA-based) which could be used to ensure that minimum GHG savings from biomass are at least 35 % compared to the EU's fossil energy mix. The report makes recommendations on sustainability criteria to be used by those Member States that wish to introduce a scheme at national level.

Table 6.1: Summary of economic, technical and social criteria to assess sustainability identified in literature



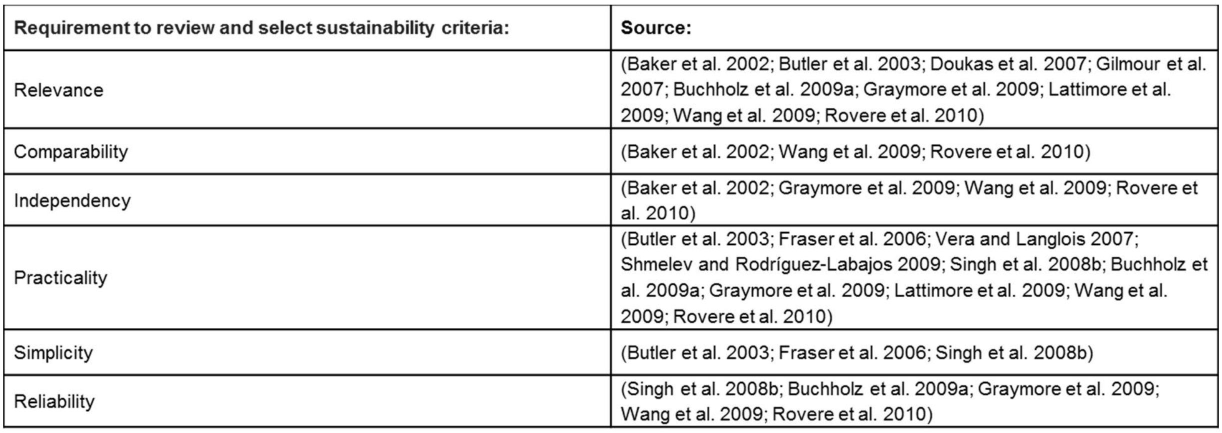
Criteria:	**Source:**
Economic Criteria:	
Economic viability	(Begic and Afgan 2007; Doukas et al. 2007; Gilmour et al. 2007; Madlener et al. 2007; Upham et al. 2007; Papadopoulos and Karagiannidis 2008; Buchholz et al. 2009a; Jovanović et al. 2009; Kowalski et al. 2009; Wang et al. 2009; Onat and Bayar 2010; Rovere et al. 2010)
Energy prices/costs for end-users	(Vera and Langlois 2007; Evans et al. 2008; Jovanović et al. 2009; Wang et al. 2009)
Macroeconomic sustainability, economic development, stability, benefit or output, balance of trade or payments	(Energy Transition Task Force 2006; Upham et al. 2007; Buchholz et al. 2009a; Kowalski et al. 2009)
Technological advantage or diversification of technologies	(Madlener et al. 2007; Vera and Langlois 2007; Kowalski et al. 2009)
Resources or fuel availability or import dependency	(Madlener et al. 2007; Upham et al. 2007; Vera and Langlois 2007; Evans et al. 2008; Kowalski et al. 2009; Rovere et al. 2010; Onat and Bayar 2010; Martchamadol and Kumar 2012)
Technical Criteria:	
Efficiency	(Pilavachi et al. 2006; Begic and Afgan 2007; Doukas et al. 2007; Vera and Langlois 2007; Afgan and Carvalho 2008; Chatzimouratidis and Pilavachi 2008; Evans et al. 2008; Chatzimouratidis and Pilavachi 2009; Jovanović et al. 2009; Pilavachi et al. 2009; Wang et al. 2009; Onat and Bayar 2010; Rovere et al. 2010)
Health or safety of energy systems	(Energy Transition Task Force 2006; Vera and Langlois 2007; Wang et al. 2009)
Maturity or knowledge level of the energy generation technology	(Beccali et al. 2003; Doukas et al. 2007; Wang et al. 2008; Wang et al. 2009)
Reliability of energy systems as well as their technological capability and limitations	(Cavallaro and Ciraolo 2005; Chatzimouratidis and Pilavachi 2008; Chatzimouratidis and Pilavachi 2009; Wang et al. 2009)
Electricity generation potential or average annual availability	(Upham and Speakman 2007; Rovere et al. 2010)
Primary energy ratio	(Beccali et al. 2003; Wang et al. 2008, Wang et al. 2009)
Energy intensities of the industrial, household and commercial level	(Vera and Langlois 2007; Jovanović et al. 2009)
Energy balance	(Lewandowski and Faaij 2006; Buchholz et al. 2009a)
Social Criteria:	
Job/employment opportunities creation	(Beccali et al. 2003; Begic and Afgan 2007; Doukas et al. 2007; Gilmour et al. 2007; Madlener et al. 2007; Upham and Speakman 2007; Afgan and Carvalho 2008; Chatzimouratidis and Pilavachi 2008; Buchholz et al. 2009a; Chatzimouratidis and Pilavachi 2009, Jovanović et al. 2009; Kowalski et al. 2009; Wang et al. 2009; Rovere et al. 2010)
Job income or working conditions	(Energy Transition Task Force 2006; Buchholz et al. 2009a; Jovanović et al. 2009; Rovere et al. 2010)
Access or rights to use land, water and other natural resources	(Energy Transition Task Force 2006; Buchholz et al. 2009a)
Food security in the context of bioenergy generation and biofuel supply	(Energy Transition Task Force 2006; Buchholz et al. 2009a)
Decision-making, participation, responsibility, confidence or empowerment, as well as planning, management or monitoring	(Gilmour et al. 2007; Buchholz et al. 2009a; Kowalski et al. 2009)
Accessibility, affordability or disparities	(Vera and Langlois 2007; Jovanović et al. 2009)
Social or cultural cohesion, acceptability or benefits	(Gilmour et al. 2007; Madlener et al. 2007; Evans et al. 2008; Buchholz et al. 2009a; Kowalski et al. 2009; Wang et al. 2009)

Based on literature, it can be concluded that processes to review and select sustainability criteria for individual projects, developments or case studies are required. A reason for that need is that a technical assessment, such as LCA’s mid-point approach, does not cover non-environmental criteria and not all environmental criteria. Furthermore, a lack of consensus on critical sustainability criteria and the high number of sustainability criteria found in relevant literature suggest the need for processes to review and select appropriate sustainability criteria for specific decision-making situations. Such review and selection process is described in section 6.3. The described process is based on previous review and selection efforts using similar selection requirements (section 6.2).

6.2 Requirements to review and select sustainability criteria

Requirements to review and select sustainability criteria enable a filtering process to choose appropriate sustainability criteria for a project, development or case study. Table 6.2 illustrates requirements found in literature covering the sustainability assessment field in general and the energy and bioenergy fields in particular. For each of the six requirements found in literature, the reviewed sources are also illustrated in Table 6.2.

Table 6.2: Requirements to review and select sustainability criteria from literature covering the sustainability assessment field in general and the energy and bioenergy fields in particular

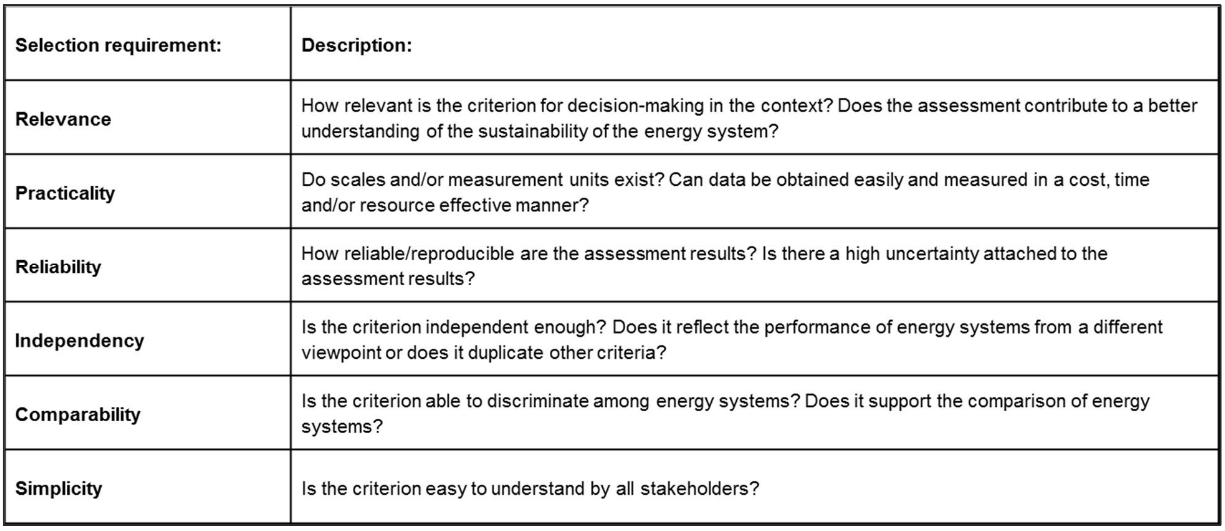


Requirement to review and select sustainability criteria:	Source:
Relevance	(Baker et al. 2002; Butler et al. 2003; Doukas et al. 2007; Gilmour et al. 2007; Buchholz et al. 2009a; Graymore et al. 2009; Lattimore et al. 2009; Wang et al. 2009; Rovere et al. 2010)
Comparability	(Baker et al. 2002; Wang et al. 2009; Rovere et al. 2010)
Independency	(Baker et al. 2002; Graymore et al. 2009; Wang et al. 2009; Rovere et al. 2010)
Practicality	(Butler et al. 2003; Fraser et al. 2006; Vera and Langlois 2007; Shmelev and Rodríguez-Labajos 2009; Singh et al. 2008b; Buchholz et al. 2009a; Graymore et al. 2009; Lattimore et al. 2009; Wang et al. 2009; Rovere et al. 2010)
Simplicity	(Butler et al. 2003; Fraser et al. 2006; Singh et al. 2008b)
Reliability	(Singh et al. 2008b; Buchholz et al. 2009a; Graymore et al. 2009; Wang et al. 2009; Rovere et al. 2010)

The number of requirements found in literature covering sustainability assessments in general and the energy and bioenergy fields in particular have been used in different ways to review and select sustainability criteria. Based on the identified requirements, a final set of requirements to review and select sustainability criteria was chosen (Table 6.3). Also, each requirement was further described for clarification. The requirement descriptions, which were also based on literature, were case study-specific. This set of requirements has been considered in selecting sustainability criteria for the work presented in this report (section 6.3).

Furthermore, it is important to note that sustainability criteria should generally be few in number to increase their understandability (Baker et al. 2002). This could be seen as an overall requirement rather than an individual selection requirement helping to decide whether a criterion should be chosen or not. In terms of having a few and manageable number of sustainability criteria to assess the sustainability of a project, development or case study, it could be observed that employing nine criteria seems to be popular and practical (e.g. Sheppard and Meitner 2005). For instance, only nine criteria showed significant rating differences among stakeholder groups in a study to assess bioenergy systems (Buchholz et al. 2009). For the work presented in this report (section 6.3), a few and manageable number of sustainability criteria was chosen as well.

Table 6.3: Requirements to review and select sustainability criteria



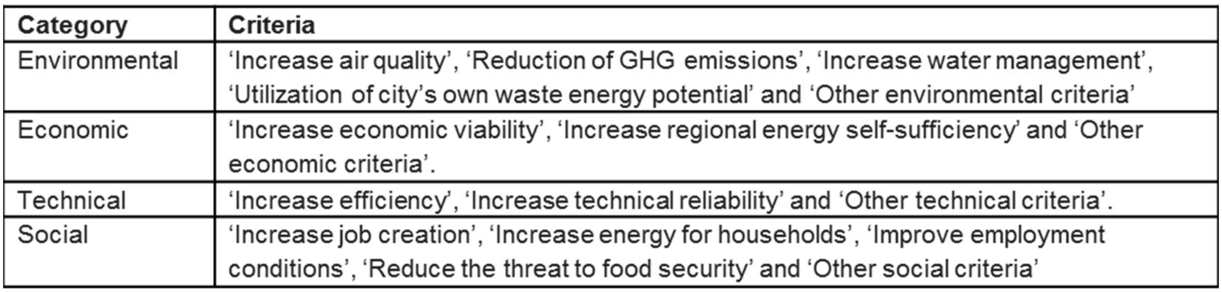
Selection requirement:	**Description:**
Relevance	How relevant is the criterion for decision-making in the context? Does the assessment contribute to a better understanding of the sustainability of the energy system?
Practicality	Do scales and/or measurement units exist? Can data be obtained easily and measured in a cost, time and/or resource effective manner?
Reliability	How reliable/reproducible are the assessment results? Is there a high uncertainty attached to the assessment results?
Independency	Is the criterion independent enough? Does it reflect the performance of energy systems from a different viewpoint or does it duplicate other criteria?
Comparability	Is the criterion able to discriminate among energy systems? Does it support the comparison of energy systems?
Simplicity	Is the criterion easy to understand by all stakeholders?

6.3 Review and selection of sustainability criteria

Multiple steps were carried out to review and select sustainability criteria. Based on the identified sustainability criteria (section 6.1) and a set of case study-specific selection requirements (Table 6.3), a set of sustainability criteria was selected. For this selection, the context including the goal (sustainable urban energy system) had to be considered at each stage of the process.

The process consisted of a series of sorting steps, before the most appropriate sustainability criteria were chosen. First, the identified sustainability criteria had to be sorted by the four sustainability categories: environmental, economic, technical and social. As a second sorting step, sustainability criteria were summarized, which resulted in the classification illustrated in Table 6.4.

Table 6.4: Classification of sustainability



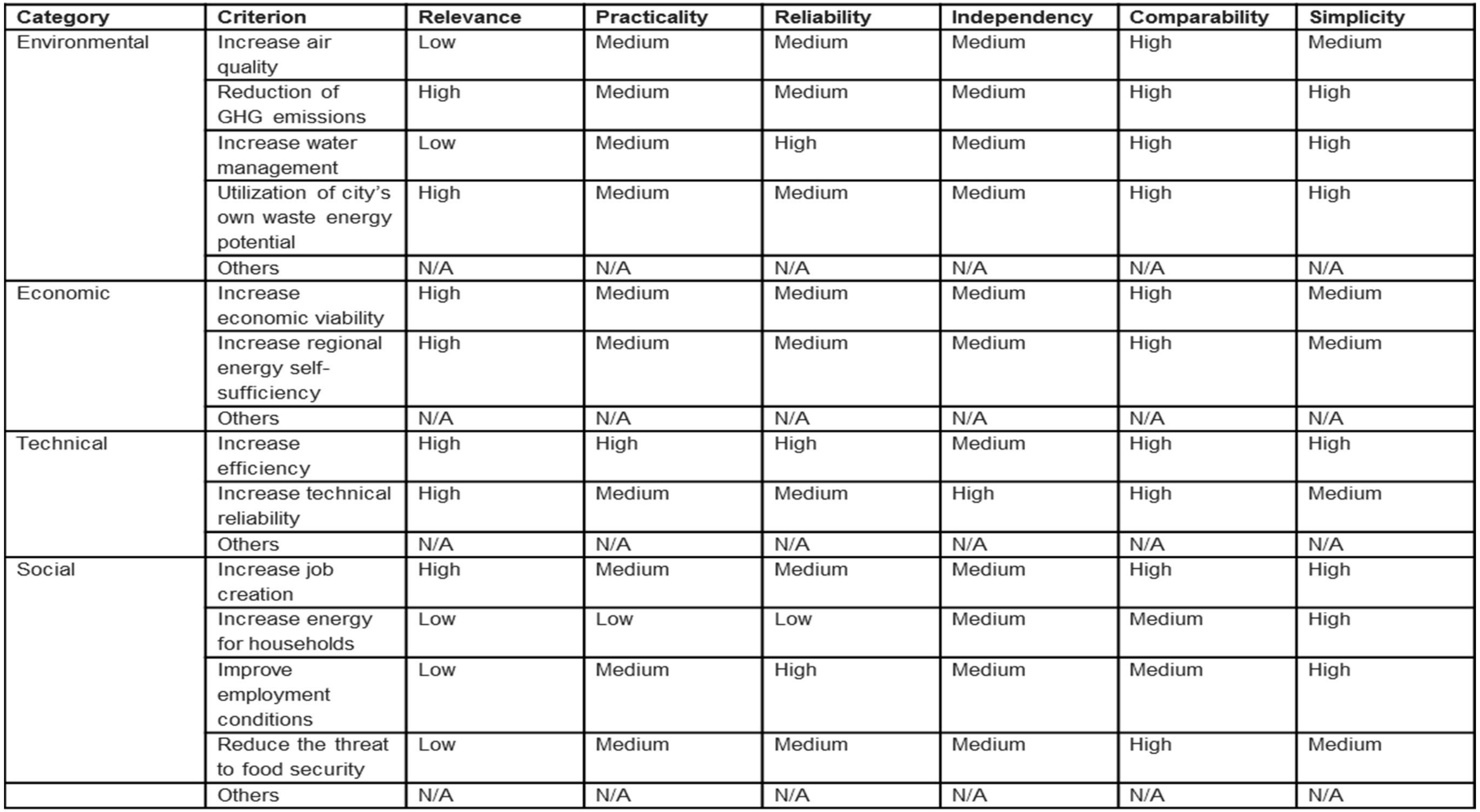
Category	Criteria
Environmental	'Increase air quality', 'Reduction of GHG emissions', 'Increase water management', 'Utilization of city's own waste energy potential' and 'Other environmental criteria'
Economic	'Increase economic viability', 'Increase regional energy self-sufficiency' and 'Other economic criteria'.
Technical	'Increase efficiency', 'Increase technical reliability' and 'Other technical criteria'.
Social	'Increase job creation', 'Increase energy for households', 'Improve employment conditions', 'Reduce the threat to food security' and 'Other social criteria'

At this point, it became apparent that some sustainability criteria were redundant, and others could be classified in more than one category. For instance, sustainability criteria related to fuel and resource availability and import dependency could have been either in the economic or in the social category due to their nature and potential effects on both aspects. Definitions of sustainability criteria, if available from literature, were of assistance to eliminate redundant sustainability criteria or to aggregate similar criteria (e.g. 'Increase job creation', 'Increase Employment generation' and 'Contribution to employment opportunities creation'). This process was characterized by selecting the most project, development or case study relevant sustainability criteria representing similar issues. In this process, the defined selection requirements (Table 6.3) were also considered.

Following the LCA approach (section 6.1), both mid- and end-point impacts can be considered to cover environmental criteria. As mentioned (section 6.1), using end-point impacts has disadvantages (increased uncertainty), but it was assumed that they are more intelligible and accessible to stakeholders from different backgrounds. Furthermore, they are more suitable for making strategic decisions and in early, tactical phases of project development decisions, because they allow more aggregation. Mid- and (mostly) end-point impacts were used in the work presented in this report.

The final selection of sustainability criteria was undertaken by comparing each of the sustainability criteria against the six selection requirements. In this process, the sustainability criteria were assessed using a three-point scale with the scores: 'low', 'medium' and 'high'. The threshold score was the score 'low', i.e. if a score against a requirement was 'low', the assessed sustainability criterion was excluded. Table 6.5 illustrates the scoring results of the selection process. In the following, the scoring results are discussed.

Table 4.5: Scoring results of the process to select sustainability criteria



Category	Criterion	Relevance	Practicality	Reliability	Independency	Comparability	Simplicity
Environmental	Increase air quality	Low	Medium	Medium	Medium	High	Medium
	Reduction of GHG emissions	High	Medium	Medium	Medium	High	High
	Increase water management	Low	Medium	High	Medium	High	High
	Utilization of city's own waste energy potential	High	Medium	Medium	Medium	High	High
	Others	N/A	N/A	N/A	N/A	N/A	N/A
Economic	Increase economic viability	High	Medium	Medium	Medium	High	Medium
	Increase regional energy self-sufficiency	High	Medium	Medium	Medium	High	Medium
	Others	N/A	N/A	N/A	N/A	N/A	N/A
Technical	Increase efficiency	High	High	High	Medium	High	High
	Increase technical reliability	High	Medium	Medium	High	High	Medium
	Others	N/A	N/A	N/A	N/A	N/A	N/A
Social	Increase job creation	High	Medium	Medium	Medium	High	High
	Increase energy for households	Low	Low	Low	Medium	Medium	High
	Improve employment conditions	Low	Medium	High	Medium	Medium	High
	Reduce the threat to food security	Low	Medium	Medium	Medium	High	Medium
	Others	N/A	N/A	N/A	N/A	N/A	N/A

The criterion ‘Increase air quality’ was not selected because the score was low against relevance. This criterion was not assumed to be a major relevant factor in the context of the work presented in this report.

Next, the criterion ‘Reduction of GHG emissions’ was scored against the selection requirements (Table 6.3). The score (high) for relevance was justified by the high importance and common use of the criterion. Data availability and reliability (whole supply chain) were assumed to be limited for the work presented in this report. The score (high) against comparability was due to the quantitative nature of the criterion. Furthermore, this criterion is influenced by several other criteria. This justifies the score (medium) against independency. This criterion scored well against simplicity. Due to its wide use, it was assumed that bioenergy stakeholders would understand this criterion easily.

The criterion ‘Increase water management’ was not selected because of the score (low) against relevance. This criterion was not assumed to be a major relevant factor in the context of the work presented in this report.

It is important to clarify that ‘Utilization of city’s own waste energy potential’ addressed the use/re-processing of waste to biofuel rather than the management of waste from the energy conversion plant. This criterion was regarded highly relevant. Using/re-processing of waste allows substitution of virgin materials. This can result in considerable GHG savings (EU Commission 2010). It can also contribute to achieving waste reduction targets. Generally, it was assumed that the data about available volumes of waste usable as a fuel resource by the bioenergy sector would be uncertain and relatively difficult to obtain in a cost, time and resource effective manner. This explains the scores (medium) against practicality and reliability. For the same reasons as for the criterion ‘Reduction of GHG emissions’, the scores against comparability (high) and independency (medium) were assigned. It was assumed that bioenergy stakeholders would understand this criterion easily.

The criterion ‘Increase economic viability’ was considered highly relevant because it allows aggregation of several costs and comparison of cash flows over time. Uncertain data availability and reliability was the reason for the scores (medium) against practicality and reliability. For the same reasons as for the criterion ‘Reduction of GHG emissions’, the scores against comparability (high) and independency (medium) were assigned. It was assumed that the level of understanding the criterion could differ among bioenergy stakeholders from different backgrounds.

The criterion ‘Increase regional energy self-sufficiency’ was considered highly relevant. Due to the dynamics of global and regional biomass feedstock supply and demand, data about fuel import dependency was assumed to be uncertain and relatively difficult to obtain in a cost, time and resource effective manner. This explains the scores (medium) against practicality and reliability. For the same reasons as for the criterion ‘Reduction of GHG emissions’, the scores against comparability (high) and independency (medium) were assigned. It was assumed that the level of understanding the criterion could differ among bioenergy stakeholders from different backgrounds.

With respect to technical criteria, the criterion ‘Increase efficiency’ is the most popular criterion to evaluate energy systems (e.g. Pilavachi et al. 2006; Onat and Bayar 2010). Efficiencies must be known for meaningful comparisons of energy technologies (Evans et al.

2008). Also, higher efficient processes will result in lower feedstock requirements as well as capital and operating costs (Evans et al. 2008). Therefore, this criterion was considered highly relevant and easy to understand. Due to its popularity and common use, measuring this criterion was also considered highly practical and reliable. For the same reasons as for the criterion ‘Reduction of GHG emissions’, the scores against comparability (high) and independency (medium) were assigned.

The criterion ‘Increase technical reliability’ addresses a technical solutions ability to perform reliably. This was considered highly relevant for bioenergy projects. Uncertain data availability and reliability was the reason for the scores (medium) against practicality and reliability. This criterion was considered to be less influenced by the other criteria. The criterion allows comparisons between alternatives (e.g. in terms of scale and type of technology). It was assumed that the level of understanding the criterion could differ among bioenergy stakeholders from different backgrounds.

In the energy sector, the criterion ‘Increase job creation’ can be considered as the key social criterion used for sustainability assessments due to its significant impact on people’s acceptance of the system (Chatzimouratidis and Pilavachi 2008). Therefore, the criterion was considered highly relevant in the context of the work presented in this report. Data availability and reliability (whole supply chain) were assumed to be limited for the work presented in this report. For the same reasons as for the criterion ‘Reduction of GHG emissions’, the scores against comparability (high) and independency (medium) were assigned. Due to its wide use, it was assumed that bioenergy stakeholders would understand this criterion easily.

The criterion ‘Increase energy for households’ was not selected as a sustainability criterion because of the scores (low) against relevance, practicality and reliability. This criterion was not assumed to be a major relevant factor in the context of the work presented in this report. Moreover, it was assumed to be highly cost, time and/or resource intensive to obtain data. This data would be based on several assumptions (e.g. house sizes, energy consumption, district heating infrastructure etc.) resulting in uncertain and unreliable data.

The criterion ‘Improve employment conditions’ was also not selected because of the score (low) against relevance. This criterion was not assumed to be a major relevant factor in the context of the work presented in this report.

The criterion ‘Threat to food security’ was related to the food versus-fuel-controversy, which covers the issue of diverting farmland or crops for biofuels production in detriment of the food supply. This criterion was also not selected because of the score (low) against relevance. This criterion was not assumed to be a major relevant factor in the context of the work presented in this report.

Other environmental, economic, technical and social sustainability criteria were not scored against the selection requirements. They were excluded in the sorting stage when most relevant sustainability criteria were chosen for the selection. Keeping the context of the work presented in this report in mind, these sustainability criteria were excluded by considering the six selection requirements, whereas relevance, practicality and reliability were the most determining requirements.

Table 6.6 below illustrates the sustainability criteria selected for the work presented in this report.

Table 4.6: Final set of selected sustainability criteria

Category	Criterion/objective	Description
Environmental	**Reduction of GHG emissions**	Avoided emissions of CO_2–equivalents by energy solution
	Utilization of city's own waste energy potential	City's waste re-used as fuel for energy solution (remaining waste after re-use and recycling)
Economic	**Increase economic viability**	Costs of energy solution
	Increase regional energy self-sufficiency	Fuel import dependency of energy solution
Technical	**Increase efficiency**	Energy efficiency of energy solution
	Increase technical reliability	Knowledge of technologies used for energy solution
Social	**Increase job creation**	Regional job creation through energy solution

7 Conclusions

Deliverable 3.1.1 focused on energy systems and the role of bioenergy in five Finnish and five German case cities. To enable applying the information obtained from the case cities in assessing the role of bioenergy in other cities, the case cities were generalized as city clusters as described in this report. This generalization or clustering can be of assistance in identifying and transferring successful practices from forerunner cities to new urban markets.

Principally, the case cities were clustered to represent a group of similar cities by using general and energy-specific characteristics with an individual classification for each characteristic. The general characteristics were population, population density, population growth, and climate zone. The energy-specific characteristics focused on GHG emission reduction targets, current energy infrastructure, and biomass availability.

Characteristics that were the same or very similar for all case cities in one of the countries were left out because they do not assist in differentiating city clusters to assess the role of bioenergy in those city clusters. Also, clusters with very similar characteristics were combined. For the Finnish city clusters, this resulted in four clusters and four characteristics (population, population growth, district heating network density, and biomass availability). It can be concluded that particularly clusters 3 and 4 can be useful in searching new Finnish markets for transferring successful urban practices. For the German cities, all characteristics apart from the climate zone characteristic were included in the clustering because of unique characteristic combinations. It can be concluded that particularly clusters 4 to 6 can be useful in searching new German markets for transferring successful urban practices.

Also, it was found that the population distributions are remarkably similar in Germany and Europe. As the five biggest city size groups used for the clustering cover 500 European cities, it could be argued that the city clusters formed for German cities provide a decent basis for assessing the adaptability of the successful practices found in the German case cities to a large number of European cities with similar population numbers. However, the population number is only one factor used in dividing the cities in different clusters.

It could be argued that the city clusters can be used as a screening tool in planning future urban energy and bioenergy systems prior to more detailed assessments. The different characteristics used can be seen as “filter” or “query” parameters for the screening, and the size of a created shortlist will depend on the characteristics considered for the screening. The screening tool can be used in two different ways. Firstly, it can be used to create a shortlist of potentially suitable cities to where a successful practice from one (case) city could be transferred. Secondly, it can be used to create a shortlist of successful urban practices that have potential in a certain city.

One example for successful urban practices that can be transferred from one city to other urban markets within the same city cluster is the technologies used for bioenergy production. Assessing the suitability of bioenergy technologies in different city clusters requires analysis of the technologies and comparison of the technology requirements to city conditions. To provide a basis for further technology analyses, the bioenergy technologies that are assumed to have importance in urban environments were briefly described in this report. These technologies included combustion, co-combustion, gasification, pyrolysis, torrefaction, pelletization, and waste-to-energy technologies. Moreover, the biochemical conversion technology anaerobic digestion was discussed, and liquid biofuel production was presented. Furthermore, CHP technology was also briefly discussed, because CHP production was mentioned in many of the energy strategies of the case cities (deliverable 3.1.1).

It can be concluded that the maturity of the technologies described varies greatly and an effort was made to classify them into different development stages. In the short term, technologies in the commercial and early commercial development stage are expected to be important in urban bioenergy systems. However, the strategies of the case cities that were presented in deliverable 3.1.1 revealed that the cities have a will to gain reputation as forerunners for modern low-carbon technologies. Therefore, also the technologies which are currently in an early development stage may be implemented in the case cities for instance as demonstration plants.

Self-sufficiency in feedstock supply for energy production was noticed to be a common aim for the case cities, and the role of bioenergy is, among others, dependent on the biomass availability in the city and surrounding area. Thus, there are cities that have more potential for biomass-fired CHP production, whereas in some cities for example co-combustion of biomass with fossil fuels is a more realistic option. In addition to the amount of biomass available, also the type and quality of the biomass affect the technologies suitable for bioenergy production.

Urban harvesting, where city-internal renewable and secondary resources are used to cover a maximal share of the energy demand, is a potential concept for future cities. Waste materials are one of the most significant city-internal feedstocks for energy production and thus have potential in future urban environments. Furthermore, there are many possibilities for heat recovery in cities. Waste heat can also be used for district cooling systems and low-temperature district heating. Moreover, biogas production from, for instance, sewage sludge or biowaste has growing potential in urban environments.

In this report, it is also outlined how sustainability criteria can be selected. In general, selecting appropriate sustainability criteria is crucial to assess the sustainability of a project, development or case study because this choice can influence the results of an assessment significantly. There is a lack of consensus on appropriate sustainability criteria critical for sustainability assessments and decision-making situations, for example in the bioenergy context. This implies a need for processes to select appropriate criteria which can be used for specific decision-making situations or sustainability assessments. The report shows how such a process can be carried out.

Based on sustainability criteria and selection requirements identified in literature, a set of sustainability criteria was selected using a series of sorting steps and a scoring process. The scores of the criteria compared against the selection requirements – relevance, practicality, reliability, independency, comparability and simplicity – were explained. The final set of criteria included the environmental criteria ‘Reduction of GHG emissions’ and ‘Utilization of city’s own waste energy potential’, the economic criteria ‘Increase economic viability’ and ‘Increase regional energy self-sufficiency’, the technical criteria ‘Increase efficiency’ and ‘Increase technical reliability’, and the social criterion ‘Increase job creation’.

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