Small-scale biogas production from organic waste and application in mid-income countries – a case study of a Lebanese community

Sebastian Huber
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Huber, S., 2019: Small-scale biogas production from organic waste and application in mid-income countries – a case study of a Lebanese community. Master thesis in Sustainable Development at Uppsala University, No. 2019/9, 48 pp. ECTS/hp

Abstract:

The controlled anaerobic digestion of organic waste in a biogas facility aggregates advantages of waste treatment, energy recovery and nutrient recycling and is a promising technology to deal with contemporary issues of waste management and energy recovery. Small-scale biogas production units can be simply designed and successfully operated even in settings where means for advanced technology equipment are low and institutional capacities limited. In the country of Lebanon, landfilling and open dumping of solid waste is common practice and anaerobic treatment of waste is applied only sporadically and hence, not well-established. The aim of this study was to assess the feasibility of small-scale biogas production using organic waste, explore options for its application and propose a business model on how feedstock sourcing, facility operation and end product utilization could be realized in the research area. Research area was Ghazir village, a community within the urbanized coastal area in Lebanon. Methods were of both quantitative and qualitative nature. A techno-economic assessment served to quantify biogas and liquid digestate production rates, based on available resources of organic waste in the research area. Costs associated with installation, operation and maintenance of the proposed facility have been projected based on present examples of similar facilities in the country. Interviews with local stakeholders and a questionnaire survey among residents in the area of research allowed to identify suitable end use options for the produced biogas and served to explore communal acceptance of local biogas production. Results show that the produced biogas can be used for thermal feedstock treatment to supply local farmers with a fertilizer alternative, i.e. the liquid digestate. Organic waste that is subject to the anaerobic treatment in a digester can be provided by multiple point sources, i.e. households and a local food market in the form of source-sorted kitchen waste and unsold fruits and vegetables, respectively. Due to the current unfamiliarity with anaerobic treatment of organic waste in the research area, tests on the effects on crop yields are advised to take place before implementation of the proposed business model, as its communal benefits hinge on the suitability of the liquid digestate as a fertilizer. Economic calculations show low investment costs for the proposed facility as well as acceptable annual revenues in case the liquid digestate proves to be of interest for commercial acquisition by local farmers. The used methods and strategies in this feasibility assessment, i.e. waste quantification, yield and cost calculations, stakeholder interviews and questionnaire survey allow for replication of the taken investigation to eventually initiate small-scale biogas production using organic waste in other settings with similar conditions.

Keywords: Sustainable Development, Lebanon, small-scale, biogas production, organic waste, liquid digestate, anaerobic digestion, feasibility study

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Summary:

The controlled decomposition of organic waste in a biogas facility aggregates advantages of waste treatment, energy recovery and nutrient recycling and is a promising technology to deal with contemporary issues of waste management and energy recovery. Small-scale biogas production units can be simply designed and successfully operated even in settings where means for advanced technology equipment are low and institutional capacities limited. In the country of Lebanon, landfilling and open dumping of solid waste is common practice and biogas technology can be found only sporadically. The aim of this study was to assess the potential of small-scale biogas production using organic waste, explore options for its application and propose a business model on how waste collection, facility operation and end product utilization could be realized in the research area. Research area was Ghazir village, a community within the urbanized coastal area in Lebanon. Methods were of both quantitative and qualitative nature. Biogas production rates, as well as volumes of treated organic waste, commonly referred to as ‘liquid digestate’, were calculated based on available resources of organic waste in the research area. Costs associated with installation, operation and maintenance of the proposed facility have been projected based on present examples of similar facilities in the country. Interviews with local stakeholders and a questionnaire survey among residents in the research area allowed to identify suitable end use options for the produced biogas and served to explore communal acceptance of local biogas production. Results show that the produced biogas can be used for thermal feedstock treatment to supply local farmers with a fertilizer alternative, i.e. the liquid digestate. Organic waste that is subject to decomposition in a digester can be provided by households and a local food market in the form of source-sorted kitchen waste and unsold fruits and vegetables, respectively. As this is a new concept of organic waste treatment in the research area, tests on the effects on crop production are advised to take place before implementation of the proposed business model, as its communal benefits hinge on the suitability of the liquid digestate as a fertilizer. Economic calculations show low investment costs for the proposed facility as well as acceptable annual revenues in case the liquid digestate proves to be of interest for commercial acquisition by local farmers. The used methods and strategies in this feasibility assessment, i.e. waste quantification, yield and cost calculations, stakeholder interviews and questionnaire survey allow for the replication of this study to eventually initiate small-scale biogas production using organic waste in other settings with similar conditions.

Keywords: Sustainable Development, Lebanon, small-scale, biogas production, organic waste, liquid digestate, anaerobic digestion, feasibility study

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<tr>
<td>AD</td>
<td>anaerobic digestion</td>
</tr>
<tr>
<td>ASG</td>
<td>Antonine Sisters School</td>
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<tr>
<td>BMP</td>
<td>bio-chemical methane potential</td>
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<tr>
<td>C</td>
<td>carbon</td>
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<tr>
<td>CHP</td>
<td>combined heat and power</td>
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<tr>
<td>CO₂</td>
<td>carbon dioxide</td>
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<tr>
<td>CO₂eq</td>
<td>carbon dioxide equivalents</td>
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<tr>
<td>C&lt;sub&gt;Sub&lt;/sub&gt;</td>
<td>specific heat capacity of substrate</td>
</tr>
<tr>
<td>CSW</td>
<td>costs for construction, installation and site works</td>
</tr>
<tr>
<td>dm&lt;sup&gt;3&lt;/sup&gt;</td>
<td>cubic decimeters (liters)</td>
</tr>
<tr>
<td>E</td>
<td>equation</td>
</tr>
<tr>
<td>E&lt;sub&gt;BG&lt;/sub&gt;</td>
<td>biogas energy content</td>
</tr>
<tr>
<td>EDL</td>
<td>Électricité du Liban</td>
</tr>
<tr>
<td>E&lt;sub&gt;el&lt;/sub&gt;</td>
<td>expenses for electrical power</td>
</tr>
<tr>
<td>E&lt;sub&gt;f&lt;/sub&gt;</td>
<td>expenses for fuel</td>
</tr>
<tr>
<td>E&lt;sub&gt;Treat&lt;/sub&gt;</td>
<td>energy required for treatment</td>
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<tr>
<td>EU</td>
<td>European Union</td>
</tr>
<tr>
<td>EUR</td>
<td>euros</td>
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<tr>
<td>E&lt;sub&gt;w&lt;/sub&gt;</td>
<td>expenses for water</td>
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<td>EWB</td>
<td>Engineers Without Borders</td>
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<td>Fig.</td>
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<td>GDP</td>
<td>Gross Domestic Product</td>
</tr>
<tr>
<td>GHG</td>
<td>greenhouse gas</td>
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<tr>
<td>GWP</td>
<td>Global Warming Potential</td>
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<tr>
<td>HDI</td>
<td>Human Development Index</td>
</tr>
<tr>
<td>K</td>
<td>Kelvin</td>
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<tr>
<td>kg</td>
<td>kilograms</td>
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<tr>
<td>kJ</td>
<td>kilojoules</td>
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<tr>
<td>km</td>
<td>kilometers</td>
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<tr>
<td>ktoe</td>
<td>kilotons of oil equivalents</td>
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<tr>
<td>kWh</td>
<td>kilowatt hours</td>
</tr>
<tr>
<td>LAB</td>
<td>costs for laboratory tests</td>
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<td>LPG</td>
<td>liquified petrol gas</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Description</td>
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<tr>
<td>LS-AD</td>
<td>liquid state anaerobic digestion</td>
</tr>
<tr>
<td>m</td>
<td>meters</td>
</tr>
<tr>
<td>m_{BG}</td>
<td>biogas mass</td>
</tr>
<tr>
<td>m_{OW}</td>
<td>organic waste mass</td>
</tr>
<tr>
<td>m_{Sub}</td>
<td>substrate mass</td>
</tr>
<tr>
<td>m_{VS}</td>
<td>volatile solids mass</td>
</tr>
<tr>
<td>MENA</td>
<td>Middle East North Africa</td>
</tr>
<tr>
<td>MSW</td>
<td>municipal solid waste</td>
</tr>
<tr>
<td>MW_{el}</td>
<td>megawatts (electrical power)</td>
</tr>
<tr>
<td>m^3</td>
<td>cubic meters</td>
</tr>
<tr>
<td>N</td>
<td>nitrogen</td>
</tr>
<tr>
<td>n</td>
<td>number of items</td>
</tr>
<tr>
<td>n_{CSW}</td>
<td>number of working hours for construction, installation and site works</td>
</tr>
<tr>
<td>n_{o}</td>
<td>number of working hours for operation</td>
</tr>
<tr>
<td>n_{m}</td>
<td>number of working hours for maintenance</td>
</tr>
<tr>
<td>NGOs</td>
<td>non-governmental organizations</td>
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<tr>
<td>OFMSW</td>
<td>organic fraction of municipal solid waste</td>
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<tr>
<td>OLR</td>
<td>organic loading rate</td>
</tr>
<tr>
<td>OM</td>
<td>costs for operation and maintenance</td>
</tr>
<tr>
<td>OW</td>
<td>organic waste</td>
</tr>
<tr>
<td>p_{ld}</td>
<td>liter price liquid digestate</td>
</tr>
<tr>
<td>p_{LPG}</td>
<td>liter price liquified petrol gas</td>
</tr>
<tr>
<td>p_{W}</td>
<td>liter price water</td>
</tr>
<tr>
<td>PP</td>
<td>payback period</td>
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<tr>
<td>R</td>
<td>revenues</td>
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<tr>
<td>RE</td>
<td>renewable energy</td>
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<tr>
<td>RQ</td>
<td>research question</td>
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<tr>
<td>RT</td>
<td>hydraulic retention time</td>
</tr>
<tr>
<td>S_{add}</td>
<td>additional savings</td>
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<tr>
<td>SDGs</td>
<td>Sustainable Development Goals</td>
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<tr>
<td>S_{ld}</td>
<td>profits sold liquid digestate</td>
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<tr>
<td>SS-AD</td>
<td>solid state anaerobic digestion</td>
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<tr>
<td>SUC</td>
<td>costs for set-up components</td>
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<tr>
<td>TPES</td>
<td>Total primary energy supply</td>
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</table>
TS total solids
USD U.S. Dollar
$V_{BG}$ biogas volumes
$V_D$ digester volume
$V_{ld}$ liquid digestate volumes
$V_{OW}$ volumes of solid organic waste
$V_w$ water volumes
vol. volume
VS volatile solids
$V_{TS}$ relative volatile solids content
w hourly wage
$^\circ C$ degrees Celsius
1. Introduction

‘One man’s trash is another man’s treasure.’

Any substance or item which is no longer considered useful and therefore discarded is generally defined as waste (Azzi, 2017; EU, 2008). According to the quote above, it rather depends on one’s perspective towards appreciation, utility and purpose when classifying an object as ‘trash’ or ‘treasure’, a trade as ‘loss’ or ‘profit’ or any matter as ‘waste’ or ‘resource’, respectively. The latter being of utmost significance in times of globally increasing consumption of goods which require substantial energy input, a growing number of consumers and accumulating amounts of abandoned products and garbage. Simultaneously, capacities of the earth system to provide live-supporting services for the human species in the long-term are limited and already stressed on a planet that is exposed to changing climate conditions and environmental degradation (Steffen et al., 2015).

Determined to tackle global issues and promoting an agenda for each country, the United Nations announced the 2030 Agenda for Sustainable Development, which serves as an action plan to foster people and planet through enhancing well-being and prosperity, as well as reducing negative impacts and deterioration of natural systems (Rosa, 2017). Access to affordable, clean and renewable energy, environmentally sound waste management, as well as efficient utilization of available resources are vital precursors for the achievement of the outlined Sustainable Development Goals (SDGs).

Waste-to-energy technologies gain more and more interest in both developing and emerging countries, which often must deal simultaneously with multiple challenges regarding waste management and energy supply in the face of increasing demands by a growing number of people (Mutz et al., 2017). The advantage of using waste as a resource for energy recovery lies at hand: abundant and eventually harmful quantities of refuse can be dealt with and replace limited sources of primary energy at the same time.

The deployment of production units that capture and enhance natural formation of a gaseous fuel from biomass, commonly referred to as biogas – of which main components are methane and carbon dioxide - is a promising approach to deal with organic waste quantities and generate economic, environmental and social benefits, which will be explained in Section 2.

1.1. Rationale of this study

Current management of Municipal Solid Waste in Lebanon is a much-debated issue since a waste crisis in 2015 disrupted vital public services and had a major effect on today’s waste management practices in the country (Azzi, 2017). An overall power deficit results in an unstable power supply by the national provider and power outages, what in turn led households and communities to adopt decentralized ways to meet daily needs (Abi Ghanem, 2018).

This work serves to assess the feasibility and potential benefits of implementing a small-scale biogas production unit in the area of interest, which utilizes organic waste generated in the vicinity of the unit. The research area is Ghazir village, located approximately 30 km north-east of the capital Beirut. It has a population of 12,000 people (Appendix A.2). Associated advantages of biogas technology in the form of local production of biogas and a nutrient rich soil enhancer, the allocation of a sink for organic waste and the fostering of communal development by including local stakeholders will be investigated in order to assess and evaluate contributions to Sustainable Development in the area of research.

Further motivation arose in the involvement with Engineers Without Borders Sweden (EWB), an organization that works in collaboration with local actors to address sustainability-related challenges around the globe, such as access to clean energy, education and sanitation (EWB Sweden, 2019). Aiming to strengthen competence in the field of biogas production from organic waste resources, the findings of this Thesis work shall serve as the basis for a framework for future project initiations to evaluate the potential of this technology and feasibility of implementation in comparable settings.
1.2. Study aims and research questions

**Aim 1** is to assess the feasibility of small-scale biogas production using organic waste in the research area under aspects of Sustainable Development (social, environmental and economic), explore options for its application and propose a business model on how feedstock sourcing, facility operation and end product utilization could be realized.

*RQ1.1* Under aspects of feedstock quality, biogas yields and costs, to what extent can biogas be produced if a small-scale production unit is installed in the research area, using available organic waste resources?

*RQ1.2* With regards to potential drawbacks and opportunities of local small-scale biogas production using available organic waste resources, how can related waste management be applied and recovered energy be utilized to increase benefits and minimize negative impacts for the local community?

**Aim 2** is to develop generally applicable strategies which are suitable to achieve **Aim 1** but can be also used to investigate other areas of interest with similar settings.

*RQ2* What strategies can be followed to generally answer the research questions under **Aim 1** but address other areas of interests with similar settings in terms of waste and energy issues?
2. Background

In the following, the scope of this work is put into the geographical and technical context regarding sustainability-related challenges in the country of interest, as well as the functionality of biogas production and relevant aspects to consider when applying this technology. It starts with a brief introduction to the contemporary discourse of Sustainable Development.

2.1. Pillars for a sustainable future

‘Humanity has the ability to make development sustainable to ensure that it meets the needs of the present without compromising the ability of future generations to meet their own needs’ (WCED, 1987).

Even though the terms ‘sustainability’ and ‘sustainable’ have been mentioned in literature long before, the idea of human-centered ‘sustainable development’ entered the arena of wider political debate in 1987 by a report of the World Commission on Environment and Development (WCED) under the chair of Gro Harlem Brundtland and has not re-disappeared ever since (Caradonna, 2014). A common illustration of the issue is given by interlinking the ‘three E’s’, i.e. environment, equity (or social equality) and economy, hence assigning the concept of ‘sustainability’, as well as the idea of ‘sustainable development’ an environmental, social and economic dimension (Fig. 1).

![Fig. 1: The three E's of sustainability](image)

Eventually misleading and causing wrong interpretation of the concept to treat every dimension in isolation from the others, hence ignoring their interconnectedness and essential relations between driving system components (Meadows and Wright, 2009) rose critique towards this categorization. The entitlement of each dimension is broadly acknowledged, however, some scholars argue for absolute precedence of the environment being the impeachable foundation for a thriving society and its economic activities (Caradonna, 2014; Dryzek, 2013). In the context of this report no such ranking between the three dimensions or pillars of Sustainable Development is followed.
2.2. Municipal solid waste – a global challenge

When looking at literature related to the subject of waste management, such as statistical reports, legislation documents or scientific papers, categories and classifications of waste can vary, which eventually creates difficulties in identifying and comparing certain waste quantities when looking at different sources for data. Analyses and discussion of waste quantities often refer to municipal solid waste (MSW), for which data is widely available on both local and global levels.

A growing number of people on the planet, as well as changing consumption patterns and increasing wealth at the same time have led to concerning levels of waste generation throughout recent years (Fischedick et al., 2014). As illustrated in Fig. 2 it is further projected that generation of MSW per capita will increase in coming decades. This, together with widely inadequate handling of such large amounts of waste pose high risks to both environment and humans, to which the poorest are exposed the most (Kaza et al., 2018).

Disposal and treatment of MSW differs from place to place. A global snapshot regarding current treatment of waste contradicts the commonly acknowledged concept of a waste-treatment hierarchy that is specified in the Waste Framework Directive of the European Union (EU) (EU, 2008). According to this, waste disposal, i.e. landfilling and open dumping\(^1\) is depicted as the least favorable option among all waste treatment alternatives. Fig. 3 illustrates the waste hierarchy as outlined in the EU directive.

Landfilling and dumping drive environmental degradation, pose health risks and cause economic losses in the form of GHG emissions and odors, soil and water contamination through leachate and unused sources for energy, material and nutrient recovery (EC, 2016; Fischedick et al., 2014; Ghasemi Ghodrat et al., 2018; Ogundiran and Afolabi, 2008). Yet, about two thirds of the total amount of MSW is treated that way, which is widely applied to address highly rising waste generation per capita, also and especially in the Middle East North Africa (MENA) region (Fischedick et al., 2014; Kaza et al., 2018). In 2016, more than 600 dump sites for MSW were identified across Lebanon (MoE and UNDP, 2017). Although waste composition is strongly correlated to the average income level of the producers, organic waste, i.e. food and green waste represents the largest share of up to more than half of total MSW produced (by weight) across the world (Kaza et al., 2018).

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\(^1\) Whereas in various literature the term ‘landfilling’ refers to waste disposal at officially managed and controlled sites (sanitary landfills), ‘open dumping’ implies uncontrolled waste disposal at sites which were not formally allocated for this purpose, eventually violating locally applying legislation (Mutz et al., 2017).
In the field of biogas research and in many waste-related statistical reports, using the term ‘organic waste’ is common. Organic waste (OW) in regards to biogas production can be classified into (i) municipal solid, (ii) manure and (iii) agro-industrial (Di Matteo et al., 2017, p. 4; Valijanian et al., 2018, p. 97). Focus of research in this study will be defined later on in the report and is primarily on (i), at times referred to as the organic fraction of municipal solid waste (OFMSW).

![Waste hierarchy according to the EU Waste Framework Directive](image)

**Fig. 3: Waste hierarchy according to the EU Waste Framework Directive**

### 2.3. The country of Lebanon

#### 2.3.1. Geography, demographics and economic background

The republic of Lebanon is located in the Middle East region, adjoining the Mediterranean Sea in the West and sharing borders with Israel/Occupied Palestine in the South as well as Syria in the North and East (Fig. 4). Being the smallest country in continental Asia it stretches up to 225 km in length and 46 km in width and its land area is comparable in size to Jamaica or Cyprus. Climate conditions and topography vary across four geographical regions that roughly follow a West-East direction, beginning with the coastal plains followed by the Mount Lebanon Range and the Békaa Valley and completing with the Anti-Lebanon Range being part of the Eastern border to Syria (MoT, 2011).

As no national population census has been conducted since the 1960s, the exact number of people living in Lebanon is uncertain, but estimated to be 6.1 million, including between 1.5 and 2 million displaced people, mostly Syrians and Palestinians. A large majority of the Lebanese live in urban areas, mostly along and near the coast in the area around the country’s capital, Beirut. The biggest religious group are Muslims, mostly Sunni and Shia, corresponding to approximately 58 % of the population, followed by Maronite Christians (36 %), Druze (5 %) and smaller minorities (CIA, 2019). The central governmental body is the democratically elected parliament called Council of Ministers. The constitution ensures balance between the main religious groups by assigning representatives of Sunni, Shia and Maronite Christians the positions of the prime minister, speaker of the parliament and president of state, respectively (Sleem and Dixon, 2018).

![The country of Lebanon](image)

**Fig. 4: The country of Lebanon (CIA, 2019)**
Distribution of economic wealth differs across the country (Oxfam, 2019). Gross domestic product (GDP) per capita in 2017 corresponds to 19,600 U.S. Dollars (USD) and puts Lebanon on state rank 91 comparable to Mexico and Iran (CIA, 2019). Main contributors to the national economy is the banking and service sector but also tourism, however, imports of goods, e.g. petroleum products and cars represent a substantial share of GDP (CIA, 2019; WorldBank, 2019). Agriculture predominantly takes place in the Békaa Valley and allows for exports of fruits and vegetables but is not a major driver of Lebanese economic activity, which has been disrupted by political instability in the region from time to time.

2.3.2. The issue of solid waste management

Current numbers and figures

The total amounts of MSW generated, as well as MSW generated per capita in Lebanon has increased throughout recent years and is estimated to be 1.05 kg per capita per day currently (GIZ and SWEEP-Net, 2014; Marett et al., 2017; MoE and UNDP, 2017). This estimate lies above global average, as well as average within the MENA region, which corresponds to 0.74 and 0.81 kg per capita per day, respectively (Kaza et al., 2018). It should be mentioned here, that there is a large population of displaced people in the country mostly living in congested areas without adequate waste management services, which substantially contributes to total MSW generation and further stresses national capacities to deal with waste issues (UNDP, 2014).

MSW composition in Lebanon shows that the organic fraction accounts for the largest share (by weight), followed by paper and cardboard, plastics, metal and glass as illustrated in Fig. 6. There are geographical differences across the country with higher fraction of organic waste and more MSW generated per capita in urban areas when compared to rural localities (Abbas et al., 2017).

The predominant way of treatment of MSW in Lebanon is disposal in either sanitary landfills or open and uncontrolled dump sites, followed by composting and recycling (Fig 5). Interestingly, the shares of MSW that was either composted and recycled or disposed at sanitary landfills have been higher before the country’s main landfill was closed and a waste crisis hit Lebanon in 2015, which led to increased open dumping of waste especially in the Beirut, Mount Lebanon area (Buchanan, 2016). A report on solid waste management in Lebanon showed that composted and recycled MSW alone accounted for 15 % and 8 %, respectively before 2015 (GIZ and SWEEP-Net, 2014, p. 19).

![MSW composition by weight](image)

**Fig. 6:** MSW composition in Lebanon (GIZ and SWEEP-Net, 2014)

![MSW treatment/ destination](image)

**Fig 5:** MSW treatment and destination in Lebanon (MoE, 2018)

Between 2011 and 2016 the total number of operational dump sites decreased from 382 to 341. However, the number of non-operational sites more than doubled from 122 to 263 nevertheless and total amounts of openly dumped MSW increased substantially by approximately 66 % to concerning levels underlining the importance of immediate action to address the issue (MoE and UNDP, 2017).

The waste crisis of 2015/2016 and environmental impacts of current practices

Disposing waste as it accumulates is common practice in countries that do not have sufficient economic resources, personal capacities and technical means with regards to energy and material recovery
Accordingly, the operation of sanitary landfills, which provides a simple solution at low economic costs, is a widely applied first step towards effective solid waste management especially in upper middle-income countries like Lebanon (Kaza et al., 2018).

However, shortsighted waste management planning by authorities, lacking transparency with regards to public tenders and commissioning of waste-related affairs, as well as repressed competition between operators in the sector and distrust in politics among citizens led to public demonstration after the disruption of vital public services such as sweeping and waste collection over eight months (Abbas et al., 2017; Azzi, 2017; Chalhoub, 2018; Maret et al., 2017). The repeatedly extension of the lifespan of the country's main landfill in Naameh, which has served for final waste disposal of Lebanon's largest part of MSW (Massoud and Merhebi, 2016) far beyond its initially designed capacity triggered public protests and ultimately resulted in the abrupt closure of the site. That in turn led to substantial volumes of MSW piling up in the streets in Beirut and ultimate uproar among citizens, protesting and disclosing wide discontent against the political inertia to appropriately deal with long prevailing issues of solid waste management in Lebanon (Azzi, 2017).

Accounting for almost 10% of total national greenhouse gas (GHG) emissions in 2011, the solid waste sector has a substantial impact on the environment, as open dumps and landfilling are a point source for the release of large amounts of methane into the atmosphere (Maret et al., 2017). Eventually, the situation became worse during and after the waste crisis as the practice of openly dumping and burning trash increased, not only degrading ecosystems but also exposing the resident population to major health risks in the form of toxic fumes, spreading viruses and disease vectors like insects, as well as a higher risk of cancer (Massoud and Merhebi, 2016).

Landfilling and open dumping still dominate waste treatment in Lebanon. Nevertheless, the population becomes more and more aware of the severity of consequences that stem from inappropriate waste management and a shift in practice and willingness for improvement can be noticed (Azzi, 2017).

2.3.3. Energy supply

Current numbers and figures

Lebanon heavily relies on fossil energy supplies, which are not sourced domestically and hence makes the country quite dependent on imports. Aiming towards more resilience and self-sufficiency, off-shore oil and gas recovery in domestic waters and on-shore wind power production on a larger scale have been outlined to start in 2018 and 2020, respectively. A transnational gas pipeline provided access to natural gas in the recent decade, however, gas imports ceased in the light of political instability in the region. A project for a national pipeline along the coast from a floating storage unit has been delayed since 2013 (El-Jamal et al., 2014; Enerdata, 2018).

Fig. 7: Total primary energy supply by source in Lebanon, 2016 (IEA, 2019a)
The largest share of total primary energy supply (TPES) in Lebanon is provided by the import of oil and coal, as illustrated in Fig. 7. Minor imports of biofuels and electricity are negligible in comparison. Domestic energy production is exclusively sourced by renewables, namely electricity generation through hydropower and heat production from solid biofuels and solar energy. Oil accounts for 98% of total electricity generation (Enerdata, 2018). According to statistics of the International Energy Agency (IEA, 2019a), transportation is responsible for 39% of total energy consumption and fully relying on oil, followed by the residential sector (35%), industry (14%), commercial and public services (5%) and non-specified consumption.

**Domestic electricity usage and national agenda**

Despite political efforts to reorganize and privatize the domestic power market in Lebanon, state owned Électricité du Liban (EDL) holds a monopoly, officially controlling 90% of the sector (Enerdata, 2018). Distribution losses caused by illegal connections to powerlines and technical shortcomings, unpaid bills by customers, heavy reliance on imported oil products as well as low prices not making up for high production costs led to substantial debts and high spending from the government in recent years to keep the national supplier alive (Abi Ghanem, 2018; El-Jamal et al., 2014; Enerdata, 2018). Due to low production capacities, EDL cannot provide full-time power access and hence power outages across the country of up to 12 hours are part of Lebanese everyday life (Abi Ghanem, 2018). This has led to wide adaptation of measures for power self-sufficiency among the population in times of power outages of the national grid. Common ways to meet daily electricity demands are the deployment of individual or community-owned diesel-generators, as well as the acquisition of power services by informal energy suppliers despite formally violating national law (Abi Ghanem, 2018).

To become less reliant on energy imports, as well as improve access to power and to follow global objectives for climate change mitigation, Lebanon put increased use and promotion of renewable energy (RE) on the political agenda aiming towards a share of 12% in heat and electricity supply by 2020 and 15% in 2030, respectively (El-Jamal et al., 2014; Enerdata, 2018; UNDP, 2012). However, RE capacities have only grown slightly in recent years, mostly in the field of solar energy as can be seen in Fig. 8. The lack of governmental support for the installation and generation of renewable energy is considered an obstacle for investments. ‘There are no feed-in tariffs for electricity production from renewables’ (Enerdata, 2018, p. 7).

![Fig. 8: Installed renewable capacity by technology in Lebanon (IRENA, 2018)](image)

**Biogas in Lebanon**

According to a report on the national bioenergy strategy for Lebanon (UNDP, 2012) liquid biofuels, as well as incineration and biogas production using organic waste resources have been declared promising...
technologies with regards to domestic energy production. Even though biogas production is now part of the landscape of RE it is not much established in Lebanon. Few farm-sized production plants treating animal manure can be found (Appendix A.1), and the biggest facility in Lebanon is the anaerobic digester in Saida, as part of a MSW treatment center (IBC s.a.l., 2016) where the produced energy is used for treatment-related energy consumption (Appendix A.5). The total biogas capacity in Lebanon accounts for 2 MWel (Fig. 8).

According to a not yet issued national law on integrated MSW management, electricity produced in waste treatment facilities can be fed into the national grid at the operators own expenses, provided a license is obtained by the Ministry of Energy and Water (MoE, n.d.). In return the national power supplier EDL shall purchase the produced electricity. This law has been approved by the parliament in 2018 but has not been implemented by the government to the date of writing (Appendix A.1).

2.4. Biogas technology

The recovery of biogas as a result of microbial decomposition of organic matter has gained increasing attention across the world throughout recent decades. Biogas formation is a natural process, that takes place in wetlands or in the stomach of ruminants, but also at disposal sites for solid waste materials, i.e. landfills or open dumps (Vasco-Correa et al., 2018). The energetic value of the biogas increases with a higher methane content. A methane content of 45 % (vol.) and higher allows combustion of the formed biogas (Deublein and Steinhauser, 2011). When methane is combusted, for example to generate electricity, carbon dioxide is formed, which has a lower global warming impact than methane.\(^2\) Hence, the recovery of biogas that is formed, for example, in landfills provides an energy carrier and can lower environmental impacts as it reduces the release of GHG into the atmosphere (Karapidakis et al., 2010). However, disadvantages of landfill operation as mentioned earlier makes other approaches more attractive.

\[\text{Fig. 9: Globally installed electricity capacity by biogas plants by region over time (IRENA, 2018)}\]

\(^2\) Global warming potential (GWP) is a parameter to compare different gases with regards to energy absorption under a certain time period, hence heating up the atmosphere and earth surface by hindering energy in the form of heat to escape into space (US EPA, 2016). Assuming a time horizon of 100 years GWP of methane is 21 times higher compared to carbon dioxide (UNFCCC, 2019).
Conventionally, biogas is captured by the deployment of so-called digesters or (bio-) reactors, in which more or less controlled bacterial activity leads to the digestion of organic substances, enabling the formation of biogas. Taking advantage of natural decomposition processes, as well as the flexibility of using a broad range of different material resources make this an interesting technology to deal with contemporary waste and energy-related challenges. ‘Organic waste treatment in bioreactors simultaneously assists with solving environmental problems, generating energy (biogas) and manufacturing high-quality fertilizers’ (Baltrėnas and Baltrėnaitė, 2018, p. 30).

The scale of deployment varies among countries and regions and depends on the geo-political and economic context, as illustrated in Fig. 9. Whereas in many Asian countries home-scale digesters locally provide cooking fuel on a households level, commercial biogas production for heat and power generation is a common business model in Europe (Scarlat et al., 2018). Global production of biogas increased substantially in recent years. However, the share of total energy production in 2014 accounted for less than 0.23 % (IEA, 2019b; Scarlat et al., 2018).

The following section serves to disclose underlying aspects both theoretically with focus on biogas formation in relation to substrate composition and practically by a brief insight of established operation modes and end use opportunities.

### 2.4.1. Anaerobic digestion process

The anaerobic digestion (AD) process describes a sequence of bio-chemical reactions, in which organic material is converted into biogas by various microorganisms, among others methane-producing bacteria whose metabolic activity is inhibited by increasing exposure to air (Li et al., 2011). In combination, the different groups of microorganisms together degrade the organic matter in four phases, i.e. hydrolysis, acidogenesis, acetogenesis and methanogenesis (Baltrėnas and Baltrėnaitė, 2018, p. 32; Deublein and Steinhauser, 2011, p. 101; Paritosh et al., 2017).

Large molecules, i.e. long-chain carbohydrates, proteins and fats are raw components of the organic material that is subject to decomposition. In the hydrolysis phase those compounds are broken down into smaller molecules, i.e. short-chain sugars, amino acids and peptides, as well as fatty acids and glycerin to be treatable by other bacteria in the process steps that follow (Deublein and Steinhauser, 2011; Paritosh et al., 2017).

During the acidification phase, i.e. both acidogenesis and acetogenesis, acetate, carbon dioxide, as well as hydrogen is formed, which are necessary precursors for the final phase of the digestion process to take place. During methanogenesis methane is produced by anaerobic bacteria mainly from acetates, along with carbon dioxide (Paritosh et al., 2017). The methane and carbon dioxide content in the generated biogas varies between 45 to 75 % (vol.) and 25 to 55 % (vol.), respectively. Besides methane and carbon dioxide, smaller fractions of nitrogen, oxygen, ammonia, hydrogen sulfides and water vapor add to the final gas mixture (Deublein and Steinhauser, 2011; Surendra et al., 2014).

### 2.4.2. Process classification and operating parameters

When it comes to the operation of biogas production units, there are different ways of classifying the process, as listed in Table 1.

<table>
<thead>
<tr>
<th>Substrate feeding continuity</th>
<th>batch</th>
<th>continuous</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating temperature</td>
<td>psychrophilic</td>
<td>mesophilic</td>
</tr>
<tr>
<td>Content of solids</td>
<td>Wet digestion</td>
<td>Dry digestion</td>
</tr>
</tbody>
</table>
Substrate feeding continuity

One distinction can be made by looking at how a digester is ‘fed’ with a substrate. Batch reactors receive one load of substrate after which the substrate remains for a certain period of time until it is removed and replaced by new material. The time period in which the substrate is subject to the AD process is referred to as hydraulic retention time (RT). Operating temperature is a determiner for the optimal RT and can be as long as 90 days under psychrophilic conditions (Ferrer et al., 2011) but can also be much lower at higher process temperature levels. Usually, the AD process residue, i.e. the digestate, is not fully removed at the end of the cycle to leave behind microorganisms in the digester which initiate the AD process with the new material once again (Deublein and Steinhauser, 2011).

When applying batch-wise feeding, biogas production is not constant over time due to fluctuating microorganism activity. Accordingly, biogas production increases after process initiation and reaches a peak after approximately half of the retention time (Deublein and Steinhauser, 2011; Stan et al., 2018; Talia, 2018). On the contrary, continuous feeding allows for stable biogas production as new substrate is being added constantly or at a very small-time interval, while digested material is removed from the reactor simultaneously. The simplicity of a batch process leads to low investment and operational costs, however, continuous systems allow for higher process stability and production predictability, as well as higher biogas yields if applied properly (Li et al., 2011; Obiukwu and Nwafor, 2016; Talia, 2018). The practice of semi-continuous feeding, for example adding feedstock in one load every day is also widely applied, especially when operating simple digesters and smaller facilities (Vögel et al., 2014).

Operating temperature

Biogas production through the AD process can take place under different temperature levels, i.e.: (i) psychrophilic, lower than 25 °C; (ii) mesophilic, between 37 and 42 °C; and (iii) thermophilic, between 50 and 55 °C (Talia, 2018, p. 55). A psychrophilic environment in general causes lower activity of methane-producing bacteria, resulting in limited methane formation and therefore lower biogas yields (Baltrėnas and Baltrėnaitė, 2018) as indicated in Fig. 10.

In terms of biogas production rates, both mesophilic and thermophilic conditions are most suitable for digestion of organic waste (Paritosh et al., 2017). However, sensitivity to rapid changes in temperature for microbial functionality increases with warmer conditions, particularly for a thermophilic process. Accordingly it is desirable to keep the temperature level of mesophilic and thermophilic processes stable during AD to not risk process inhibition and consequently miss out on considerable biogas yields (Deublein and Steinhauser, 2011; Talia, 2018). Psychrophilic and mesophilic conditions require less energy input into the process compared to thermophilic conditions, since temperature levels are lower. Faster bacterial treatment of the substrate during thermophilic operation modes allow for higher biogas production rates, which eventually offset higher energy demands to maintain the temperature level (Baltrėnas and Baltrėnaitė, 2018; Li et al., 2011; Paritosh et al., 2017). Fat-rich substrates further fuel the reaction process (Deublein and Steinhauser, 2011), which in the regards of biogas yields favors OFMSW as a substrate (Li et al., 2011) especially under thermophilic conditions. On the other hand, the excessive formation of volatile fatty acids results in a decrease in pH, which in turn affects the overall methane production negatively during the process (Cabbai et al., 2013).

Content of solids

Another type of classification points to the content of solid parts in the substrate that is subject to decomposition. Different terms for this distinction can be found in the literature, i.e. dry and wet.
digestion (Talia, 2018), dry and wet fermentation (Deublein and Steinhauser, 2011) or solid-state and liquid-state anaerobic digestion (SS-AD and LS-AD, respectively) (Li et al., 2011). Indicators to assign a ‘dry’ classification commonly relate to the dry biomass or total solid (TS) content in the feedstock, to be between 15 to 20 % (Shi et al., 2013; Talia, 2018) or a water content of less than 85 % (Deublein and Steinhauser, 2011), respectively. Dry digestion was initially used for organic wastes, especially OFMSW, however, to date also wet digestion is widely applied when using organic waste resources as a substrate for biogas production (Talia, 2018). Advantages of a ‘dry’ substrate include lower investment costs for commercial facilities due to simple plant design, as well as an easy handling of the digested output material because of its solid form.

On the contrary, LS-AD allows for better substrate mixing to optimize substrate properties, as well as a stable biogas production rate and smooth substrate transfer for example by pumps (Deublein and Steinhauser, 2011; Li et al., 2011; Talia, 2018). Biogas production performance is comparable between the two types of digestion. However, wet digestion shows slightly better energetic and economic characteristics in commercial and large-scale production units (Angeloni and Smith, 2015; Li et al., 2011; Talia, 2018). A scheme of a design for small-scale digesters based on wet digestion using manure as main substrate is shown in Fig. 11.

![Fixed dome digester scheme](Rakotojaono, 2013, p. 11, reused in accordance with copyright policy)

**Organic loading rate, pH and inoculation**

The organic loading rate (OLR) describes how much feedstock, i.e. volatile solids are added to the digester over time and higher biogas production rates have been reported by an increase in the OLR (Paritosh et al., 2017). However, the overall process performance within a digester can also be deteriorated by overloading due to higher concentrations of volatile fatty acids which can inhibit bacterial digestion activity (Xu et al., 2018). This is because accumulation of volatile fatty acids leads to a decrease in the pH in the substrate, which in turn negatively affects the methane producing microorganisms that thrive best under medium pH-levels (Deublein and Steinhauser, 2011; Talia, 2018; Weiland, 2010). More advanced technology in the form of continuously stirred digesters can operate under higher OLR than simpler applications, for example small-scale fixed-dome type digesters that are predominant in Sub-Sahara African countries, as well as India or China. If no stirring equipment is included in biogas production unit Vögeli et al. (2014, p. 28) suggest OLR of around 2 kg VS per m³ digester volume per day.

To initiate the AD process within a digester, the addition of feedstock in which digesting bacteria are already accumulated is widely applied during the start-up phase of biogas production, regardless of the scale of the facility. Common substrates are sewage water or animal manure and slurry (Paritosh et al., 2017; Vögeli et al., 2014).

**2.4.3. Feedstock and biogas yields**

The material, which is subject to decomposition in the AD process is widely referred to as feedstock, i.e. ‘feeding a digester. However, when discussing material properties that are critical for the formation
of biogas and methane, respectively, the term ‘substrate’ instead of ‘feedstock’ is commonly used both in the literature and this report.

As long as carbohydrates, proteins and fats are main components of the substrate, basically all types of biomass can be used for biogas production (Deublein and Steinhauser, 2011, p. 55). Since numerous processes take place simultaneously during the anaerobic digestion process and various types of microorganisms are involved, final biogas yields depend on a number of key parameters and conditions. These are partly affected by process parameters which can be controlled and maintained within the production unit during the actual proceeding of biogas formation, for example temperature level, bacteria inoculation or retention time of the substrate (Deublein and Steinhauser, 2011; Li et al., 2011; Paritosh et al., 2017). Yet, another major parameter for the efficiency of the intermediate activity and metabolism of bacteria to produce biogas is the biomass composition or quality, respectively. This is determined by the choice of substrate. Indicator for the potential rate and extend of organic matter to methane is the so-called bio-chemical methane potential (BMP) (Alibardi and Cossu, 2015; Nallathambi Gunaseelan, 1997; Paritosh et al., 2017).

Not the entire volume of the original substrate which is fed to a digester is suitable for bacterial decomposition, hence methane production. This is either because of inhibiting or detrimental components of the matter towards microbial activity or the existence of larger molecular formations like cellulose and most synthetic polymers which are very slowly decomposable (Deublein and Steinhauser, 2011). Furthermore, not all of the organic material which is suitable for bacterial decomposition is actually digested at the end of the retention time. This is due to technical and operational limitations in a biogas facility. The share of organic material that theoretically can be digested by microorganisms is in the following referred to as volatile solids (VS).

Another important characteristic of the substrate is the balance between carbon (C) and nitrogen (N), commonly termed as C/N ratio. Since the bacteria that are involved in the decomposition of the substrate use up carbon faster than nitrogen, a C/N ratio of between 25 and 30:1 has been identified being optimal for the process (Li et al., 2011; Paritosh et al., 2017), but can be up to 1000:15 for methane formation being sufficient (Deublein and Steinhauser, 2011, p. 128). Nitrogen overshoot leads to higher concentrations of ammonia, whereas a lack of nitrogen constrains protein formation which is vital for metabolite activity of microorganisms (Deublein and Steinhauser, 2011; Paritosh et al., 2017). Both cases inhibit the anaerobic digestion process, which is why it is important to stay within the tolerable C/N ratio. Different substrates can be mixed in order to achieve suitable nutrient and C/N ratios or stimulate bacterial activity for process initiation (Stan et al., 2018; Weiland, 2010). Table 2 lists examples of substrate types showing relevant parameters for biogas production.

Table 2: Characteristics of some substrates

<table>
<thead>
<tr>
<th>Substrate type</th>
<th>VS/TS [%]</th>
<th>C/N ratio</th>
<th>Methane yields [m³/kgVS]</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Potatoes</td>
<td>85-96</td>
<td>44</td>
<td>0.3-0.9</td>
<td>(Deublein and Steinhauser, 2011; Nallathambi Gunaseelan, 1997)</td>
</tr>
<tr>
<td>Cow manure</td>
<td>68-85</td>
<td>14-40</td>
<td>0.1-0.8</td>
<td>(Deublein and Steinhauser, 2011; Paritosh et al., 2017)</td>
</tr>
<tr>
<td>Maize (whole crop, fresh)</td>
<td>41-50</td>
<td>42-51</td>
<td>0.27-0.29</td>
<td>(Kalač, 2011)</td>
</tr>
<tr>
<td>OFMSW</td>
<td>43-95</td>
<td>16-39</td>
<td>0.06-0.58</td>
<td>(Cabbai et al., 2013; Campuzano and González-Martínez, 2016; Pavi et al., 2017)</td>
</tr>
</tbody>
</table>
2.4.4. Organic waste as a resource for biogas production

In regards to bio-chemical properties, the composition of OFMSW varies and depends among other things on geographic region, population density, season and social status of the waste producers (Alibardi and Cossu, 2015; Campuzano and González-Martínez, 2016; Di Matteo et al., 2017). Further, the properties and hence, the quality of such a substrate depends on the waste collection strategy. For example, source-sorted kitchen waste provides higher BMPs when compared to mechanical sorting (Li et al., 2011). Accordingly, the BMP of, for example, household waste when used as substrate for biogas production, differs from sample to sample and place to place, respectively.

A study by Alibardi and Cossu (2015) revealed effects on methane production potential of different OFMSW-compositions, thus assigning higher methane yields from samples with bigger fraction of meat, fish and cheese, due to higher fat content. On the contrary, large shares of bread, pasta and fruits, which are rich in carbohydrates, resulted in lower methane output. Campuzano and González-Martínez (2016) reviewed studies on BMP from OFMSW that were conducted in 43 cities across 22 countries. Potential methane yields were lowest in Cadiz, Spain (0.061 m$^3$/kgVS) and highest in Gistrup, Denmark (0.58 m$^3$/kgVS). BMP of OFMSW sourced in Beirut, Lebanon showed a potential of 0.35 m$^3$/kgVS (Ghanimeh et al., 2012). It must be mentioned, that the given numbers stem from various studies that showed yields from digesters under different operation settings, such as digester size, temperature level and OLR.

2.4.5. Merits in the light of Sustainable Development

Although it has been mentioned that treating each dimension of Sustainable Development in isolation can impede the finding of sustainable solutions, merits of biogas production can be categorized into (i) environmental, (ii) social and (iii) economic benefits. The following attempt nevertheless reveals limitations as prosperity and well-being of the environment, society and economy are mutually influential and therefore a distinction between the different benefits can be somewhat difficult.

Environmental

The combustion of oil, coal and gas is responsible for most global carbon dioxide emissions (IEA, 2016). Accordingly, substituting fossil fuels with biogas lowers anthropocentric GHG impacts, since biogas combustion only releases carbon to the atmosphere that was initially captured through the growth of the biomass that is subject to anaerobic digestion when the biogas is formed (Capodaglio et al., 2016; Paolini et al., 2018; Vögel et al., 2014). Biogas production using OFMSW also reduces absolute volumes of openly dumped or landfilled solid waste. Reported groundwater contamination through leachate, increased soil toxicity, as well as uncontrolled GHG emissions at landfills and dumpsites are of great concern with regards to both human health and ecosystem well-being (Donevska et al., 2013; El-Naq, 2005; Ghasemii Ghodrat et al., 2018; Ogundiran and Afolabi, 2008). Redirecting organic waste flows towards alternative sinks, such as biogas facilities can diminish total amounts of disposed solid waste and therefore lower the magnitude of environmental degradation. Further benefits are created in countries, where wood is primary energy source for heating and cooking. Replacement with biogas mitigates deforestation, which in turn reduces negative effects, such as soil erosion and land degradation and allocates additional carbon sinks as more forest area remains (Surendra et al., 2014).

Social

Biogas is a versatile energy carrier. It can be used directly to fuel combustion engines, gas turbines or fuel-cells to produce heat and generate power simultaneously in a combined heat and power plant (CHP) attached to the production unit (Rios and Kaltschmitt, 2016; Rodero et al., 2018; Scarlat et al., 2018).

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3 Theoretical biogas yields and biogas composition depend on the energetic content of the biomass that is subject to decomposition, which is higher in fats than in proteins or carbohydrates, respectively (Baltrėnas and Baltrėnaitė, 2018; Di Matteo et al., 2017). The reasoning behind this lies in the chemical reaction balances of the anaerobic digestion process, which can be studied in more detail in Buswell and Mueller (1952) and Deublein and Steinhauser (2011, Chapters 9 and 10).
Reliable availability and increased access to clean energy are strongly correlated to public health, improved education and economic development (Haines et al., 2007). For example, in Asian and African countries, small-scale biogas plants that are commonly fed with animal manure provide cooking and lighting fuel for rural communities and households, creating socio-cultural benefits as indoor air pollution decreases through better combustion of a gaseous cooking fuel when compared to charcoal or firewood (Stoddard, 2010; Surendra et al., 2014). Reduced physical labor time, for example when collecting firewood results in increased capacities to attend school and generate additional income (Orskov et al., 2014; Surendra et al., 2014).

Furthermore, biogas production is associated with the creation of jobs on a local level, as the installation, operation and maintenance of production units, as well as resource flows of waste and end products to and from production sites require labor force regardless of the scale of the facility (Guenther-Lübbers et al., 2016; Orskov et al., 2014; Vögeli et al., 2014).

**Economic**

Commercial deployment of biogas plants to generate monetary value is common in Europe. Economic incentives in the form of feed-in tariffs for generated electricity for example and other subsidies which are implemented in national legislation were a major driver for boosting the biogas sector in countries such as Germany (Kaup and Selbmann, 2013). Lack of governmental support for biogas project investments are seen as obstacles for project initiation, especially for large-scale production units. Biogas production combined with heat and electricity generation and distribution to near-by users in a communal context, however, might still prove to be successful if fast execution allows for early profits (Capodaglio et al., 2016). A study in Mexico⁴ by Rios and Kaltschmitt (2016) estimated economically viable electricity production potential through the deployment of biogas plants using national organic waste resources to be as high as 2% of total national electricity generation in the year 2016 (IEA, 2019c). This is remarkable, as there was no financial support for biogas-based power generation provided by the government at that time.

The AD process not only forms a gas mixture of mostly methane and carbon dioxide that can be captured at the end of the process. Bacterial decomposition of the organic matter further provides a fairly inodorous residue, commonly referred to as digestate, which is rich in nutrients (Weiland, 2010). Studies show that its effects on agricultural yields are comparable to mineral fertilizers and better than raw manure, oftentimes with lower environmental impacts on soil, water bodies and the atmosphere when applied (Nkoa, 2014; Riva et al., 2016; Seadi and Lukehurst, 2012; Tampio et al., 2016). Hence, biogas production plants not only generate a gaseous energy carrier, but also provide substances, which can be used as a soil additive for agriculture. Especially in developing countries this holds high potentials to increase yields and replace mineral fertilizers which in turn reduces expenses and saves both resources and GHG emissions related to artificial fertilizer fabrication (Orskov et al., 2014; Surendra et al., 2014). Moreover, holistic applications suggest the combined deployment of biogas plants and aquaculture (Orskov et al., 2014). Liquid effluent from the AD process can be used to feed plankton in ponds serving as a natural food source for fish (Balasubramanian and Kasturi Bai, 1996).

2.4.6. Clarification of some terms

Working focus in this study is on *small-scale biogas production and application from organic waste* in the area of research. In the following, the term *small-scale* refers to applications of rather home-sized digesters that can treat organic waste quantities of a single point source such as a school or restaurant or multiple sources like a number of households. Biogas applications on a larger scale, for example a municipal solid waste treatment center or commercialized farm-scale production units are not included when potential solutions in the case at hand are considered. The term *organic waste* refers to the organic

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⁴ The country of Mexico is similar to Lebanon in some respects. Also considered an upper-middle-income country, most of its MSW is disposed in landfills (Kaza et al., 2018). The Human Development Index (HDI), which is a measure for a countries state of socio-economic development, considering aspects like GDP, life expectancy and level of education differs only slightly between the two countries that were ranked 74th and 80th, respectively among all nation states in 2017 (UNDP, 2019).
fraction of household garbage, i.e. kitchen waste and food leftovers or any other solid organic matter that was once edible by humans, for example market refuse or residues of food-making processes.

2.5. Area of research

2.5.1. Geographical context and demographics

The republic of Lebanon is divided into eight administrative governorates (Mohafazah). The area of research belongs to the municipality of Ghazir whose administrative territory adjoins the Mediterranean Sea to the West and stretches Eastwards towards the Mount Lebanon range. It is part of the district Keserwan that belongs to the governorate of Mount Lebanon.

The area of research is the old village of Ghazir - in the context of this report referred to as Ghazir village – located approximately 30 km north-east of Beirut (Fig. 12) at an altitude of about 380 m above sea level (Localiban, 2016). Accordingly, the spatial scope of the investigations is defined by the geographical extent of Ghazir village. The population of Ghazir village is estimated to be 12,000 people (Appendix A.2), most of which are Maronite Christians.

Due to its strategic position in the hillside, overlooking the bay of Jounieh (Fig. 12), Ghazir village was an important economic and political center in pre-modern times, but lost influence and power after the creation of the Lebanese republic in the 1940s with the Beirut region becoming major hub of the new country (MEDA, 2003). Most of the main industries of the past such as silk production, tapestry, oil pressing and wine making have ceased to exist or being substantially diminished and economic activities in Ghazir village nowadays are mainly driven by small enterprises and shops.

The coastal region of Lebanon in general and the municipality of Ghazir in particular witness a constant increase in real estates, which has also been driven by domestic migration of Christians during and after the civil war in Lebanon in the 1970s and 1980s. Also Ghazir village is affected by this as cultural heritage in the form of traditional houses, as well as water mills and staircases that date back to the Roman times has given way to new buildings (MEDA, 2003). Small-scale farming and horticulture, which has been an important source of income and self-sufficiency for the local community ever since humans settled in the area, can be found only sporadically in the research area, mainly towards the more mountainous East and inland away from the heavily urbanized sea side.

2.5.2. Current energy supply and waste management

Residents in Ghazir municipality, and hence also of Ghazir village commonly pay two electricity bills. One for the national supplier EDL, and one for private suppliers that run diesel generators to cover households power demands throughout a day. Most households cook with liquified petrol gas (LPG),
which is stored in gas bottles. There is no natural gas grid as can be found in some countries of Europe in place (Appendix A.2).

The collection and disposition of MSW in Ghazir municipality is provided by one operator. MSW is sorted on a household level to enhance recycling of plastics and paper. Plastics and paper are pressed and bailed and pelletized elsewhere. At the time of writing, organic household waste was not collected separately and hence a mix of the non-recycled solid waste is transported to the sanitary landfill Bourj Hammoud, in Beirut. The municipality is bound to a long-term contract with the current waste collection operator and hence, capacities and financial resources for alternative waste management systems to be implemented by local authorities are limited (Appendix A.2).

2.5.3. Motivation and starting point of the investigation

Motivated by the aim to replicate the conducted investigations of this Thesis work in other settings with similar conditions as part of a general framework for EWB projects, a starting point had to be identified. The initial idea of approaching schools to decide on a research area was motivated by (i) the possibility to involve educational institutions to spark interests in eventually new fields of applied approaches of waste management and energy supply alternatives, (ii) the possibility to reach out to the local community by using local schools as an intermediate, as well as (iii) the assumption that schools eventually produce substantial quantities of organic waste and hence could be a potential point source of feedstock for a small-scale biogas production unit. As will become clear later, (iii) did not hold up in the case of the schools in Ghazir village. However, using the schools as an institution to spread the project idea and getting in touch with residents of the village proved to be effective.

Before the field study, contact was initiated with the biggest school in Ghazir village, Antonine Sisters School (ASG), a private Christian school with some 2500 students (ASG, 2018). A teacher at this school showed interest in project cooperation after approaching the school via E-Mail. ASG also participated in the Green School Certification Program, a national competition aiming to promote environmental awareness among students at an early stage in life (e-EcoSolutions, 2019). During the field study the two other schools, which are located in Ghazir village - one public school and the other private - were additionally approached in order to find out organic waste quantities on the schools’ premises.
3. Methods

Before finalizing the Thesis in the last weeks prior to final submission, the project work was divided into two main blocks, i.e. eight weeks for study and field work preparation and eight weeks for conducting field work in the research area. Site visits of biogas production sites both in Sweden and in Lebanon served to gain insights related to challenges and practicalities when operating AD facilities.

The preparation block comprised a literature review to obtain background information about the country of Lebanon, to acquire relevant knowledge related to biogas production and application using organic waste resources as a feedstock, as well as selecting suitable methods to answer the research questions in order to fulfill the study aims. With regards to the second study aim methods were chosen in respect of supposedly easy application for broad replicability in other settings. The selected methods are subject to a critical reflection in the Discussion chapter. A site visit at a commercial biogas plant in Uppsala owned by Uppsala Vatten och Avfall AB, which runs on OFMSW collected from households across the region contributed to better apprehend the reviewed theory. Furthermore, some relevant local actors in Lebanon were approached and introduced to the Thesis project for establishing a network of local contacts to facilitate on-site investigations in the area of research. A first action plan was developed to specify and prepare main steps for data collection and utilization for the overall feasibility assessment during the field visit (Appendix H).

On-site investigations included identifying sources of organic waste and examining available quantities, reviewing local energy supply and waste management practices, as well as approaching and consulting stakeholders to understand local conditions and challenges when it comes to potential small-scale biogas production in the area of research. A large-scale MSW treatment center in Saida (IBC s.a.l., 2016), as well as a smaller anaerobic digester set-up in a Lebanese community have been visited during the field study. In the following, the strategies, that serve to answer the research questions are explained in more detail.

3.1. Quantitative assessment

Underlying determinants to estimate technological potentials and economic aspects of local biogas production using available organic waste resources are (i) biogas and digestate volumes that can be produced and utilized in one way or another and (ii) monetary costs associated with installation, operation and maintenance of a small-scale biogas production unit. From a holistic point of view further aspects of the supply chain are taken into account as well, such as waste collection and transport to the facility. For a first projection of expenses for potential facility implementation the focus will be directed towards estimates of investment costs and running expenses of the biogas facility.

3.1.1. Achievable biogas yield

Estimation of achievable biogas volumes are based on the absolute quantities of organic waste resources that can be allocated for the AD process of a facility in Ghazir and the BMP of those resources. Fig. 14 illustrates the taken approach to assess the technical biogas potential of available quantities of organic waste.

![Fig. 14: Approach for assessing the technical potential](image-url)
**Sampling and quantifying organic waste resources**

Sampling original material, i.e. often referred to as ‘lot’, for example a stockpile or a lorry load, which is subject to closer analyses is a way of projecting material properties onto larger volumes, assuming that the samples taken represent the lot (Petersen et al., 2005). Accordingly, the average amount of organic waste that is produced in households in Ghazir village was assessed by looking at the residential organic waste of only a few households. Using one local school as an intermediate platform, five households in or nearby the area of research offered project support and served as proxies for the community after being introduced to the study project. In order to enhance strong representativeness for the lot, some strategies are suggested in the literature both for sampling theory in general (Petersen et al., 2005) and household waste studies in particular (Dahlén and Lagerkvist, 2008). For example, a larger number of samples, as well as taking samples over a longer time period, i.e. several days or weeks can reduce sample errors and increase accuracy of the following projection.

Daily waste quantities of the proxy households in the form of kitchen waste and food leftovers were either measured by the author (Fig. 16) or the household members themselves and reported throughout a time period of four weeks.

Organic waste quantities that are generated on the premises of two of the local schools were quantified by the set-up of self-made organic waste bins (Fig. 15) as sorting at source on the school grounds did not apply for organics but for paper, plastics and cans. The waste quantities in the bins were measured with a scale twice a week after classes.

**Fig. 16: Quantifying organic waste with a scale**

**Fig. 15: School bin for organic waste**

**Biogas yields**

Due to differences in waste composition, substrate quality with regards to relative VS content, as well as process parameters and digester design, absolute biogas yield and methane content vary from case to case. The review by Campuzano and González-Martínez (2016) considered many different biogas production experiment set-ups using both source-sorted and mechanically sorted OFMSW samples as substrate and also range from wet or dry AD processes to meso- and thermophilic temperature levels in either batch wise or continuously fed reactors. Accordingly, results of reported methane yields differ by a factor of almost ten (Campuzano and González-Martínez, 2016).
Nevertheless, a reference value for the BMP based on findings of a literature review for potential biogas and methane yields serve to estimate achievable volumes of biogas produced from locally available organic waste resources. Bio-chemical analyses of waste samples to determine material properties, such as TS and VS content, humidity and pH of the substrate may increase accuracy of such projections. However, the availability of numerous studies also provides a solid basis for a deductive approach which will be applied in this study. Also, equipment for such analyses might not be always at hand when trying to replicate the assessment in other settings.

Various studies draw on analyzing the BMP of a substrate when digested under anaerobic conditions in a laboratory, which is a more or less standardized and commonly acknowledged way of determining a substrates potential in terms of methane formation (Holliger et al., 2016; Schievano et al., 2008). Yet, ambiguous guidelines allow for variations of experimental set-ups, for example both mesophilic and thermophilic conditions are applied (Raposo et al., 2012). To estimate potential biogas yields in the context of this study, mean values of twelve experiments that show similar process conditions during the AD process under mesophilic temperature level using source sorted kitchen and household waste samples were used. These values account for TS content, relative VS content and volumes of methane formed per unit of VS mass (Fig. 17 and Table 3).

![Mean value: 394](image)

**Fig. 17:** Reported methane potential of OFMSW

Assuming a methane content of 55% (vol.), absolute achievable biogas volumes ($V_{BG}$) by using locally available organic waste resources are approximated. Central to this estimation is the collection of data on-site in the research area with regards to organic waste quantities ($m_{OW}$). Using the findings in other studies as summarized in Table 3, TS content ($TS$) of locally available organic waste is assumed to be 20%. Relative VS content ($VS_{TS}$) is conservatively assumed to be 80% considering substrate quality after waste separation at source and allows for minor fractions of non-organics such as paper or plastics.

$$V_{BG} = (m_{OW} \times TS \times VS_{TS} \times BMP) \times \frac{1}{0.55} = m_{OW} \times 0.2 \times \frac{kgTS}{kgow} \times 0.8 \times \frac{kgVS}{kgTS} \times 394 \times \frac{dm^3}{kgVS} \times \frac{1}{0.55}$$

$$= m_{OW} \times 114.6 \frac{dm^3}{kgow} \quad (E \ 3.1)$$
The assumed energy content of the produced biogas \((E_{BG})\) is based on comparable calculations found in other literature (Rios and Kalschmitt, 2016; Vögeli et al., 2014) and corresponds to 0.006 kWh/dm\(^3\) (gas pressure and temperature 1 bar and 25 °C, respectively).

\[
E_{BG} = V_{BG} \times 0.006 \text{ kWh/dm}^3 = V_{BG} \times 21.6 \text{ kJ/dm}^3
\]

\((E 3.2)\)

### Table 3: Reported TS and relative VS content of OFMSW samples

<table>
<thead>
<tr>
<th>Study by</th>
<th>TS content [%]</th>
<th>Relative VS content [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alibardi and Cossu (2015)</td>
<td>n.a.</td>
<td>93.0</td>
</tr>
<tr>
<td>Alibardi and Cossu (2015)</td>
<td>n.a.</td>
<td>93.0</td>
</tr>
<tr>
<td>Alibardi and Cossu (2015)</td>
<td>n.a.</td>
<td>92.0</td>
</tr>
<tr>
<td>Browne and Murphy (2013)</td>
<td>29.4</td>
<td>95.3</td>
</tr>
<tr>
<td>Cabbai et al., (2013)</td>
<td>n.a.</td>
<td>91.8</td>
</tr>
<tr>
<td>El-Mashad and Zhang (2010)</td>
<td>28.0</td>
<td>86.1</td>
</tr>
<tr>
<td>Michele et al. (2015)</td>
<td>22.3</td>
<td>88.3</td>
</tr>
<tr>
<td>Pavi et al. (2017)</td>
<td>19.9</td>
<td>96.5</td>
</tr>
<tr>
<td>Pavi et al. (2017)</td>
<td>19.5</td>
<td>96.4</td>
</tr>
<tr>
<td>Ponsá et al. (2011)</td>
<td>29.0</td>
<td>77.0</td>
</tr>
<tr>
<td>Schievano et al. (2010)</td>
<td>24.2</td>
<td>91.6</td>
</tr>
<tr>
<td>Zhang et al. (2013)</td>
<td>18.5</td>
<td>91.6</td>
</tr>
<tr>
<td><strong>Mean value</strong></td>
<td><strong>23.1</strong></td>
<td><strong>91.1</strong></td>
</tr>
</tbody>
</table>

### 3.1.2. Cost assessment

Having estimated absolute volumes of biogas that can theoretically be utilized, monetary aspects are considered in an economic assessment. According to Whyte and Perry (2001), cost assessments for AD technology over the expected life time of a site include (i) capital costs, (ii) operation and maintenance costs and (iii) monetary savings and revenues. Capital costs for a simple biogas production unit are of major relevance when it comes to spark interests for potential implementation in the area of research (Pérez et al., 2014). In addition, running expenses for operation and maintenance will be estimated to pinpoint financial efforts for real-life execution.

Due to short payback periods with regards to low investment costs no interest rate is considered. The lifespan of the proposed facility is assumed to be 10 years in respect to other reports when similar digester designs have been analyzed (Ferrer et al., 2011; Pérez et al., 2014; Vögeli et al., 2014). The time dimension for revenues, savings and operation costs is based on the number of weeks the facility is in operation during one year, i.e. 52 weeks. Calculation for maintenance costs and spare part acquisition are based on monthly and yearly expenses, respectively. The following approach to determine the payback period of a proposed biogas production unit in Ghazir village is adopted from Ali et al. (2019) who considered relevant aspects pointed out by Whyte and Perry (2001) in a cost analyses of small-scale biogas plants in rural Bangladesh.

\[
Payback \, period \, (PP) = \frac{\text{Investment required}}{\text{Annual cash flow}} = \frac{\text{SU}+\text{CSW}}{R-\text{OM}} \quad (E 3.3)
\]

- **SUC - costs for AD set-up components**

Retail prices in local shops of each component \((i)\) according to dimension and number of items \((n)\)
\[ SUC = \sum_{i=1}^{n} \text{component} \]  

\text{**CSW - costs for construction, site work and installation**}

Labor costs based on number of working hours \( n_{CSW} \) and local wages (per hour) \( w_{CSW} \)

\[ CSW = n_{CSW} \times w_{CSW} \]  

\text{**R - revenues from product sale and savings through fuel replacement**}

Revenues come from sale of liquid digestate to local farmers \( S_{ld} \) based on price per liter for acquisition \( p_{ld} \) and total volumes of the sold product \( V_{ld} \) in a year.

\[ S_{ld} = p_{ld} \times V_{ld} \times \frac{1}{\text{year}} \]  

Additional savings \( S_{add} \) are achieved by using the produced biogas for heat to treat the feedstock, hence replacing conventional heating fuel, based on LPG prices for acquisition \( p_{LPG} \) and replaced volumes \( V_{LPG} \) in a year.\(^5\)

\[ S_{add} = p_{LPG} \times V_{LPG} \times \frac{1}{\text{year}} \]  

\[ V_{LPG} = V_{BG} \times \frac{1}{1350 \text{dm}^3_{BG}} \]  

\[ R = S_{ld} + S_{add} \]  

\text{**OM - costs for operation and maintenance during the lifespan of the biogas unit**}

Operation costs include labor costs for operation tasks and waste collection based on working hours \( n_{o} \) and local wages (per hour) \( w_{OM} \). Additional expenditures in the form of water demands for feedstock dilution \( E_{W} \), electricity \( E_{El} \) to run a gas compressor and fuel costs for the waste transportation tour \( E_{F} \) are considered. Maintenance costs include necessary replacement of set-up components when the lifespan of the component is lower than the expected lifespan of the whole biogas unit, according to retail prices of replaced items \( SUC \). Additional labor time for regular maintenance checks and monitoring is considered \( n_{M} \). Regular tests in laboratories \( (LAB) \) to analyze nutrient content and identify contamination levels in the liquid digestate are advised and considered in the calculation, based on testing costs in relevant institutes.

\[ OM = (n_{o} \times w_{OM} + E_{W} + E_{El} + E_{F} + n_{M} \times w_{OM} + SUC_{i} + \sum LAB_{i}) \times \frac{1}{\text{year}} \]  

The outlined cost assessment does not account for logistics associated with the distribution of the AD products to the end users as biogas will be used on-site and local farmers are expected to pick up the liquid digestate at the production site themselves. Following the idea of a sensitivity analyses, parameters in the cost estimations will be subject to variation in order to disclose effects on the payback period. Among others, this includes different selling prices for the liquid digestate, as acquisition by farmers is major determiner of the economic assessment for the proposed facility.

\(^5\) One liter (\text{dm}^3) of pressurized LPG (propane) as stored in a conventional gas bottle expands to 270 \text{dm}^3 under normal conditions (i.e. 15 °C and 1 bar air pressure) (BOC, 2019). This in turn corresponds to 1350 \text{dm}^3 of biogas, as the energy content per unit of volume of LPG compared to biogas is five times higher under normal conditions (Vögeli et al., 2014).
3.1.3. Determining digester size

In accordance to the few cases of current small-scale application in Lebanon, wet AD digestion in a fixed-dome model digester will be considered for a finally proposed facility in Ghazir village. The choice of the digester design will be subject for discussion later.

A common approach when it comes to decide on the size of a fixed-dome digester is to use figures of available quantities or volumes of daily added feedstock, the RT that depends on operation temperature within the digester and suitable storage space for the produced biogas within the digester (Rakotojaona, 2013).

Volumes of added feedstock depend on the volumes of solid organic waste ($V_{OW}$) and water for dilution ($V_W$). The RT describes the average time the feedstock stays in a digester and hence how long it is subject to bacterial decomposition. Advisable retention times depend on process temperature during AD in the digester (Vögeli et al., 2014). Following previous assumptions of mesophilic conditions for biogas yield calculations a hydraulic retention time ($RT$) of 45 days is subject for the following determination of the digester size. Considering occupied digester volumes by the ‘active’ slurry of 75% of the total digester volume - as suggested by Rakotojaona (2013) and Vögeli et al. (2014) - the volume of a fixed-dome digester ($V_D$) can be determined as follows (Rakotojaona, 2013):

$$V_D = \frac{RT \times (V_{OW} + V_W)}{0.75} \quad (E\ 3.11)$$

3.1.4. Mass balance

For a stable AD process and with respect to the determined digester size ($E\ 3.11$) the volume of the active slurry that is digested should be kept constant in the digester. Hence, when feedstock is added, the same amount of liquid digestate should be withdrawn. Due to the bacterial decomposition of the organic matter with resulting biogas formation in the AD process, a decrease in the volume of the digested slurry must be expected, as biogas will be withdrawn regularly. To maintain the mass balance, these losses should be accounted for when feedstock is added to the digester. Accordingly, mass of daily withdrawn biogas volumes is to be compensated by the added feedstock. A reference value of reported biogas density by Deublein and Steinhauser (2011) of 1.2 kg/m³ is assumed for the following estimation of mass loss through biogas withdrawal from the digester ($m_{BG}$). However, exact biogas densities depend on gas composition and methane content.

$$m_{BG} = V_{BG} \times 1.2 \ \frac{kg}{m^3} \quad (E\ 3.12)$$

3.2. Qualitative assessment

Facilitating early success, as well as the creation of benefits in the long-term in many cases has been more likely when a proposed project is deeply anchored within the local community (Eswarlal et al., 2014; Heaslip et al., 2016; Schweizer-Ries, 2010; Vögeli et al., 2014). This requires communication during the planning process and long-term acceptance of a facility after project implementation. Social aspects are assessed using communicative tools such as interviews and questionnaire surveys.

3.2.1. Identifying stakeholders

To holistically analyze a projects feasibility, the identification of the actors that either have an interest in, are affected by or can substantially influence the decision making and implementation process of a project is vital. Those so-called stakeholders can include both organizations and individuals, as well as networks of such or different individuals within organizations (Varvasovszky, 2000). There are various ways to make such an analyzes as to who is a stakeholder, what are the interests and how strong are power relations and influence with regards to the issue at hand. Each approach, whether conducted by an individual or a group, by an insider or by an outsider, in a qualitative or quantitative way bears both advantages and drawbacks. According to Varvasovszky (2000) an iterative process of direct communication with potential stakeholders in the form of interviews, as well as asking relevant actors
to point out further stakeholders is a common and effective approach and will be applied in the issue at hand.

In the case of small-scale biogas production in developing countries, Lohri et al. (2013, p. 124) proposes a list of relevant actors that potentially have interests and can play a crucial role either in favor of or against successful project implementation, and hence are considered when stakeholders of biogas application in the research area are identified:

- Funding agency
- Governmental authorities
- Legislator and enforcement agencies
- Waste generators
- Design and installation specialists
- Future operation & maintenance staff
- End-users of AD products
- Research institutions
- National and international NGOs
- Site residents

### 3.2.2. Approaching stakeholders

Once individual stakeholders or stakeholder groups are identified, their interests and influence can be found out through interviews or surveys. Insights of how certain actors perceive and view different aspects of an issue can be of importance for further planning. The following steps serve to obtain such knowledge.

When it comes to concrete means for successful project implementation and long-term deployment of renewable energy facilities in its local context, the involvement and participation of all stakeholders in an early stage of the planning process is promising (Schweizer-Ries, 2008). As cases of decentralized renewable energy production and consumption in Europe and India show, direct engagement with residents and potential end users in the form of information events, round table discussions and the promotion of part-ownership of the facility fosters transparency of the project planning process and execution and builds trust towards planners and operators (Eswarlal et al., 2014; Heaslip et al., 2016; Schumacher and Schultmann, 2017; Schweizer-Ries, 2010). This in turn positively affects local acceptance of a site, which avoids non-appreciation and active resistance against the implementation and deployment of a facility that ultimately can lead to project failure. Civil protests led to the destruction of a waste-to-energy facility in Lebanon in 1997, due to the incinerator’s black smoke emissions (Azzi, 2017).

In the context of small-scale local biogas production from organic waste a questionnaire survey serves to explore perceptions and expectations associated with renewable energy in general and biogas production in particular among residents in the area of research. Question design is based on principles proposed by Iarossi (2006, p. 30), according to whom interview questions should be (i) brief, (ii) objective, (iii) simple and (iv) specific. The questions were further inspired by former studies, when local acceptance of the people living in the vicinity of a biogas plant and civil contentment with regards to the overall implementation process was investigated (Schumacher and Schultmann, 2017; Schweizer-Ries, 2010). The questionnaire can be found in Appendix E.

Communication with stakeholders, as well as the results of the questionnaire survey are central for a final proposal of a biogas facility with choice of end use.
3.2.3. Feasibility categories for proposal evaluation

As mentioned before, determining relevant aspects and elements that affect contributions toward sustainable development, as well as its interrelations between each other requires a holistic systems perspective that takes into account the different dimensions of the issue at hand, in this case the potential of biogas-related project implementation in the area of research. It is further essential to understand the relevance of each dimension in the given context, as local conditions and challenges differ from case to case.

Ilskog (2008) proposes indicators of rural electrification projects in developing countries based on five sustainability dimensions in order to evaluate the performance of these projects with regards to sustainable development. The approach builds on previous frameworks by international organizations such as the UN and suggests a categorization between a technical, economic, social/ethical, environmental and organizational/institutional dimension, and hence provides a somewhat more specified sustainability assessment as described in Sub-Section 2.1. Similar categories are proposed from a sustainability perspective for the feasibility of project success in the specific case of AD projects. In the framework by Lohri et al. (2013, p. 126) a sixth dimension, i.e. ‘policy and legal’ is added (Fig. 18).

On-site observations and stakeholder consultation allow a better understanding of local conditions and potential challenges for the implementation of a small-scale biogas production unit in the area of research. Accordingly, the final biogas application proposal is evaluated under feasibility categories proposed by Lohri et al. (2013) as part Section 5.
4. Results

Results are presented in the following and divided into (i) theoretical feasibility, making use of quantitative data inquiry and (ii) practical feasibility, mostly using results of the qualitative assessment with respect to a realistic scenario in the area of research. The chapter is closed by reflecting on some research strategies that have been used during the field work to answer RQ1.1 and RQ1.2.

4.1. Theoretical feasibility

4.1.1. Available organic waste resources

Places or sources of solid organic waste that were identified in the research area can be categorized into (i) commercial, (ii) schools and (iii) households.

‘Commercial’

On-site investigations showed no big point sources of organic waste in Ghazir village, i.e. no places where substantial amounts of organic waste are produced. One exception is the winery Château Musar that produces large amounts of grape residues during the wine-making process. To date, those residues are entirely used as soil additive in the vineyards where the vine grapes are grown. An interview with the senior winemaker revealed that some parts of the grape residues could be allocated for local biogas production in Ghazir (Appendix A.5). This would save transportation costs since residue volumes are driven from the winery to the vineyards, which are located in the Békaa valley, a 2-3 hours’ drive away from the winery. However, the size of the batches (4-5 tons) and seasonal availability of this substrate – i.e. between August and October - are not considered suitable for small-scale biogas production in Ghazir.

There are no larger restaurants in the area of research either, only a few smaller diners, whose waste quantities are comparable to those of households. The biggest food market ets. Louis Zeenny & fils keeps records of market refuse in the form of vegetables and fruits, which varied between 0 kg and 23 kg during the time of the field-study, with an average of about 6 kg daily (Appendix F.3). Half of those leftovers are fed to pigs. Rather than throwing away the other half, the owner of the supermarket would be willing to provide it for local biogas production (Appendix A.5). Also, some smaller food shops can be found in Ghazir village, however, conversations with the owners showed that market refuse in such markets is either very little, fed to chicken or allocated for free to, for example, refugees.

Schools in Ghazir village

Results of the school bin monitoring showed that during four weeks the amount of organic waste that found those bins ranged between 0.5 kg and 0.8 kg weekly, with a daily average of 0.22 kg at both schools added together (Appendix F.1). Those results confirmed the statement of a teacher of ASG – the biggest school in Ghazir village- which has not been investigated since sorting organic waste has already been tried out in that school prior to the field study. According to the teacher, results showed, that there are only few discarded organics (Appendix A.5). None of the schools in Ghazir village hosts a school kitchen and students usually eat fruits, vegetables and sandwiches prepared at home and ready to eat. Fig. 19 shows an organic waste sample of the organic waste that was discarded in the bins in one of the schools during three days, consisting of banana peels, partly eaten apples and sandwiches. This and other samples also
show, that despite explanatory bin labels and introduction of the new bins to the students by the teachers, in both schools minor fractions of non-organics such as paper tissues and plastics were thrown together with organic waste from time to time.

**Households in Ghazir village**

Using sampling results and considering the size of the proxy households, a mean value was calculated to conservatively estimate realistic waste quantities of an average household of four to six persons, that could be allocated as feedstock for local biogas production in Ghazir.

Table 4 shows the average organic waste of the five households that were willing to separately discard kitchen waste and food leftovers over a period of four weeks. Frequent measurements allowed for an estimate of 1.5 – 3.7 kg kitchen waste and food leftovers per household daily, depending on the number of people in the household (Appendix F.2). Household members that were younger than 18 years old during the field study were considered as kids. The number of members of some households at times varied throughout the weeks, due to, for example, family members who would spend most week days somewhere else because of studies or work. The number of samples was complemented by sporadic reports of other households, which however, was not monitored on a frequent basis.

**Table 4: Organic waste samples in households**

<table>
<thead>
<tr>
<th>#</th>
<th>Household size</th>
<th>Average quantity daily [kg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ghazir Household 1</td>
<td>3 – 4 adults</td>
<td>1.8</td>
</tr>
<tr>
<td>Ghazir Household 2</td>
<td>2 adults, 3 kids</td>
<td>2.6</td>
</tr>
<tr>
<td>Ghazir Household 3</td>
<td>3 – 4 adults, 3 kids</td>
<td>3.7</td>
</tr>
<tr>
<td>Ghazir Household 4</td>
<td>2 adults, 4 kids</td>
<td>1.6</td>
</tr>
<tr>
<td>Ghazir Household 5</td>
<td>3 adults</td>
<td>1.5</td>
</tr>
</tbody>
</table>

### 4.1.2. Potential biogas yields and end use choice

As there are no bigger point sources in the area of research, feedstock resources for potential small-scale biogas production in Ghazir village would come from homes in the form of kitchen waste and food leftovers, as well as from the local food market in the form of unsold vegetables and fruits.

Table 5 displays two scenarios of small-scale biogas applications in Ghazir village with different quantities of organic waste being used as feedstock for biogas production. The ratio of solid organic waste and water for feedstock dilution is 1, which will be justified later. The first case represents potential biogas yields of a household that generates 3 kg of organic waste daily. It could also be the specific case of the local food market with its average amount of daily market refuse in the form of vegetables and fruits. The other case is an example of multiple organic waste sources, resulting in a weekly digestate withdrawal of 200 dm$^3$. As will be explained in later on in this chapter, the latter case represents the finally proposed application in Ghazir village. The first case serves for better illustration of some aspects of home-scale biogas production in the research area.

If biogas is used as a cooking fuel in a gas stove, reported consumption rates in the literature vary between 180 and 1100 dm$^3$ per hour, depending on the stove design and gas pressure (Orskov et al., 2014; Rakotojaona, 2013; Surendra et al., 2014; Vögeli et al., 2014). Accordingly, 3 kg of organic waste produced by a single household everyday eventually generates enough biogas for one hour of cooking. The biogas volume of 344 dm$^3$ corresponds to approximately 0.25 dm$^3$ of LPG, assuming a methane content of 55% (vol.) in the biogas. If full usage of the produced biogas for cooking is assumed, weekly
monetary savings of a little more than one USD can be achieved. Calculation details can be found in Appendix C.1.

Table 5: Application examples in Ghazir village

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>One household/food market</td>
<td>344</td>
<td>1.8</td>
<td>1.2</td>
<td>42</td>
<td>2.9</td>
</tr>
<tr>
<td>14.3</td>
<td>5-8 households</td>
<td>1639</td>
<td>8.5</td>
<td>5.7</td>
<td>200</td>
<td>13.8</td>
</tr>
</tbody>
</table>

Another potential end use of biogas is power generation. Assuming an energy efficiency of 33 %, approximately 0.7 kWh of electrical power can be generated if the biogas in the first case is entirely used to fuel a generator. Accordingly, a 100 W light bulb could be powered for 7 hours a day. Home-scale combined heat and power units (CHP) make use of the heat loss during power generation, for example heating water for sanitary application (Surendra et al., 2014). However, in practice this would require constant deployment of the aggregates. Accordingly and following up the calculations, daily waste quantities of more than 200 kg would be required to continuously run, for example, a 2 kW power generator over 24 hours (Vögeli et al., 2014).

Obviously, if a biogas digester is shared between several households and daily feeding rates are increased as organic waste quantities are added together, higher biogas yields can be achieved and would eventually allow for the deployment of bigger aggregates under economically acceptable conditions. However, small-scale biogas application for domestic use in households will not be further elaborated on, as the practical feasibility in the case of Ghazir village is not given due to current wealth and living standards of most residents in the research area. However, the following digester design and set-up components of comparable sizes are generally applicable and investment costs remain similar regardless of the conditions for final application.

4.1.3. Digester design

The so-called fixed-dome model is a widely used type of digester, especially for small-scale biogas production units in countries like Nepal and China, but also in African countries of the Sub-Saharan region (Mungwe et al., 2016; Surendra et al., 2014). The set-up of this digester type can be kept quite simple which in turn allows for relatively easy daily operation.

The small-scale digester in Bkassine village that has been visited during the field study (Appendix A.3) can be considered a fixed-dome model as well, which shows that some level of expertise and experience with this technology is at hand within the country. However, to the date of writing and the best of the authors knowledge, small-scale biogas application in the country of Lebanon is rather the exception when treating organic waste or producing energy. Nevertheless, the present small-scale biogas production unit in Bkassine village serves as a role model for the design of a potential application in Ghazir village. The digester is fed semi-continuously every day or every second day and feedstock consists of source-sorted organic household waste diluted in water with a ratio OW to water being 1 (Appendix A.3).
Considering the approach to determine the digester size \( V_D \) according to \( E \, 3.11 \) in Sub-Section 3.1.3, as well as a ratio between organic waste and water for feedstock dilution as applied at the facility in Bkassine village, total digester volume and required digestate withdrawal per day can be put into relation to daily organic waste amounts added to the digester. This relation is shown in Fig. 21. Calculation details can be found in Appendix C.2. Accordingly, the size of the digester can be pinpointed in the graph not only by deciding on daily amounts of organic waste, but also by identifying the demand for liquid digestate. It will become apparent, that the latter will be of main relevance in the case of Ghazir village.
4.1.4. Cost estimations

Main components of the application as sketched in Fig. 22, which will be further explained in the following sections are listed in Table 6, along with costs for its acquisitions. A detailed overview can be found in Appendix B. With regards to the payback period of the proposed set-up, a base line scenario illustrates the case of continuous deployment of the production unit over a year, i.e. 52 weeks, as well as full acquisition of the liquid digestate by farmers, i.e. 200 dm$^3$ per week, based on a selling price of 1 USD per dm$^3$. The reasoning for choosing those numbers follows in Sub-Section 4.2. The hourly wage for labor in Lebanon corresponds to 3.2 USD (Appendix A.5). Weekly labor time for unit operation and waste collection is estimated to be 11 hours. Calculations show a payback period for the proposed set-up according to the base line scenario of 1.3 months and annual cashflow accounts for 7588 USD. Calculation details can be found in Appendix C.3.

Table 6: Cost estimation of proposed set-up

<table>
<thead>
<tr>
<th>#</th>
<th>Component</th>
<th>Dimension/Properties</th>
<th>Nr.</th>
<th>Price in shops</th>
<th>Availability and source</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Self-made digester (Water tank)</td>
<td>2,000 dm$^3$</td>
<td>1</td>
<td>150 USD</td>
<td>Classica Sanitary Shop, Jbeil</td>
</tr>
<tr>
<td>2</td>
<td>Storage tank for liquid digestate</td>
<td>1,000 dm$^3$</td>
<td>1</td>
<td>75 USD</td>
<td>Classica Sanitary Shop, Jbeil</td>
</tr>
<tr>
<td>3</td>
<td>Storage tank for water</td>
<td>1,000 dm$^3$</td>
<td>1</td>
<td>75 USD</td>
<td>Classica Sanitary Shop, Jbeil</td>
</tr>
<tr>
<td>4</td>
<td>Hoses (gas and water)</td>
<td>15 m</td>
<td>-</td>
<td>15 USD</td>
<td>Classica Sanitary Shop, Jbeil; Chidiac Plastic Systems, Jbeil</td>
</tr>
<tr>
<td>5</td>
<td>Fittings and valves</td>
<td>-</td>
<td>5</td>
<td>20 USD</td>
<td>Classica Sanitary Shop, Jbeil; Chidiac Plastic Systems, Jbeil</td>
</tr>
<tr>
<td>6</td>
<td>Biogas compressor with storage tank</td>
<td>8 bar, 50 dm$^3$</td>
<td>1</td>
<td>200 USD</td>
<td>Zaarour Trading, Jbeil</td>
</tr>
<tr>
<td>7</td>
<td>Desulphurization unit</td>
<td>-</td>
<td>1</td>
<td>15 USD</td>
<td>Abroad (Alibaba, 2019a)</td>
</tr>
<tr>
<td>8</td>
<td>Gas stove</td>
<td>-</td>
<td>1</td>
<td>10 - 20 USD</td>
<td>Maroun Center, Jbeil</td>
</tr>
<tr>
<td>9</td>
<td>Feedstock treatment pot</td>
<td>50 dm$^3$</td>
<td>1</td>
<td>30 USD</td>
<td>Jbeil Supermarket, Jbeil</td>
</tr>
<tr>
<td>10</td>
<td>Low pressure biogas storage (rubber bag)</td>
<td>1000 dm$^3$</td>
<td>1</td>
<td>20 USD</td>
<td>Abroad (Alibaba, 2019b)</td>
</tr>
<tr>
<td></td>
<td>Additional items for assembling (glue, silicon to seal cracks) and adding feedstock</td>
<td>-</td>
<td>50 USD (estimated)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Storage room for collected organic waste (water tank)</td>
<td>1,000 dm$^3$</td>
<td>1</td>
<td>75 USD</td>
<td>Classica Sanitary Shop, Jbeil</td>
</tr>
<tr>
<td>SUM</td>
<td></td>
<td></td>
<td></td>
<td>745 USD</td>
<td></td>
</tr>
</tbody>
</table>

6 Conventional soil enhancing substances that are applied in the area can be acquired for 5 to 6 USD per dm$^3$ (Appendix D). Accordingly, a price of 1 USD per dm$^3$ of liquid digestate can be an alternative, provided nutrient content are comparable and pathogens are removed during feedstock treatment for safe application (Appendix A.4).
Changes of parameters in the cost calculation serve for a comparison to the base line scenario and effects on the payback period ($PP$), annual revenues ($R$) and cashflow ($R-OM$), which are listed in Table 7. Considered were the reduction of the operational time in one year down to 26 weeks, halving the selling price of the liquid digestate, as well as omitting LPG replacement savings by the produced biogas for feedstock treatment. Applying those parameter changes simultaneously, i.e. so to say the 'worst' case, calculations show a payback period of little more than a year. Regardless of those scenarios, a selling price for the liquid digestate of less than 0.28 USD per dm$^3$ does not allow for a positive cashflow, hence not creating economic profit.

Table 7: Sensitivity analyses for cost estimation (Appendix C.3)

<table>
<thead>
<tr>
<th>Parameter changed</th>
<th>Payback period (PP)</th>
<th>Revenues (R)</th>
<th>Cash flow (R-OM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>None (base line)</td>
<td>1.3 months</td>
<td>10,695 USD</td>
<td>7,588 USD</td>
</tr>
<tr>
<td>Deployment for 26 weeks a year</td>
<td>2.8 months</td>
<td>5,347 USD</td>
<td>3,510 USD</td>
</tr>
<tr>
<td>Price for liquid digestate 0.5 USD per dm$^3$</td>
<td>4.1 months</td>
<td>5,495 USD</td>
<td>2,388 USD</td>
</tr>
<tr>
<td>LPG savings not considered</td>
<td>1.4 months</td>
<td>10,400 USD</td>
<td>7,293 USD</td>
</tr>
<tr>
<td>Deployment for 26 weeks a year, price for liquid digestate 0.5 USD per dm$^3$, LPG savings not considered</td>
<td>12.9 months</td>
<td>2,600 USD</td>
<td>763 USD</td>
</tr>
</tbody>
</table>

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7 This would also correspond to reduced volumes of the liquid digestate sold to farmers by 50% if the selling price accounts for 1 USD per dm$^3$.

8 In fact, the making of an alternative fertilizer by the anaerobic treatment of organic waste is currently not done in Ghazir village. Hence, it can be argued if LPG is 'saved' by using the produced biogas on-site, as the implementation of the production unit obviously requires additional heat energy for the pre-treatment of the feedstock, which would not be needed if it was not for the facility in the first place.
Fig. 22: Components of proposed set-up
4.2. Practical feasibility

4.2.1. Application in Ghazir village

Aiming to take full advantage of the benefits associated with local biogas production from organic waste, maximum use of the biogas, but also the liquid digestate is desirable, as this – in the case of Ghazir municipality - would reduce absolute volumes that are landfilled and provide an energy carrier to be used on-site. At the same time no by-products of the process would need to be disposed in case the liquid digestate is fully acquired by local farmers.

Observations and interviews during the field work showed that residents in Ghazir enjoy full access to energy in form of electricity and heat, and also use rather harmless and affordable\(^9\) cooking fuel in the form of LPG. Accordingly, interests in alternative forms of decentralized energy production for domestic supply are considered rather low, especially with regards to the effort one would have to make for installation and daily operation of even a very simple home-sized digester to obtain biogas for about one hour of cooking daily, saving 1.2 USD a week (Table 5). Hence motivation for local biogas production in the area of research would rather come from a more environmentally friendly treatment of residential garbage or the acquisition of a cheap fertilizer for agricultural production. The latter describes the case of Bkassine village, a small Lebanese community, where source-sorted organic household waste is anaerobically digested (Fig. 25) to produce a liquid fertilizer that is sold to farmers to increase their produce (Appendix A.3).

As a matter of fact, agricultural production takes place on the outskirts of Ghazir village. Interviews with local farmers revealed that there is an interest in applying the liquid digestate from the anaerobic treatment of organic waste in Ghazir village as fertilizer, complementary to other forms of soil enhancing substances (Appendix A.4). Discussions with one farmer and a professor of the Lebanese University\(^10\), based on literature findings on nutrient content and composition of different liquid digestate samples (Appendix D) led to a volume estimate of about 200 dm\(^3\) being applicable for agricultural production in the area.\(^11\)

\(^9\) A medium sized LPG bottle (Fig. 23) can be purchased in local shops for 11 USD, containing 16.5 dm\(^3\) fuel (Appendix C.1).

\(^10\) The Lebanese University holds an agricultural research institute that geographically belongs to Ghazir village. It is located on its outskirts nearby the local agricultural farms (Fig. 27).

\(^11\) The farmer and the professor estimated that some 40 greenhouses are located in the area and cultivated all year around, each of which could take up about 5 dm\(^3\) of digestate every week. In fact, weekly fertilizer application is considered unlikely. However, those figures rather add up to annual demands but for the sake of better illustration, weekly amounts are used in the calculations. Further it is not expected that full usage of the liquid digestion in the area would become a challenge, as volume overshoot can be further applied for residential gardening (Appendix A.4).
Considering the ratio between organic waste and water in the feedstock as applied in facility in Bkassine village, absolute amounts of organic waste that would be necessary for a weekly withdrawal of 200 dm$^3$ of liquid digestate account for 14.3 kg daily (Table 5). Accordingly, the size of the digester corresponds to 1.7 m$^3$, using Fig. 21 and E 4.4 to determine the digester volume. According to the potential biogas yield calculation (Appendix C.1) this corresponds to daily produced biogas volumes of 1,639 dm$^3$. The produced biogas can be finally used for pre-treatment of the feedstock by heating it up to 70 °C for one hour, as this eliminates pathogens for safe application of the liquid digestate in agricultural production after the digestion process (Khan and Nordberg, 2019; Seadi and Lukehurst, 2012; Vögeli et al., 2014). Appendix C.4 contains calculations for required biogas volumes to heat the substrate, showing a promising relation between daily biogas demand and production rates. A potential set-up was inspired by the facility in Bkassine village. Fig. 24 shows a sketch of how the set-up and the system components could look like in Ghazir village.

4.2.2. Proposing a business model

Location of the production unit

A suitable location for the biogas production unit are the premises of the Agricultural Research Institute of the Lebanese University as both spatial and working capacities allow for a set-up and daily operation. In addition to that, proximity to the local farms brings advantages for delivery or pick-up of the liquid digestate by the farmers in the form of short transportation distances. Looking at organic waste sources in the area of research, longer distances must be expected for waste collection, since organic waste resources are sourced from a number of places in Ghazir village (Fig. 26).

Fig. 26: Geographical identification of potential ‘waste suppliers’ in Ghazir village

Collection of organic waste resources

For the treatment of the organic waste in order to produce required volumes of liquid digestate, organic household waste can be collected regularly, for example on a weekly pick-up tour by one worker of the research institute, driving to ‘waste suppliers’ in Ghazir village, i.e. households, the food market or schools. A survey among residents to identify households that are willing to participate in local biogas production by allocating source-sorted organic household waste has been conducted (Appendix E). The results can help to plan the weekly collection tour and are shown in Fig. 26. However, considering the demand for organic waste resources, not all of those households are needed. Drawing on the results of waste quantification in Ghazir village, daily amounts of organic waste of between five and eight households are enough to provide the required volumes of feedstock. Households that are located close to each other, or even in the same building can agree on a common pick-up spot to facilitate weekly waste collection. Feedstock resources can be temporarily stored nearby the production unit to enhance daily feeding of the digester with stable volumes of added feedstock.
Daily operation, maintenance and digestate distribution

Daily operation tasks include

i. preparing the feedstock by mixing organic waste with water,

ii. pre-treatment of the feedstock by heating it up on a gas stove, combusting the biogas that has been produced in the digester previously,

iii. adding feedstock to the digester, as well as

iv. withdrawing liquid digestate from the digester into suitable containers, for pick-up by local farmers.

To avoid rapid temperature changes in the digester which could lead to AD process failure due to temperature sensitivity of the micro-organisms, adding the heated feedstock right after the pre-treatment is not advisable. Accordingly, the treated feedstock can be added when cooled down to ambient temperatures if the digester is not insulated. Insulation of the digester would allow for a higher feedstock temperature if the temperature level in the digester is kept stable and accordingly, the AD process can be optimized when a mesophilic temperature level, i.e. between 37 and 42 °C, is maintained. On the other hand, this would require controlling the temperature levels of both the feedstock and the digester and adds to daily operational efforts.

To facilitate the utilization of the biogas for pre-treatment of the feedstock, a gas compressor with gas tank in combination with a low-pressure gas storage can be utilized to capture the formed biogas. This would release the gas pressure in the digester and create buffer capacities if daily biogas demand for heating differs from biogas production rates in the digester. The low-pressure gas storage in the form of a rubber bag should be connected to the digester before the gas compressor (Fig. 22 and Fig. 24). Hence, a blown-up rubber bag indicates how much gas was formed and can be safely withdrawn without risking the creation of a vacuum inside the digester, which could lead to air inflow which inhibits the AD process.

Regular check-ups on all set-up components are advised to avoid and detect risks for operational failures that can harm successful deployment of the facility in the long-term. Vögeli et al. (2014) provide a collection of activities that are recommendable. On a weekly to monthly basis, this includes removal of condensed water in gas pipes, cleaning of the gas stove and its air intake holes, controlling tightness of the digester, as well as measuring pH of the digestate to identify eventual instabilities of the anaerobic digestion process in the digester. Annual monitoring activities include the removal of accumulated sludge on the bottom of the digester, eventual blockage of inlet and outlet pipes, as well as checking tightness of gas pipes and gas-productivity of the withdrawn liquid digestate.

Liquid digestate can be picked up directly by the local farmers on the site of production, since distances to the farms are rather short. Commercial acquisition compensates for efforts of the fertilizer production and profits can be used by the Research Institute to purchase spare parts and additional equipment to improve process performance, for example a food shredder to reduce particle size of organic waste. Delivery of the digestate to the farms are also conceivable, as delivery tours can be combined with the weekly pick up of the organic waste.

4.2.3. Identified stakeholders

Local authorities: Municipality of Ghazir

The municipality of Ghazir as a local authority offered support for a communal small-scale biogas production site as described above with the Agricultural Research Institute of the Lebanese University in Ghazir village being the operator of the facility. According to a representative of the municipality, this includes covering initial investment costs as stated in Sub-Section 4.1.4 (Appendix A.2). Exploring

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12 Reducing the particle size increases the surface of the organic matter exposed to the microorganisms in the anaerobic digestion process, hence enhancing biodegradability (Seadi and Lukehurst, 2012) and leading to higher biogas yields (Izumi et al., 2010).
alternative ways to treat residential organic waste of Ghazir village, with benefits for local farmers in the form of inexpensive fertilizers might become advantageous when national legislation assigns local authorities the task to propose solutions to meet targets of reduced volumes of landfilled waste (Appendix A.1). Despite the small scale of a first application, experience of the deployment of such a pilot set-up creates knowledge, which eventually enhances the realization of biogas production in Ghazir on a larger scale.

**National authorities: Ministry of Environment**

Any initiatives by municipalities to handle MSW that is in line with the waste management hierarchy, hence favoring sorting at source, recycling and energy recovery are encouraged by the Ministry of Environment. However, no direct financial incentives are provided. According to a proposed strategy to improve waste management practices in the country, the Ministry will announce national and municipal targets to meet the objectives of lower MSW volumes that are landfilled, as well as increased recycling, composting and energy recovery rates, as soon as the new ISWM-law is in place (Appendix A.1). The Ministry of Environment will be the instance that finally approves every plan that is proposed by municipalities to meet these targets and further serves as an advisory and supportive body if local authorities lack the means for execution (MoE, 2018). However, the implementation of the new ISWM-law has not taken place yet and might be subject to further delay.

**Waste ‘suppliers’**

Due to the lack of big point sources of organic waste, the resources for local biogas production would be mainly provided by residents that are dedicated to the cause of helping to make use of their residential garbage in the form of kitchen waste and food leftovers. The market refuse of the larger food market in the form of unsold fruits and vegetables contribute to the number of suppliers. The local schools produce no substantial amounts of organic waste. However, participation in a communal project might be beneficial to enhance local awareness and acceptance of this technology in the long-term. Manure from farm animals of the Research Institute, as well as from a near-by dairy farm, although not located in the research area (Appendix A.5) can be used for co-digestion to enhance biogas formation and compensate fluctuations of available volumes of organic household waste and market refuse.

**Potential installer and operator**

Technical expertise for the installation can be provided by the same installer of the other small-scale biogas applications in the country, for example in Bkassine village (Appendix A.3). Daily operation tasks can be explained and assigned to workers at the Research Institute, who would also be in charge of organic waste pick-up and transport to the facility; mixing and pre-treating the feedstock, as well as capturing the produced biogas and withdrawing the liquid digestate in suitable containers for pick-up by or delivery to the local farmers.

**Potential end users**

Operators of the production unit are at the same time end users of the biogas, since this serves to provide the heat energy for the pre-treatment of the feedstock (Appendix C.4).

Since the liquid digestate is supposed to be applied in local agriculture in the vicinity of the production unit, the role of the local farmers is crucial. Success of the proposed facility largely relies on the willingness of the local farmers to actually apply it. The acceptance of the liquid digestate as an appreciated soil additive by the farmers hinges on its effects on agricultural produce. Accordingly, it is advised to make tests and experiments with digestate samples of a micro-scale digester, treating little quantities of organic waste before making a final decision in favor of the proposed set-up realization. By including local farmers in such field tests, end users can be introduced to the new product at an early stage, which in turn strengthens trust in the effects and reduce suspicions towards a yet-unknown substance.
4.2.4. Local acceptance

The conducted questionnaire survey drew upon importance of aspects of residential energy supply, as well as the perception of renewable energy and organic household waste. Also, openness among residents towards local biogas production from organic waste has been explored. Addressees – i.e. respondents of the survey - were households in Ghazir village and the survey questions were forwarded through the local schools from students to their parents.

An environmentally friendly residential energy supply followed by a low price for acquisition have been viewed by the respondents as more important aspects than decentralized energy production and continuous supply. Average scores of each aspect subject to evaluation are shown in Fig. 27.

![Fig. 27: Survey results question 1](image)

As illustrated in Fig. 28, survey results further show, that the majority of respondents would support local biogas production from organic waste in Ghazir. Besides, most respondents would be willing to start collecting their organic household waste in a separate bin for this purpose, as sorting at source of organics is not required for the current waste management in Ghazir. In case participants answered in favor of sorting organic waste at source, they were further asked to indicate on a map where the household is located. By doing so, a total of 59 potential point-sources of organic waste could be geographically identified in Ghazir village, as already shown in Fig. 26.

![Fig. 28: Survey results questions 4 and 5](image)

Further results of the questionnaire survey disclosed broad sympathy towards renewable energy in general, as wind and hydropower, solar energy and biofuels were assigned an important role for future energy supply in Ghazir. By many survey participants organic household waste was viewed as a resource of value with regards to potential benefits of compost substrates or animal fodder for chickens, pigs and rabbits. Sporadically the importance of reusing and recycling of waste has been pointed out by survey participants, also with regards to the energetic potential of discarded organics. Detailed figures of the survey results can be found in Appendix E.2, along with the English and Arabic version of the survey questionnaire.
4.3. Reflection on the used strategies and lessons learned

Reflecting on the used methods that were conducted in order to answer RQ 2, comments are made on personal experiences and lessons learned during the field study. The literature study on AD technology in general and cases of applied biogas production, as well as on-site exchange with relevant players in the field allowed for knowledge acquisition to come up with a possible scenario in the area of research. Yet, the overall accuracy of the projected concept performance remains uncertain with regards to practical execution and success of implementation. Nevertheless, the holistic nature of the assessment provides relevant aspects to analyze the feasibility of small-scale biogas production in similar settings.

4.3.1. Identifying and contacting stakeholders

Getting into contact with a representative of the municipality in Ghazir early on in the Thesis work and already before on-site investigations took place has been of advantage. Bringing this key stakeholder ‘on-board’ and sparking interest in the study project proved beneficial with regards to further networking within the local community, as more helpful contacts could be pin-pointed after a first meeting. Approaching the local community was further facilitated by the engagement of one teacher of one of the local schools who also showed interest in project support prior to the field work.

The open and curious nature of some local actors, such as, for example, the administration of one of the local schools allowed for meaningful project cooperation as a result of self-initiated networking when key stakeholders did not hold own relations. As it turned out in the specific case of this school, further important contacts could be created that way. The school’s administration directly called the local Agricultural Research Institute for project support after the motives and objectives of the field study were explained.

Initial efforts of reaching out in all directions to establish a network of local contacts and relevant players in the field of biogas applications were rewarded in the case of contacting a one-man enterprise, specialized in anaerobic treatment of organic household waste for fertilizer production (Appendix A.3). An early first meeting with this stakeholder led to arranged site visits getting to see examples of digester set-ups, including the large-scale municipal solid waste treatment center in Saida and a smaller sized application in Bkassine village.

4.3.2. Waste quantification

Non-households

Amounts of organic waste from non-household sources like the local food market and the vinery have been found out by directly confronting the owners with the issue. Due to the commercial nature of those facilities, records of unsold products were available in the case of the food market, as well as adequate estimations based on long-term experience in running a business in the case of the vinery. In both cases the relevant information, i.e. organic waste quantities over time could be obtained after explaining the context of the request and the objective of the research project in a brief meeting with the relevant persons.

Schools

Waste quantities of the local schools could not be quantified in the same way, as no data on the organic waste that is generated within the school’s premises has been collected by the administration prior to the field study. The set-up of organic waste bins delivered such data. However, the effectiveness of this strategy seemed to depend highly on the level of support from the school administration. The principal’s office of each of the two schools have been introduced to the study project and motives for the bin set-up explained. As total waste quantities that were disposed in the bins from the bigger school (500 students) were substantially lower compared to the smaller school (350 students), the impression became apparent that the request to actually use the bins has not been sufficiently forwarded to the students by the administration of the bigger school.

Weights of the taken samples differed on average by a factor of 7 (Appendix F.1).
Households

Zooming into some households in Ghazir village was to a large extent facilitated by using one local school as an intermediate between investigator and residents of the research area. Families of some students that one teacher thought are open for project participation were approached and introduced to the study project by a brief project description leaflet (Appendix G). Motives for organic household waste quantification were at times further explained during home visits. The same procedure was followed when other engaged and motivated residents have been conveyed by the same teacher, who further spread the word among friends and relatives, which resulted in additional households that reported organic household waste quantities during the field study. Accordingly, the taken approach proved to be effective to obtain the relevant data on a household level. Considering number of household members and official figures of the organic fraction of MSW per capita per day in the country of Lebanon (Sub-Section 2.3.2), sample results come close to the national average. In that case, national statistics could have been used instead if approaching local residents would have been more difficult.

4.3.3. Exploring local acceptance

Entering an unknown community in a foreign country to conduct fieldwork creates a number of both expected and unexpected challenges when it comes to obtain data that is needed to answer the research questions. Delivering a questionnaire survey through the schools to households in Ghazir village proved to be an effective way of exploring local perceptions and opinions, but also to introduce residents to a supposedly new concept of both treating organic waste and energy recovery. For receiving the information that was aimed to be delivered by the survey, opinions on the questionnaire format by the schools’ administration proved to be essential. Concerns, that some parents might have difficulties to fully understand the initially proposed questions in English led to final delivery of a translated questionnaire in Arabic (Appendix E.1). A 100 % return rate of all delivered questionnaires in the case of this school rewarded the additional efforts in consulting a professional translator prior to the survey.

The fact that the underlying study theme – biogas production from organic waste - is not as apparent in the country of research required wide explanations and thorough clarification to overcome initial misconceptions when stakeholders were met. This in turn proved to be quite time consuming at times and additional language barriers eventually led to failed attempts of sparking interests in project cooperation and finding relevant information. For example, asking households to separately throw kitchen waste and food leftovers in a separate bin for waste quantification in some cases was refused, despite initially stated willingness in the questionnaire survey to do so. Several times this was reasoned by concerns of luring insects and increased odors in the house. Also, the idea of re-using organic household waste was commonly appreciated among many residents that have been interviewed. During many conversations it became apparent that the underlying decomposition process in the anaerobic treatment of organic waste was falsely interpreted as the more commonly applied practice of composting. In many cases, safety concerns were raised as the natural formation of biogas was explained to differentiate the two concepts from one another. This, in some cases led to the dismissal of small-scale biogas production as a concept for local and decentralized energy production in residential areas.

Obviously, there is no silver bullet to eliminate negative biases and misconceptions towards a supposedly unknown subject, as strong opinions at times remain despite efforts of providing objective information about the issue at hand. Accordingly, the shift from a theoretical concept to practical execution of any proposed project might be much easier in a local context where positive experiences have already been made.
5. Discussion

In the following, the results of the assessment are discussed, limitations identified and its meaning for eventual replication in other settings considered.

5.1. Techno-economic potential

5.1.1. Predicting biogas yields

Due to multiple factors that influence the anaerobic digestion performance in a digester, the accuracy of estimated biogas yields is limited, especially with regards to the simplicity of the proposed set-up and the supposedly minimalistic efforts for operation. Aiming to keep the number of set-up components on a minimum, no auxiliary equipment for process temperature regulation inside the digester was considered. Accordingly, microorganisms that decompose the organic matter are exposed to ambient temperature levels if the digester is not insulated.

In Ghazir village, air temperature changes throughout the year, as can be seen in Fig. 29, with average temperature levels of up to 25 °C in summer and 11°C during winter. Thus, conditions for the anaerobic digestion process are rather psychrophilic in the proposed application for Ghazir village, contrary to the applied BMP value of 394 dm$^3$/kg VS in previous calculations (Sub-Section 4.1.2.), which derived from mesophilic conditions (Sub-Section 3.1.1.), i.e. temperature levels of between 37 and 42 °C. A study by Rajagopal et al. (2017) on anaerobic digestion of domestic food waste under psychrophilic conditions (20°C) shows BMP values between 348 and 449 dm$^3$/kg VS, at an OLR of 1.8 kg VS/m$^3$ per day, hence coming close to estimation results in this study, when mesophilic conditions were assumed. Findings of the literature research revealed a gap of further studies on psychrophilic AD of organic household waste as cases were mostly limited to the use of swine and cattle manure, for example Ferrer et al. (2011) and Pham et al. (2014). The results of a study by Khalil et al. (2016) on experimental biogas production under ambient temperature levels in the Lebanese community of Okaibeh showed weekly methane yields of 23 dm$^3$. The digester was fed batch-wise with a mix of food and landscape waste, at a feeding rate of 4 kg/week. Vögeli et al. (2014) report cases of unheated small-scale digester set-ups using kitchen, canteen or market waste as feedstock on a daily basis for biogas production. Methane yields correspond to between 225 and 580 dm$^3$/kg VS, considering absolute biogas production rates and measured methane content. Reported average process temperature levels account for between 28 and 30 °C, hence between psychrophilic and mesophilic conditions.

Accurate prediction of biogas production rates is further challenged by the inhomogeneity of the digester feedstock, consisting of organic household waste provided from multiple sources. Even supposedly comparable studies on BMPs of similar substrates under same temperature levels differ by a factor higher than 3 (Fig. 17). Inoculum and start-up phase for bacterial activity are vital determinants for digestion performance (Vögeli et al., 2014) and might be the reason for the lack of conformity. In the

![Temperature level and precipitation in Ghazir](https://example.com/temperature-precipitation.png)

**Fig. 29:** Climate conditions in Ghazir (Climate Data, 2019)
event of implementation of the production unit in Ghazir village, daily biogas yields should be monitored and compared to the initial estimation, when theoretical yields were calculated based on feedstock volumes and methane content of the biogas. Empirical data collection should show, if the applied BMP value in this study (Sub-Section 3.1.1.) has been an accurate estimate in the case of Ghazir village.

5.1.2. Choice of unit design and digestion mode

The digester proposed in Sub-Section 4.1.3. is made from a polyethylene water tank, in Lebanon commonly used for residential water storage (Appendix B). As the volume of the chamber for digestion of the organic matter and intermediate biogas capture remains constant, the proposed digester design is comparable to the fixed-dome model (Fig. 11). This digester type has been established in countries of Sub-Saharan Africa and China due to its long lifespan, as well as low investment costs and maintenance requirements (Rupf et al., 2016). Other simple small-scale biogas production units include the floating-drum type, where biogas pressures can be kept stable as the digester volume increases with biogas formation, as well as the flexible-balloon type digester, which can be constructed at minimum costs (Morgan et al., 2018; Stoddard, 2010).

Considering the exposure of digesters to relatively low ambient temperatures, Surendra et al. (2014) raise general concerns about the suitability of small-scale biogas production in temperate climates. Yet, as findings by Orskov et al. (2014) show, the fixed-dome model might still represent the most suitable choice among those three digester types in cooler and hilly environments where temperature vary throughout the seasons, as digesters can be insulated relatively easily. Kalla and Kanwar (1998) examined the performance of a fixed-dome digester in India at an altitude of 1300 m over a period of 10 years. Temperatures in the digester ranged between 24 °C in summer and 13 °C during winter and led to reduction of biogas production by up to 27 % during winter. The digester was placed underground and hence, some level of insulation by the earth allowed for continuous digestion of animal slurry even in cold winter months.

Wet digestion of solid organic waste like kitchen waste, food leftovers or market refuse requires additional freshwater resources for preparation of the feedstock to be anaerobically treated in a digester. Accordingly, water can be a limiting factor for wet digestion application in areas where access to water is restrained by a lack or long distances to water bodies and springs (Orskov et al., 2014; Rupf et al., 2016). Insufficient water supply can lead to a poor performance of a fixed-dome digester model as a case by Mungwe et al. (2016) shows, where anaerobic digestion was inhibited as feedstock could not be sufficiently diluted, which led to high TS contents in the substrate. Snow cover in the mountains, numerous springs and streams, as well as large groundwater reserves provide the country of Lebanon with relatively large water reserves compared to other countries in the MENA region. However, hydrological droughts as a result of climate change (Shaban, 2009), contamination of water bodies due to pesticide and chemical fertilizer use in agriculture (Kouzayha et al., 2013), as well as poor water management (Halwani, 2009) pose an increased risk of supply shortages in Lebanon if such issues will not be sufficiently addressed in the future.

On the contrary, the process of dry digestion is applied without the need for additional water input. Common application include the deployment of batch reactors, however, production units are used for rather large quantities of organic waste and commonly applied in industrialized countries like Germany (Li et al., 2011; Rupf et al., 2016). Accordingly, small-scale application of this digestion mode is not as established when compared to wet digestion (Vögel et al., 2014, p. 41). In the case of Ghazir village, additional absolute water resources are not expected to be limiting for long-term deployment of the proposed set-up, especially considering full usage of the liquid digestate for agricultural production on near-by farms. Consequently, water losses in the process are negligible. On the contrary, large-scale application of wet digestion in Lebanon - as practiced in the MSW treatment plant in Saida - eventually creates substantial water demands in the face of declining resources in the country. Accordingly, benefits of reduced volumes of landfilled waste and energy recovery might come at the cost of increased water footprints, which in turn create problems of other dimensions. On the other hand, wet digestion can be a suitable approach when waste shows a high water content in its original form. Absolute fresh water demand during treatment can be reduced by the anaerobic co-digestion of organic household waste and
sewage water, which can be realized in an integrated home-scaled application that is connected to the sewage network (Compost Baladi, 2019).

5.1.3. Cost estimation

Figures and numbers used in the cost assessment of the proposed facility in Ghazir village are based on prices for acquisition of the components in local shops and in the case of the desulfurization unit and the low pressure gas storage on online orders. Labor time for installation and operation has been estimated by the author based on conversations with the installer of the digester in Bkassine village. Maintenance costs were found to be difficult to assume due to lack references in the literature and little experience to operate such a facility in the country. Accordingly, conservative replacement intervals for components and time efforts for monitoring and repair service have been assumed (Appendix C.3).

The cost assessment (Table 7) of the proposed set-up showed that initial investments for the facility are estimated to be below 1,000 USD due to the simple design of a self-made digester, as well as low costs for manpower in Lebanon. Investment costs for small-scale facilities of the fixed-dome type in Cameroon and Peru have been reported to be 1,236 EUR (Mungwe et al., 2016) and 1,729 USD (Pérez et al., 2014), including manpower which accounted for 50 % and 30 % of total investment costs respectively. Estimated labor costs for construction, installation and site work in the case of the proposed facility in Ghazir village correspond to less than 10 % of total investment costs (Appendix C.3). The difference to the other examples in required manpower are assumed to be caused by the fact that no excavation and masonry work is required in the case of Ghazir village as the digester is placed above ground and somewhat prefabricated as a result of using a water storage tank. Cases of small-scale floating drum type production units above ground in Africa and India are reported by Vögeli et al. (2014), showing investment costs of between 420 USD and 2,135 USD, with digester volumes of between 1 m³ and 4 m³.

Expected life span of the proposed facility in Ghazir village is 10 years, considering findings of other reports, evaluating different types of simple digester designs (Ferrer et al., 2011; Pérez et al., 2014; Vögeli et al., 2014). However, low investment costs and the prospect of a short payback period allow for long-term practice of biogas and fertilizer production in Ghazir village if the proposed concept gets a chance to be established. Maintenance work for the proposed facility in Ghazir village are based on assumed component replacement intervals, as well as estimated labor time for regular checks, monitoring and component replacement. According to the cost assessment, annual maintenance costs of the base line scenario (Table 7) account for more than 30 % of total investment costs. Common estimates of annual maintenance work for commercial biogas plants of larger scale are of about 3 % of total capital costs (Klavon et al., 2013). However, capital costs of such facilities are beyond comparability to the proposed small-scale digester set-up in Ghazir village. Reviewing literature revealed a gap of reported maintenance costs for home-sized digester set-ups. Pérez et al. (2014) leave out maintenance costs when evaluating different home-sized digesters under economic aspects, pointing out that relevant costs in such cases account for initial investments for implementation.

According to the list of components for the proposed set-up (Table 6 and Appendix B) the air compressor for biogas storage is the most costly item, but is considered to be of advantage as daily biogas demand might differ from produced volumes in the digester (Appendix C.4). Not making the investment, obviously reduces initial investment costs, as well as item replacement costs since replacement of the compressor was assumed to be necessary every five years (Appendix C.3). Nallamothu et al. (2013) and Ray et al. (2016) point out that a biogas buffer application in any form is advisable nevertheless, as it facilitates gas handling and utilization. Their studies on do-it-yourself biogas compression and bottling in the context of home-sized digesters in India show that this can be achieved at low costs.
5.2. Implementation and successful application

Relevant aspects of the feasibility categories by Lohri et al. (2013) (Fig. 18) provide perspectives for evaluation of the proposed biogas facility and business model concept in Ghazir village, as far as its not-yet-implemented nature allows.

5.2.1. Technical-operational perspective

Prerequisites for deployment

Feedstock availability in the required substrate quality is not expected to become an issue, as a number of willing households to sort organic waste at source and provide it for local biogas production have been identified by the questionnaire survey (Appendix E.2). Feedstock sources, i.e. local households and a food market are located close-by the production site that further facilitates waste collection and reduces transportation efforts (Fig. 26).

Most of the set-up components for the biogas production unit can be acquired within the country of Lebanon (Appendix B). However, a desulfurization unit and the rubber bag as listed in Table 6 might have to be purchased from abroad. This poses a risk for long-term deployment of the site with regards to expected item replacement due to reduced gas cleaning effects over time, as well as delays of item acquisition when not regionally available. On the other hand, simple self-made applications with iron wool in the case of the desulfurization unit (Nallamothu et al., 2013; Ray et al., 2016), as well as polyethylene plastic in the case of a low pressure storage system (Stoddard, 2010) can be used instead.

Facility deployment

Introduction of the workers at the Research Institute to AD technology in general, as well as clear instructions on how to operate and which process parameters are important for successful operation of the unit in particular is crucial. Technical support and advice can be provided by more experienced players in the field, as small-scale biogas production already takes place in the country (Appendix A.3). Cases of successful biogas applications despite limited institutional means and capacities show that the technology as such can be adopted without much of prior experience, provided system set-up is simple and easy-to-use (Vöge1 et al., 2014). The fact, that the production unit will be operated by and at a research institute can be of advantage, as a new technology can be explored and monitored in the light of experimental research with benefits of successful operation in the long run.

As long as attention is paid to basic requirements that are necessary for a sound AD process within the digester, an effective metabolic activity by microorganisms and hence continuous digestate and biogas formation can be expected. Those requirements include high volatile solids content in total solids of the substrate (i.e. organic waste volumes without substantial impurities in the form of plastics or paper for example), as well as substrate feeding rates that correspond to the digesting capacities of the microorganisms. Varying composition of organic household waste might negatively affect substrate properties, such as the C/N ratio. An acceptable C/N ratio can be enhanced by the co-digestion of organic household waste with animal manure (Sub-Section 2.4.). Monitoring and feedstock analyses can be realized by regular tests on feedstock samples.

Considering a working week of five days from Monday to Friday and accordingly the absence of workers to execute daily operation tasks during the weekends, substrate feeding intervals will vary. How this affects the overall digester performance should be monitored and eventually alternative feeding schedules must be proposed to not risk significant inhibitions of the AD process. One approach can be to only feed the digester Mondays, Wednesdays and Fridays with increased feedstock loads in order to maintain output volumes of the liquid digestate. Feeding intervals would be more regular this way.

5.2.2. Environmental perspective

Physical degradation and destruction of nature as a result of the implementation of the proposed facility is not expected, due to the small dimensions of the unit. Use of non-renewable energy that is needed to realize the proposed business model corresponds to fuel consumption for the weekly waste collection
tour, its transportation to the production unit, as well as pick-up and transport of the liquid digestate by local farmers.

**Global: GHG emissions**

Associated high potentials for GHG emission mitigation drew wide attention to the controlled anaerobic digestion of organic waste in biogas facilities, as a promising RE technology. Bruun et al. (2014) challenges this view by pointing out the wide practice of insufficient and poor handling of small-scale biogas production units, resulting in large volumes of intentional and unintentional release of methane, hence risking supposedly achieved savings from biogas production. Thus, there is a risk that environmental benefits of a biogas production unit in Ghazir village might be reduced if methane escapes into the atmosphere during facility operation.

Provided biogas formation and application takes place without accidental leakage of the biogas into the atmosphere, GHG savings can be expected as landfill disposal is assumed to lead to higher GHG emissions when compared to a sound treatment of the same volumes of organic waste in a biogas production unit (David et al., 2013; Manfredi et al., 2009; Soriano, 1999). Additional transport-related GHG emissions for waste collection and distribution of the liquid digestate to the nearby farms is considered to not substantially diminish overall GHG savings, as the following assessment shows.

Referring to other studies (David et al., 2013; Manfredi et al., 2009; Soriano, 1999), the alternative treatment of 100 kg organic waste in a biogas production unit can save between 60 and 100 kg CO₂ eq.. Weekly driving distances for waste collection and digestate distribution within the area of research are estimated to be within a range of between 5 and 10 km (see scale and map in Fig. 26). Assuming CO₂ emissions of 0.35 kg per km driven in a medium-sized vehicle (Seo et al., 2016), the additional transport-related emissions account for between 1.75 and 3.5 kg CO₂, hence being substantially lower than initially achieved GHG emission savings.

Replacement of commonly applied fertilizer in the area of research can result in reduced agriculture-related GHG emissions. Due to bio-chemical stability of digested matter, i.e. reduced content of degradable molecules, nitrous oxide release of applied digested is lower when compared to raw manure, but higher when compared to mineral fertilizer (Paolini et al., 2018). On the other hand, fossil energy demand in relation to mineral fertilizer fabrication (Surendra et al., 2014) can be decreased by replacing for example urea with liquid digestate from the biogas production process (Riva et al., 2016).

**Regional and local: environmental effects of the liquid digestate**

Liquid digestates as a result of anaerobic treatment of organic waste have been reported to cause higher emissions of ammonia than raw manure when distributed superficially (Riva et al., 2016). This affects regional air quality, ultimately posing risks for surface water eutrophication and ecosystem acidification as a result of chemical reactions with atmospheric humidity (Nkoa, 2014). On the contrary, local odor emissions are substantially reduced when compared to raw manure (Paolini et al., 2018; Riva et al., 2016). This might be of minor relevance in the case at hand, as few residential houses are affected by agricultural practices that take place on the outskirts of Ghazir village.

Application of the liquid digestion on local farms for crop cultivation implies some concentration level of nutrients in the soil that can further affect water bodies and the atmosphere. Levels of heavy metal content in liquid digestates in many cases comply with international standards for organic fertilizer requirements, however, repeated application on soils might cause high levels of local concentrations (Nkoa, 2014) which can have toxic effects on the ecosphere (Seadi and Lukehurst, 2012). Safe application of digestate requires the removal of pathogens before application, which can be realized by heat treatment of the feedstock. In general, transmission of viruses, parasites and diseases are considered to be of less concern when source-sorted household waste is used as feedstock for anaerobic digestion, compared to substrates of animal or human origin, i.e. manure or sewage water (Seadi and Lukehurst, 2012).
5.2.3. Financial-economic perspective

Low financial efforts for the installation of the proposed facility motivates the municipality of Ghazir to fund the set-up components and hence facilitating the process of execution, as the Agricultural Research Institute in Ghazir in return agreed to be in charge of facility operation.

Running expenses in the form of water input and labor time for operation, as well as initial investment costs for the proposed set-up are not expected to be of a limiting factor when it comes to long-term deployment of the facility. Wages in Lebanon and the investment costs of the proposed set-up are quite low and the sale of the liquid digestate provides profits even at low prices and volumes (Table 7). However, estimated revenues are based on the assumption that farmers buy the product, and hence if there is no market, the justification of the facility to exist is questionable from an economic point of view.

5.2.4. Socio-cultural perspective

The acceptance of the liquid digestate as a fertilizer among the local farmers is considered the most important condition for the proposed biogas application in Ghazir village to be realized. As already mentioned, close interaction during first field tests of the effects of such a new substance can spark interests and create motivation for application in local agricultural production.

Willingness among the residents of Ghazir village to participate by providing organic household waste has already been confirmed by conducting a questionnaire survey. Involvement of this stakeholder group in local biogas production can strengthen social cohesion in the community and facilitate other communal projects. The common phenomena of Not-In-My-Back-Yard (NIMBY), i.e. appreciating the idea of local biogas production as long as the facility in question does not physically affect residential environments (Appendix A.1) is avoided, since the proposed set-up will be located in rather non-residential part of the research area.

A fair distribution of burdens and benefits among the stakeholders is considered to be of much importance for successful deployment in the long-term of any AD facility, according to Lohri et al. (2013). Considering responsibilities by the Research Institute and its staff when being in charge of frequent waste collection, preparing and pre-treating feedstock, as well as operation of the biogas facility, this is provided by the monetary compensation by the beneficiaries, i.e. local farmers. Other than that, motivation by the operator stems from general research on the field of AD treatment of organic waste and its potential for application. In fact, the Research Institute also runs farms for experimental research in agricultural science.

5.2.5. Institutional perspective

Despite sporadic application of AD technology and conducted feasibility studies on biogas production from organic waste within the country of Lebanon (Azzi, 2017; UNDP, 2012), local stakeholders in Ghazir village are confronted with a new field of waste treatment. Regarding current inexperience of dealing with anaerobic waste treatment, this poses a challenge towards successful set-up implementation and long-term operation of even a small-scale facility as described in Sub-Section 4.2. Accordingly, fundamental knowledge of the AD treatment of organic waste must be acquired by the operators of the facility. This is considered a minor obstacle regarding the fact that a research institute would be directly involved with the deployment of the biogas production unit. Being confronted with the unknown is part the exploratory nature of scientific research and central to daily activities that take place in the Agricultural Research Institute in Ghazir village.

Close interaction and communication between ‘waste suppliers’, i.e. households, food market and schools, the future operator, i.e. staff of the research institute, as well the local farmers as end users of final product are fundamental for a working system according to the idea of the proposed business model. Meetings where all those parties are gathering can facilitate the organization and planning of weekly waste pick-up and digestate distribution to the farms, as present parties can propose and agree on waste pick-up time and location.
5.2.6. Policy and legal perspective

Use of organic fertilizer in Lebanon is subject to the not-yet issued Lebanese compost ordinance that is going to be similar to EU legislation (Appendix A.1). According to findings in the literature, in many cases liquid digestates that derive from the anaerobic treatment of organic waste comply with European standards and regulation (Nkoa, 2014; Seadi and Lukehurst, 2012). With regards to varying feedstock properties due to the inhomogeneous nature of organic household waste, conclusions from other studies should not be expected to apply in the specific case of produced liquid digestate characteristics in Ghazir village.

Seadi and Lukehurst (2012) provide guidelines on quality management of digestate form biogas plants used as fertilizer, referring to examples of good practice in Europe. Accordingly, content analyses of both the feedstock and digestate should be made regularly and compared with the relevant regulations on organic fertilizers. Practical execution of such testing is considered to be facilitated by the capacities and experience of the Agricultural Research Institute in Ghazir village.

Anaerobic treatment of organic waste for energy recovery is acknowledged by national legislation, however, no Lebanese regulations or laws are specifically dedicated to this technology (Appendix A.1). The legal context of the biogas application in Ghazir village is not expected to be an obstacle for its implementation, as other AD facilities, namely in Bkassine village and Saida, have been installed under the supervision of local authorities (Appendices A.3 and A.5).

5.3. Prospects of assessment replication

Fieldwork in Ghazir village showed that, from a socio-economic point of view, benefits associated with decentralized energy recovery from organic waste do not always coincide with a remarkable local need for the products of small-scale anaerobic waste treatment, i.e. biogas as an energy carrier and the liquid digestate as an alternative fertilizer for agricultural production. Consequently, immediate effects towards the local community, as well as the appreciation of such facilities might be much lower in urbanized and developed areas, when compared to places where infrastructure is undeveloped, access to energy limited and agricultural activity high because of, for example, subsistence farming by a poor population.

In Lebanon, 88 % of the population live in urban areas where most of the economic wealth is accumulated, mostly in the coastal region (Fig. 31), with the Mount Lebanon governorate accounting for the highest share of the total population (Sleem and Dixon, 2018; Yaacoub and Badre, 2012), including residents of Ghazir village. On the other hand, about 27 % of the total population in Lebanon are estimated to live in poverty (Salti and Chaaban, 2010; Skeem and Dixon, 2018), a phenomenon which is not limited to urbanized areas. High levels of deprivation can be found in less populated hinterlands of the country, namely governorates of Békaa and Baalbek/ El-Hermel (OCHA, 2018). In fact, actual power supply is far from being provided at all times (Abi Ghanem, 2018) and even fuel availability for cooking and heating is not necessarily a given. Those governorates are affected the most by the Syrian conflict as displaced people, mostly Syrians, represent half of the local population (OCHA, 2018). Informal Tented Settlements have substantial impacts on local ecosystems due to increased deforestation and illegal felling for firewood supplies, as well as soil and water contamination by solid waste disposal at open dump sites (UNDP, 2014). On the other hand, large parts are dedicated for agricultural

![Fig. 30: Agriculture in Békaa](image1)

![Fig. 31: Coastal area, view from Ghazir village](image2)
production in the case of Békaa (Fig. 30) and hence the anaerobic treatment of organic waste for biogas and fertilizer production can be considered as a promising approach to address the needs of local communities there.

In general, the replication of the assessment with the methods and strategies used in the case at hand should not be challenged by the choice of the community, since organic waste is omnipresent in human settlements and full utilization of its energetic and fertilizing potential are likely to be not fully exploited.

Obviously, the very adoption of the business model as proposed for Ghazir village to be realized elsewhere is limited for several reasons. The presence of an Agricultural Research Institute proved to be of a crucial vantage point, as labor and spatial capacities, as well as vicinity to local farms and research-motivated interests aggregate, which forms a promising basis to establish small-scale biogas and fertilizer production and utilization in the area. In other areas, the feasibility for facility implementation, operation and full use of biogas and the liquid digestate must be expected to be restrained due to the case of an ultimate non-existence of such an institution.

On the other hand, multiple examples of home-scale biogas applications in rural and less developed settings across the world show that potential obstacles in the form of inexperience and initial concerns by end users, labor time allocation and financial efforts can be overcome even on a household level. In numerous countries, namely China, India, Peru or Indonesia to only name a few, financial challenges are addressed by governmental support and development programs by NGOs which ultimately led to broad acceptance of biogas technology and a wide deployment of small-scale digesters, especially in rural communities (Bruun et al., 2014; Ferrer et al., 2011; Rakotojaona, 2013; Stoddard, 2010). Low national diffusion of AD technology in Lebanon reflects the lack of biogas promotion and incentives for application and facility implementation, despite the current struggle of authorities to sufficiently address waste management issues by implementing contemporary treatment concepts (Appendix A.1).

Referring to the discourse of Sustainable Development and the SDGs (Sub-Sections 2.1 and 2.4.5), the deployment of small-scale AD facilities not only results in ultimate access to cheap and clean energy for residents, but further embodies a promising pillar for a more holistic concept, as the anaerobic treatment of organic waste can lower environmental and economic burdens at the same time. In the case of Ghazir village, volumes of MSW which are destined to be disposed at a landfill would be transformed into a nutritious plant thriving substance, recycling nutrients and recovering energy at the same time. Obviously, absolute quantities of treated waste, and hence reduced landfill volumes and related GHG emissions, as well as replaced quantities of conventional fertilizer and monetary savings are not of major magnitude in the event of proposal realization in the research area. This relates to the attempt of keeping feedstock sourcing, AD facility deployment and end product application within the geographical boundaries of the community. In Ghazir village the availability of organic waste is relatively large when compared to potential demand for fertilizer alternatives in the area. In other places - not limited to communities in Lebanon - where agricultural activity relative to accumulating organic waste quantities is higher, more organic waste can be allocated to produce a liquid digestate and hence increase the merits associated with this concept.
6. Conclusion

The feasibility of small-scale biogas production in the area of research using locally available organic waste resources as feedstock has been assessed and a final application along with a business model for implementation proposed, applying methods of both quantitative and qualitative nature. The choice of methods was motivated for being widely applicable in other setting with similar conditions to replicate the investigation for further feasibility studies in the future. Language barriers, as well as different perceptions towards and associations with biogas production among residents challenged the data collection during the field work. Nevertheless, support by local stakeholders and the simplicity of the applied methods allowed to conduct a holistic feasibility assessment.

This study showed that the anaerobic treatment of organic waste in Ghazir village can be applied on a small scale, creating benefits for the local community in the light of Sustainable Development. Main conclusions are:

- Feedstock can be provided by households and one local food market in the form of source-sorted kitchen waste and unsold fruits and vegetables, respectively. Biogas can be utilized for thermal pre-treatment of the feedstock in order to produce a liquid digestate that can be safely applied as an alternative fertilizer on local farms.

- From an economic point of view the estimation of costs for installation, operation and maintenance revealed promising perspectives for both facility operator and local farmers, provided nutrient content in the liquid digestate and its effects on farm yields prove to be of interest for commercial acquisition.

- Accordingly, and with regards to present unfamiliarity with biogas technology in the research area, first experiments on anaerobic treatment of organic waste and fertilizing effects of the liquid digestate are advised to take place prior to the implementation of the proposed facility.

- Stable bacterial activity in the digester throughout the year is expected to be restrained by annual changes in air temperature since the digester is exposed to ambient air conditions as the proposed facility is planned without external heat sources. Insulation of the digester, as well as controlling temperature level of the feedstock and digester can reduce annual production rate fluctuations.

- The overall strategies followed, and the methods applied in this study are considered suitable to repeat this investigation in other places, not limited to the country of Lebanon. Replication of the assessment in rural areas, where issues in the form of open waste dumping and energy shortage aggregate with agriculture being a central source of income, might turn out to disclose benefits of a larger magnitude to local communities.
7. Acknowledgements

I would like to thank my supervisors, Ershad Ullah Khan and Gunnar Larsson, as well as my subject reviewer Åke Nordberg for all the input, support and feedback they provided during my Thesis work, as well as the Department of Energy and Technology at SLU to offer a very pleasant working environment and place to study. A big ‘thank you’ goes to Christian Naccache, who tipped me off with making a feasibility assessment on biogas production in Lebanon in the first place, initiated some first networking for my field study and was ready to help out at any time.

Further gratitude goes to all the people that immensely supported me throughout my field work in Lebanon, namely but not limited to Elie and Anthony Haddad, Mony Yammine, Hani Dagher, Beshr Sukkariyah and Carmen Haddad. Special thanks goes to the Nuns, teachers and staff of l’École Saint François de la Croix for always welcoming me warm-heartedly at my school visits and the big help they have been when collecting data in Ghazir village. Thank you, Manal Moussallem, Rami Nassif and Nicolas Gharib from the Lebanese Ministry of Environment to provide insights in current waste-related challenges and perspectives in the country of Lebanon, as well as Elias Azzi for initiating this contact in the first place.

Despite the likeliness that only few people actually read this, I want to take this chance to expand the scope of thanking a little further, point fingers at some lovely souls and reflect on the (almost) two years I was allowed to spend in Uppsala trying to internalize the idea of ‘Sustainable Development’ which I still find hard to grasp, yet inevitable to pursue. Thank you to all course coordinators, lecturers and especially my fellow students of this program. You all have been a huge source of inspiration beyond any expectations. It makes me both proud and optimistic to stand in line with you, being motivated to the core and thirsting to make a change for the better and to leave behind a sound planet for the generations of our children and grandchildren to live a decent life.

Wishing the best of luck, looking forward to meeting again and already missing to the date of writing: Adam, Daan, Elena, Esmée, Fredrik, Hanna, Jan, Johnny, Josefine, Oliver, Lucas, Lucia, Luise, Mariia, Mostafa, Torry and Valerie. You are truly wonderful, tack så mycket för vår gemensamma tid! Hold on to the memories we share, because memories are the only thing that will keep us connected through invisible network.

Last but not least I would like to thank my dearest friends back home, as well as my mum, dad and brother Julian. My limited writing skills do not allow to express in words what you mean to me. I cannot (and don’t want to) imagine a life without you ♥
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Appendices

A. Stakeholder consultations

A.1 Ministry of Environment

represented by Manal Moussallem, Rami Nassif and Nicolas Gharib

manal.moussallem@undp.org
rami.nassif@gmail.com
nicolas.gharib@undp.org

Stakeholder meeting

Beirut – 29/03-2019

Main findings of the meeting and review of the new law on Integrated-Solid-Waste-Management (ISWM) which was approved by the parliament:

Current Snapshot of MSW-management in Lebanon

- Situation of MSW (treatment practices) in Lebanon has not changed much since waste crisis in 2015 despite increased awareness of risks and impacts associated with insufficient waste management strategies
- Nevertheless initiatives of alternative treatment practices by municipalities and the private sector have been emerging across the country in order to face and deal with current challenges of MSW-management

Legal context

- New law on ISWM was ratified by the Parliament, assigning municipalities the responsibility to deal with waste management issues and propose plans and strategies to achieve targets of the national agenda on ISWM that is supposed to be announced by the MoE after the law is finally issued
  → ISWM of MSW stresses the importance of the first steps of the waste management hierarchy, i.e. reducing, reusing and recycling
  → policy is not put into action as it needs to be confirmed by the Council of Ministers, nevertheless its implementation is only a matter of time (which might be delayed due to postponed decision-making)
  → a national SWM agency shall serve to complement the decentralized approach of ISWM in case municipalities do not have sufficient capacities and expertise to operate large scale facilities such as sanitary landfills
- any plan on SWM proposed by municipalities must be approved by the MoE
  → it is aimed for in the future that a share of municipal taxes shall be allocated to for the actual treatment of MSW (at the moment, sweeping waste from the streets is the only service that is funded by municipal budgets)
  → according to the new law feed-in-tariffs can be laid claim on for example when an AD facility uses the biogas to generate electricity, provided the electricity producer takes responsibility of feeding the power to the national grid at own expenses after obtaining a license from the Ministry of Energy and Water

Application and examples in Lebanon
- there are several cases in Lebanon, where municipalities initiated sorting at source (also for organic waste), but only in few cases an integrated approach is actually applied (e.g. Bkazime) → in most cases the waste is sorted but final treatment and disposal is not further paid attention to by the municipalities, meaning that the sorted waste might end up all together again in a landfill (good intention but not consequently executed)
- there are few AD facilities in Lebanon on a small to larger scale, namely in Saida, Bkassine and Bakka, as well as landfill gas capture in Nameh → except for Bakka (which is not operational at the moment) the AD facilities in Saida and Bkassine apply wet fermentation process (brings drawbacks in terms of a large water footprint especially Saida; Bkassine is also sewage-water treatment plant)

Challenges for AD technology to become an established treatment alternative in Lebanon

- positive marketing of the technology and examples of good practice in order for improve the reputation of AD technology
- local acceptance and negative perceptions towards biogas technology by the population (NIMBY)
- lack of technical expertise and knowledge in the field, especially when it comes to operation and maintenance the long-term
- requires initiative and strong will for implementation by municipalities to propose such a facility
- would also need private investors and donors for implementation, since lack of financial support by central authorities in the form of economic incentives challenges means for investment

E-mail exchange

29/03-2019

Von: Manal Moussallem <manal.moussallem@undp.org>
An: Sebastian Huber <Sebastian.Huber.1898@student.uu.se>
Cc: 'Rami Nassif' <rami.nassif@gmail.com>; Nicolas Gharib <nicolas.gharib@undp.org>
Betreff: RE: Study project Biogas in Lebanon

Hello Sebastian,

Nice meeting you.

Attached the English version of the ISWM law approved by the Parliament in September 2018; also attached a brochure summarizing environmental safeguards and the 2017 MoE memo on ISWM guidelines (sorting at source etc.)

Best wishes for your work,

Manal
Dear Sebastian,

Thank you for sharing with us the updates.

Concerning your inquiries, kindly find below my feedback

1- There are no local regulations or laws specifically dedicated to anaerobic digestion. Law 80/2018 (solid waste law), recognizes, the anaerobic treatment through Article 1 (clause 7, and 17), and thereafter through various articles of the law under energy recovery, since the main objective of aerobic treatment is recovery of energy prior to final treatment of the organic material (whether through composting or any other technique). As for regulations and as it is mentioned in most Lebanese technical and environmental regulations, whenever local regulations and standards are missing international ones are adopted especially, those of WB, and EU.

2- Concerning organic fertilizers, MoE has prepared a Composting Ordinance, however, it has not been issued yet. The Lebanese Compost ordinance is relatively similar to that of the EU. Accordingly, you may use the EU compost ordinance as a reference as well.

Regards,
Rami Nassif

On Wed, Apr 24, 2019 at 2:17 PM Sebastian Huber <Sebastian.Huber.1898@student.uu.se> wrote:

Good afternoon Manal,

to keep you posted on my field study and the results I have come up with:

A potential small-scale biogas application in my research area (Ghazir) can be the production of an organic fertilizer as a by-product from the anaerobic digestion treatment of organic household waste (eventually mixed with animal manure). The biogas that is formed during the process can be used for pre-treatment of the feedstock (by heating it up) that goes into the digester in order to kill pathogens for a safe application in agricultural production. End users of the digestate can be local farmers. Source-sorted organic waste resources can be provided by a couple of households in the area. The set-up (see sketch) can be located and operated at the research institute of the Lebanese University in Ghazir, which is located close-by the local farms. The municipality would even be willing to cover initial investment costs, provided it does not exceed a certain limit.

For my Thesis report it would be interesting to discuss some legal aspects in the context of Anaerobic Digestion projects in Lebanon, which is why I have some questions for you:
1. Are there any regulations or laws one must consider when applying small-scale anaerobic digestion in Lebanon, according to the proposed scenario described above?

2. Are there any regulations or laws one must follow as a farmer when applying an organic fertilizer as a by-product of the anaerobic treatment of source-sorted organic household waste? (This could also be very general rules for the application of fertilizers in agricultural production)

Thank you for your help and I am looking forward to hearing from you.
Best regards, Sebastian

--
Rami Nassif
Solid Waste Expert
Lake Qaraoun Pollution Prevention Project
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Tel: +961-1-976 555 ext 548
Mob: +961-3-361 547
A.2 Elie Haddad

Member elect. of Ghazir Municipality, civil engineer

eliehadd@yahoo.com

Stakeholder meeting

Kfarhbab, Ghazir – 15/03-2019
19/03-2019
16/04-2019
10/05-2019

- 8 t/day of MSW in Ghazir municipality
- Source separation on household level: paper, plastic, metal, glass, and other (incl. organic)
  → not recycled waste (incl. organic waste) is landfilled in Bourj Hammoud, Beirut
- ‘people learn fast’, as source separation was implemented some years ago and it works
- Municipality is ‘trapped’ in a long-term contract with current waste collection operator
  → this operator must be paid anyways, hence no resources available from a ‘tight’ budget for new strategies
- No space capacities for production unit available from Municipality
- ‘How much does a production unit cost?’
- Could initiate a cell phone survey on municipal level, asking people about willingness to source-separate organic waste and perception of biogas technology
- Residents in Ghazir pay two electricity bills
  → public supplier (EDL)
  → private supplier (diesel generator)
- LPG dominant cooking fuel
- If investment costs of biogas facility is not too high (1000-1500 USD), the municipality can provide financial support if research institute would be in charge of facility operation

E-mail exchange

15/03-2019

On Friday, April 12, 2019, 11:38 AM, Elie Haddad <liehadd@yahoo.com> wrote:

Good morning Sebastien:

I am pleased to answer your questions about some statistics about our city Ghazir:
- the population of the center of Ghazir, without the suburbs (kefarhbab, and Maameltein) Will be around 12000 persons originally Ghaziriot and resident.
- number of voters - registered: 5200 voter
  - effective: 3100 voter
- number of units registered: (tax payers) residential and commerce: is around 1800 units, only in Ghazir center.
- Daily weigh of household wast is 8 tonnes per day for all Ghazir, for just the center will be 4 tonnes daily.
If there is another question, please let me know, I will be happy to answer them.
Good day. Eng. Elie Haddad, member elect of Ghazir municipality.
A.3 BiogazLebanon

Lebanese enterprise specialized in home-scale digester technology
represented by Hani Daghe

sales@biogaslebanon.com
http://www.biogaslebanon.com/

Stakeholder meeting

Jbeil – 17/03-2019

- Installed and runs two bigger production unit in Bkassine and Bikfaya, treating 0.6 and 1 t/day source-separated household waste from the community
- No smell
- Energy input to keep temperature level (mesophilic)
- Biogas is currently not used (it’s burned), however liquid digestate is more interesting for him
  ➔ run tests on flowers and crops and fertilizer is quite effective (‘almost double yields’) ➔ also gave samples to a lab for analyses
  ➔ expects revenues from selling the fertilizer which then pays off quickly for investment costs
  ➔ main focus on getting farmers on board and convince them of the good quality fertilizer
- Main challenge is getting attention and appreciation of the ‘biogas idea’, promoting it and spread the word
- End use for biogas might take more time to be accepted and become established (issue of what
to do with it, you can fill it up in gas bottles but density is not as good as conventional cooking
gas, power generation makes sense only on larger scale
- Would be open to provide the equipment for a small pilot test in Ghazir if they want to try it out (so he gets attention and can promote his ideas)
Site visit: AD unit residential organic waste in Bkassine

- Not yet in full operation (‘process of bacteria formation’)
- Capacity designed for 600 kg of source-sorted organic household waste
  → is mixed with 600 litres of water and at time with 5 kg manure
- Biogas is currently not made use of (burned)
- Liquid digestate is currently tested in lab and partly sold to farmers
  → goal is to sell it all to farmers and create profit
  → profit is shared between operator and municipality
- Municipality funded the AD unit
  → waste separation at household level was implemented before and has been treated in the sewage plant so far (motivation?)
  → AD unit takes advantage of the pre-existence of the sewage treatment plant as the organic waste can be pre-treated at the shredding station
- 4 employees from the municipality are in charge of running both sewage-water-treatment plant and AD unit
A.4 Beshr Sukkariyah

Professor at the Lebanese University and the Agricultural Research Centre Ghazir

Beshr.sukkariyah@ul.edu.lb

Stakeholder meeting

Ghazir village – 11/04-2019

- mostly small-scale farmers in the Mount Lebanon region follow GAP guidelines and hence ‘organic fertilizer’ as a by-product of biogas production could find a market not so far away from Ghazir (however, GAP does not explicitly encourage ‘organic’ farming)
  → there might be an interest for liquid digestate since chemical fertilizer is expected to become more expensive in the future
  → also farmers follow GAP guidelines in case local produce is to be exported and hence, has to be certified for consumption in Europe for example
  → GAP practices also consumer driven, since the reputation of conventional agriculture in Lebanon has suffered due to some incidences of contaminated produce (‘people want safe food’)
- there are (or at least were) some examples in the North of Lebanon, where biogas was produced locally at farms, using manure as feedstock
  → establishment of AD for waste treatment and biogas production needs time, but has high potential in Lebanon
- economic profits are a more efficient driver for change of practices towards waste treatment alternatives, rather than environmental concerns
  → ‘if you can’t make money, than at least you can save money’
- people need to see and understand the point and benefits of for example sorting their waste at source, otherwise they stay detached from issues related to insufficient waste management (since they do not fell the immediate consequences as waste disposal for example does not happen at their backyard)
- proposes to make tests of the liquid digestate at the Research Institute, to find out the effectiveness of fertilization properties
- assumes that it won’t be an issue to bring the liquid digestate among the local farmers, regardless of volumes, provided it is treated and free from pathogens and contaminants
- regular tests to monitor nutrient content and eventually identify harmful levels of contamination in the liquid digestate are advisable
  → samples can be send to laboratory facility that charges about 25 USD for each testing

Discussion with Sami Khalil, local farmer

Ghazir village – 18/04-2019

- cultivates 4 greenhouses in the valley, 16 more in the area
  → biggest farmer in the area
  → in total he estimates a number of 40 greenhouses in the area, which potentially could make use of the liquid digestate
- uses fertilizer all year around
  → liquid digestate would be complementary to other additives and fertilizers
- realistic volumes to be applied per week per greenhouse: 5 liter (all year round)
- is ready to pick it up from the site of production in Ghazir, and is ready to pay a little bit (1 USD/liter according to Eshr
  → wants to try it out first on one greenhouse and see the results and what it does to the crops
  → in case test results are acceptable, he would speak to the other farmers in order to make use of all the digestate that comes with biogas production in Ghazir
Discussion with Elie, local parsley farmer

- cultivates 28 greenhouses in the area (parsley) all year round
- would apply the liquid digestate, if first tests show satisfying results on crop growth and produce
- applied volumes of the liquid digestate might be about 100 liters every month
- currently applies a plant growth regulator, whose NPK content is similar to liquid digestate samples in the literature
  \[ \rightarrow \text{price per liter 8 000 LBP (5,3 USD)} \]
  \[ \rightarrow \text{two liters of digestate might replace one liter of this fertilizer (assumption by Beshr)} \]
- if effects in tests show, price per liter of 1 USD is feasible for acquisition (self pick-up at the production site by farmer)
A.5 Other stakeholders

Mony Yammine – teacher at ASG, in charge of Env. Club, worked for the FAO  
Ghazir village, 19/03-2019  
monynnehme@gmail.com

- Tried out separation at source for organic waste at ASG a couple of years ago  
  ➔ no substantial amounts of organic waste available (might be the case for any other school that does not run a canteen/ kitchen)  
- Only source is the nuns home (‘consider it as a household’) where they already have a compost area  
- Idea of reaching out to households of students that live near-by (or in Ghazir)  
  ➔ carry out questionnaire survey  
  ➔ select a couple of households to try out organic waste separation at source over a couple of weeks to see what and how much is actually produced (eventually extrapolate from samples to the neighborhood/ whole community)  
  ➔ suggests to also target the big restaurants at the sea side, being point source of organic waste by throwing away many leftovers that comes with Lebanese cuisine (Mezze)  
- School grounds are large enough to provide a site for a production unit  
  ➔ not sure how schools administration likes the idea, concerns about other people throwing there trash there

Tree Nursery Al-Mashtal  
Kfarhbab, Ghazir, 19/03-2019

- Generally open towards the idea of replacing current solid fertilizer (2 t/year) with a liquid digestate, provided that NPK-ratio is reasonable and allows application  
  ➔ however, there might be practical issues when applying since current fertilizer is solid and added manually to the soil of the trees  
  ➔ only ‘maintains’ trees, hence demand for fertilizer is not stable throughout a year  
  ➔ open to re-discuss matters when there are results to present (amount of digestate, NPK-ratio maybe Hani has lab-test results)  
- Referred Yazbek nursery, because he has irrigation pipes and maybe can apply liquid digestate more efficient

Yazbek Plant Nursey  
Ghazir village, 19/03-2019

- Applies fertilizer all year around, grows plants from ‘seed to trunk’  
- Composts plant residues and uses it as soil additive  
- Would be interested to partly apply the liquid digestate, provided that NPK-ratio is reasonable and allows application (again, maybe Hani has some results to present)  
- Suggests organic farmers as a target group, however not located in Ghazir, but provided a contact (Fadi +961 3456336)  
- Open to re-discuss matters if necessary

Restaurant Salsa – Diner  
Ghazir village, 19/03-2019

- More like a imbiss place, no considerable amounts of organic waste  
  ➔ what is left over, is fed to the chicken  
- Provided contact of olive oil press  
  ➔ the oil is stored next door, however, the acutal press might not be in Ghazir (Anthony wants to call the person to ask for a meeting)

Elias Kamel – Director of Ghazir Public School  
Ghazir village, 19/03-2019

- School hosts about 500 students  
- Currently they throw everything into one bin
- Not particularly interested in my Thesis work
- Is ok with my proposal of setting up a couple of garbage bins for the organic waste on the school premises, **provided** I take care of emptying them twice a week (and also before the weekend so the trash doesn’t remain there too long)
  → teacher **Rania Nawfal** is going to set up collection system in order to separate recyclables, hence another ‘organic bin’ would complement the set up

**Soeur Elisabeth** – **Principal of l’École des Soeurs de la Croix**  
Ghazir village, 19/03-2019
sfgsc@ymail.com

- School hosts about 350 students
- Currently they sort after paper, metal and plastic
  → organic waste from the Nuns kitchen is fed to the chicken
- Participated in a project by the Lebanese University, when they set up small composting units to fertilize the vegetable patch
  → they have separated organic waste during the project
  → they want to continue this practice at some point
  → referred me to Dr. Carmen Haddad
- Interested into my project work and want to support me
- is ok with my proposal of setting up a couple of garbage bins for the organic waste on the school premises
- I can also look at the organic waste in the Nuns kitchen (which now is fed to the chicken)

**Hannibal** – **Dairy farmer at Trappiste Covent**  
Dlebta, 19/03-2019
05/04-2019

- Farm has 70 cows (recently increased production from 14 to 70 (!))
- Does not make use of manure (no agriculture in the area)
- Is aware of environmental impact of cow dung
  → wants to use cow dung for biogas production
  → end use electricity generation (his main motivation is the climate impact)
- Is interested in my study project and wants to be involved and informed about proceedings and outcomes
- Owner considers to set up a medium-scale production unit at the farm, as this is done already somewhere else (since he gives away the manure to another farmer that uses it for biogas production)
- Eventually the priest (owner of the land) would allow to dedicate a little space for a smaller digester for a communal application

**Joseph Kabbas** – **Engineer at Saida MSW treatment plant**  
Saida, 22/03-2019
josephkkassab@gmail.com

- AD plant treats up to 400 t mechanically sorted organic waste (incl. paper, solid state AD, thermophilic) that is collected from various villages and towns nearby and including Saida
- Produced biogas is cleaned and feeds two CHP units which generates electricity and heat that covers energy demand of the whole treatment plant (incl. sorting, AD operation, plastic recycling)
  → compost is used as soil additive for trees and parks
- Points out the difficulties of keeping the added volumes stable in order to maintain the retention time which is important for efficient operation
- Sees AD technology as a good solution if waste quantities allow for larger biogas yields (ideally sorted at source, hence no mechanical application necessary)
- Also operates a sewage water treatment plant in Bkassine, where source-sorted organic waste from households is currently treated
→ operates under psychrophilic conditions, temperature level is kept stable by using the formed biogas for heating

Marc Aoun – entrepreneur Compost Baladi SAL

Wet digestion makes sense if waste is already wet (e.g. slurry, sewage water, whey from cheese making), because then you have to treat the waste water anyway (at least you should for environmental reasons)
→ accordingly if you want to do it properly with the treatment of the waste water you are adding an process step
- Dry digestion of food waste is more suitable, because end product and input is in solid state and hence easier to handle
→ can be made modular in order to treat waste more frequently (continuous, e.g. daily)
- If biogas production is supposed to take place somewhere, you need end use (demand and application) for both biogas and digestate
- Advice: try to find big point sources of organic waste (i.e. vinery, restaurants)
→ business model: unit run by the vinery → committed residents can contribute with their household waste if they are willing
→ ‘would you be willing to pay 10 USD a day for collection services of your source-sorted organic waste?’
- Trust of people in the point of sorting their waste is very important (‘why does my effort in sorting at source makes sense?’)
→ ambitious and convinced local authorities (e.g. mayor) can make a big impact on how waste is handled on a municipal level

Carmen Haddad – researcher at Agric. Research Institute of the Lebanese University in Ghazir

Interested in project outcomes
- Willing to support in the form of any contacts, data for Ghazir
- Use manure of farm animals to set-up experiments of fertilizer from fermentation process
- Work with and promote GAP certificate for ‘clean and environmentally friendly’ farming practices
- Wants to introduce me to chief researcher so I get help also from him
→ might even be interested in setting up a small-scale digester for experiments

Tarek Sakr – Vine maker at Vinery Château Musar

- Produces substantial amounts of organic waste (fermented dryish grape matter) during the vine-making process seasonally between August and October
→ accounts for 100 tons, which is used as soil additive in the vineyards in Békaa
- The waste is too effective as a fertilizer to be substituted by liquid digestate, even though vineyards are organically cultivated
- Seems curious about biogas technology
- Would be willing to ‘donate’ some of the organic waste he produces to local biogas production unit (even for free, as he would save transportation expenses from Ghazir to Békaa)
→ however, this would come in large quantities (one or several tonnes) and only seasonally
- Doubts the acceptance of small-scale private application by Lebanese people
→ might make more sense if it’s for a public or common purpose, initiated by the municipality (e.g. applied in a public school)
- Practical challenges of local biogas production associated with operation and maintenance duties (clear distribution of responsibilities) and handling of the biogas.

**Louis - Food market ets. Louis Zeenny & Fils**

- gives approximately half of the daily market refuse (fruits and vegetables) to the chickens, but has no further use for the other half
  → would be willing to give it for local biogas production in Ghazir
- keeps daily records of the market refuse
  → makes it easy to quantify

**Lina Azar – researcher at Agric. Research Institute of the Lebanese University in Ghazir**

- basic salary of an employee at a public institution like the Agric. Research Institute of the Lebanese University in Ghazir corresponds to 450 USD a month
  → 35 hours per week
  → assuming 4 weeks in a month this corresponds to a wage of 3.2 USD per hour
  → in private sectors basic salary is about double
## B. Price list Set-up components

<table>
<thead>
<tr>
<th>#</th>
<th>Component</th>
<th>Dimension/ Properties</th>
<th>Nr.</th>
<th>Price in shops</th>
<th>Availability and source</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Self-made digester (Water tank)</td>
<td>2,000 dm³</td>
<td>1</td>
<td>150 USD</td>
<td>Classica Sanitary Shop, Jbeil</td>
</tr>
<tr>
<td>2</td>
<td>Storage tank for liquid digestate</td>
<td>1,000 dm³</td>
<td>1</td>
<td>75 USD</td>
<td>Classica Sanitary Shop, Jbeil</td>
</tr>
<tr>
<td>3</td>
<td>Storage tank for water</td>
<td>1,000 dm³</td>
<td>1</td>
<td>75 USD</td>
<td>Classica Sanitary Shop, Jbeil</td>
</tr>
<tr>
<td>4</td>
<td>Hoses (gas and water)</td>
<td>15 m</td>
<td>-</td>
<td>15 USD</td>
<td>Classica Sanitary Shop, Jbeil; Chidiac Plastic Systems, Jbeil</td>
</tr>
<tr>
<td>5</td>
<td>Fittings and valves</td>
<td>-</td>
<td>5</td>
<td>20 USD</td>
<td>Classica Sanitary Shop, Jbeil; Chidiac Plastic Systems, Jbeil</td>
</tr>
<tr>
<td>6</td>
<td>Biogas compressor with storage tank</td>
<td>8 bar, 50 dm³</td>
<td>1</td>
<td>200 USD</td>
<td>Zaarour Trading, Jbeil</td>
</tr>
<tr>
<td>7</td>
<td>Desulphurization unit</td>
<td>-</td>
<td>1</td>
<td>15 USD</td>
<td>Abroad (Alibaba, 2019a)</td>
</tr>
<tr>
<td>8</td>
<td>Gas stove</td>
<td>-</td>
<td>1</td>
<td>10 - 20 USD</td>
<td>Maroun Center, Jbeil</td>
</tr>
<tr>
<td>9</td>
<td>Feedstock treatment pot</td>
<td>50 dm³</td>
<td>1</td>
<td>30 USD</td>
<td>Jbeil Supermarket, Jbeil</td>
</tr>
<tr>
<td>10</td>
<td>Low pressure biogas storage (rubber bag)</td>
<td>1000 dm³</td>
<td>1</td>
<td>20 USD</td>
<td>Abroad (Alibaba, 2019b)</td>
</tr>
<tr>
<td></td>
<td>Additional items for assembling (glue, silicon to seal cracks) and adding feedstock, estimated</td>
<td></td>
<td></td>
<td>50 USD</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>Storage room for collected organic waste (water tank)</td>
<td>1,000 dm³</td>
<td>1</td>
<td>75 USD</td>
<td>Classica Sanitary Shop, Jbeil</td>
</tr>
</tbody>
</table>

**SUM**  745 USD
### Water tanks

<table>
<thead>
<tr>
<th></th>
<th>Available at</th>
</tr>
</thead>
<tbody>
<tr>
<td>1a:</td>
<td>Water storage tank 1,000 dm³ 75 USD</td>
</tr>
<tr>
<td>1b:</td>
<td>Water storage tank 2,000 dm³ 150 USD</td>
</tr>
</tbody>
</table>

### Hoses

<table>
<thead>
<tr>
<th></th>
<th>Available at</th>
</tr>
</thead>
<tbody>
<tr>
<td>4a:</td>
<td>Irrigation hose 10 m 1 USD/m</td>
</tr>
<tr>
<td>4b:</td>
<td>Gas hose 5 m 0.5 - 2 USD/m</td>
</tr>
</tbody>
</table>
### Fittings and valves

<table>
<thead>
<tr>
<th></th>
<th>Item</th>
<th>Price</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>5a</td>
<td>Fittings</td>
<td>0.5 - 2 USD</td>
<td>Classica Sanitary Shop, Jbeil</td>
</tr>
<tr>
<td>5b</td>
<td>Metal valve</td>
<td>8 USD</td>
<td>Classica Sanitary Shop, Jbeil</td>
</tr>
<tr>
<td>5c</td>
<td>Plastic valve</td>
<td>0.6 USD</td>
<td>Chidiac Plastic Systems, Jbeil</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>George Nasr, Jbeil</td>
</tr>
</tbody>
</table>

### Compressor with storage tank

<table>
<thead>
<tr>
<th></th>
<th>Item</th>
<th>Price</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>Air compressor with 50 dm³ storage tank</td>
<td>200 USD</td>
<td>Zaourer Trading, Jbeil</td>
</tr>
</tbody>
</table>

### Gas stove

<table>
<thead>
<tr>
<th></th>
<th>Item</th>
<th>Price</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td></td>
<td>10 – 20 USD</td>
<td>Maroun Center, Jbeil</td>
</tr>
</tbody>
</table>

### Feedstock treatment pot

<table>
<thead>
<tr>
<th></th>
<th>Item</th>
<th>Capacity</th>
<th>Price</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>9</td>
<td>Steel cooking pot</td>
<td>50 dm³</td>
<td>50 USD</td>
<td>Jbeil Supermarket, Jbeil</td>
</tr>
</tbody>
</table>
C. Calculations

C.1 Biogas yields, LPG replacement and mass loss

Daily biogas yields from daily quantities of organic waste 3 kg:

\[ m_{OW} = 3 \text{ kg} \]
\[ V_{BG} = m_{OW} \times 11.6 \frac{dm_{BG}}{kg_{OW}} = 3 \text{ kg}_{OW} \times 114.6 \frac{dm_{BG}}{kg_{OW}} \]
\[ = 343.8 \text{ dm}^3 \] (E 3.1)

Weekly LPG replacement through daily biogas yields on seven days a week:

\[ V_{LPG} = V_{BG} \times \frac{1}{1.350} \frac{dm_{LPG}}{dm_{BG}} \times 7 = 343.8 \text{ dm}^3 \times \frac{1}{1.350} \frac{dm_{LPG}}{dm_{BG}} \times 7 \]
\[ = 1.8 \text{ dm}^3_{LPG} \] (E 3.7)

Weekly savings through LPG replacement with biogas yields

\[ S_{add} = p_{LPG} \times V_{LPG} = 11 \frac{USD}{16.5 \text{ dm}^3_{LPG}} \times 1.8 \text{ dm}^3_{LPG} \]
\[ = 1.2 \text{ USD} \] (E 3.6)

Weekly mass loss assuming full biogas withdrawal on seven days a week:

\[ m_{BG} = V_{BG} \times \frac{1.2 \text{ kg}}{m^3} \times 7 = 343.8 \text{ dm}^3 \times \frac{1.2 \text{ kg}}{1,000 \text{ dm}^3} \times 7 \]
\[ = 2.9 \text{ kg} \] (E 3.10)

Daily biogas yields from daily quantities of organic waste 14.3 kg:

\[ m_{OW} = 14.3 \text{ kg} \]
\[ V_{BG} = m_{OW} \times 114.6 \frac{dm_{BG}}{kg_{OW}} = 14.3 \text{ kg}_{OW} \times 114.6 \frac{dm_{BG}}{kg_{OW}} \]
\[ = 1,638.8 \text{ dm}^3 \] (E 3.1)

Weekly LPG replacement through biogas yields on seven days a week:

\[ V_{LPG} = V_{BG} \times \frac{1}{1.350} \frac{dm_{LPG}}{dm_{BG}} \times 7 = 1,638.8 \text{ dm}^3 \times \frac{1}{1.350} \frac{dm_{LPG}}{dm_{BG}} \times 7 \]
\[ = 8.5 \text{ dm}^3_{LPG} \] (E 3.7)

Weekly savings through LPG replacement with biogas yields

\[ S_{add} = p_{LPG} \times V_{LPG} = 11 \frac{USD}{16.5 \text{ dm}^3_{LPG}} \times 8.5 \text{ dm}^3_{LPG} \]
\[ = 5.7 \text{ USD} \] (E 3.6)

Weekly mass loss assuming full biogas withdrawal on seven days a week:

\[ m_{BG} = V_{BG} \times \frac{1.2 \text{ kg}}{m^3} \times 7 = 1,638.8 \text{ dm}^3 \times \frac{1.2 \text{ kg}}{1,000 \text{ dm}^3} \times 7 \]
\[ = 13.8 \text{ kg} \] (E 3.10)
C.2 Determining digester sizes

It is assumed that 1 kg of solid organic waste corresponds to a volume of 1 dm³ (Vögeli et al., 2014). Accordingly, volumes of solid organic waste \( V_{OW} \) and volumes of water for feedstock dilution \( V_W \) are equal when the ratio is 1, as applied at the site in Bkassine village (Appendix A.3).

Hydraulic retention time \((RT)\): 45 days

Ratio added water to added amount of organic waste \( (V_W/V_{OW}): 1 \)

\[
V_{OW} = m_{OW} \times \frac{1}{kg_{OW}} = V_W
\]

\[
V_D = \frac{RT \times (V_{OW} + V_W)}{0.75} = \frac{45 \times (m_{OW} + \frac{1}{kg_{OW}})}{0.75} \quad (E\ 3.11)
\]

<table>
<thead>
<tr>
<th>Amounts of solid organic waste added daily ( m_{OW} ) [kg]</th>
<th>Digester size ( V_D ) [dm³]</th>
<th>Daily withdrawal of digestate ( V_{LD} ) [dm³]</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>360</td>
<td>6</td>
</tr>
<tr>
<td>4</td>
<td>480</td>
<td>8</td>
</tr>
<tr>
<td>5</td>
<td>600</td>
<td>10</td>
</tr>
<tr>
<td>6</td>
<td>720</td>
<td>12</td>
</tr>
<tr>
<td>7</td>
<td>840</td>
<td>14</td>
</tr>
<tr>
<td>8</td>
<td>960</td>
<td>16</td>
</tr>
<tr>
<td>9</td>
<td>1,080</td>
<td>18</td>
</tr>
<tr>
<td>10</td>
<td>1,200</td>
<td>20</td>
</tr>
<tr>
<td>11</td>
<td>1,320</td>
<td>22</td>
</tr>
<tr>
<td>12</td>
<td>1,440</td>
<td>24</td>
</tr>
<tr>
<td>13</td>
<td>1,560</td>
<td>26</td>
</tr>
<tr>
<td>14</td>
<td>1,680</td>
<td>28</td>
</tr>
<tr>
<td>15</td>
<td>1,800</td>
<td>30</td>
</tr>
<tr>
<td>16</td>
<td>1,920</td>
<td>32</td>
</tr>
<tr>
<td>17</td>
<td>2,040</td>
<td>34</td>
</tr>
</tbody>
</table>

For a weekly digestate withdrawal of 200 dm³, daily added organic waste amounts correspond to about 14,3 kg, assuming constant digester feeding and digestate withdrawal on 7 days in a week. The digester size in that case corresponds to:

\[
V_D = \frac{RT \times (V_{OW} + V_W)}{0.75} = \frac{45 \times (14.3 \times kg_{OW} + \frac{1}{kg_{OW}})}{0.75} \quad (E\ 3.11)
\]

Mass losses assuming full biogas withdrawal correspond to 13,8 kg weekly, which can be compensated by additional water input of 13,8 dm³ once a week.
C.3 Cost estimation

\[
Payback\ period\ (PP) = \frac{Investment\ required}{Annual\ cash\ flow} = \frac{SUC + CSW}{R - OM}
\]  
(E 3.3)

The price list for the set-up components can be found in Appendix B.

\[
SUC = \sum_{i=1}^{n} \text{component} = 745\ USD
\]  
(E 3.4)

Costs for construction, installation and site works are estimated to require three working days with 8 working hours per day \((n_{CSW})\) Labor wages \((w_{CSW})\) correspond to 3.2 USD per hour (Lina Azar, 2019, see Appendix A.5).

\[
CSW = n_{CSW} \times w_{CSW} = 24\ hours \times 3.2\ \text{USD/hour} = 76.8\ USD
\]  
(E 3.5)

Weekly revenues from the sale of the liquid digestate assume a total of 200 dm\(^3\) sold to the local farmers. Depending on the price per liter, different revenues are expected:

\[
S_{ld} = p_{ld} \times V_{ld} = p_{ld} \times 200\ dm^3
\]  
(E 3.6)

<table>
<thead>
<tr>
<th>Price for liquid digestate (p_{ld}) [USD/dm(^3)]</th>
<th>Weekly revenues (S_{ld}) [USD]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>20</td>
</tr>
<tr>
<td>0.5</td>
<td>100</td>
</tr>
<tr>
<td>1</td>
<td>200</td>
</tr>
<tr>
<td>2</td>
<td>400</td>
</tr>
</tbody>
</table>

Weekly savings of LPG assuming full use of biogas for feedstock treatment without additional energy expenditures:

\[
S_{add} = p_{LPG} \times V_{LPG} = \frac{11\ USD}{16.5\ dm^3_{LPG}} \times 8.5\ dm^3_{LPG} = 5.7\ USD
\]  
(E 3.7)

Annually revenues and savings assuming 52 weeks in a year and a price of 1 USD per dm\(^3\) of liquid digestate:

\[
R = (S_{ld} + S_{add}) \times 52
= \left(1\ \text{USD/dm}^3 \times 200\ dm^3 + 5.7\ USD\right) \times 52
= 10,696\ USD
\]  
(E 3.9)

Weekly labor time for facility operation and waste collection \((n_O)\) are estimated to account for 11 hours. Labor wages \((w_{om})\) correspond to 3.2 USD per hour (Appendix A.5). Expenditures for water \((E_W)\) account for 0.1 USD per dm\(^3\) and corresponds to 11.38 USD per week, assuming 113.8 dm\(^3\) of weekly water demand including mass loss compensation. Power demand by the compressor is estimated to be 5 kWh per week, which corresponds to weekly costs of 0.75 USD \((E_{el})\) assuming an electricity price per kWh of 0.15 USD. Weekly fuel costs \((E_F)\) for transportation of waste are estimated to be 1.5 USD, assuming fuel consumption of 1 liter for the weekly tour. Site operation is assumed to take place all year round assuming 52 weeks in a year. Additional working time for regular maintenance checks and monitoring is estimated to account for 3 hours per month \((n_M)\). Every two months samples of the liquid digestate are sent to a laboratory for analyses of nutrient content and contamination level. 25 USD is
charged for each test (Appendix A.4) and hence annual testing costs account for 300 USD in total (LAB). Replacement of set-up components are estimated to be necessary

- every three months for the desulfurization unit, annual expenses $SUC_7 = 4 \times 15 \text{ USD}$
- every two years for hoses, valves and fittings, an. exp. $SUC_{4,5} = 0.5 \times (15 \text{ USD} + 20 \text{ USD})$
- every two years for gas stove and feedstock pot, an. exp. $SUC_{8,9} = 0.5 \times (20 \text{ USD} + 50 \text{ USD})$
- every five years for gas compressor and storage tank, an. exp. $SUC_6 = 0.2 \times 200 \text{ USD}$

Tanks for water and liquid digestate, as well as the digester are expected to last for 10 years which is at the same time the expected life span of the site.

Accordingly, annual costs for operation and maintenance account for:

$$OM = n \omega \omega m + E_E + E_W + E_{E_l} + E_F + n_M \omega m + LAB + \sum SUC_i$$

$$= \left(11 \text{ hours} \times 3.2 \frac{\text{USD}}{\text{hour}} + 11.38 \text{ USD} + 0.75 \text{ USD} + 1.5 \text{ USD}\right) \times 52 +$$

$$= 3,107 \text{ USD}$$  

(E 3.9)

$$\text{Payback period } (PP) = \frac{\text{Investment required}}{\text{Annual cash flow}} = \frac{SUC + CSW}{R - OM} = \frac{745 \text{ USD} + 76.8 \text{ USD}}{10,696 \text{ USD/year}} \times 3.107 \text{ USD/year}$$

$$= 0.11 \text{ years} = 1.3 \text{ months}$$  

(E 3.3)

<table>
<thead>
<tr>
<th>Parameter changed</th>
<th>Payback period (PP)</th>
<th>Revenues (R) [USD]</th>
<th>Cash flow (R-OM) [USD]</th>
</tr>
</thead>
<tbody>
<tr>
<td>None (base line)</td>
<td>1.3 months</td>
<td>10,695</td>
<td>7,588</td>
</tr>
<tr>
<td>Deployment for 26 weeks a year</td>
<td>2.8 months</td>
<td>5,347</td>
<td>3,510*</td>
</tr>
<tr>
<td>Price for liquid digestate 0.5 USD per dm$^3$</td>
<td>4.1 months</td>
<td>5,495</td>
<td>2,388</td>
</tr>
<tr>
<td>LPG savings not considered</td>
<td>1.4 months</td>
<td>10,400</td>
<td>7,293</td>
</tr>
<tr>
<td>Deployment for 26 weeks a year, price for liquid digestate 0.5 USD per dm$^3$, LPG savings not considered</td>
<td>12.9 months</td>
<td>2,600</td>
<td>763*</td>
</tr>
</tbody>
</table>

* Assuming that replacement rates for set-up components, as well as number of laboratory tests and maintenance labor time remain as in the baseline scenario, however, operational labor time is reduced by 50 %.
C.4 Required biogas volumes for feedstock heat treatment

Calculations are based on the specific heat capacity of the substrate \(c_{\text{Sub}}\), the temperature level gradient \(\Delta T\), substrate mass subject to heat treatment \(m_{\text{Sub}}\), energy content of the fuel, i.e. biogas \(E_{BG}\) and energy efficiency of the gas stove \(\eta_{GS}\).

Required energy to heat a mass from one temperature level to another is calculated as follows (Deublein and Steinhauser, 2011):

\[
E_{\text{Treat}} = c_{\text{Sub}} \times \Delta T \times m_{\text{Sub}}
\]  

\((E\ C.4.1)\)

Following figures are fundamental for the calculation that follows:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Reference/justification</th>
</tr>
</thead>
<tbody>
<tr>
<td>(c_{\text{Sub}})</td>
<td>4.2 kJ/(kgK)</td>
<td>Deublein and Steinhauser, 2011</td>
</tr>
<tr>
<td>(\Delta T)</td>
<td>50 K</td>
<td>Treatment of the feedstock to remove pathogens for safe application is achieved by heating up the feedstock to 70°C (Khan and Nordberg, 2019; Vögeli et al, 2014, Seadi and Lukehorst, 2012). Assuming a starting temperature level of 20 °C, the temperature gradient then accounts for 50 K.</td>
</tr>
<tr>
<td>(m_{\text{Sub}})</td>
<td>30 kg</td>
<td>Daily added feedstock mass accounts for roughly 30 kg, assuming a ratio of organic waste to water of 1, as well as feedstock density of 1 kg/dm(^3) (Appendix C.1).</td>
</tr>
</tbody>
</table>

Required energy in the form of heat to treat daily amounts of added feedstock:

\[
E_{\text{Treat}} = \frac{4.2\ \text{kJ}}{\text{kg} \cdot \text{K}} \times 50\ \text{K} \times 30\ \text{kg}
\]

\(= 6,300\ \text{kJ}\)

\((E\ C.4.1)\)

Required volumes of biogas to daily treat the feedstock, assuming an energy content of the biogas \(E_{BG}\) of 21.6 kJ/dm\(^3\) and a gas stove efficiency \(\eta_{GS}\) of 40 % (Ferrer et al., 2011):

\[
V_{BG} = \frac{E_{\text{Treat}}}{E_{BG}} \times \frac{1}{\eta_{GS}} = \frac{6,300\ \text{kJ}}{21.6\ \text{kJ/dm}^3} \times \frac{1}{0.4}
\]

\(= 729.2\ \text{dm}^3\)

\((E\ C.4.2)\)

Repeating the calculation steps for the example of heating one liter of water from 20 °C to boiling temperature (100 °C), results for required biogas volumes are slightly higher as reported consumption rates in cases by Vögeli et al., 2014. Accordingly, theoretical assessment of biogas requirements for feedstock treatment is considered to be confirmed by practical studies.

According to Seadi and Lukehorst (2012), the temperature level of the feedstock, i.e. 70 °C should be kept stable for one hour, in order to effectively remove pathogens for safe application of the liquid digestate in agricultural production. Considering biogas consumption rates of conventional cooking stoves (Sub-Section 4.1.2), as well as daily biogas yields of 1,639 dm\(^3\) in the proposed production unit (Appendix C.1), daily treatment of the feedstock by heating it up to 70 °C is expected to be feasible without additional energy sources. Drawing on limitations of the prediction of practically achieved biogas yields (Sub-Section 5.1.1), only real-life execution will show how daily biogas demand relates to production rates in the proposed application.
D. Fertilizer comparison

<table>
<thead>
<tr>
<th>Medium</th>
<th>Total nitrogen (N)</th>
<th>Total phosphorus (P)</th>
<th>Total potassium (K)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Digestate</td>
<td>3.1-14.0 % DM</td>
<td>0.2-3.5 % DM</td>
<td>1.9-4.3 % DM</td>
<td>Nkoa, 2014</td>
</tr>
<tr>
<td></td>
<td>0.12-1.5 % FM</td>
<td>0.04-0.26 % FM</td>
<td>0.12-1.15 % FM</td>
<td></td>
</tr>
<tr>
<td>Digestate</td>
<td>0.3-0.6 % FM</td>
<td>0.01-0.03 % FM</td>
<td>0.19-0.32 % FM</td>
<td>Tampio et al., 2016</td>
</tr>
<tr>
<td>Conventional growth regulator</td>
<td>2.8 % DM</td>
<td>0.24 % DM</td>
<td>0.03 % DM</td>
<td>Belneftesorb, 2019</td>
</tr>
</tbody>
</table>

Manufacturer: CJSC ‘Belneftesorb’, Republic of Belarus

http://belneftesorb.by/

Price of the shown product, as shown on price tag on the lid: 8,000 LBP or 5.3 USD, considering the fixed currency exchange rate in Lebanon (CIA, 2019).
E. Local acceptance

E.1 Questionnaires

Attached are the English and the translated version in Arabic.
1) How important are the following aspects of energy supply (e.g. electricity, gas for heating or cooking) to you?

Please weigh each aspect between (1) least important and (10) most important. Feel free to add and weigh further aspects that are not listed.

( ) decentralized energy production ( ) low price
( ) environmentally friendly ( ) no interruptions of the supply
( ) other (pls. specify): ……………… ( ) other (pls. specify): ………………

__________________________________________________________________________________

2) Biofuels, solar, wind and hydropower are often discussed as alternatives to conventional forms of energy like natural gas, coal or diesel. Such alternatives should play an important role for the energy supply in Ghazir.

Please mark your answer with a cross in the box.

☐ I agree  ☐ I do not agree  ☐ I don’t know

__________________________________________________________________________________

3) Do you see any potential value in the organic waste (kitchen waste, food leftovers) that is produced in your household?

Please mark your answer with a cross in the box.

☐ No  ☐ Yes  ☐ I don’t know

If yes, what kind of value?
……………………………………………………………………………………………………
……………………………………………………………………………………………………

__________________________________________________________________________________

4) Natural decomposition of organic waste (kitchen waste, food leftovers) leads to the formation of a combustible gas, known as biogas. If effectively applied, the biogas can be used for cooking, as well as for heat and power generation. What is left after the decomposition process can be used as a fertilizer in agriculture.

Would you rather oppose or support biogas production from organic waste in Ghazir?

Please mark your answer with a cross in the box.

☐ Oppose  ☐ Support  ☐ I don’t know

Why?
……………………………………………………………………………………………………
……………………………………………………………………………………………………

__________________________________________________________________________________

5) Would you be willing to collect the organic waste in your household in a separate bin in order to support biogas production in Ghazir?

Please mark your answer with a cross in the box.

☐ Yes  ☐ No  ☐ I don’t know

84
6) Have a look at the map. Do you live in this part of Ghazir?

*Please mark your answer with a cross in the box.*

☐ Yes  ☐ No

If yes, please indicate the area with a loop or cross.
ما هي بالنسبة لك أهمية النواحي التالية لتوريد الطاقة (مثلًا: الكهرباء، الغاز للتدفئة أو الطبخ)؟

لطفا تقييم كل ناحية بين (1) الأقل أهمية و (10) الأكثر أهمية. كليك الحرية في إضافة وتقدير نواحي أخرى غير موجودة.

(  ) نتاج طاقة مركزية
(  ) عدم توقف التوريد
(  ) صديق للبيئة
(  ) غاز منخفض
(  ) غير ذلك (لطفا حدّد):

(  ) إنتاج طاقة لامركزية
(  ) ثمن منخفض
(  ) صديق للبيئة
(  ) عدم توقف التوريد
(  ) غير ذلك (لطفا حدّد):

(Answer in English appreciated!)

(2) تطرح غالبًا الوقود الحيوي، والطاقة الشمسية والهوائيّة، والطاقة المائية، بمثابة بدائل عن أشكال الطاقة التقليدية مثل الغاز الطبيعي والفحم أو الديزل. هل يجب أن تلعب مثل هذه البدائل دورًا مهمًا لتوريد الطاقة في غزير؟

لطفا أشار إلى جوابك بعلامة صليب في المربع المناسب.

(  ) أوافق
(  ) لا أوافق
(  ) لا أعرف

(3) هل ترى أي قيمة محتملة في النفايات العضوية (نفايات المطبخ وباقي الأطعمة) التي تنتج عن منزلك؟

لطفا أشار إلى جوابك بعلامة صليب في المربع المناسب.

(  ) نعم
(  ) لا
(  ) لا أعرف

في حالة الإجابة بنعم، ما هو نوع القيمة؟

...............................................................................................................................

...............................................................................................................................

(Answer in English appreciated!)

(4) يؤدي التحلل الطبيعي للنفايات العضوية (نفايات المطبخ وباقي الأطعمة) إلى تكون غاز يعرف بإسم البيوغاز. في حال استخدامه بفعالية، يمكن استعمال البيوغاز للتدفئة وأيضًا لإنتاج الطاقة. وما يبقى بعد عملية التحلل يمكن استخدامه بمثابة سماد للزراعة. هل تفضل معارضًا أو دعم إنتاج البيوغاز من النفايات العضوية في غزير؟

لطفا أشار إلى جوابك بعلامة صليب في المربع المناسب.

(  ) أعارض
(  ) أدعم
(  ) لا أعرف

لماذا؟

...............................................................................................................................

...............................................................................................................................

(Answer in English appreciated!)

(5) هل انت على استعداد لجمع النفايات العضوية في منزلك في صندوق منفصل من أجل دعم إنتاج البيوغاز في غزير؟

لطفا أشار إلى جوابك بعلامة صليب في المربع المناسب.

(  ) نعم
(  ) لا
(  ) لا أعرف

(Answer in English appreciated!)
6) الق نظرة على الخريطة. هل تعيش في هذا الجزء من غزير؟
لطفاً أشر إلى جوابك بعلامة صليب في المربع المناسب.

نعم □ لا □

في حال الإيجاب، أشر إلى المنطقة بعقدة أو بصليب.
E.2 Results of the questionnaire survey

Aspects of residential energy supply
(79 participating households)

1) How important are the following aspects of energy supply (e.g. electricity, gas for heating or cooking) to you?

Please weigh each aspect between (1) least important and (10) most important.

<table>
<thead>
<tr>
<th>Score</th>
<th>Average</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>No answer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low price</td>
<td>8.4</td>
<td>2</td>
<td>3</td>
<td>0</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>5</td>
<td>11</td>
<td>6</td>
<td>35</td>
<td>12</td>
</tr>
<tr>
<td>decentralized energy production</td>
<td>7.1</td>
<td>0</td>
<td>0</td>
<td>8</td>
<td>0</td>
<td>12</td>
<td>0</td>
<td>10</td>
<td>3</td>
<td>16</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>no interruptions of supply</td>
<td>7.4</td>
<td>2</td>
<td>3</td>
<td>1</td>
<td>3</td>
<td>10</td>
<td>2</td>
<td>2</td>
<td>8</td>
<td>4</td>
<td>23</td>
<td>22</td>
</tr>
<tr>
<td>environmentally friendly</td>
<td>8.9</td>
<td>4</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>3</td>
<td>3</td>
<td>7</td>
<td>46</td>
<td>13</td>
<td></td>
</tr>
</tbody>
</table>

Renewable energy in Ghazir
(79 participating households)

2) Biofuels, solar, wind and hydropower are often discussed as alternatives to conventional forms of energy like natural gas, coal or diesel. Such alternatives should play an important role for the energy supply in Ghazir.

<table>
<thead>
<tr>
<th>Answer</th>
<th>Nr. respondents</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Agree</td>
<td>71</td>
<td>89.9%</td>
</tr>
<tr>
<td>Disagree</td>
<td>2</td>
<td>2.5%</td>
</tr>
<tr>
<td>Don't know</td>
<td>5</td>
<td>6.3%</td>
</tr>
<tr>
<td>No answer</td>
<td>1</td>
<td>1.3%</td>
</tr>
</tbody>
</table>

Perception of organic household waste
(79 participating households)

3) Do you see any potential value in the organic waste (kitchen waste, food leftovers) that is produced in your household?

<table>
<thead>
<tr>
<th>Answer</th>
<th>Nr. respondents</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>No</td>
<td>7</td>
<td>8.9%</td>
</tr>
<tr>
<td>Yes</td>
<td>58</td>
<td>73.4%</td>
</tr>
<tr>
<td>Don't know</td>
<td>12</td>
<td>15.2%</td>
</tr>
<tr>
<td>No answer</td>
<td>2</td>
<td>2.5%</td>
</tr>
</tbody>
</table>
Attitude towards local biogas production in Ghazir
(123 participating households)

4) Natural decomposition of organic waste (kitchen waste, food leftovers) leads to the formation of a combustible gas, known as biogas. If effectively applied, the biogas can be used for cooking, as well as for heat and power generation. What is left after the decomposition process can be used as a fertilizer in agriculture.

Would you rather oppose or support biogas production from organic waste in Ghazir?

<table>
<thead>
<tr>
<th>Answer</th>
<th>Nr. respondents</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oppose</td>
<td>10</td>
<td>8.1</td>
</tr>
<tr>
<td>Support</td>
<td>106</td>
<td>86.2</td>
</tr>
<tr>
<td>Don't know</td>
<td>6</td>
<td>4.9</td>
</tr>
<tr>
<td>No answer</td>
<td>1</td>
<td>0.8</td>
</tr>
</tbody>
</table>

Willingness to sort organic household waste for local biogas production at source
(123 participating households)

5) Would you be willing to collect the organic waste in your household in a separate bin in order to support biogas production in Ghazir?

<table>
<thead>
<tr>
<th>Answer</th>
<th>Nr. respondents</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yes</td>
<td>106</td>
<td>86.2</td>
</tr>
<tr>
<td>No</td>
<td>13</td>
<td>10.6</td>
</tr>
<tr>
<td>Don't know</td>
<td>4</td>
<td>3.3</td>
</tr>
<tr>
<td>No answer</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Identifying household location on a map of Ghazir village

6) Have a look at the map. Do you live in this part of Ghazir? If yes, please indicate the area with a loop or cross.

59 households indicated the location of the household on the map.
F. Records of waste sampling

F.1 Schools

DLC school - École Saint François Seours de la Croix

GP school - l’École d’officielle Ghazir (Public school in Ghazir)

<table>
<thead>
<tr>
<th>Date</th>
<th>Organic waste [kg]</th>
<th>during # days</th>
<th>averaged</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>29.3</td>
<td>0.26</td>
<td>1</td>
<td>0.26</td>
<td>DLC school</td>
</tr>
<tr>
<td>3.4</td>
<td>0.84</td>
<td>3</td>
<td>0.28</td>
<td>DLC school</td>
</tr>
<tr>
<td>3.4</td>
<td>0.07</td>
<td>1</td>
<td>0.07</td>
<td>GP school</td>
</tr>
<tr>
<td>5.4</td>
<td>0.63</td>
<td>2</td>
<td>0.32</td>
<td>DLC school</td>
</tr>
<tr>
<td>5.4</td>
<td>0.11</td>
<td>2</td>
<td>0.06</td>
<td>GP school</td>
</tr>
<tr>
<td>10.4</td>
<td>0.89</td>
<td>3</td>
<td>0.30</td>
<td>DLC school</td>
</tr>
<tr>
<td>10.4</td>
<td>0.26</td>
<td>3</td>
<td>0.09</td>
<td>GP school</td>
</tr>
<tr>
<td>12.4</td>
<td>0.43</td>
<td>1</td>
<td>0.43</td>
<td>DLC school</td>
</tr>
<tr>
<td>12.4</td>
<td>0</td>
<td>1</td>
<td>0.00</td>
<td>GP school</td>
</tr>
<tr>
<td>16.4</td>
<td>0.07</td>
<td>2</td>
<td>0.04</td>
<td>GP school</td>
</tr>
<tr>
<td>18.4</td>
<td>1.52</td>
<td>3</td>
<td>0.51</td>
<td>DLC school</td>
</tr>
<tr>
<td>6.5</td>
<td>0.14</td>
<td>2</td>
<td>0.07</td>
<td>GP school</td>
</tr>
<tr>
<td>6.5</td>
<td>1.26</td>
<td>3</td>
<td>0.42</td>
<td>DLC school</td>
</tr>
</tbody>
</table>

F.2 Households in Ghazir

<table>
<thead>
<tr>
<th>Date</th>
<th>Organic waste [kg]</th>
<th>during # days</th>
<th>averaged</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>11.4</td>
<td>2</td>
<td>3</td>
<td>0.67</td>
<td>Nassour</td>
</tr>
<tr>
<td>11.4</td>
<td>1.75</td>
<td>1</td>
<td>1.75</td>
<td>Sacca</td>
</tr>
<tr>
<td>12.4</td>
<td>9</td>
<td>2</td>
<td>4.50</td>
<td>Monique</td>
</tr>
<tr>
<td>12.4</td>
<td>4.2</td>
<td>2</td>
<td>2.10</td>
<td>Neighbour Nassour</td>
</tr>
<tr>
<td>12.4</td>
<td>0.43</td>
<td>1</td>
<td>0.43</td>
<td>Nassour</td>
</tr>
<tr>
<td>13.4</td>
<td>4.86</td>
<td>1</td>
<td>4.86</td>
<td>Sacca</td>
</tr>
<tr>
<td>13.4</td>
<td>1.5</td>
<td>1</td>
<td>1.50</td>
<td>Nassour</td>
</tr>
<tr>
<td>13.4</td>
<td>3</td>
<td>1</td>
<td>3.00</td>
<td>Friend Nassour</td>
</tr>
<tr>
<td>13.4</td>
<td>2.8</td>
<td>1</td>
<td>2.80</td>
<td>Neighbour Nassour</td>
</tr>
<tr>
<td>14.4</td>
<td>1.5</td>
<td>1</td>
<td>1.50</td>
<td>Mum Nassour</td>
</tr>
<tr>
<td>15.4</td>
<td>1.89</td>
<td>1</td>
<td>1.89</td>
<td>Sacca</td>
</tr>
<tr>
<td>16.4</td>
<td>4</td>
<td>1</td>
<td>4.00</td>
<td>Nassour</td>
</tr>
<tr>
<td>16.4</td>
<td>2</td>
<td>1</td>
<td>2.00</td>
<td>Neighbour Nassour</td>
</tr>
<tr>
<td>16.4</td>
<td>14</td>
<td>3</td>
<td>4.67</td>
<td>Monique</td>
</tr>
<tr>
<td>16.4</td>
<td>6</td>
<td>1</td>
<td>6.00</td>
<td>Nassour</td>
</tr>
<tr>
<td>16.4</td>
<td>1.7</td>
<td>2</td>
<td>0.85</td>
<td>Neighbour Nassour</td>
</tr>
<tr>
<td>16.4</td>
<td>1</td>
<td>1</td>
<td>1.00</td>
<td>Friend Nassour</td>
</tr>
<tr>
<td>17.4</td>
<td>2.6</td>
<td>1</td>
<td>2.60</td>
<td>Sacca</td>
</tr>
<tr>
<td>18.4</td>
<td>7.7</td>
<td>2</td>
<td>3.85</td>
<td>Monique</td>
</tr>
<tr>
<td>21.4</td>
<td>1.4</td>
<td>1</td>
<td>1.40</td>
<td>Mum Nassour</td>
</tr>
<tr>
<td>Date</td>
<td>Organic waste [kg]</td>
<td>Date</td>
<td>Organic waste [kg]</td>
<td></td>
</tr>
<tr>
<td>-------</td>
<td>--------------------</td>
<td>-------</td>
<td>--------------------</td>
<td></td>
</tr>
<tr>
<td>10.3</td>
<td>6.6</td>
<td>28.3</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>11.3</td>
<td>22</td>
<td>29.3</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>12.3</td>
<td>23</td>
<td>30.3</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>13.3</td>
<td>13</td>
<td>31.3</td>
<td>0</td>
<td></td>
</tr>
</tbody>
</table>

F.3 Market refuse of local food market

ets. Louis Zeenny & fils, Ghazir village
<p>| | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>14.3</td>
<td>1.7</td>
<td>1.4</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>15.3</td>
<td>5</td>
<td>2.4</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>16.3</td>
<td>6</td>
<td>3.4</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>17.3</td>
<td>3.5</td>
<td>4.4</td>
<td>3.5</td>
<td></td>
</tr>
<tr>
<td>18.3</td>
<td>10</td>
<td>5.4</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>19.3</td>
<td>15</td>
<td>6.4</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>20.3</td>
<td>0.8</td>
<td>7.4</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>21.3</td>
<td>3.5</td>
<td>8.4</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>22.3</td>
<td>18</td>
<td>9.4</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>23.3</td>
<td>0.5</td>
<td>10.4</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>24.3</td>
<td>4</td>
<td>11.4</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>25.3</td>
<td>11</td>
<td>12.4</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>26.3</td>
<td>8</td>
<td>13.4</td>
<td>9</td>
<td></td>
</tr>
<tr>
<td>27.3</td>
<td>10</td>
<td></td>
<td></td>
<td><strong>Average 6.05</strong></td>
</tr>
</tbody>
</table>
Study Project: Small-scale biogas production in Ghazir

Marhaba! My name is Sebastian Huber. I am from Germany and during the next couple of weeks I will stay in Lebanon for a study project of my Master Program ‘Sustainable Development’. I want to find out if biogas production from organic waste (e.g. kitchen waste, food leftovers) could work in Ghazir.

In order to make my investigation I need the help of interested residents that are open to change their waste sorting habits for the next 4 weeks.

When organic waste is mixed with water and put into a closed container, after some time a natural fermentation process takes place, during which bacterial activity leads to the formation of methane and carbon dioxide. This gas mix is called biogas and when it is captured it can be used for electricity and heat generation or as a cooking fuel. Another product of this fermentation process is the liquid ‘digestate’, which is rich in nutrients and can be applied like a fertilizer for agricultural production.

Biogas production from organic waste is a way to re-use kitchen waste or food leftovers from a household and provides energy and fertilizer at the same time.

![Biogas unit](image)

Biogas units can look quite differently. It can be a large-scale production plant like in Saida where the organic waste from all households in the city is treated. It can also be a simple system, not much bigger than a large bin (see the picture) which treats small quantities of waste generated by a couple of households on a daily basis. Restaurants can apply it to make use of their kitchen waste and fuel their gas stoves.

What I am asking you, is to throw your organic waste in one separate bin or bag, and let me come by twice a week to have a look and weigh what is inside. If you want I can dispose it for you as well!

And don’t worry! This is just an experiment so after the four weeks you can go back to normal 😊

Please do not hesitate if you have any questions about myself or my study project. You can call me anytime (07425620) or send a message on What’s App (+46702186739).

Shokran!
H. First action plan for field study

- Identify and approach stakeholders (Interviews/questionnaire)
- Analyze organic waste resources
- Analyze local waste management
- Biogas potential calculation
  - Yields
  - Propose plant design
  - Energetic contribution (kWh el./heat)
  - Cooking fuel replacement
  - Mon. Savings

PD Workshop
- Propose business model
  - Substrate chain
  - AD technology
  - Product chain
- Cost calculation and sensitivity analysis