ENERGY from Wastewater Sewage Sludge in Lebanon

2013

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Country Energy Efficiency and Renewable Energy Demonstration Project for the Recovery of Lebanon

Energy from Wastewater Sewage Sludge in Lebanon; 'Transforming a Waste Disposal Problem into an Opportunity'

February 2013

LEBANESE REPUBLIC MINISTRY OF ENERGY AND WATER

UNITED NATIONS DEVELOPMENT GROUP

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This study has been implemented by the Consortium of SQ Consult, Zero Emissions, Amane Energy and ECE Consultants with a contribution on the economics of energy from wastewater treatment plants from Dr. William Mezullo, biogas expert based in the UK. It has been initiated and guided by Mr. Karim Osseiran, Power Generation Advisor to the Ministry of Energy and Water, Lebanon.

Republic of Lebanon
Ministry of Energy and Water
The Minister
January 2013

The "Policy Paper for the Electricity Sector" was launched back in 2010 and the Government of Lebanon approved this national strategy during that same year. Although a large share of the policy paper is dedicated to the upgrade of the electricity sector in terms of conventional energy, one major concern in the policy paper deals with the need to *"ensure a fuel sourcing policy based on diversity and security".*

We firmly believe that a stable energy sector is one that is *diverse* and *secure*. It is within this mindset that the Ministry of Energy and Water is considering all available options for the development of the national energy sector. Our commitment to ensure a stable energy sector goes hand in hand with our intention to develop this sector according to the highest standards of environmental sustainability. Needless to say, the Ministry of Energy and Water is investing all needed efforts to ensure that the 12% of the electricity production in 2020 is based on renewable energy sources.

In this regard, the Ministry of Energy and Water has investigated most types of renewable energy sources available in the country. With the support of the UNDP-CEDRO project, the national wind atlas for Lebanon was published in 2010. The efforts of the CEDRO project are also clear and useful in the development of the national bioenergy strategy for Lebanon, as well as the potential for hydropower and solar energy.

Once more, the successful partnership with UNDP gives birth to a new untapped potential of renewable energy in Lebanon, and that is energy produced from wastewater sludge. This current report has identified five WWTPs that meet the condition to implement at least one sludge Anaerobic Digester, i.e., Sour, Aabde, Sarafand, Saida and Majdal Anjar. An AD unit has already been implemented in Tripoli. Altogether, the total primary energy expected from these plants is estimated at 143,000 MWh, for an **installed electrical power of 5.9 MW.** The sludge Anaerobic Digestion of these WWTPs allows the reduction of greenhouse gas emissions by approximately **20,500 tons of CO_2 equivalent.**

This report also shows that the addition of sludge from small to medium WWTP and co-substrates allows an average **increase in energy production of 70%** compared to the digestion of sludge only, for an **installed electrical power of 11.6 MW.** The total primary energy is estimated at 237,700 MWh. Altogether, these projects allow the reduction of greenhouse gas emissions by approximately **35,000 tons of CO_2 equivalent**.

The energy production of these projects could represent 3% to 4% of the national bioenergy potential identified in the Bioenergy Strategy Plan.

Over the past few years, Lebanon witnessed some impressive developments in energy efficiency and the renewable energy sectors, both at practical and planning levels. We, hereby, reconfirm the commitment of the Ministry of Energy and Water to keep investing all needed efforts to push for this growing momentum in Lebanon towards strengthening and developing the energy sector and finding new ways and opportunities to fight climate change. It is a real pleasure to share this report "Energy from the Waste Water Sludge", hoping that all these strategies come to life very soon. One thing is sure; the Ministry will not spare any occasion to push for the actual realization of these projects.
On behalf of the Ministry of Energy and Water, I would like to thank all those who contributed to the development of the report, hoping that all solutions mentioned in this report will turn into actual national projects very soon.

Gebran Bassil
Minister of Energy and Water
Republic of Lebanon

Ministry of Energy and Water
United Nations Development Programme
Beirut, Lebanon
January 2013

Once more the UNDP-CEDRO project is delivering a study that aims at initiating a new sector with respect to energy generation; that of energy valorization from sewage sludge, with and without co-digestion. Lebanon needs every cost-effective power source it can obtain to close the 1000-1500 MW demand-supply deficit and to diversify its energy sources so to increase the stability and resilience of the power sector. Stemming from the National Bioenergy Strategy of Lebanon, published early in 2012, this current study takes one of the identified streams, that of wastewater treatment, and details how we can successfully combine projects that are required to treat wastewater, yet at the same time are built to take into account energy generation. Assessing seven potential wastewater treatment plants (WWTPs) projects that are either in the design phase or the construction phase by the Council of Development and Reconstruction, approximately 6 MW of power can be established from these WWTPs, doubled if co-digestion is included, where 11.6 MW is achievable with various inputs such as wheat residues, chicken manure, and so forth.

This study is the fruit of the direct cooperation between the CEDRO project and the Ministry of Energy and Water. We remain committed to align our efforts to the objective and policy of the Ministry, so that we, together, pave the way for the achievement of the 12% renewable energy target by 2020."

Robert Watkins
UNDP Resident Representative

EXECUTIVE SUMMARY

The Ministry of Energy and Water (MEW) and the Council for Development and Reconstruction (CDR) are considering investing in energy produced from wastewater sludge through anaerobic digestion (AD). Currently, Lebanon has only a few constructed wastewater treatment plants (WWTPs), however many others are either under construction, under design-phase assessment, or are envisioned to be assessed in the future.

The goal of this study is to undergo a feasibility assessment to identify the WWTPs that meet the conditions to implement AD and elaborate the related technical specifications. None of the WWTPs are operating at this moment. The reality of the sector is that most of the plants that are constructed have yet to be connected to a sewage network, whereas in other cases, the WWTPs have yet to be constructed.

Therefore the scope of the study has been redefined to be as follows:

- To recommend prescriptions for future projects;
- To identify WWTPs where AD is conceivable;
- To define and develop sludge AD and co-digestion scenarios, based on the co- substrates identified during the National Bioenergy Strategy Study;
- To assess the economics involved in selected options.

The report is divided into the following chapters with related description:

- Chapter 1 indicates the methodology used for this study.
- Chapter 2 provides an overview of the different wastewater treatment processes to understand the consequences on sludge quality, energy production and energy consumption.
- Chapter 3 summarizes all the information gathered during the WWTPs data collection as well as their current status.
- Chapter 4 exposes the technology allowing to boost the energy production of a sludge AD and provides the main technical specifications for the dimensioning and the operation of an anaerobic co-digestion plant.
- Chapter 5 presents the guidelines for each future WWTP project, summarized below:

  - For large-scale plants (>200,000 Population Equivalent (PE)), each time a primary treatment is planned, anaerobic digestion with energy valorization must be studied. The possibility to oversize digestion and sludge dewatering to treat additional products (sludge from small plants, industrial and agricultural organic residues) must be evaluated.
  - For medium-scale plants (from 100,000 to 200,000 PE) a solution with primary treatment must be studied to evaluate the economic viability of onsite digestion with energy generation.
  - For small-scale plants, a larger nearby WWTP with onsite digestion must be identified to find a destination for the sludge and improve biogas production.

- Chapter 6 considers select projects for possible implementation. Considering the information gathered, the study identified WWTPs that meet the conditions to implement sludge AD. To increase the renewable energy production of these WWTPs, six co-digestion scenarios with local co-substrates and sludge produced in other nearby WWTPs, have been elaborated. Additionally and based on the Bioenergy Strategy For Lebanon published by CEDRO (2012), co-substrates, such as manure, agricultural residues and agro food industries co-products, have been selected according to the regional production, the estimated availability and allowing the required balanced mixture. Table I below presents the main findings of the select projects.

Project	Recommendation	Output and CO_{2e} related emission reduction
Tripoli	The sludge of the nearby WWTPs of Jbeil (50,000 PE), Batroun (24,000 PE) and Chekka (21,000 PE) is to be transported and treated in the existing anaerobic digester of Tripoli to increase the biogas production. Only a slight modification of the existing facility is required for this addition.	• An increase in energy production of 9.3%, i.e., for an installed electrical power of 3.0 MW converted through co-generation, as follows: o Electricity: 2,051MWh/year o Heat: 2,156 MWh/year • 83% of the WWTP electricity consumption to be self-generated instead of the 75% in the present case of the digestion of Tripoli sludge only; • Greenhouse gas emissions reduction of 9,000 tons of CO2 equivalent per year.
Sour	The sludge from the nearby Tebnine & Chaqra WWTP (100,000 PE) is to be transported and treated in the future anaerobic digester of Sour to increase biogas production. This scenario involves an extension of Sour's sludge anaerobic, which has to be immediately planned before the completion of the Sour WWTP, and land will have to be reserved for this extension now.	• An increase in energy production of 29.4%, i.e. 4,200 MWh of primary energy, for an installed electrical power of 0.90 MW converted through co-generation, as follows: o Electricity: 1,638 MWh/year o Heat: 1,722 MWh/year • 100% of the WWTP electricity consumption to be self-generated instead of 75% in the case of the digestion of Sour sludge only. • Greenhouse gas emissions reduction of 2,700 tons of CO2 equivalent per year.
Aabde	Aabde WWTP is under design, therefore it is suggested to plan anaerobic co-digestion with local co-substrates, instead of a simple sludge AD, and add the sludge produced in the nearby WWTPs of Bakhoun (48,000 PE) and Michmich (68,000 PE), to boost energy production. The co-substrates identified, in the local area, are the following: Wheat residues; chicken manure: two main producers of poultry (Hawa Chicken and Wilco) are located in North Lebanon; cattle manure; Ovine manure; olive oil cake by-products; and agro-food industry by-products.	• An increase in energy production of 167% compared to the sludge digestion initially planned, for an installed electrical power of 1.38 MW. The total primary energy is estimated at 28,233MWh converted through co-generation, as follows: o Electricity: 11,011 MWh per year o Heat: 11,575 MWh per year • 205% of the WWTP electricity consumption can be self-generated instead of 75% in the case of the digestion of Sour sludge only, therefore an opportunity to make use of net metering exists; • Greenhouse gas emissions reduction of 4,180 tons of CO2 equivalent per year.
Sarafand	Sarafand WWTP is under design; therefore it is recommended to plan an anaerobic co-digestion plant, fed with local co-substrates, and sludge produced in the nearby Nabatiyeh (68,000 PE) and Yahmor (35,000 PE) WWTPs, to produce renewable energy and therefore, enable the facility to reduce its energy consumption. The co-substrates identified in the local area are the following: Wheat residues; yellow grease; goat/sheep manure; and agro-food industry by-products.	• An increase in energy production of 41% compared to the digestion of Sarafand only, for an installed electrical power of 1.49 MW. The total primary energy is estimated at 30,560 MWh primary energy, split as follows, depending on the valorization method: o Energy production through co-generation: Electricity: 11,920MWh/year; Heat: 12,530 MWh/year. o Electricity production only: 11,920 MWh/year o Heat production only: 25,980 MWh/year •126% of the WWTP electricity consumption would be self-generated instead of 75% in the case of the digestion of Sour sludge only; again a case for net metering. • Greenhouse gas emissions reduction of 4,500 tons of CO2 equivalent per year.

Saida	Saida WWTP is under design, therefore we suggest planning an anaerobic co-digestion, fed with local co-substrates, and add to it the sludge produced in the nearby WWTP of Ras Nabi Younes (88,000 PE), to produce renewable energy and therefore, enable the facility to reduce its energy consumption. The co-substrates identified, in the local area, are the following: Slaughterhouse waste and grease from Saida and Jezzine slaughterhouses; wheat residues; and olive oil cake by-products.	• An increase in energy production of 56% compared to the digestion of Saida only, for an installed electrical power of 1.70 MW. The total primary energy is estimated at 34,900 MWh primary energy, as follows, depending on the valorization method: o Energy production through co-generation: - Electricity: 13,610 MWh/year; - Heat: 14,300 MWh/year. o Electricity production only: 13,610 MWh/year o Heat production only: 29,660 MWh/year • 120% of the WWTP electricity consumption could be self-generated instead of 75% in the case of the digestion of Sour sludge only; a case for net metering. • Greenhouse gas emissions reduction of 5,160 tons of CO2 equivalent per year.
Majdal Anjar	Majdal Anjar WWTP is under design, therefore we suggest planning an anaerobic co-digestion, fed with local co-substrates, and add the sludge produced in the nearby WWTP of Zahle (100,000 PE), to produce renewable energy and therefore, enable the facility to reduce its energy consumption. The co-substrates identified, in the local area, are the following: Agricultural residues: Barley and wheat residues; liquid and solid manure (cattle, sheep and goat); slaughterhouse waste and grease from Zahle; and agro-food industry by-products.	• An increase in energy production of 100% compared to the digestion of Majdal Anjar only, for an installed electrical power of 1.69 MW. The total primary energy is estimated at 34,766 MWh primary energy, as follows, depending on the valorization method: o Energy production through co-generation: Electricity: 13,560 MWh/year; Heat: 14,250 MWh/year. o Electricity production only: 13,560 MWh/year o Heat production only: 29,550 MWh/year • 156% of the WWTP electricity consumption would be self-generated instead of 75% in the case of the digestion of Sour sludge only; a case for net metering. • Greenhouse gas emissions reduction of 5,160 tons of CO2 equivalent per year.
Bekaa	It is recommended to implement a co-digestion platform to group the wastewater treatment sludge of Baalbek, Laboueh, Tamnine Altahta, the co-products from the main milk processing facility in Lebanon, Libanlait and other available co-products. Libanlait has at least the following co-substrates: Liquid and solid cattle manure and lactoserum. The additional co-substrates identified, in the local area, are the following: Residues from cereals: wheat and barley residues; manure (sheep and goat); and agro-food industry by-products.	• A total primary energy estimate of 29,218 MWh, for an installed electrical power of 1.42 MW, as follows, depending on the valorization method: - Energy production through co-generation: Electricity: 11,395 MWh/ year; Heat: 11,980 MWh/year. - Electricity production only: 11,395 MWh/year - Heat production only: 24,830 MWh/year • Greenhouse gas emissions reduction of 4,300 tons of CO_2 equivalent per year.

Table I. Main recommendations; 7 projects, annual energy output, and equivalent CO_2 savings.

Altogether, the projects listed in Table I allow an average increase in energy production of 70% compared to the digestion of sludge-only scenarios, for a total installed electrical power of 11.6 MW. The total primary energy is estimated at 237,700 MWh, as follows (with a valorization through co-generation engines):

- Electricity: 92,700 MWh/year
- Heat: 97,400 MWh/year

The related greenhouse gas emissions reduction is 35,000 tons of CO_2 equivalent per year, compared to the use of natural gas, a conservative assumption for Lebanon.

Table II summarizes the main findings of the study in terms of energy (heat and/or electricity) output.

	Primary Energy	**Energy production through CHP**	**Electricity production only**	**Heat production only**	**Electrical Power**	
	kWh/year	Electricity MWh/year	Heat MWh/year	MWh/year	MWh/year	MW_{el}
Tripoli Project	61,455,882	23,968	25,197	23,968	52,238	3.00
Sour Project	18,505,290	7,217	7,587	7,217	15,729	0.90
Aabde Project	28,232,775	11,011	11,575	11,011	23,998	1.38
Sarafand Project	30,567,253	11,921	12,533	11,921	25,982	1.49
Saida Project	34,898,904	13,611	14,309	13,611	29,664	1.70
Majdal Anjar Project	34,898,904	13,611	14,309	13,611	29,664	1.70
Bekaa Project	29,218,369	11,395	11,980	11,395	24,836	1.42
TOTAL	237,777,377	92,733	97,489	92,733	202,111	11.59

Table II. Main energy output findings

The energy production of these seven projects could represent 3% to 4% of the national bioenergy potential identified in the Bioenergy Strategy Study for Lebanon (CEDRO, 2012).

- Chapter 7 analyses the economics involved in most of the options listed in Table I (or Table II above). The current industrial electricity prices for Lebanon were used to assess the basic payback of the capital investment from the annual returns (gross will be used for simplicity), and the levelised cost of electricity was estimated, taking into account a 15-year lifetime and an 8% discount rate. The economics are applied to the projects that are earmarked in this study for co-digestion (i.e., Projects 3 – 7). Table III indicates the expected payback period of the initiatives, while Table IV indicates the levelised cost of electricity delivered.

PROJECT	**CAPEX**	**Annual Electricity Generation (kWh)**	**Revenue/year**	**Payback (yrs)**
Project 3 WWTP	€ 5,535,000	5,961,592	€ 344,640	16
Project 3 Co-dig	€ 6,320,530	11,809,720	€ 682,720	9
Project 4 WWTP	€ 7,925,244	8,840,598	€ 511,075	16
Project 4 Co-dig	€ 8,287,734	12,340,056	€ 713,379	12
Project 5 WWTP	€ 9,273,863	10,652,801	€ 615,838	15
Project 5 Co-dig	€ 9,550,153	13,984,145	€ 808,423	12
Project 6 WWTP	€ 7,396,849	8,240,278	€ 476,370	16
Project 6 Co-dig	€ 8,079,675	14,374,669	€ 831,000	10
Project 7 WWTP	€ 3,939,370	3,919,844	€ 226,606	17
Project 7 Co-dig	€ 5,320,316	12,642,687	€ 730,874	7

Table III. Payback period of identified options with and without co-digestion

As can be seen from Table III above, without financial incentives to generate clean renewable energy from AD in Lebanon the payback periods are not favourable if co-digestion is not followed. These payback periods are calculated using gross revenue from the AD plant. Co-digestion is very important to boost the economics of the system. When considering the introduction of feed-in tariffs in Lebanon, energy from WWTP should not be excluded.

Project 3		Project 4		Project 5	
Without Co-digestion	With Co-digestion	Without Co-digestion	With Co-digestion	Without Co-digestion	With Co-digestion
19.7	8.7	16.1	10.6	15.6	10.7

Project 6		Project 7	
Without Co-digestion	With Co-digestion	Without Co-digestion	With Co-digestion
16.2	9.0	7.7	7.1

Table IV. Levelised electricity costs ($c/kWh) from 5 selected WWTPs in Lebanon

Table IV shows that all scenarios are below the current average generation costs of the Lebanese electricity system that range between $c20-30/kWh, depending on international oil prices. Combining co-digestion delivers a much better levelised cost estimate and therefore should be targeted.

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AD	Anaerobic Digestion
BMP	Biochemical Methane Potential
CAL	Calorie
CEDRO	Country Energy Efficiency and Renewable Energy Demonstration Project for the recovery of Lebanon
CDR	Council for Development & Reconstruction
DM	Dry Matter
GHG	Greenhouse Gas
GTZ	Deutsche Gesellschaft für Technische Zusammenarbeit (GTZ) GmbH or German technical cooperation
MEW	Ministry of Energy &Water
NCV	Net Calorific value
OM	Organic Matter
ORP	Oxidation Reduction Potential
PE	Population Equivalent
SS	Suspended Solids
UNDP	United Nations Development Program
VM	Volatile Matter
W	Watt
WW	Wastewater
WWTP	Wastewater Treatment Plant

CONTEXT of the Study

The Ministry of Energy and Water (MEW) and the Council for Development and Reconstruction (CDR) are considering investing in energy produced from wastewater sludge through anaerobic digestion (AD). Currently, Lebanon has only a few constructed wastewater treatment plants (WWTPs). However, many others are either under construction, under design-phase assessment, or are envisioned to be assessed in the future.

The recently published National Bioenergy Strategy for Lebanon (2012) indicated that there is viable energy potential for the ten largest Wastewater Treatment Plants in the country. A more detailed assessment was needed for the other WWTPs that have a sludge production above 1 ton of dry matter per day.

The addressed AD in WWTPs was written by the reliance on the published Wastewater Master Plan conducted by Tecsult International Limited and KREDO Consulting Engineers "Etude du plan directeur pour la valorisation ou l'élimination des boues d'épuration" (2002).

In coordination with the MEW and the CDR, the potential from this bioenergy stream was assessed through available documentation and on-site surveys of the wastewater treatment plants deemed to have favorable conditions for AD of sewage sludge.

INITIAL SCOPE OF THE STUDY

The energy potential from sludge production was assessed for the 10 largest WWTP.. In this context, the requirements were:

- Review and comment on the analysis being made by the CDR consultants on energy from the 10 largest WWTP (Task 1).
- Undergo a feasibility assessment for the WWTP that have a sludge production above 1 ton of dry matter per day and yet are smaller than the 10 largest identified WWTP (Task 2).
- Elaborate the technical specifications (and other engineering requirements and protocols) for the preparation of the bidding documents for the most promising selected sites (Task 3).

The feasibility assessment was limited to a maximum of 20 WWTP, where sludge production is or will be above 1 ton of dry matter per day and smaller than the 10 largest WWTP identified.

The list of the 30 Wastewater treatment plants should have originally been provided by CDR as well as:

- Location
- Size of WWTP (Population equivalent)
- Status
- Design Flow
- Wastewater Treatment Process and Components
- Method of sludge treatment
- Effluent standard (BOD5, SS, Total N)
- Name and contact of the person in charge to be interviewed

INITIAL METHODOLOGY

The WWTP analysis for a biogas project covers the following key areas:

- Physical analysis of the WWTP site and specifications;
- Potential energy valorization In and Ex-Situ;
- Potential valorization of the residual produced.

The methodology focuses on these key elements to define the importance of pursuing a project or not.

1 **Elaboration of questionnaire:** A detailed questionnaire to WWTP operators have been developed with the aim of a better understanding of the local context and in order to determine the technical and physical feasibility of AD on the WWTP sites concerned.

2 **Elaboration of an analysis tool:** Development of a methodological tool to analyze the information collected during the survey. A qualitative scorecard with a ranking system has been developed.

3 **Interviews:** Interviews with key players such as plant operators have been performed through phone calls or face to face interviews. In addition, some visits have been conducted to make sure data collected through interviews fit with the on-site reality.

4 **Processing and analysis of information and data collected during interviews.** A project scorecard will be developed for each WWTP site. Projects will be compared to each other.

5 **Ranking and selection of projects:** Ranking and Selection of the 4 most promising WWTP site for the implementation of an AD.

CHANGES IN THE SCOPE

Information on the 10 largest wastewater treatment plants was obtained mostly from the Wastewater Master Plan, conducted by Tecsult International Limited and KREDO Consulting Engineers "Etude du plan directeur pour la valorisation ou l'élimination des boues d'épuration" which dates from 2002. Indeed, since the publication of the document in 2002, limited progress has been made on WWTPs projects, as well as limited updated information.

This study elaborated the list of WWTP projects and the available related information (location, size of WWTP, wastewater treatment process and components, name and contact of the person in charge to be interviewed…) based on the following documents obtained during the data collection of the National Bioenergy Strategy and information provided by CDR:

- Council for Development and Reconstruction, 2002 - Plan directeur de valorisation ou de disposition des boues d'épuration
- CDR Document Appendix 4.
- Inventory of wastewater projects made by GTZ, 2007

Following the different meetings and interviews held with the CDR, with the engineering consultant company, Cabinet Merlin, and with various WWTP operators, it was confirmed that the present information available does not allow for the initial scope of the study to be undertaken.

Furthermore, only a few WWTPs are ready for operation and yet most of them are waiting to be connected to the sewage network.

Within this context, the scope of the study has been redefined to match available information with the objective of the assignment:

- WWTPs data collection:
    - Interview phase: Description of the information and data collected during the interview phase and during the different meetings held;
    - Reports of the sites visited;
    - Updating of the list of WWTP projects with information gathered;
- Elaborate the technical specifications:
    - Technical recommendation for future wastewater treatment plants;
    - Sludge anaerobic digestion;
    - Sludge and co-products anaerobic co-digestion;
- Improvement options, identification of scenarios and recommendations.

The main objective is to identify WWTPs where sludge anaerobic digestion is feasible and to propose co-digestion projects, based on the co-substrates identified during the National Bioenergy Strategy (2012), allowing for the increase in the energy production potential of the selected WWTPs.

OVERVIEW OF WASTEWATER TREATMENT

1.1. List of wastewater treatment plants projects

1.2. Questionnaire for interviews

1.3. Analysis tool for project ranking

1

1. Preliminary work & Methodological tools

1.1 List of wastewater treatment plants Projects

The consortium elaborated the list of the WWTP projects and the available related information (location, size of WWTP, wastewater treatment process and components) based on the following documents obtained during the data collection of the National Bioenergy Strategy Study:

- Council for Development and Reconstruction, 2002 - Plan directeur de valorisation ou de disposition des boues d'épuration
- CDR document Appendix 4
- Inventory of wastewater projects made by GTZ, 2007

Table 1 shows the list of WWTP projects.

N°	Location	Caza	Size of WWTP
			Population Equivalent (PE)
Beirut - Mount Lebanon			
1	Bourj Hammoud / Dora	Metn	1,664,000 – 2,000,000
2	Al Ghadir	Aley	800,000 – 850,000
3	Kesrouan/ Tabarja	Kesrouan	400,000
4	Jiyeh Ras Nabi Younes	Jiyeh	88,000
5	Jbeil	Jbeil	49,500
6	Hrajel	Kesrouan	37,000 – 40,000
7	Jeita & Kferzebiane	Kesrouan	35,000
Bekaa			
8	Majdal/ Anjar	Zahle	275,000 – 300,000
9	Zahle	Zahle	120,000 – 150,000
10	Tammine Altahta	Baalbek	100,000
11	Baalbek	Baalbek	89,000 – 100,000
12	Joub Jannine	West Bekaa	77,000 – 100,000
13	Laboueh	Baalbek-Hermel	47,000 – 53,000
14	Aitanit	West Bekaa	35,700
North Lebanon			
15	Tripoli	Tripoli	792,000 – 1,000,000
16	Aabde	Minieh-Dinnieh	185,000
17	Koura	Koura	68,000
18	Bakhoun	Minieh-Denniye	48,000
19	Michmich	Akkar	42,000 – 68,000
20	Batroun	Batroun	24,000
21	Chekka	Batroun	21,000
South Lebanon			
22	Saida	Saida	390,000
23	Sarafand	Saida	325,000
24	Sour	Sour	250,000
25	Tebnine & Chaqra	Bent Jbeil	100,000
26	Nabatieh	Nabatieh	100,000
27	Yahmor, Zaoutar, Kfar Sir	Nabatieh	35,000

Table 1: List of WWTP projects

1.2. Questionnaire for interviews

The elaborated questionnaire was intentionally made to be thorough. The questionnaire covers the following key areas:

- **Physical analysis of the WWTP site and specifications** to determine if the site can accommodate a biogas project (availability of land, neighborhood, capacity of the WWTP to receive the nitrogen-rich juice from residuals, optimization of existing facilities …);
- Wastewater treatment process and components;
- **Method of sludge treatment;**
- **Effluent characteristics;**
- **Potential available co-products**, such as agricultural waste in order to maximize the biogas production;
- **Potential energy valorization In and Ex-Situ:** Determine the energy needs of the WWTP and the Ex-situ valorization options;
- **Potential valorization of the residual produced.**

The questionnaire template is presented in the document called "Energy from Sludge – WWTP Questionnaire & Analysis Tool", found on the accompanying CD.

1.3. Analysis tool for project ranking

An analysis tool has been designed to analyze the questionnaire and determine the feasibility of the various projects. However, the tool has not been used during the study because of the limited availability of information gathered. Nevertheless, the tool may be useful for the CDR and the MEW to qualify future WWTP projects with respect to energy production.

The analysis tool is a qualitative scorecard with a ranking system and has the following elements;

- The analysis tool is divided into different crucial points that determine the feasibility of a project, i.e.; site characteristics, co-substrates, energy, and equipment. Each category has different qualitative criteria.
- By cross-referencing the different qualitative criteria with the results of the questionnaire, each criteria is weighted automatically and therefore, the project is attributed a score. The comparison of each score allows the comparison and ranking of the project to establish priorities and decide to proceed with a more detailed assessment.

The analysis tool is presented in the document called "Energy from Sludge – WWTP Questionnaire & Analysis Tool", found on the accompanying CD.

2

OVERVIEW OF WASTEWATER TREATMENT DIGESTION

2

2. Overview of wastewater treatment

This chapter defines the main wastewater treatment lines and their consequences on sludge quality, energy consumption and energy production. Depending on the objectives set on water quality, the wastewater treatment line of a WWTP is generally divided into:

- Pre-treatment
- Primary treatment
- Secondary treatment
- Tertiary treatment

This chapter can be found as a softcopy in Appendix 1.

2.1 Pre-treatment

Urban wastewater sewers carry a wide range of matter. A pre-treatment is necessary to protect the whole water treatment line:

- Water lifting systems
- Protection of pipelines against blockages
- Protection against abrasion of other equipments
- Protection of tanks against settlement that might decrease their load capacity

The following constitute the pre-treatment operations and can be implemented in WWTPs depending on the raw water quality:

- Bar screening
- Straining
- Comingling
- Grit removal
- Grease removal (frequently combined with grit removal)
- By-products treatment

Grease is the only by-product from the pre-treatment that can be used to produce energy. The different steps that commonly compose a pre-treatment plant are presented in Figure 1.

Since the pre-treatment phase is not a main energy consumer and does not produces sludge, all the steps of a standard pre-treatment are not further detailed.

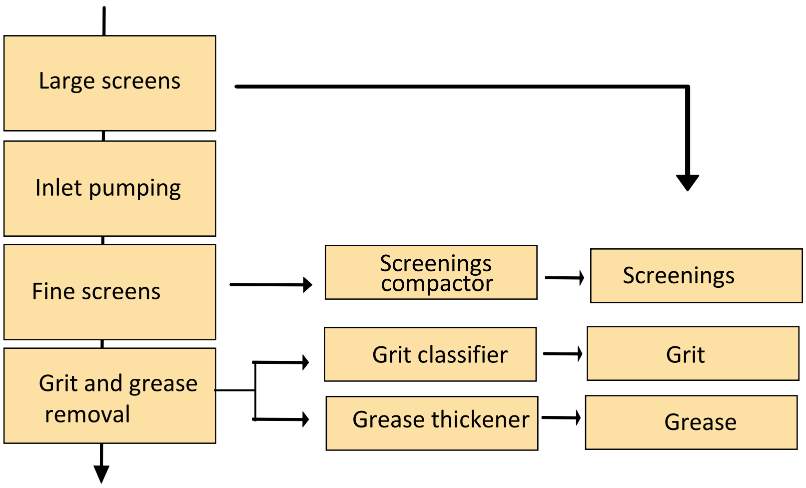


Figure 1: Pre-treatment diagram

2.1 Treatment LINES in Lebanon

Three kinds of wastewater treatment processes are used in Lebanon:

- Primary treatment and biological treatment for large scale plants;
- Secondary treatment only for medium/small plants;
- Biofiltration when limited surface area is available.

The corresponding treatment lines are illustrated in Figure 2, Figure 3 and Figure 4, respectively.

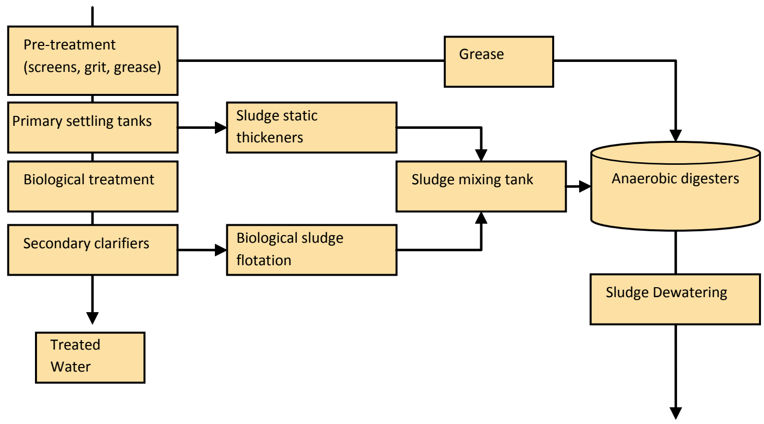


Figure 2: Large scale WWTP diagram (>200,000 PE)

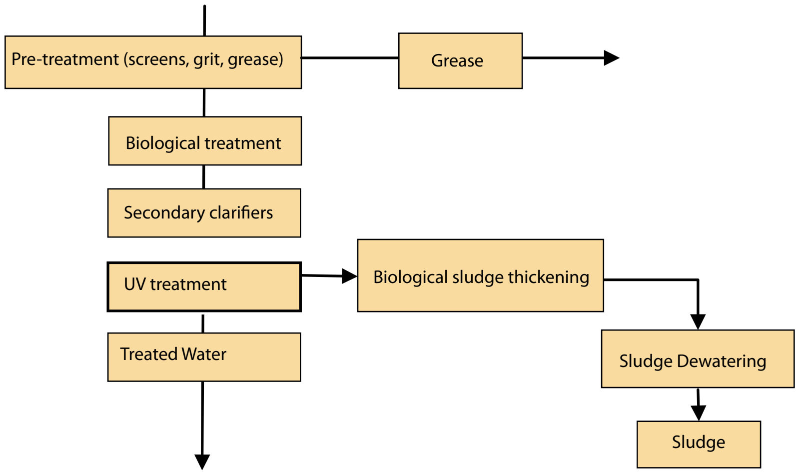


Figure 3: Medium / small scale WWTP diagram

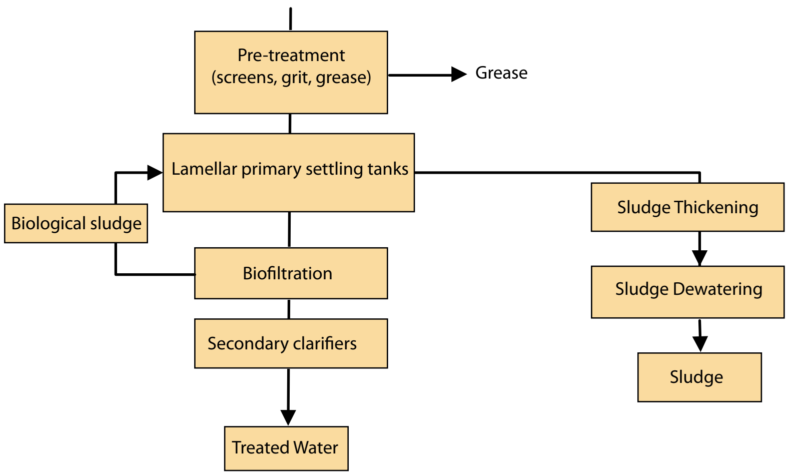


Figure 4: Biofiltration WWTP diagram

The sections below expand in each of the wastewater treatment plant processes outlined in Figures above.

2.2 Primary treatment

Primary and secondary treatments are at the core of wastewater treatment lines. Primary treatment extracts the pollution that can be easily settled, while secondary treatment, also known as biological treatment, treats the soluble pollution through the addition of oxygen to increase biological activity.

Primary treatment is used in the following cases:

- Large WWTPs require a primary reduction of the pollution load to reduce the secondary treatment size and the related energy costs of aeration and mixing. This is the most common case in the Lebanese projects when primary treatment is used.
- Primary treatment will allow equilibrating the different pollution parameters before the secondary treatment. It is the case for wastewater typology with a particularly high load, for example, as in suspended solid (SS).
- The standards on treated water discharge are low enough to meet the treatment objectives with the primary phase.

Primary treatment might be simple settling or chemical (coagulation / flocculation) settling. Primary treatment is operated in a circular or rectangular settling tank. Circular tanks (see Figure 5) are more common, given that they are often more economical. Rectangular tanks are an alternative solution used in very large plants to save surface area.

2.3. Secondary treatment (biological treatment)

Secondary treatment or biological treatment is generally an aerobic biological treatment to insure the treatment of a part of the soluble pollution. The biological process is the consumption/transformation of biodegradable organic matter by a wide range of micro-organisms.

This treatment is usually divided in two different families presented in Figure 6.

- Suspended growth process: a bacterial culture is developed as a floc. To maintain the floc in suspension the tank must be mixed.
- Attached growth process: the micro-organisms attach themselves on a substrate by forming a biofilm.

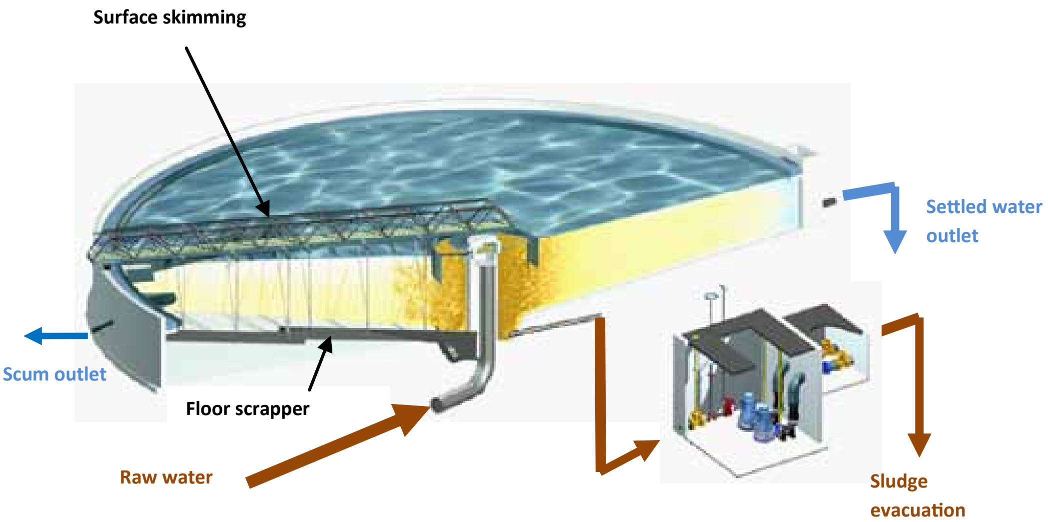


Figure 5: Typical circular primary settling tank process

Primary treatment produces a primary sludge with a high content of organic matter. The resulting primary sludge is often stabilized through Anaerobic Digestion. Primary treatment has a high investment cost. Thus it is only implemented in medium to large size plants (over 200,000 Population Equivalent)

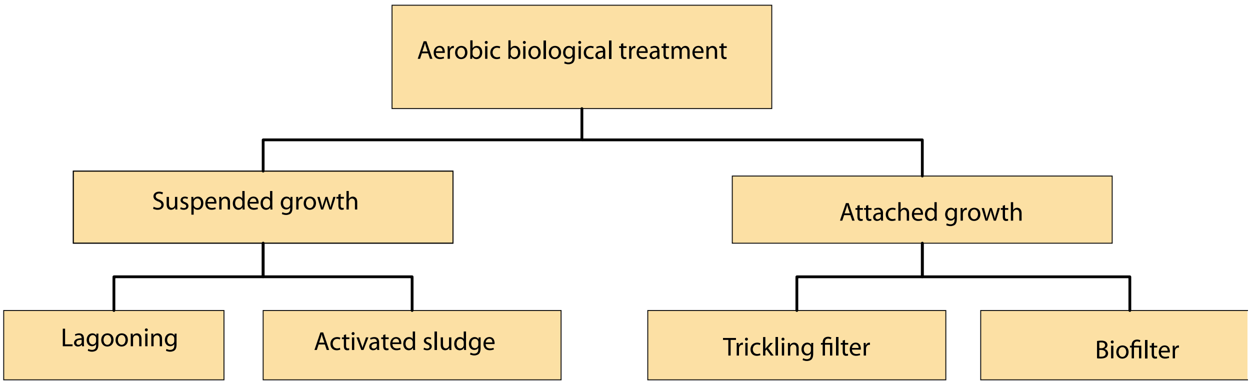


Figure 6: Aerobic biological treatment families

These processes include the biological reactor and a system to separate the bacterial culture (suspended or excess biofilm detached from the substrate in attached growth). The main secondary treatments used in Lebanon are activated sludge and, to a lesser extent, Bio-filtration.

Secondary treatment is the main energy consumer of a plant through the aeration system and the aeration tanks mixing. It represents 50% to 70% of the total energy consumption depending on:

- The need to treat nitrogen (increase aeration tanks and aeration);
- The implementation of large pumping stations (inlet our outlet).

Activated sludge

Activated sludge is the combination of:

- An aeration tank
- A separation system of the biomass which is commonly a settling tank
- A recirculation arrangement to return excess biological sludge
- An excess sludge extraction
- A mechanism to supply oxygen
- A mixing arrangement of the tank

Figure 7 shows the activated sludge mechanism.

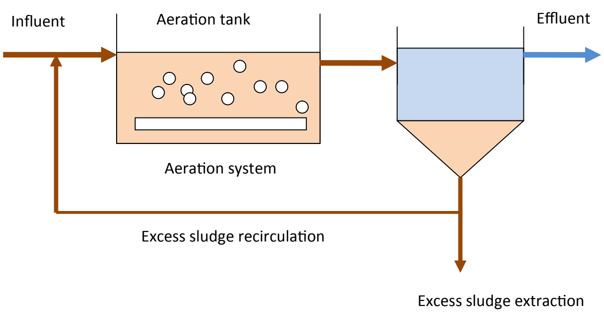


Figure 7: Activated sludge simplified diagram

The secondary treatment produces biological sludge. The larger the volume of the aeration tank, the better the sludge will be stabilized.

Biofiltration

Bio-filtration is a treatment that includes all the processes that combine biological purification through attached growth with the retention of suspended solids.
The main advantages are the following:

- Space saving by eliminating the clarification stage;
- Easily covering of the structures;
- No danger of leaching;
- Appropriate use for diluted water with high hydraulic variation acceptance;
- Modular construction.

Historically, this very compact process was invented to treat diluted water and be able to react favorably to high variation in carbon load. This technology is still in a "proprietary" process with very few manufacturers. However, it is the only technology able to face major constraints such as the very high compactness needed for:

- Underground construction
- Limited surface area available
- Construction on coastal area

This technology has been used in the plants of:

- Jbeil constructed by Degrémont (Figure 8)
- Jiyeh Ras Nabi Younes constructed by OTV (Figure 9)

The installation is made on a battery of filters that are in operation.

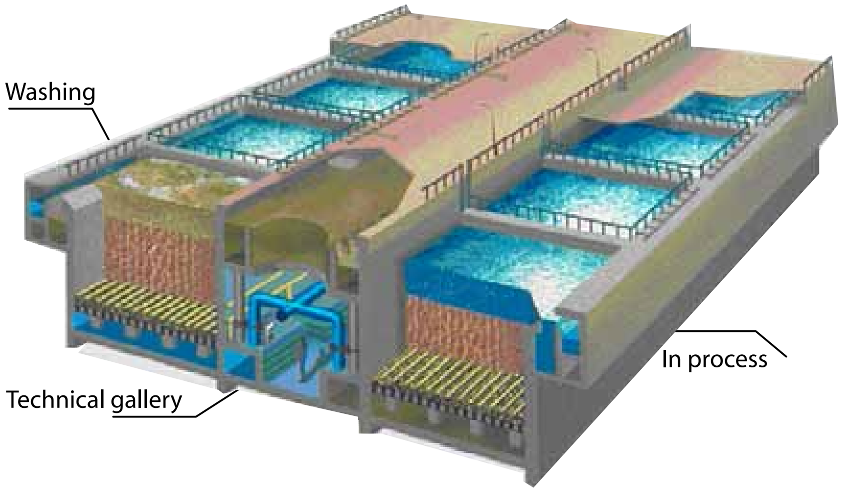


Figure 8: BIOFOR Battery (Jbeil WWTP)

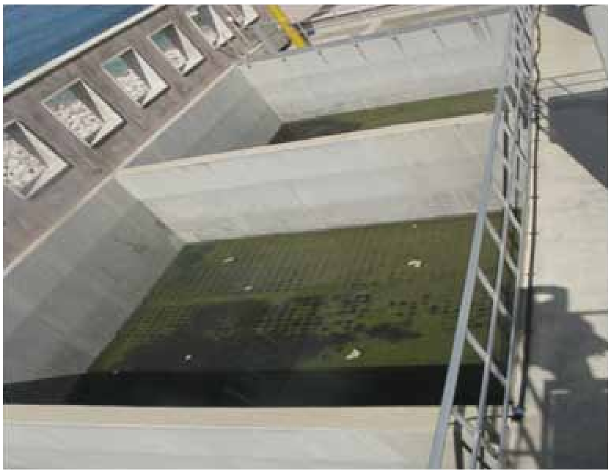


Figure 9: Ras Nabi Younes WWTP Biofilters waiting for commissioning

The bio-filters are usually put in operation after primary settling, which can be physical chemical treatment to continue the search of surface saving.

The sludge produced in the bio-filter is not directly extracted but taken off when the filter is washed and sent to the inlet where it is settled in the primary settling tanks. Thus, the sludge produced has a high organic content comparable to primary sludge.

Sludge treatment

Thickening

In all cases (primary, biological sludge), the extracted sludge has to be stabilized (decrease the organic content) and to be treated to increase the dry solid content to:

- Decrease transportation costs;
- Make it acceptable by landfill or other treatment technologies;
- Make it acceptable for land application.

Sludge extracted is mainly composed by water: 99% to 99.8% (dry solid concentration is variable but around 2 to 10 g/l).

Thickening is a first step to decrease the water content. The two kinds of sludge (primary and biological) react differently to the processes and are often thickened separately.
Following this step, sludge is:

- Stabilized in anaerobic digestion when there is primary sludge and then dewatered to reach a dry content of more than 20%.
- Directly dewatered when there is no digestion.

In the existing projects in Lebanon, the technology used for dewatering is a centrifuge that allows for:

- Odor control;
- Smaller surface areas needed;
- Control of the final dry content by dosing the polymer.

Sludge anaerobic digestion

Sludge anaerobic digestion is a very interesting sludge stabilization process as it produces biogas that can be used for energy production.

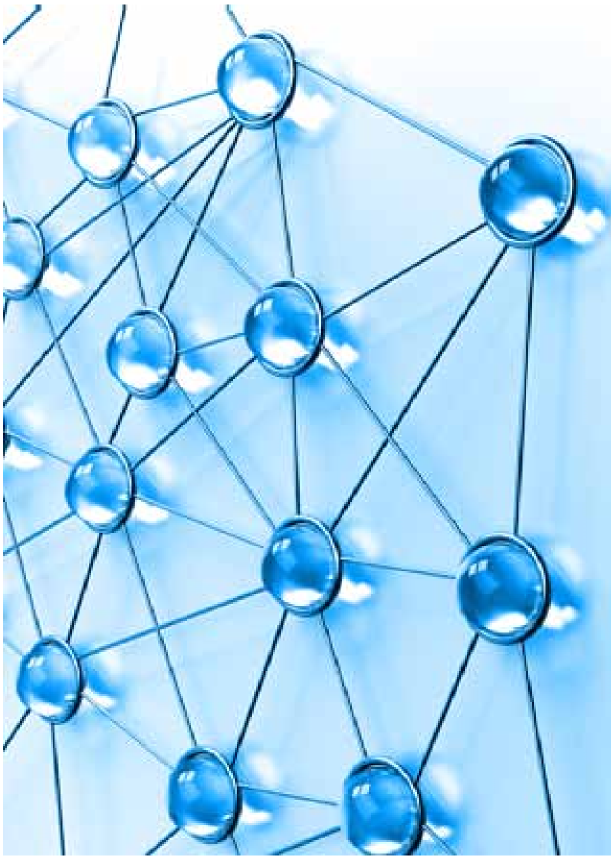
Beyond a certain capacity (around 200,000 PE) a WWTP requires a preliminary treatment to reduce the biological stage. This preliminary treatment produces primary sludge that contains significant amounts of organic matter.

Historically, digestion has been set up to face the constraint of the primary sludge and anaerobic digestion is one of the most powerful cell destroyers used to eliminate large quantities of organic matter (OM). The destruction of OM produces biogas.

DATA COLLECTION ON WWTP

3

3. Data Collection on WWTP



The construction of the WWTPs, as outlined in the WWTP Master Plan, has has been delayed and not gone according to schedule. A few WWTP have been constructed but these constructed plants, more often than not, are not connected to the sewage network. Other projects have been put on hold for political reasons, Bourj Hammoud WWTP for instance, or are under the preliminary design stage and will not be constructed in the near future (at least not before 2018).

During the interview phase, information and data on each WWTP was only partially obtained. The only information that the consortium succeeded in obtaining from the CDR are photocopied extracts from engineering reports for five WWTPS with limited useful data details (Appendix 4, on accompanying CD).

This chapter presents the list of the Lebanese WWTP projects updated with available information gathered during the interview phase and the sites' visits.

3.1. Interview Phase

Seven interviews were successfully conducted. For the rest of the WWTPs, adequate information was not obtainable.

N°	Location	Mohafazat	Caza	Contact	Company/ Agency	Date of interview
1	Tripoli	North Lebanon	Tripoli	Alain POULIQUEN Blondie MIRAD	Degrémont	25/01/2012
2	Jbeil	Mount Lebanon	Jbeil	Alain POULIQUEN Blondie MIRAD	Degrémont	25/01/2012
3	Batroun	North Lebanon	Batroun	Alain POULIQUEN Blondie MIRAD	Degrémont	25/01/2012
4	Chekka	North Lebanon	Batroun	Alain POULIQUEN Blondie MIRAD	Degrémont	25/01/2012
5	Ras Nabi Younes	Mount Lebanon	Jiyeh	Nicolas HASBANI Imad EL HAJJAR	OTV	02/03/2012
6	Nabatiyeh	South Lebanon	Nabatieh	Nicolas HASBANI Imad EL HAJJAR	OTV	02/03/2012
7	Aitanit, El Fourzol, Ablah	Bekaa	West Bekaa	Matthew Antill	CDM Smith / USAID	21/03/2012

Table 2: List of interviews

The wastewater treatment plants financed by USAID i.e, Aitanit, El Fourzol and Ablah, were not selected in the initial list, as these plants are too small (respectively being 35,000, 4,000 and 8,000 population equivalent) to consider a sludge anaerobic digestion plant.

All the interviews are presented in Appendix 5, attached in the accompanying CD.

3.2. Wastewater Treatment Plant sites visits

This chapter describes the information collected during the visits of plants. Only 3 WWTP sites could be visited, i.e. Tripoli, Ras Nabi Younes and Nabatiyeh.

The report of the site visits is presented in Appendix 2, found in the accompanying CD.

N°	Location	Mohafazat	Caza	Contact	Company/ Agency	Date of visit
1	Tripoli	North Lebanon	Tripoli	Blondie MIRAD	Degrémont	06/03/2012
2	Jiyeh Ras Nabi Younes	Mount Lebanon	Jiyeh	Imad EL HAJJAR	OTV	07/03/2012
3	Nabatieh	South Lebanon	Nabatieh	Imad EL HAJJAR	OTV	07/03/2012

Table 3: List of site visits

3.3. Update oN the status and data of studied wastewater treatment plants

Following the interviews and data collection, the list of WWTP projects have been updated with information that the consortium gathered during the first task. The complete list can be found in the Excel file called "WWTP Projects Database.xls", found in the accompanying CD.

The information related to the WWTP projects constructed or under construction is presented in Table 4. None of these plants are operational at this moment.

When constructed, plants are waiting to be connected to sewers that are under construction or in some cases not designed yet. For instance, the Jbeil WWTP was constructed in 2005 but the collection network is waiting to be designed.

The only large-scale constructed project is the Tripoli WWTP. The Sour WWTP remains under construction.

Table 5 presents the data collected regarding the other WWTPs.

Location	Mohafazat	Caza	Size of WWTP	Design Flow	Status of WWTP	Commissioning estimation	Network	Components			Funding	Source of information	
			Population Equivalent (PE)	m^3/day				Primary treatment	Biological treatment	Sludge stabilization	CHP		
Tripoli	North Lebanon	Tripoli	792 000 – 1 000 000	135 000	Construction completed	2012	Not finished 20% of flow expected for summer 2012	X	X	X	X	AFD BEI	Degremont
Nabatiyeh	South Lebanon	Nabatiyeh	100 000	9 800	Construction completed	2012	Almost finished	No	Aerated sludge	No	No	French protocol	OTV Cabinet Merlin
Chekka	North Lebanon	Batroun	21 000	2 174	Construction completed	N.A.	Not finished	X	Biofiltration	No	No	French protocol	Degremont
Batroun	North Lebanon	Batroun	24 000	4 094	Construction completed	N.A.	Not finished	no	Aerated sludge	No	No	French protocol	Degremont
Jiyeh Ras Nabi Younes	Mount Lebanon	Jiyeh	88 000	11 900	Construction completed	N.A.	Not finished	X	Biofiltration	No	No		OTV Cabinet Merlin
Jbeil	Mount Lebanon	Jbeil	49 500	9 052	End of construction Not operational Main collector pending	>2018	Not constructed - No design	X	Biofiltration	No	No	French protocol	Degremont
Sour	South Lebanon	Sour	250 000	45 000	Beginning of construction	> 2014	N.A.	X	X	X	X	BEI	OTV Cabinet Merlin
Zahle	Bekaa	Zahle	120 000 – 150 000	18 000	Under construction Contract signed in 2003 Delay due to funding issues	N.A.	N.A.	No	X	No	No	Italy	
Baalbek	Bekaa	Baalbek	89 000 – 100 000	12 500	Construction completed Operational	Old plant	Low rate connected	No	X	No	No		
Joub Jannine	Bekaa	West Bekaa	77 000 – 100 000	10 500	Construction completed	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.		CDR
Aitanit	Bekaa	West Bekaa	35 700	5 000	Construction completed	2009	N.A.	X	Thricklinig filter	N.A.	No		USAid Website
El Fourzol	Bekaa	West Bekaa	4 000	1 000	Construction completed	2009	N.A.	X	Thricklinig filter	N.A.	No		USAid Website
Ablah	Bekaa	West Bekaa	8 500	2 000	Construction completed	2009	N.A.	X	Thricklinig filter	N.A.	No		USAid Website

Table 4: Constructed or under construction WWTPs

Location	Mohafazat	Caza	Size of WWTP	Design Flow	Status of WWTP	Commissioning estimation	Components				Source of information	Funding
			Population Equivalent (PE)	m^3/day			Primary treatment	Biological treatment	Sludge stabilization	CHP		
Ghazir /Adma (Casino)	Mount Lebanon	Kesrouan	320 000	N.A.	Under preparation	>2018	N.A.	Biofiltration	N.A.	N.A.	Hydratec document provided by CDR	BEI ready
Zouk Mikhael	Mount Lebanon	Kesrouan	193 000	48 000	Under preparation	>2018	N.A.	Biofiltration	N.A.	N.A.	Hydratec document provided by CDR*	BEI ready
Saida	South Lebanon	Saida	390 000	70 200	Pre-treatment completed & operational Upgrading under preparation	>2018	N.A.	N.A.	N.A.	N.A.		N.A.
Sarafand	South Lebanon	Saida	325 000	N.A.	Under preparation	>2018	X	X	Aerobic digestion	No	SETI Drawings provided by CDR*	N.A.
Tebnine & Chaqra	South Lebanon	Bent Jbeil	100 000	N.A.	Under preparation	>2018	N.A.	N.A.	N.A.	N.A.		N.A.
Majdal Anjar	Bekaa	Zahle	275 000 - 300 000	44 500	Under preparation	>2018	X	X	Aerobic digestion	No	Document not identified provided by CDR*	N.A.
Laboueh	Bekaa	Baalbek-Hermel	47 000 – 53 000	7 000	Under preparation	>2018	N.A.	N.A.	N.A.	N.A.	CDR	N.A.
Aabde	North Lebanon	Minieh-Dinnieh	185 000	30 000	Under preparation	>2018	X	X	X	X	Document not identified provided by CDR	N.A.

Bakhoun	North Lebanon	Minieh-Denniye	48 000	N.A.	Under preparation	>2018	N.A.	N.A.	N.A.	N.A.	CDR	N.A.
Hrajel	Mount Lebanon	Kesrouan	37 000 – 40 000	6 000	No design	>2018					CDR	
Tammine Altahta	Bekaa	Baalbek	100 000	N.A.	No design	>2018	N.A.	N.A.	N.A.	N.A.	CDR	N.A.
Michmich	North Lebanon	Akkar	42 000 – 68 000	6 800	No design	>2018					CDR	
Yahmor, Zaoutar, Kfar Sir	South Lebanon	Nabatieh	000 35	.N.A	No information	2018<	.N.A	.N.A	.N.A	.N.A		.N.A
Jeita & Kferzebiane	Mount Lebanon	Kesrouan	000 35	.N.A	No information	2018<	.N.A	.N.A	.N.A	.N.A		.N.A
Bourj Hammoud/ Dora	Beirut - Mount Lebanon	Metn	– 000 664 1 000 000 2	000 325	Upgrading project stopped Primary treatment only	2018<	X				Cabinet Merlin	BEI to be done
Al Ghadir	Beirut - Mount Lebanon	Aley	– 000 800 000 850	000 138	Upgrading project stopped Primary treatment only	2018<	X				Cabinet Merlin	.N.A
Kesrouan/ Tabarja	Mount Lebanon	Kesrouan	000 400	Project cancelled and replaced by Zouk Mikhael & Ghaziz / Adma	Cabinet Merlin							
Koura	North Lebanon	Koura	000 68	Project cancelled, linked to Tripoli WWTP	CDR							

Table 5: Other WWTP projects

ANAERODIC DIGESTION

4

4. Anaerobic digestion

4.1. Methane Production Principle

Anaerobic Digestion is the continuous physical and chemical process for treating liquids, or pasty substrates (sludge and organic matter), in order to produce methane**.**

This treatment generates two by-products:

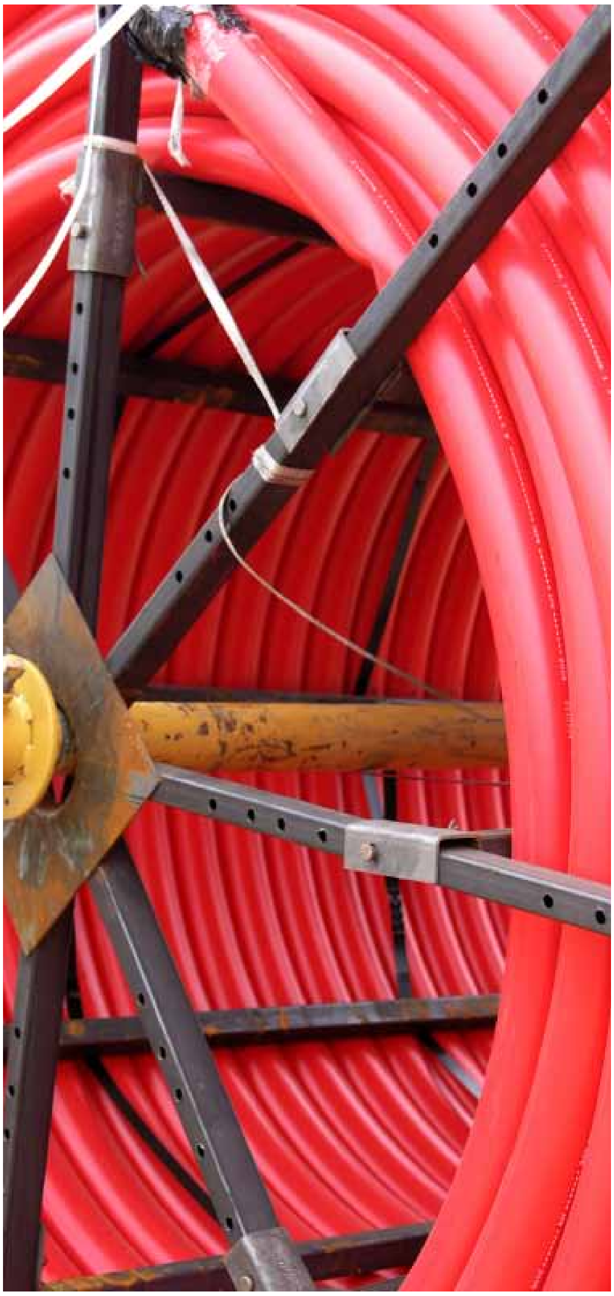
- Biogas, mainly containing methane (CH_4), which is an energy source comparable to `natural gas;
- Valuable digested residues that can be used as fertilizer for land application.

The biogas produced in a digester is composed of the following elements:

- 50% to 70% of Methane (CH_4);
- 30% to 50% of Carbon Dioxide (CO_2);
- 5% of Water (H_2O);
- 0.02% to 0.5% of Hydrogen Sulphide (H_2S);
- 0% to 5% of Nitrogen Gas (N_2).

Methanisation has four important advantages (see Figure 10):

- **To generate renewable** energy through the control of the methanisation process which occurs naturally through organic matter degradation and which contributes 21 times more than carbon dioxide (CO_2) to the greenhouse effect;
- **Treatment of organic wastes** from industries, agriculture, wastewater treatment plants, and municipalities. A ton of organic matter destroyed produces approximately 0.9 to 1.1 Nm^3 of biogas;
- **Production of valuable fertilizer**.



Sludge & Waste Treatment
High yields (70 to 90%)
Odor Control
Sludge volume reduction (1/3)

Renewable Energy Source
Biogas: 1m3=0,6l of Oil
Substitute for Natural Gas or Fuel
Thermal & Electrical renewable energy production

Valuable Residual
High Ammonia content
Stable and hygenic (class A)
Fertilizer: P and K

Emissions
Fossil fuel substitution
GH4 radiation is 21 times the CO2 potential

Figure 10: Quadruple benefits of methanisation

4.1.1 BIOGAS ENERGY CONTENT AND GENERATED ENERGY

The energy content is directly related to the proportion of methane (CH_4) content in biogas. The methane content of biogas produced is generally comprised between 50% and 70% (and more). A cubic meter of methane has an energy content of 9.94 kWh, comparable to the energy content of natural gas.

- The calorific value of biogas, depending on the methane content, is between 5.0 to 7.5 kWh/Nm^3 with an average of 6.0 kWh/Nm^3 or 21.6 MJ/Nm^3.
- The Oil Equivalent is of 1 Nm^3 of biogas or 0.6 liter of fuel.

Following the methanisation process, a purification phase is needed, to concentrate the methane, remove the other gases and contaminants and decrease the water content. Once purified, the produced methane is burnt into a gas engine or gas turbine to produce electricity, heat or both (combined heat and power or co-generation).

In general, the efficiency of a gas engine is considered to be around 75% to 80% for co-generation:

- Between 35% and 41% for electricity production;
- Between 39% and 45% for heat recovery.

A common assumption is to consider an operating time for the gas engines of around 8,000 hours/year.

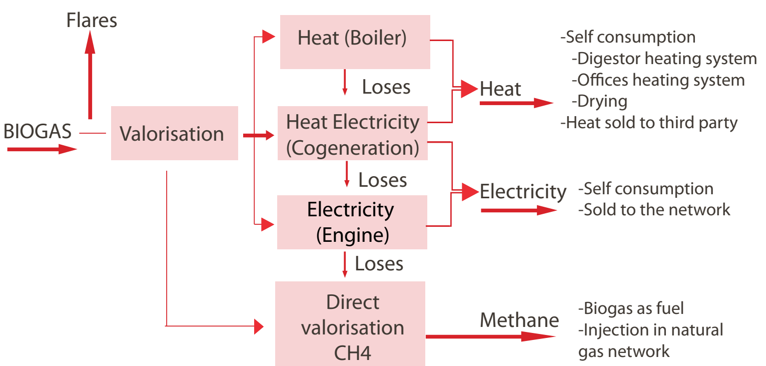


Figure 11: Energy generation from biogas project

Once refined, biogas has the same properties as natural gas. To date, some European cities are already using biogas as a fuel to supply city buses and waste trucks. The option of injecting biogas into the national natural gas network is also an alternative if such a network is constructed in Lebanon. Biogas can also be distributed in domestic gas tanks but it has to be treated and packaged in a liquefaction plant.

The heat produced by the gas engines is usually transformed into hot water (90°C). If the biogas is burnt into micro-turbines, the heat can be transformed into steam (250°C). Hot water and steam are of great interest for industries in general and for agro-food industries in particular (cooking, cleaning). These industries usually use fuel or natural gas boilers to produce the steam or hot water consumed.

4.2. SLUDGE ANAEROBIC DIGESTION AND ENERGY PRODUCTION

Nowadays the main issue with digestion is the sludge management and destination. The process of digestion reduces sludge quantities facilitating sludge management. Moreover, the biogas produced during digestion is an energy source that can be used to reduce the WWTP energy consumption.

The net calorific value (NCV) of the biogas will directly depend on the CH_4 proportion which itself depends on the effluent quality, the average values observed are in Table 6, for one ton of organic matter destroyed.

Parameter	Unit	Value
OM destroyed	Kg / day	1,000
Biogas produced	Nm^3/day	900
Heating power ratio	kCal / Nm^3	5,500
Energy ratio	W/kCal/h	1.163
Energy	kWh/day	5,757

Table 6: Energy production calculation

1,000 kg of organic matter (OM) destroyed produces 900 Nm^3/h of biogas. Biogas net calorific value (NCV) is approximately 5,500 kCal/Nm^3 and the energy ratio between watts (W) and calorie (cal) is 1,163 W/Kcal/h. We obtain an energy production of 5,757 kWh/day.

When applied to the Tripoli WWTP (1,000,000 PE), which treats 32,000 kg of OM per day at design load, we will have the following results:

- Total energy: 7.8 MW
- Electrical output: 2.3 MW
- Hot Water: 1.6 MW
- Combustion products: 3.1 MW

The higher the OM content in the digesters, the higher is the biogas production. This encourages the digestion of products and OM from different origins:

- Sludge from small plants in replacement of landfilling, which is possible by conventional sludge digesters;
- Organic waste from agriculture and food industries (oil, milk, grease...) in a special dedicated co-digester.

In a WWTP with a secondary treatment, the global needs for energy are higher than the potential of energy production so the energy produced can be used directly by the plant to decrease its energy demand. For example, the WWTP of Tripoli at design load will consume approximately 80,000 kWh/day, while the potential energy production from AD of sludge is 56,000 kWh/day, i.e. 68.75%.

Boosting SLUDGE digestion

The efficiency of digestion is much higher on primary sludge (55%) than on biological sludge (45%). A lot of research is focused on how to "boost" the digestion and increase the organic matter destruction and biogas production.

The principal is to pre-treat the sludge before digestion.

Many techniques have been put forward and have the same basis which is the lysis of bacteria cells. However only a few have started this process on an industrial scale;

- **Pre-treatment using ultrasonics** of the biological sludge in order to create a partial solubilization of the OM;
- **Thermal pre-treatment (thermal hydrolysis)** in order to heat the sludge to 150°C – 180°C to fracture the organic matrix;
- **Mechanical pre-treatment** to break the sludge structure by a ball mill-type crusher. The industrial application has not been proved (abrasion, resistance over time...);
- **Enzymatic pre-treatment** by adding enzymes to enhance the kinetic degradation. It is still under development and will probably represent a major cost in operation by adding the enzymes.

Only the first 2 technologies have actual industrial references. Their description can be found in Appendix 3, found in the accompanying CD.
Depending on the technology used and the quality of the sludge, the following results have been recorded:

- Increase of biogas production (15% to 30%)
- Increase of sludge dryness (5% to 10% of dryness)

4.3 ANAEROBIC CO-DIGESTION

The energy production of wastewater treatment sludge through digestion can be optimized if a co-digestion plant is implemented, to treat co-substrates in addition to sludge, instead of a simple sludge digestion unit. Moreover, WWTP are ideal places to accept Ex-situ by-products. WWTP is an industrial platform that can treat other waste instead of only wastewater and sludge.
Sludge also brings dilution and essential trace elements that are fundamental to the functioning of anaerobic co-digestion.

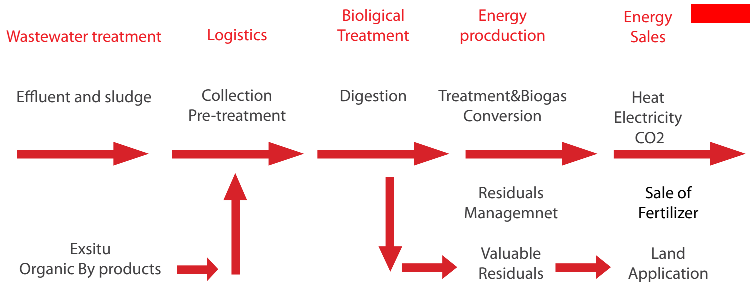


Figure 12: Supply chain of methane through co-digestion plant

4.3.1 WASTE TREATMENTAND BIOGAS PRODUCTION POTENTIALS

The organic waste that can be used in addition to wastewater sludge, to produce biogas, comes from the following sectors:

- Animal breeding: manure;
- Agriculture: cereals, corn, energy crops;
- Agro-food industries: slaughterhouse residues, dairy wastes, meat wastes;
- Communities: domestic and restaurant wastes.

The methane yield highly depends on the type of substrates that is put into the co-digester and on the property of the mix e.g. methane production potential, water content, C/N ratio equilibrium.

Some Biochemical Methane Potentials (BMP) of various substrates are listed in Table 7 below.

Waste Family	Waste Type	BMP
		(m^3 of CH_4 per Ton of waste)
Animal refuses	Pork liquid manure	10
	Beef liquid manure	20
	Beef manure	45
	Pork manure	48
	Chicken manure	60
Crops residues	Potatoes	50
	Corn residues	150
	Cereals residues	300
	Rape mill residues	350
Agro-food residues	Intestines content	30
	Brewery residues	75

	Decantation sludge	125
	Slaughterhouse grease	180
	Molasses	235
Communities' wastes	Sewage sludge	30
	Domestic waste	65
	Mowed grass	125
	Grease from waste treatment plant	245
	Used greases	250

Table 7: Substrates BMP

4.3.2 MAIN CHARACTERISTICS OF VARIOUS TYPES OF SUBSTRATES:

Depending on the substrate composition, different key elements are provided to the digestion process. The main characteristics of the different types of substrates are the following:

- **Liquid manure:**
  - Low biogas production;
  - Stabilizes the process due to a high buffering effect;
  - Provides humidity for dilution;
  - Contains necessary trace elements;
  - Consistent supply.
- **Agro-food waste:**
  - High biogas production, but often seasonal;
  - Some presence of unwanted components.
  - • Agricultural refuse (straw, vegetable…):
  - High biogas production potential due to high carbon content.
- **Crop for energy:**
  - High biogas potential;
  - Constant good quality.
- **Organic waste from municipal collect:**
  - High biogas production potential due to high carbon content (grease, green waste);
  - Not recommended because it requires a very intense sorting and can highly complicate the operation of a digester.

4.3.3 Digestion TECHNICAL SPECIFICATIONS

4.3.3.1 Co-substrates and biogas production

The quality of the treated co-products is one of the most important determinants in biogas production. Variations in biogas are mainly related to co-products' composition that determines its biogas production potential per unit of organic matter destroyed. Substrates have neither the same degradation time nor the same degradation rate (biodegradation). The more a substrate is readily and completely biodegradable, the more biogas is produced, in a given time.

These observations may explain the fact that despite an equivalent amount in OM, two different substrates will not necessarily produce the same amount of biogas. Thus, the amount of biogas generated is directly proportional to the amount of degraded OM and its quality provided as input to the co-digester.

4.3.3.2 DESIGN OF THE CO-PRODUCTS MIX

The composition of a substrate determines its biogas production potential: for maximum production, it is preferable to use substrates high in fat, protein and carbohydrates. During the identification of raw materials, it is fundamental to estimate quantities and ensure that the mixture of co-products is potentially well balanced. Indeed, some co-products such as manure or sludge have a low biogas production but are essential to stabilize the process. The most sensitive point of a co-digestion unit operation is the choice of the co-products used and their method of incorporation: amount and frequency.

Indeed, an unbalanced and badly controlled feed can cause a dysfunction of bacteria or their death by acidosis. Once a digester is in acidosis, it cannot be restarted without a complete drainage and a gradual recovery that takes three to four months.

Lipids are compounds that have the strongest methane production potential, followed by carbohydrates, polysaccharides (cellulose) and proteins. However, a too large proportion of lipids has an inhibitory effect on methane yield due to the accumulation of long-chain fatty acids. Readily biodegradable soluble molecules are quickly digested. On the other hand, as they are not accessible to hydraulic enzymes, polymers such as lignin are not digested. The incorporation of energy crops, such as maize or residue from agriculture such as straw, has to be limited and the addition of wood should be completely avoided.

The diversity of co-substrates is an asset to a project since the variability of sources allows a reduction of influence of seasonal fluctuations. A good mix of co-substrates fosters the biogas production without altering the process of digestion.

4.3.3.3 DIGESTION INHIBITORS

Among the various organic materials, wood waste (wood, branches...) are not able to be digested by bacteria.

Inorganic matter such as sand, glass or plastic should not be introduced, because they are not biodegradable and because they may cause disturbances in the process (phase separation, sedimentation, flotation, appearance of foam) and will pollute farmland if the digestate is spread.
Materials containing hazardous substances such as heavy metals, organic pollutants and substances presenting a health risk (antibiotics) should not enter into the digester. These substances can doubly disrupt the bacterial process and affect the quality of the digestate.

Some substances are inhibitors of methanogenesis. WWTP sludge and effluents of some industries, such as pharmaceuticals or industries using heavy metals in their production processes, may result, in the composition of sludge, in the presence of unwanted elements (Table 8) such as antibiotics, chemotherapy, biocides, toxic salts and heavy metals.

Category	Active substance
Antibiotics	Avoparcin
	Bacitracin
	Lincomycin
	Monensin
	Spiramycin
	Tylosin
	Virginiamycin
Chemotherapy	Arsanilic acid
	Furazolidon
	Olaquindox

Table 8: List of AD inhibitors

4.4.3.4 CO-DIGESTION PARAMETERS

RHEOLOGY

The physical properties of the substrates are not always suited to available technologies. Thus substrates such as straw may block pumps and mixers. Prior treatments may be necessary to ensure the smooth operation of the co-digestion unit. Depending on the substrates, it can include physical treatments (sorting, grinding) or chemical treatment (dissolution).

Substrates pretreatment is the major technological and economical constraint to Co-Digestion. Indeed, the addition of co-substrates can bring germs and pathogens that can limit the effectiveness of the system and create risks for digestate spreading. These risks can justify the need for thermal pretreatment for some substrates.

In addition, crop residues have to be chopped or shredded before being incorporated into the digester. Waste from catering or restaurants must be sorted (separation of metals, plastics, bones...) and hygienized.

STORAGE

The choice of co-substrates must also take into account the extra cost of storage and transport. To reduce transportation costs and greenhouse gas emissions, the supply must be near the site, within 20 km and with a maximum of 40 km for high methane producing substrates.

HOMOGENEITY

The digester operates continuously, therefore the homogeneity in the chemical composition and physical properties of the mixture must be guaranteed throughout the year.

VOLATILE MATTER CONTENT

The volatile matter (VM) content is one of the most important parameters affecting the methane yield. The higher the volatile matter content, the higher is the methane yield.

DRY MATTER CONTENT

The optimal dry matter (DM) content of the co-substrates mixture depends on the technology used. Technology for completely mixed (CSTR), have the best performance with mixtures with a content of around 14% in DM. Some facilities in Germany are up to 15% to 20% in DM.

RESIDENCE TIME

Co-digestion residence time is relatively long and is linked to the quantity and quality of substrates:

- Between 50 and 100 days for installation of low or very low capacity (< 5000 tons/ year);
- Shorter as the Co-digestion unit capacity increases: from 20 to 50 days for facilities processing between 20,000 and 100,000 tons of co-products per year. The shorter the co-digestion residence time, the higher the OM destruction and therefore the higher energy production.

TEMPERATURE

Temperature changes have a major influence on bacterial activity. Metabolism increases with temperature as when the temperature increases from 20 to 35 ° C, the yield increases by 50%.
There are optimum and specific temperature intervals

for the different micro-organisms. Outside these intervals, inhibition or destruction is observed:

- Mesophilic: 35-40 ° C. The activity range of mesophilic bacteria is between 20 and 40 °C and optimum between 35 and 40 ° C. This is the most common behavior in continuous digester.
- Thermophilic: 50-60 ° C. Thermophilic fermentation is rarely used due to its energy consumption

In both cases a good homogenization of the substrate (continuous measurement) is needed.

PH

As with temperature, there are optimum and specific pH ranges for the different micro-organisms. Outside these intervals, inhibition or destruction can be observed. Two major types of bacteria affected:

- Hydrolytic and acidifying bacteria: optimum pH between 4.3 and 6.5 but this kind of bacteria also accept a pH of around 7.0
- Acetogenic and Methanogenic bacteria: pH between 6.8 and 7.5

The objective for a continuous digester is to control and maintain the pH between 7.0 and 7.5. It is generally accepted that the optimum pH in anaerobic digestion is within a range between 6.8 and 7.4 in the reactor. If the pH is above 9, the methane production stops. If the pH is below 5, a destruction of the bacterial population is observed. The pH drop in the reactor is often a sign of an accumulation of volatile fatty acids.

Attention has to be given to a rise in pH which may occur due to protein nitrogen-rich effluent or co-product such as animal blood or manure that makes the degradation fatty acids volatile and their degradation gives off ammonia, which in turns becomes toxic at a high concentration.

VOLATILE FATTY ACIDS

Volatile fatty acids are either intermediate products from the fermentation and/or are introduced with the substrate. Measuring the content of volatile fatty acids is the best source of information.

A presence in small quantities indicates their consumption by methanogenic bacteria and therefore the good course of the digestion process. On the contrary, when there is an accumulation of volatile fatty acids, loss of buffering capacity and risk of decrease in pH will occur.

The objective in a continuous digester is to control and maintain the total quantity of volatile fatty acids below 5 to 7g/L.

BUFFERING CAPACITY

The buffering capacity is the neutralization of acids, which allows maintaining the pH of the digester.

It is important to provide a buffering capacity to control pH variations. Wastewater often gives a «natural» alkalinity due to the presence of cations residues from the degradation of proteins, fats and organic acids.
The objective in a continuous digester is to control and maintain the quantity of bicarbonates between 8 to 14 g/L carbonic acid equivalent.

CARBON / NITROGEN (C/N) RATIO INFLUENCE

Methanogenic bacteria growth is dependent on its environment. The C/N ratio of substrate is an important parameter to be considered by anaerobic degradation, since a high content of nitrogen may cause a too high content of ammonium nitrate in the biogas reactor. Ammonium nitrogen levels of about 4 g/L of wet sludge bring the risk of process inhibition. If the ammonium content is too high, it is necessary to dilute the substrate with water or nitrogen-poor material.

- Carbon / Nitrogen < 15:1: Danger of inhibiting the formation of methane due to the formation of ammonia to toxic levels.
- Carbon / Nitrogen > 40:1: Incomplete digestion of carbon linked to a lack of nitrogen.
- Carbon / Nitrogen between 20:1 and 40:1: the Carbon / Nitrogen ratio is well balanced. The digestion of organic matter can occur easily.

AMMONIA

Ammonia is an important inhibitor if the concentration is too high:

Substrates rich in nitrogen (poultry manure, blood) have to be limited
Effect increased with increasing temperature and pH

The objective in a continuous digester is to control and maintain the ammonium quantity below (NH_4+) below 3g/ L.

TRACE ELEMENTS

Enzymatic reactions require trace elements. Methanogen bacteria have a specific need for Nickel (Ni), Cobalt (Co) and Molybdenum (Mo) elements.

Table 9 shows the minimum recommended concentrations of these trace elements.

Trace elements	Concentration (mg/L)
Iron (Fe)	1 – 10
Nickel (Ni)	0.0005 – 0.5
Cobalt (Co)	0.003 – 0.06
Molybdenum (Mo)	0.005 – 0.05

Table 9: Minimum concentration in trace elements required for AD

OTHER PARAMETERS

Other main parameters to be closely monitored are the following:

- Absence of oxygen
- Oxidation Reduction Potential (ORP) below -300 miliVolts (mV)
- Hydrogen partial pressure between 0.5 and 10 Pascal (Pa)

4.3.3.5 THE IMPORTANCE OF COUNTINUOUS MIXING

Continuous mixing allows the following;

- Mixing the fresh substrate with the matter already in digestion;
- Inoculating the fresh substrate with active bacteria;
- Distributing the heat in the reactor;
- Avoiding / Destroying the scum and buildup of sediment;
- Improving bacterial exchanges.

4.3.3.6 RULES TO OPTIMIZE THE PROCESS:

A good anaerobic digestion has high yields of biogas production and small variations in yields of OM degradation (around 50%). To ensure such a process, the following must be observed;

- Accurately maintain the temperature level;
- Ensure uniform heating of the substrate;
- Introducing the substrates almost continuously;
- Avoid introducing a large amount of cold substrates;
- Make slow changes in the composition by stages;
- Avoid inhibitory substances (antibiotics, disinfectants...).

4.3.4 TYPICAL CO-DIGESTION PLANT DESCRIPTION

A biogas production unit comprises the following elements:

- Two unloading systems: one for the solid wastes and one for the liquids;
- One or two digesters (tank reactors) in which the waste mix is continually stirred up and where the methanisation process takes place in approximately 30 days;
- One post digester to receive and store the digested waste and to collect the last cubic meters of biogas that continues to be released by the waste;
- One biogas treatment unit to remove the sulphur (activated carbon, ferrous sponge), the water (bi-phase separator) and the organics (activated carbon).
- One co-generation unit (gas engines or gas turbine, generators and heat recovery systems).

PRESCRIPTIONS FOR FUTURE PROJECTS

5

5 Prescriptions for future projects

To maximize the energy production and low energy consumption of WWTPs, this chapter will present the recommended guidelines for each several possible WWTP projects.

5.1 Sludge treatment

- When the size of the plant is over 200,000 PE, a primary treatment is highly likely to be economically viable. Each time a primary treatment is constructed, anaerobic digestion with energy valorization should be studied. Each time, the possibility to oversize digestion and sludge dewatering to accept other products (sludge from small plants, industrial organic products) must also be evaluated.
- For average plants (100,000 to 200,000 PE), a solution with primary treatment must be studied to see if onsite digestion with energy production is economically viable.
- For small plants, a larger plant with onsite digestion must be identified to find a destination for the sludge and improve biogas production.

IMPORTANT NOTE ON AEROBIC DIGESTION:

According to the preliminary design of Sarafand (350,000 PE) and Majdal Anjar (300,000 PE) provided by CDR (Appendix 4.2), Aerobic Digestion has been proposed by the consultant. **Eliminating this kind of process is strongly recommended.**
As opposed to Anaerobic Digestion, Aerobic Digestion is a process that stabilizes sludge by the destruction of organic matter **in the presence of oxygen**. This process has been abandoned in many countries due to **its very high energy consumption** and due to the **necessary oxygen device,** despite its easy construction and lower investment costs compared to anaerobic digestion.

5.2 Sludge and co-digestion

To increase the organic matter at the inlet of the digestion of large plants, bringing in sludge from nearby smaller plants is one solution to increase energy production as well as being a solution for the final destination for the sludge of those small plants, thereby replacing land filling.

To decrease transportation costs, the sludge from the small plants must be dewatered. The solution of centrifuge for the small plants is adequate to adjust the optimum dry content to 18%-22%.

The best place for external sludge or the byproduct to be introduced would be the mixing tank before digestion. It has to be well studied and properly mixed.

Figure 13 below shows the typical diagram of a WWTP with sludge digestion.

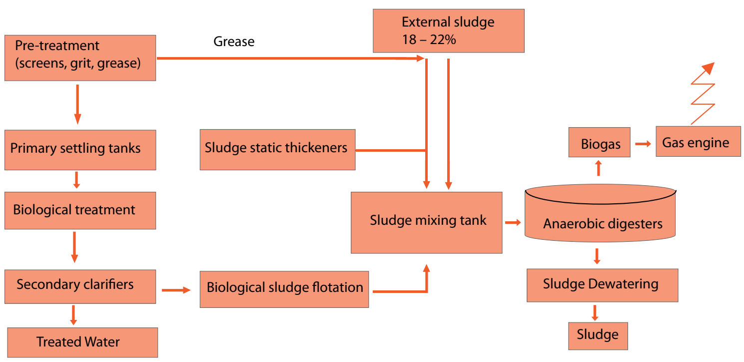


Figure 13: Typical WWTP diagram with sludge digestion

Depending on the size of the WWTP, three main cases can be identified and are indicated subsequently.

5.2.1 Case 1: large plant and external sludge

This situation is based on a large plant with a primary/ secondary treatment, anaerobic digestion and energy production. To accept sludge from the small plants in the surrounding area (around 20 km to 30 km away), a slight technical adjustment can be made to the large projects to accept additional external sludge;

- A proper discharge device in the sludge mixing tank
- A proper mixing design of this tank
- An overdesign of the rest of the sludge line (digestion, energy production, gas holders, dewatering) to accept the external sludge.

We could consider that an overdesign of around 20% will not affect the water treatment line of the plant.

5.2.2 Case 2: medium plant and external sludge

In this situation, the external sludge represents an important addition (from 40% to more than 100%). The entire WWTP must be designed to manage the process of a form of centralization of sludge digestion.

5.2.3 Case 3: one co-digestion central unit

In this situation a complete plant has to be largely designed, with its dedicated pre-treatment to accept sludge from nearby small scale WWTP and external industrial organic wastes.
The oversizing of the anaerobic digestion plant has to be studied, case by case, depending on the substrates identified during a preliminary study:

- Preparation of mixture before injection in the digester;
- Addition of a digester accepting co-products;
- Increase volume of each digester;
- Digestate treatment line for both liquid and solid phases.

5.3 Encourage boosting digestion

The tender documents for the construction must clearly encourage the bidders to propose options for boosting digestion. Each contractor has its own technologies with references and is able to propose a solution to boost digestion, when the tender documents allow it.

As an option, the constructor shall be allowed to propose a technology to boost digestion with:

- References;
- Investment costs;
- Operation costs;
- Estimated gain in energy production.

Technologies to boost digestion are detailed in Appendix 3, found in the accompanying CD.

5.4 Water treatment and air production

5.4.1 Air production

Air production is the major energy consumer of WWTP (more than 50% of the energy). Historically, oxygen was brought by surface mixing aerators. Despite their low investment costs and easy operation, this technology has been abandoned in many countries due to its high energy consumption and low depth aeration tank (4 meters) requirements.

The modern trend is a combination of an air production system and an air diffusing system. There is a large choice of air production technology depending on the oxygen requirement and the size of the plant.

Figure 14: Fine bubbles diffuser

SCENARIOS AND RECOMMENDATIONS

6

6 SCENARIOS and RECOMMENDATIONS

6.1 Assumptions related to biogas conversion

SLUDGE PRODUCTION ESTIMATE

All the sludge quantities are estimated at nominal capacity, i.e. at designed capacity.

BIOCHEMICAL METHANE POTENTIAL

Biochemical Methane Potential (BMP) as well as dry matter content and organic matter content, comes from the compilation of data[1] on the characteristics of substrates or parameters that have been determined by Amane Energy during laboratory tests. It is to be noted that theoretical BMP are subject to variation depending on the substrate quality and its interaction with other substrates.

BIOGAS CONVERSION

Table 10 summarizes the assumptions used to convert biogas into methane and methane into energy production. It is to be noted that, as a pre-caution, the consortium applies a rate of 10% of losses on the primary energy production.

Parameters	Unit	Value
Methane content in biogas	%	60.00
Methane Net Calorific Value	kWh/Nm^3	9.94
Estimated losses	%	10.00
Gas engine operating time	hour/year	8,000.00
Electrical output	%	39.00
Heat output through CHP	%	41.00
Total output through CHP	%	80.00
Heat output through Boiler	%	85.00

Table 10: Energy production assumptions

6.2 Project 1: TRIPOLI

6.2.1 Tripoli Sludge production at nominal and biogas production

It is expected that the Tripoli WWTP will be the first WWTP to enter into operation and therefore it is the reference plant to estimate data and parameters of future WWTP in construction or under preparation.

At the design load the WWTP of Tripoli will produce 51,704 kg of dry solids per day of primary sludge and 26,120 kg of dry solids per day of biological sludge. The organic matter of the primary sludge and biological sludge has been estimated respectively at 78.5% and 85.0%, due to the raw water organic content estimate.

Considering the rates of organic matter elimination (55% for primary sludge and 45% for biological sludge), the total destruction of organic matter is of 32,314 kg/day, which gives a biogas production of 29,083 Nm^3/day.

Table 11 below summarizes the sludge production of Tripoli WWTP and the related biogas production.

Parameter	Unit	Value
Primary sludge production	Kg DS/day	51,704
Organic matter content	%	78.50
Mineral matter content	%	21.50
Organic matter	kg OM/day	40,588
Mineral matter	kg MM/day	11,116
Biological sludge production	Kg DS/day	26,120
Organic matter content	%	85.00
Mineral matter content	%	15.00
Organic matter	kg OM/day	22,202
Mineral matter	kg MM/day	3,918
Anaerobic digestion		
Destruction of OM on primary sludge	%	55.00
Destruction of OM on primary sludge	kg/day	22,323
Destruction of OM on biological sludge	%	45.00
Destruction of OM on primary sludge	kg/day	9,991
Total OM destruction	kg/day	32,314
Biogas ratio	Nm^3/kg OM	0.9
Biogas production	Nm^3/day	29,083

Table 11: Tripoli sludge and biogas production

[1] Sources : Fachagentur Nachwachsende Rohstoffe, Domaix-Energie and Agence de l'Environnement et de la Maîtrise de l'Energie (ADEME)

6.2.2 Suggested improvement

It is currently planned that Tripoli WWTP will receive and treat, by incineration, the sludge of the following WWTP:

- Jbeil (50,000 PE)
- Batroun (24,000 PE)
- Chekka (21,000 PE)

Each of these plants is constructed and is waiting for connection to the sewer network to be operational.

It is recommended to treat the sludge from these three small scale WWTPs into the existing anaerobic digester of Tripoli, to increase the quantity of organic matter destroyed, rather than burning this sludge directly in the incinerator, and therefore increasing the biogas production of Tripoli.

This scenario will involve only a slight modification of the existing facility to receive the sludge before the digestion stage and for adequate mixing.

Tripoli WWTP is completed and operational; therefore it seems difficult to significantly modify its design at this stage. The introduction of a co-digestion plant instead of an anaerobic sludge digestion unit is not recommended as it will involve too many modifications to the existing facility and this would not be economically viable.

JBEIL SLUDGE PRODUCTION AT NOMINAL AND BIOGAS PRODUCTION

Given a population equivalent size of 49,000 and a production of 1,485 tons of dry matter per year through a bio-filtration process, the biogas production from Jbeil WWTP sludge is estimated at 555,984 Nm^3/year.

Table 12 below summarizes the sludge production of Jbeil WWTP and the related biogas production.

Parameter	Unit	Value
Name		Jbeil
Size	PE	49,500
Process		Biofiltration
Biological sludge ratio	Kg DS/year/PE	30.00
Biological sludge production	Kg DS/year	1,485,000
Organic matter content	%	80.00
Organic matter quantity	Kg DS/year	1,188,000
Organic matter destruction through Anaerobic Digestion:		
Biological sludge	%	52.00
Biological sludge	Kg DS/year	617,760
Biogas production	Nm^3/year	555,984

Table 12: Jbeil sludge and biogas production

CHEKKA SLUDGE PRODUCTION AT NOMINAL AND BIOGAS PRODUCTION

Given a population equivalent size of 21,000 and a production of 630 tons of dry matter per year through a bio-filtration process, the biogas production from Chekka WWTP sludge is estimated at 235,872 Nm^3/year.

Table 13 below summarizes the sludge production of Chekka WWTP and the related biogas production.

Parameter	Unit	Value
Name		Chekka
Size	PE	21,000
Process		Biofiltration
Biological sludge ratio	Kg DS/year/PE	30.00
Biological sludge production	Kg DS/year	630,000
Organic matter content	%	80.00
Organic matter quantity	Kg DS/year	504,000
Organic matter destruction through Anaerobic Digestion:		
Biological sludge	%	52.00
Biological sludge	Kg DS/year	262,080
Biogas production	Nm^3/year	235,872

Table 13: Chekka sludge and biogas production

BATROUN SLUDGE PRODUCTION AT NOMINAL AND BIOGAS PRODUCTION

Given a population equivalent size of 24,000 and a production of 579 tons of dry matter per year through aerated sludge process, the biogas production from Batroun WWTP sludge is estimated at 187,790 Nm^3/year. Table 14 below summarizes the sludge production of Batroun WWTP and the related biogas production.

Parameter	Unit	Value
Name		Batroun
Size	PE	24,000
Process		Aerated sludge
Biological sludge ratio	Kg DS/year/PE	24.15
Biological sludge production	Kg DS/year	579,600

Organic matter content	%	80.00
Organic matter quantity	Kg DS/year	463,680
Organic matter destruction through Anaerobic Digestion:		
Biological sludge	%	45.00
Biological sludge	Kg DS/year	208,656
Biogas production	Nm^3/year	187,790

Table 14: Batroun sludge and biogas production

6.2.3 Energy production

At the design load, sludge from Tripoli WWTP will produce 56,197,532 kWh/year primary energy. The plant is equipped with co-generation engines allowing the simultaneous production of electricity and heat. Therefore the energy production is the following:

- Electricity: 21,917 MWh/year;
- Heat: 23,041 MWh/year.

The addition of the sludge from Jbeil, Chekka and Batroun WWTPs in the Tripoli sludge digester, will permit an increase in energy production of 9.3%, i.e., 5,258 MWh primary energy, split as follows for an installed electrical power of 3.0 MW;

- Electricity: 2,051 MWh/year
- Heat: 2,156 MWh/year

Table 15 summarizes the quantity, biogas production, methane production, primary energy production and the electricity and heat generation for sludge from each different WWTP.

6.3 Project 2: Sour

6.3.1 Sour Sludge production at nominal and biogas production

Sour WWTP is currently under construction. At the design load, the WWTP will produce 4,732 tons/year of dry solids of primary sludge and 2,400 tons/year of dry solids of biological sludge. The organic matter content of the primary sludge and biological sludge has been estimated respectively at 78.5% and 85.0%, on the Tripoli WWTP basis.

Due to rates of organic matter elimination (55% for primary sludge and 45% for biological sludge), the total destruction of organic matter is approximately 2,961 tons/year, which entails a biogas production of 2,665,131 Nm^3/year.

	Quantity	Organic Matter content	Biogas Production	Methane Production	Primary Energy	Energy production through CHP	
	t DM/y	%	m^3/year	m^3/year	kWh/year	Electricity MWh/year	Heat MWh/year
Sludge from Tripoli WWTP	28,017		10,469,769	6,281,861	56,197,532	21,917	23,041
Primary sludge	18,613	78.50	7,232,717	4,339,630	38,822,334	15,141	15,917
Biological sludge	9,403	85.00	3,237,052	1,942,231	17,375,198	6,776	7,124
Sludge from Jbeil WWTP	1,485	80.00	555,984	333,590	2,984,300	1,164	1,224
Sludge from Chekka WWTP	630	80,0	235,872	141,523	1,266,067	494	519
Sludge from Batroun WWTP	580	80.0	187,790	112,674	1,007,984	393	413
TOTAL	30,711		11,449,415	6,869,649	61,455,882	23,968	25,197

Table 15: Tripoli project - Energy production

Table 16 summarizes the sludge production of Sour WWTP and the related biogas production.

Parameter	Unit	Value
Name		Sour
Size	PE	250,000
Process	Primary treatment, Secondary treatment	
Primary sludge ratio	kg DS/year/PE	18.9
Primary sludge production	kg DS/year	4,732,500
Organic matter content	%	78.50
Organic matter quantity	kg DS/year	3,715,013
Biological sludge ratio	kg DS/year/PE	9.6
Biological sludge production	kg DS/year	2 400 000
Organic matter content	%	85.00
Organic matter quantity	kg DS/year	2,040,000
Organic matter destruction through Anaerobic Digestion:		
Destruction of OM on primary sludge	%	55.00
Destruction of OM on primary sludge	kg DS/year	2,043,257
Biogas production of primary sludge	Nm^3/year	1,838,931
Destruction of OM on biological sludge	%	45.00
Destruction of OM on biological sludge	kg DS/year	918,000
Biogas production of biological sludge	Nm^3/year	826,200
Total biogas production	Nm^3/year	2,665,131

Table 16: Sour sludge and biogas production

6.3.2 Suggested improvement

The future WWTP of Tebnine & Chaqra (100,000 PE) is under preparation which means that it will not be commissioned, as an optimistic scenario, before 2018. The plant is too small to recommend a sludge anaerobic digestion, however it is located approximately 28 km from Sour. Therefore the sludge from Tebnine & Chaqra could be more easily treated at the Sour WWTP. It is recommended to add the sludge from Tebnine & Chaqra WWTP into the planned anaerobic digester of Sour to increase the quantity of organic matter destroyed and therefore the biogas production. This scenario involves an extension of Sour sludge anaerobic digestion, which has to be immediately planned before the completion of the Sour WWTP, where available land would have to be reserved for this extension beforehand.

The Sour WWTP is under construction; therefore it seems hard to significantly modify its design at this stage. The introduction of a co-digestion plant instead of a sludge anaerobic digestion unit is not recommended as it will involve too many modifications making it uneconomical.

TEBNINE & CHAQRA SLUDGE PRODUCTION AT NOMINAL AND BIOGAS PRODUCTION

Given a population equivalent size of 100,000 and a production of 2,415 tons of dry matter per year through an aerated sludge process, the biogas production from the Tebnine & Chaqra's future WWTP sludge is estimated at 782,460 Nm^3/year.

Table 17 summarizes the sludge production of Tebnine & Chaqra WWTP and the related biogas production.

Parameter	Unit	Value
Name		Tebnine & Chaqra
Size	PE	100,000
Process		Aerated sludge
Biological sludge ratio	Kg DS/year/PE	24.15
Biological sludge production	Kg DS/year	2,415,000
Organic matter content	%	80.00
Organic matter quantity	Kg DS/year	1,932,000
Organic matter destruction through Anaerobic Digestion:		
Biological sludge	%	45.00
Biological sludge	Kg DS/year	869,400
Biogas production	Nm^3/year	782,460

Table 17: Tebnine & Chaqra sludge and biogas production

6.3.3 Energy production

At design load, sludge from the Sour WWTP will produce 14,305,358 kWh/year primary energy. The plant will be equipped with co-generation engines allowing the simultaneous production of electricity and heat. Therefore the energy production will be as follows:

- Electricity: 5,579 MWh/year;
- Heat: 5,865 MWH/year.

The addition of the sludge from Tebnine & Chaqra WWTPs in the Sour sludge digester, will allow an increase in energy production of 29.4%, i.e., 4,200 MWh primary energy, split as follows (for an installed electrical power of 0.9 MW);

- Electricity: 1,638 MWh/year
- Heat: 1,722 MWh/year

Table 18 summarizes the quantity, biogas production, methane production, primary energy production and the electricity and heat generation for sludge from each different WWTP.

	Quantity	Organic Matter content	Biogas Production	Methane Production	Primary Energy	Energy production through CHP	
	t DM/y	%	m^3/year	m^3/year	kWh/year	Electricity MWh/year	Heat MWh/ year
Sludge from Sour WWTP	7,133		2,665,131	1,599,079	14,305,358	5,579	5,865
Primary sludge	4,733	78.50%	1,838,931	1,103,359	9,870,647	3,850	4,047
Biological sludge	2,400	85.00%	826,200	495,720	4,434,711	1,730	1,818
Sludge from Tebnine & Chaqra WWTP	2,415	80.00%	782,460	469,476	4,199,932	1,638	1,722
TOTAL	9,548		3,447,591	2,068,555	18,505,290	7,217	7,587

Table 18: Sour project - Energy production

6.4 Project 3: Aabde

6.4.1 Aabde Sludge production at nominal and biogas production

According to an extract of the Final Preliminary Design Report provided by CDR (Appendix 4, found in accompanying CD), Aabde WWTP is under design and the wastewater processes are planned for primary treatment, biological treatment and sludge stabilization through anaerobic digestion and biogas valorization through co-generation engines. The size of the plant, 185,000 population equivalent, is just within the range to implement a sludge AD independently.

At the design load, the WWTP will produce 3,502 tons/year of dry solids primary sludge and 1,776 tons/year of dry solids biological sludge. The organic matter content of the primary sludge and biological sludge has been estimated respectively at 78.5% and 85.0%, based on the WWTP of Tripoli.

Due to rates of organic matter elimination (55% for primary sludge and 45% for biological sludge), the total destruction of organic matter is of 2,191 tons/year which entails a biogas production of 1,972,197 Nm^3/year.

Table 19 summarizes the sludge production of Aabde WWTP and the related biogas production.

Parameter	Unit	Value
Name		Aabde
Size	PE	185,000
Process	Primary treatment, Secondary treatment	
Primary sludge ratio	kg DS/year/PE	18.93
Primary sludge production	kg DS/year	3,502,050
Organic matter content	%	78.50
Organic matter quantity	kg DS/year	2,749,109
Biological sludge ratio	kg DS/year/PE	9.6
Biological sludge production	kg DS/year	1,776,000
Organic matter content	%	85.00%
Organic matter quantity	kg DS/year	1,509,600
Organic matter destruction through Anaerobic Digestion:		
Destruction of OM on primary sludge	%	55.00
Destruction of OM on primary sludge	kg DS/year	1,512,010
Biogas production of primary sludge	Nm^3/year	1,360,809
Destruction of OM on biological sludge	%	45.00
Destruction of OM on biological sludge	kg DS/year	679,320
Biogas production of biological sludge	Nm^3/year	611,388
Total biogas production	Nm^3/year	1,972,197

Table 19: Aabde sludge and biogas production

6.4.2 Recommended scenario

Aabde WWTP is currently being designed, therefore it is suggested to plan an anaerobic co-digestion with local co-substrates, instead of a simple sludge AD, and add the sludge produced in nearby WWTPs, to boost energy production.
The future WWTPs of Bakhoun (48,000 PE) and Michmich (68,000 PE) are too small to suggest anaerobic digestion. On the other hand, both plants are located 20 km and 24 km, respectively, from Aabde.

Furthermore, the co-substrates identified during the Bioenergy Strategy Plan, in the local area, are the following:

WHEAT RESIDUES

Chicken manure: Two leaders of the poultry production (Hawa Chicken and Wilco) are located in North Lebanon;
Cattle manure;
Ovine manure;
Olive oil cake by-products: 36% of national production is located in North Lebanon;
Agro-food industry by-products.

Bakhoun WWTP is currently being designed, while no design has been elaborated for the Michmich WWTP. This entails that neither will be commissioned before 2018, similar to the Aadbe WWTP situation.

Bakhoun sludge production at nominal and Biogas production
Bakhoun wastewater treatment process is, at this moment, unknown. Given a population equivalent size of 48,000, the assumption has been made that the planned process is aerated sludge, to estimate the sludge production.

Given the size of the WWTP and a production of 1,159 tons of dry matter per year through the aerated sludge process, the biogas production from the Bakhoun sludge is estimated at 375,581 Nm^3/year.

Table 20 summarizes the sludge production of the future Bakhoun WWTP and the related biogas production.

Parameter	Unit	Value
Name		Bakhoun
Size	PE	48,000
Process		Aerated sludge
Biological sludge ratio	Kg DS/year/PE	24.15
Biological sludge production	Kg DS/year	1,159,200
Organic matter content	%	80.00
Organic matter quantity	Kg DS/year	927,360
Organic matter destruction through Anaerobic Digestion:		
Biological sludge	%	45.00
Biological sludge	Kg DS/year	417,312
Biogas production	Nm^3/year	375,581

Table 20: Bakhroun sludge and biogas production

MICHMICH SLUDGE PRODUCTION AT NOMINAL AND BIOGAS PRODUCTION

Michmich WWTP is currently being designed and the wastewater treatment process is currently unknown. Given a population equivalent size of 68,000, the assumption has been made that the planned process is aerated sludge, to estimate the sludge production.

Given the size of the WWTP and a production of 1,642 tons of dry matter per year through aerated sludge process, the biogas production from the Michmich sludge is estimated at 532,073 Nm^3/year.

Table 21 summarizes the sludge production for the future Michmich WWTP and the related biogas production.

Parameter	Unit	value
Name		Michmich
Size	PE	68,000
Process		Aerated sludge
Biological sludge ratio	Kg DS/year/PE	24.15
Biological sludge production	Kg DS/year	1,642,200
Organic matter content	%	80.00
Organic matter quantity	Kg DS/year	1,313,760
Organic matter destruction through Anaerobic Digestion:		
Biological sludge	%	45.00
Biological sludge	Kg DS/year	591,192
Biogas production	Nm^3/year	532,073

Table 21: Michmich sludge and biogas production

CO-SUBSTRATES BIOGAS PRODUCTION

This scenario proposes adding 20,000 tons/year of co-substrates for a methane production of 1,428,000 Nm^3/year and an energy production of 12,775 MWh/year primary energy.

Table 22 shows the selected co-substrates for this scenario as well as the related parameters, BMP and energy production.

Co-Products	Quantity	Dry Matter Content	Organic Matter content	Biogas content	BMP	Methane production	Primary Energy
	t RM/year	%	%	m^3/t RM	m^3/t RM	m^3/year	kWh/year
Wheat residues	3,000	89.00	84.50	263	171	513,000	4,589,298
Wet chicken manure	6,000	19.50	76.00	44	29	174,000	1,556,604
Dry cattle manure	5,000	22.00	75.00	77	50	250,000	2,236,500
Ovine manure	1,000	27.50	80.00	99	64	64,000	572,544
Olive oil cake by-products	3,000	28.00	N.A.	148	89	267,000	2,388,582
Agro-Food industries by-products	2,000	32.00	N.A.	133	80	160,000	1,431,360
TOTAL	20,000					1,428,000	12,774,888

Table 22: Aabde project - selected co-substrates

6.4.3 Energy production

At design load, sludge from Aabde WWTP will produce 10,585,965 kWh/year primary energy. As planned, in the design document, the plant will be equipped with a co-generation engine allowing the simultaneous production of electricity and heat. Therefore energy production will include the following:

- Electricity: 4,129MWh/year;
- Heat: 4,340 MWh/year.

The addition of sludge from Bakhroun and Michmich WWTPs in the Aabde digester will allow an increase in energy production of approximately 46% as compared to the treatment of Aabde sludge on its own, i.e., 4,872 MWh primary energy, split as follows:

- Electricity: 1,900 MWh/year
- Heat: 1,997 MWh/year

The addition of the various co-substrates to the Aabde co-digester will allow an increase in energy production of approximately 120% compared to the treatment of

Aabde sludge by itself, i.e., 12,775 MWh primary energy, split as follows:

- Electricity: 4,982 MWh/year
- Heat: 5,238 MWh/year

Altogether, this scenario will allow an increase in energy production of approximately 167% compared to the sludge digestion initially planned, for an installed electrical power of 1.38MW. The total primary energy is estimated at 28,233MWh, split as follows:

- Electricity: 11,011 MWh per year
- Heat: 11,575 MWh per year

Table 23 summarizes the quantity, primary energy production and the electricity and heat generation for sludge from each different WWTP and for each co-substrate.

	Quantity	Primary Energy	Energy production through CHP	
	t RM/year	kWh/year	Electricity MWh/year	Heat MWh/year
Sludge from Aabde WWTP	85,549	10,585,965	4,129	4,340
Sludge from Michmich WWTP	8,211	2,855,954	1,114	1,171
Sludge from Bakhoun WWTP	5,796	2,015,968	786	827
Wheat residues	3,000	4,589,298	1,790	1,882
Wet chicken manure	6,000	1,556,604	607	638
Dry cattle manure	5,000	2,236,500	872	917
Ovine manure	1,000	572,544	223	235
Olive oil cake by-products	3,000	2,388,582	932	979
Agro-food industries by-products	2,000	1,431,360	558	587
TOTAL	119,556	28,232,775	11,011	11,575

Table 23: Aabde project - Energy production

6.5 Project 4: SARAFAND

6.5.1 Sarafand Sludge production at nominal and biogas production

According to the preliminary design document provided by the CDR (Appendix 4), the Sarafand WWTP is under preparation and the wastewater processes planned are primary treatment, biological treatment and sludge stabilization through aerobic digestion. It is strongly recommended, as previously stated, to replace aerobic digestion, which is a very energy-intensive process, with anaerobic digestion and cogeneration to produce energy from the biogas.

At the design load, the WWTP will produce 6,152 tons/year of dry solids primary sludge and 3,120 tons/year of dry solids biological sludge. The organic matter content of the primary sludge and biological sludge has been estimated, respectively, at 78.5% and 85.0%, on the Tripoli WWTP basis.

Due to rates of organic matter elimination (55% for primary sludge and 45% for biological sludge), the total destruction of organic matter is of 3,849 tons/year, which brings a biogas production of 3,464,671 Nm^3/year.

Table 24 summarizes the sludge production of Sarafand WWTP and the related biogas production.

Parameter	Unit	Value
Name		Sarafand
Size	PE	325,000
Process	Primary treatment, Secondary treatment	
Primary sludge ratio	kg DS/year/PE	18.93
Primary sludge production	kg DS/year	6,152,250
Organic matter content	%	78.50
Organic matter quantity	kg DS/year	4,829,516
Biological sludge ratio	kg DS/year/PE	9.60
Biological sludge production	kg DS/year	3,120,000
Organic matter content	%	85.00
Organic matter quantity	kg DS/year	2,652,000
Organic matter destruction through Anaerobic Digestion:		
Destruction of OM on primary sludge	%	55.00
Destruction of OM on primary sludge	kg DS/year	2,656,234
Biogas production of primary sludge	Nm^3/year	2,390,611
Destruction of OM on biological sludge	%	45.00
Destruction of OM on biological sludge	kg DS/year	1,193,400
Biogas production of biological sludge	Nm^3/year	1,074,060
Total biogas production	Nm^3/year	3,464,671

Table 24: Sarafand sludge and biogas production

6.5.2 Recommended scenario

The Sarafand WWTP is under design and therefore it is recommended to plan an anaerobic co-digestion plant, fed with local co-substrates, including sludge produced from nearby WWTPs, to produce renewable energy and enable the facility to reduce its energy consumption.

The Nabatiyeh WWTP is constructed and will be operational in the next few months. The sludge production, given a size of 68,000 population equivalent, is too small to consider an anaerobic digestion unit. It is currently planned to send the produced sludge to landfill.

The future WWTPs of Yahmor (35,000 PE) is also too small to suggest anaerobic digestion.
Both plants are located 23 km and 24 km, respectively, from Sarafand.

The co-substrates identified during the Bioenergy Strategy Plan, in the local area, are the following:

- Wheat residues;
- Yellow grease;
- Goat/sheep manure;
- Agro-food industry by-products.

NABATIYEH SLUDGE PRODUCTION AT NOMINAL AND BIOGAS PRODUCTION

Given the size of the WWTP and a nominal production of 1,642 tons of dry matter per year, through aerated sludge process, the biogas production from the Nabatiyeh sludge is estimated at 532 073 Nm^3/year.
Table 25 below summarizes the sludge production of the Nabatiyeh WWTP and the related biogas production.

Parameter	Unit	Value
Name		Nabatiyeh
Size	PE	68,000
Process		Aerated sludge
Biological sludge ratio	Kg DS/ year/PE	24.15
Biological sludge production	Kg DS/year	1,642,200
Organic matter content	%	80.00
Organic matter quantity	Kg DS/year	1,313,760
Organic matter destruction through Anaerobic Digestion		
Biological sludge	%	45.00
Biological sludge	Kg DS/year	591,192
Biogas production	Nm^3/year	532,073

Table 25: Nabatiyeh sludge and biogas production

The dewatering equipment by centrifuge allows the production of sludge with 22% dry matter, i.e., a volume of 20 m^3 per day to be transported to Sarafand.

YAHMOR SLUDGE PRODUCTION AT NOMINAL AND BIOGAS PRODUCTION

No information was available on the Yahmor WWTP. Given a population equivalent size of 35,000, the assumption used to estimate the sludge production, is that the process planned is an aerated sludge. Given the size of the WWTP and a production of 845 tons of dry matter per year through the aerated sludge process, the biogas production from Yahmor sludge is estimated at approximately 273,861 Nm^3/year.

Table 26 summarizes the sludge production of the future Yahmor WWTP and the related biogas production.

Parameter	Unit	Value
Name		Yahmor
Size	PE	35,000
Process		Aerated sludge
Biological sludge ratio	Kg DS/year/PE	24.15
Biological sludge production	Kg DS/year	845,250
Organic matter content	%	80.00
Organic matter quantity	Kg DS/year	676,200
Organic matter destruction through Anaerobic Digestion		
Biological sludge	%	45.00
Biological sludge	Kg DS/year	304,290
Biogas production	Nm^3/year	273,861

Table 26: Yahmor sludge and biogas production

CO-SUBSTRATES BIOGAS PRODUCTION

This scenario proposes to add 9,000 tons/year of co-substrates for a methane production of 854,500 Nm^3/year and an energy production of 7,645 MWh/year primary energy.

Table 27 shows the selected co-substrates for this scenario as well as the related parameters, BMP and energy production.

Co-Products	Quantity	Dry Matter Content	Organic Matter content	Biogas content	BMP	Methane production	Primary Energy
	t RM/year	%	%	m^3/t RM	m^3/t RM	m^3/year	kWh/year
Wheat residues	1,500	89.00	84.50	263	171	256,500	2,294,649
Goats manure	5,000	27.50	80.00	99	64	320,000	2,862,720
Yellow grease	100	100.00	92.00	1,200	780	78,000	697,788
Agro Food industries by-products	2,500	32.00	N.A.	133	80	200,000	1,789,200
TOTAL	9,100					854,500	7,644,357

Table 27: Sarafand project - Selected co-substrates

6.5.3 Energy production

At design load, sludge digestion from Sarafand WWTP will produce approximately 18,600,000 kWh/year of primary energy. Depending on the valorization method, the energy production will be the following:

- Energy production through co-generation:
  - Electricity: 7,250MWh/year
  - Heat: 7,620 MWh/year
- Electricity production only: 7,250 MWh/year
- Heat production only: 15,800 MWh/year

The addition of the sludge from Nabatiyeh and Yahmor WWTPs in the Sarafand digester will allow an increase in energy production of 23% compared to the treatment of the Sarafand sludge on its own, i.e., approximately 4,325 MWh primary energy.

The addition of the various co-substrates in the Sarafand co-digester will allow an increase in energy production of 41% compared to the treatment of Sarafand sludge by itself, i.e., 7,640 MWh of primary energy.

Altogether, this scenario will allow, for an installed electrical power of 1.49MW, the production of 30,560 MWh of primary energy, split as follows (depending again on the valorization method):

Energy production through co-generation:
Electricity: 11,920MWh/year
Heat: 12,530 MWh/year
Electricity production only: 11,920 MWh/year
Heat production only: 25,980 MWh/year

Table 28 summarizes the quantity, primary energy production and the electricity and heat generation for sludge from each different WWTP and for each co-substrate.

	Quantity	Primary Energy	Energy production through CHP	Electricity production only	Heat production only	
	t RM/ year	kWh/year	Electricity MWh/year	Heat MWh/year	MWh/year	MWh/year
Sludge from Sarafand WWTP	150,289	18,596,966	7,253	7,625	7,253	15,807
Sludge from Nabatiyeh WWTP	8,211	2,855,954	1,114	1,171	1,114	2,428
Sludge from Yahmor WWTP	4,226	1,469,976	573	603	573	1,249
Wheat residues	1,500	2,294,649	895	941	895	1,950
Goats manure	5,000	2,862,720	1,116	1,174	1,116	2,433
Yellow grease	100	697,788	272	286	272	593
Agro-food industries by-products	2,500	1,789,200	698	734	698	1,521
TOTAL	171,827	30,567,253	11,921	12,533	11,921	25,982

Table 28: Sarafand project - Energy production

6.6 Project 5: Saida

6.6.1 Saida Sludge production at nominal and biogas production

According to the CDR, the pretreatment of Saida WWTP is completed and operational and the planned upgrading is under preparation. No more information was available and the water treatment process is, at this moment, unknown. Given a population equivalent size of 390,000, the assumption has been made that the water treatment process will be a preliminary treatment followed by a biological treatment.

At the design load, the WWTP will produce 7,380 tons/year of dry solids primary sludge and 3,740 tons/year of dry solids biological sludge. The organic matter content of the primary sludge and biological sludge has been estimated respectively at 78.5% and 85.0%, on the Tripoli WWTP basis.

Due to rates of organic matter elimination (55% for primary sludge and 45% for biological sludge), the total destruction of organic matter is of 4,610 tons/year, which brings a biogas production of 4,157,600 Nm^3/year.

Table 29 summarizes the sludge production of Saida WWTP and the related biogas production.

6.6.2 Recommended scenario

The Saida WWTP is currently being designed, and therefore an anaerobic co-digestion is recommended, fed with local co-substrates, and further supplied from the sludge produced in nearby WWTPs so that renewable energy can be produced.
The Ras Nabi Younes WWTP in Jiyeh is constructed and will be operational in the next few months. The plant process is a compact bio-filtration, implemented along the coastal area where no additional plot of ground is available to consider an anaerobic digestion unit. It is currently planned to send the produced sludge to the landfill.

The co-substrates identified during the National Bioenergy Strategy, in the local area, are the following:

- Slaughterhouse waste and grease from Saida and Jezzine slaughterhouses;
- Wheat residues;
- Olive oil cake by-products.

RAS NABI YOUNES SLUDGE PRODUCTION AT NOMINAL AND BIOGAS PRODUCTION

Given a population equivalent size of 88,000 and a production of 2,640 tons of dry matter per year through

Parameter	Unit	Value
Name		Saida
Size	PE	390,000
Process	Primary treatment, Secondary treatment	
Primary sludge ratio	kg DS/year/PE	18.93
Primary sludge production	kg DS/year	7,382,700
Organic matter content	%	78.50
Organic matter quantity	kg DS/year	5,795,420
Biological sludge ratio	kg DS/year/PE	9.60
Biological sludge production	kg DS/year	3,744,000
Organic matter content	%	85.00
Organic matter quantity	kg DS/year	3,182,400
Organic matter destruction through Anaerobic Digestion:		
Destruction of OM on primary sludge	%	55.00
Destruction of OM on primary sludge	kg DS/year	3,187,481
Biogas production of primary sludge	Nm^3/year	2,868,733
Destruction of OM on biological sludge	%	45.00
Destruction of OM on biological sludge	kg DS/year	1,432,080
Biogas production of biological sludge	Nm^3/year	1,288,872
Total biogas production	Nm^3/year	4,157,605

Table 29: Saida sludge and biogas production

the bio-filtration process, the biogas production from the Ras Nabi Younes sludge is estimated at 988,410 Nm³/year.

Table 30 summarizes the sludge production of the Ras Nabi Younes WWTP and the related biogas production.

Parameter	Unit	Value
Name		Ras Nabi Younes
Size	PE	88,000
Process		Bio-filtration
Biological sludge ratio	Kg DS/ year/PE	30.00
Biological sludge production	Kg DS/ year	2,640,000
Organic matter content	%	80.00
Organic matter quantity	Kg DS/ year	2,112,000
Organic matter destruction through Anaerobic Digestion:		
Biological sludge	%	52.00
Biological sludge	Kg DS/ year	1,098,240
Biogas production	Nm³/year	988,416

Table 30: Ras Nabi Younes

The water treatment process produces dewatered primary sludge that can be easily transported to Saida. The dewatering equipment by centrifuge allows the production of sludge with 27% dry matter, i.e., a volume of 25 m³ per day.

CO-SUBSTRATES BIOGAS PRODUCTION

This scenario proposes to add 6,900 tons/year of co-substrates for a methane production of 813,450 Nm³/year and an energy production of 7,270 MWh/year primary energy.

Table 31 shows the selected co-substrates for this scenario as well as the related parameters, BMP and energy production.

Co-Products	Quantity	Dry Matter Content	Organic Matter content	Biogas content	BMP	Methane production	Primary Energy
	t RM/year	%	%	m³/t RM	m³/t RM	m³/year	kWh/year
Slaughterhouse waste -Saida	2,500	50.00	90.00	153	92	230,000	2,057,580
Slaughterhouse grease - Saida	400	2% to 70	92.00	313	188	75,200	672,739
Slaughterhouse waste - Jezzine	1,500	50.00	90.00	153	92	138,000	1,234,548
Slaughterhouse grease - Jezzine	250	2% to 70	92.00	313	188	47,000	420,462
Wheat residues	1,500	89.00	84.50	263	171	256,500	2,294,649
Olive oil cake by-products	750	28.00	N.A.	148	89	66,750	597,146
TOTAL	6,900					813,450	7,277,124

Table 31: Saida project - Selected co-substrates

6.6.3 Energy production

This scenario will allow a total primary energy production estimated at 34,900 MWh, for an installed electrical power of 1.70MW, split as follows (depending on the valorization method):

- Energy production through co-generation:
  - Electricity: 13,610 MWh/year
  - Heat: 14,300 MWh/year
- Electricity production only: 13,610 MWh/year
- Heat production only: 29,660 MWh/year

That represents a 56% increase in energy production compared to the energy production from the digestion of Saida sludge only.

Table 32 summarizes the quantity, primary energy production and the electricity and heat generation for sludge from each different WWTP and for each co-substrate.

	Quantity	Primary Energy	Energy production through CHP	Electricity production only	Heat production only	
	t RM/year	kWh/year	Electricity MWh/year	Heat MWh/year	MWh/ year	MWh/year
Sludge from Saida WWTP	180,347	22,316,359	8,703	9,150	8,703	18,969
Sludge from Ras Nabi Younes WWTP	13,200	5,305,422	2,069	2,175	2,069	4,510
Slaughterhouse waste -Saida	2,500	2,057,580	802	844	802	1,749
Slaughterhouse grease - Saida	400	672,739	262	276	262	572
Slaughterhouse waste - Jezzine	1,500	1,234,548	481	506	481	1,049
Slaughterhouse grease - Jezzine	250	420,462	164	172	164	357
Wheat residues	1,500	2,294,649	895	941	895	1,950
Olive oil cake by-products	750	597,146	233	245	233	508
TOTAL	200,447	34,898,904	13,611	14,309	13,611	29,664

Table 32: Saida project - Energy production

6.7 Project 6: Majdal Anjar

6.7.1 Majdal anjar Sludge production at nominal and biogas production

According to the preliminary design provided by CDR (Appendix 4), the Madjal Anjar WWTP is under design and the processes planned are primary treatment, biological treatment, and sludge stabilization through aerobic digestion**.** It is strongly recommended, as previously stated, to replace aerobic digestion, which is a very energy intensive process, with anaerobic digestion and cogeneration to produce energy from biogas.

At the design load, the WWTP will produce 5,680 tons/year of dry solids primary sludge and 2,880 tons/year of dry solids biological sludge. The organic matter content of the primary sludge and biological sludge has been estimated respectively at 78.5% and 85.0%, taking assumptions from the Tripoli WWTP.

Due to rates of organic matter elimination (55% for primary sludge and 45% for biological sludge), the total destruction of organic matter is of 3,350 tons/year, which brings a biogas production of 3,198,150 Nm^3/year.

Table 33 summarizes the sludge production of Majdal Anjar WWTP and the related biogas production.

Parameter	Unit	Value
Name		Majdal Anjar
Size	PE	300,000
Process	Primary treatment, Secondary treatment	
Primary sludge ratio	kg DS/year/PE	18.93
Primary sludge production	kg DS/year	5,679,000
Organic matter content	%	78.50
Organic matter quantity	kg DS/year	4,458,015
Biological sludge ratio	kg DS/year/PE	9.60
Biological sludge production	kg DS/year	2,880,000
Organic matter content	%	85.00
Organic matter quantity	kg DS/year	2,448,000
Organic matter destruction through Anaerobic Digestion:		
Destruction of OM on primary sludge	%	55.00
Destruction of OM on primary sludge	kg DS/year	2,451,908

Biogas production of primary sludge	Nm^3/year	2,206,717
Destruction of OM on biological sludge	%	45.00
Destruction of OM on biological sludge	kg DS/year	1,101,600
Biogas production of biological sludge	Nm^3/year	991,440
Total biogas production	Nm^3/year	3,198,157

Table 33: Majdal Anjar sludge and biogas production

6.7.2 Recommended scenario

Majdal Anjar WWTP is currently being designed; therefore, it is recommended to plan an anaerobic co-digestion plant, fed with local co-substrates, and further add sludge produced in nearby WWTPs in order to produce renewable energy and reduce the facility's energy consumption.

The Zahle WWTP is under construction. The sludge production, given a size of 100,000 population equivalent, is too small to consider an anaerobic digestion unit. The plant will be located 15 km from Majdal Anjar.
The co-substrates identified during the Bioenergy Strategy Plan, in the local area, are the following:

- Agricultural residues: Barley and wheat residues;
- Liquid and solid manure (cattle, sheep and goat);
- Slaughterhouse waste and grease from Zahle;
- Agro-food industry by-products.

ZAHLE SLUDGE PRODUCTION AT NOMINAL AND BIOGAS PRODUCTION

Given the size of the WWTP and a production of 2,415 tons of dry matter per year, at nominal, through aerated sludge process, the biogas production from the Zahle sludge is estimated at 782,460 Nm^3/year.

Table 34 below summarizes the sludge production of the Zahle future WWTP and the related biogas production.

Table 35 shows the co-substrates selected for this scenario as well as the related parameters, BMP and energy production.

Parameter	Unit	Value
Name		Zahle
Size	PE	100,000
Process		Aerated sludge
Biological sludge ratio	Kg DS/year/PE	24.15
Biological sludge production	Kg DS/year	2,415,000
Organic matter content	%	80.00
Organic matter quantity	Kg DS/year	1,932,000
Organic matter destruction through Anaerobic Digestion:		
Biological sludge	%	45.00
Biological sludge	Kg DS/year	869,400
Biogas production	Nm^3/year	782,460

Table 34: Zahle sludge and biogas production

Co-substrates biogas production
This scenario proposes to add 17,400 tons/year of co-substrates for a methane production of 1,497,900 Nm^3/year and an energy production of 13,400 MWh/year primary energy.

Co-Products	Quantity	Dry Matter Content	Organic Matter content	Biogas content	BMP	Methane production	Primary Energy
	t RM/year	%	%	m^3/t RM	m^3/t RM	m^3/year	kWh/year
Slaughterhouse waste -Zahle	800	50.00	90.00	153	92	73,600	658,426
Slaughterhouse grease - Zahle	100	2% to 70	92.00	313	188	18,800	168,185
Cattle manure	4,000	22.00	75.00	77	50	200,000	1,789,200
Sheep & goat manure	6,000	27.50	80.00	99	64	384,000	3,435,264
Wheat residues	3,000	89.00	84.50	263	171	513,000	4,589,298
Barley residues	1,500	35.00	92.00	153	99	148,500	1,328,481

Agro-food industry by-products	2,000	32.00	N.A.	133	80	160,000	1,431,360
TOTAL	17,400					1,497,900	13,400,213

Table 35: Majdal Anjar Project - Selected co-substrates

6.7.3 Energy production

Altogether, this scenario will allow an increase in energy production by 100% compared to the digestion of Majdal Anjar sludge only, for an installed electrical power of 1.69MW. The total primary energy is estimated at 34,766 MWh, split as follows (depending on the valorization method):

- Energy production through co-generation:
  - Electricity: 13,560 MWh/year
  - Heat: 14,250 MWh/year
- Electricity production only: 13,560 MWh/year
- Heat production only: 29,550 MWh/year

Table 36 summarizes the quantity, primary energy production and the electricity and heat generation for sludge from each different WWTP and for each co-substrate.

	Quantity	Primary Energy	Energy production through CHP		Electricity production only	Heat production only
	t RM/year	kWh/year	Electricity MWh/year	Heat MWh/year	MWh/year	MWh/year
Sludge from Majdal Anjar WWTP	138,729	17,166,430	6,695	7,038	6,695	14,591
Sludge from Zahle WWTP	12,075	4,199,932	1,638	1,722	1,638	3,570
Slaughterhouse waste -Zahle	800	658,426	257	270	257	560
Slaughterhouse grease - Zahle	100	168,185	66	69	66	143
Cattle manure	4,000	1,789,200	698	734	698	1,521
Sheep & goat manure	6,000	3,435,264	1,340	1,408	1,340	2,920
Wheat residues	3,000	4,589,298	1,790	1,882	1,790	3,901
Barley residues	1,500	1,328,481	518	545	518	1,129
Agro-food industry by-products	2,000	1,431,360	558	587	558	1,217
TOTAL	168,204	34,766,575	13,559	14,254	13,559	29,552

Table 36: Majdal Anjar project - Energy production

6.8 Project 7: Bekaa

6.8.1 Recommended scenario

It is recommended to implement a co-digestion platform to group the wastewater treatment sludge of Baalbek, Laboueh, Tamnine Altahta, the co-products from the milk processing facility in Lebanon, Libanlait, and other available co-products.

During the on-ground survey of the National Bioenergy Strategy, Libanlait had expressed interest in finding an environmental treatment solution for its waste, particularly its liquid cattle manure.

Libanlait has at least the following co-substrates:

- Liquid cattle manure: 200 m^3/day;
- Solid cattle manure: 16.5 tons/day, i.e., 6,000 tons/year of which 3,000 tons/year are composted;
- Lactoserum.

The other co-substrates identified during the Bioenergy Strategy Plan, in the local area, are the following:

- Residues from cereals: wheat and barley residues;
- Manure (sheep and goat);
- Agro-food industry by-products.

The platform could be implemented in Baalbek WWTP or nearby the Libanlait facility, in Haouch Snaid. The Baalbek plant is an old plant with a very low connection rate of approximately 15% and needs to be upgraded before considering an AD unit. On the other hand, in the case of an implementation of the co-digestion plant close to Libanlait, the heat produced could be directly used for milk processing.

A feasibility study has to be conducted to determine the best location for the platform.

BAALBEK SLUDGE PRODUCTION AT NOMINAL AND BIOGAS PRODUCTION

The sludge production has been estimated based on the total capacity of an upgraded WWTP. Given the size of the WWTP and a nominal production of 2,150 tons of dry matter per year, through an aerated sludge process, the biogas production from the Baalbek sludge is estimated at 696,390 Nm^3/year.

Table 37 summarizes the sludge production of the Baalbek upgrade WWTP and the related biogas production.

Parameter	Unit	Value
Name		Baalbek
Size	PE	89,000
Process		Aerated sludge
Biological sludge ratio	Kg DS/year/PE	24.15
Biological sludge production	Kg DS/year	2,149,350
Organic matter content	%	80.00
Organic matter quantity	Kg DS/year	1,719,480
Organic matter destruction through Anaerobic Digestion:		
Biological sludge	%	45.00
Biological sludge	Kg DS/year	773,766
Biogas production	Nm^3/year	696,389

Table 37: Baalbek sludge and biogas production

TAMNINE ALTAHTA SLUDGE PRODUCTION AT NOMINAL AND BIOGAS PRODUCTION

Given the size of the WWTP and a nominal production of 2,415 tons of dry matter per year, through an aerated sludge process, the biogas production from the Tamnine Altahta sludge is estimated at 782,460 Nm^3/year.

Table 38 summarizes the sludge production of the Tamnine Altahta future WWTP and the related biogas production.

Parameter	Unit	Value
Name		Tamnine Altahta
Size	PE	100,000
Process		Aerated sludge
Biological sludge ratio	Kg DS/year/PE	24.15
Biological sludge production	Kg DS/year	2,415,000
Organic matter content	%	80.00
Organic matter quantity	Kg DS/year	1,932,000
Organic matter destruction through Anaerobic Digestion:		
Biological sludge	%	45.00
Biological sludge	Kg DS/year	869,400
Biogas production	Nm^3/year	782,460

Table 38: Tamnine Altahta sludge and biogas production

LABOUEH SLUDGE PRODUCTION AT NOMINAL AND BIOGAS PRODUCTION

Given the size of the WWTP and a nominal production of 1,280 tons of dry matter per year, through an aerated sludge process, the biogas production from the Laboueh sludge is estimated at 414,700 Nm^3/year.

Table 39 summarizes the sludge production of the Laboueh future WWTP and the related biogas production.

Parameter	Unit	Value
Name		Laboueh
Size	PE	53,000
Process		Aerated sludge
Biological sludge ratio	Kg DS/year/PE	24.15
Biological sludge production	Kg DS/year	1,279,950
Organic matter content	%	80.00
Organic matter quantity	Kg DS/year	1,023,960
Organic matter destruction through Anaerobic Digestion:		
Biological sludge	%	45.00
Biological sludge	Kg DS/year	460,782
Biogas production	Nm^3/year	414,704

Table 39: Laboueh sludge and biogas production

Co-substrates biogas production

This scenario proposes to add 38,000 tons/year of co-substrates for a methane production of 2,130,000 Nm^3/year and an energy production of 19,000 MWh/year primary energy.

Table 40 shows the co-substrates selected for this scenario as well as the related parameters, BMP and energy production.

Co-Products	Quantity	Dry Matter Content	Organic Matter content	Biogas content	BMP	Methane production	Primary Energy
	t RM/ year	%	%	m^3/t RM	m^3/t RM	m^3/year	kWh/year
Slaughterhouse waste -Zahle	800	50.00	90.00	153	92	73,600	658,426
Slaughterhouse grease - Zahle	200	2 to 70	92.00	313	188	37,600	336,370
Solid cattle manure - Libanlait	3,000	22.00	75.00	77	50	150,000	1,341,900
Liquid cattle manure - Libanlait	15,000	8.00	76.00	23	15	225,000	2,012,850
Lactoserum - Libanlait	5,000	6.00	86.00	39	25	126,750	1,133,906
Sheep & goat manure	6,000	27.50	80.00	99	64	384,000	3,435,264
Wheat residues	5,000	89.00	84.50	263	171	855,000	7,648,830
Barley residues	2,000	35.00	92.00	153	99	198,000	1,771,308
Agro-food industry by-products	1,000	32.00	N.A.	133	80	80,000	715,680
TOTAL	38,000					2,129,950	19,054,533

Table 40: Bekaa project - Selected co-substrates

6.8.2 Energy production

Altogether, the total primary energy of this scenario is estimated at 29,218 MWh, for an installed electrical power of 1.42 MW, split as follows, depending on the valorization method:

Energy production through co-generation:
Electricity: 11395 MWh/year
Heat: 11,980 MWh/year.

Electricity production only: 11,395 MWh/year
Heat production only: 24,830 MWh/year

Table 41 summarizes the quantity, primary energy production and the electricity and heat generation for sludge from each different WWTP and for each co-substrate.

	Quantity	Primary Energy	Energy production through CHP	Electricity production only	Heat production only	
	t RM/ year	kWh/year	Electricity MWh/year	Heat MWh/year	MWh/ year	MWh/ year
Sludge from Tamnine Altahta WWTP	48,300	4,199 932	1,638	1,722	1,638	3,570
Sludge from Baalbek WWTP	10,747	3,737 940	1,458	1,533	1,458	3,177
Sludge from Laboueh WWTP	6,400	2,225 964	868	913	868	1 892
Slaughterhouse waste -Zahle	800	658,426	257	270	257	560
Slaughterhouse grease - Zahle	200	336,370	131	138	131	286
Solid cattle manure - Libanlait	3,000	1,341,900	523	550	523	1,141
Liquid cattle manure - Libanlait	15,000	2,012,850	785	825	785	1,711
Lactoserum - Libanlait	5,000	1,133,906	442	465	442	964
Sheep & goat manure	6,000	3,435,264	1,340	1,408	1,340	2,920
Wheat residues	5,000	7,648,830	2,983	3,136	2,983	6,502
Barley residues	2,000	1,771,308	691	726	691	1,506
Agro-food industry by-products	1,000	715,680	279	293	279	608
TOTAL	103,447	29,218,369	11,395	11,980	11,395	24,836

Table 41: Bekaa project - Energy production

ECONOMICS OF AD USING WWTP OUTPUTS

7

7. Economics of AD using WWTP outputs[2]

7.1 Objectives of this chapter

The aim of this chapter is to understand the economics associated with the use of AD as an energy recovery technology for the sludge generated by the WWTPs. It is important to understand whether there is a financial case for the use of co-digestion to boost the energy yields of sludge AD plants.

The chapter also aims to outline the main considerations when assessing the economic viability of co-digestion AD projects offering conclusions and recommendations for the seven associated projects.

7.2 Understanding the economics of AD

Anaerobic Digestion (AD) is an established technology. For example, the European AD industry is amongst the largest across the world with around 12,000 operational plants. The growth of this industry has been heavily influenced by incentives available for end-use energy production. Experience has taught the European AD industry that setting the right level of incentives is crucial in developing a healthy, sustainable and economically attractive market which can prosper but not have detrimental impacts on other markets. Direct incentives such as electricity Feed-in Tariffs (FiTs), heat tariffs and transport fuel incentives are all end-use energy production incentives. They have a knock-on effect on the costs associated with obtaining feed-stocks and, more importantly, the capital costs of this technology. Other incentives such as direct capital grant schemes, landfill tax avoidance schemes and other local regional incentives also play a part in determining the costs of this technology.

7.2.1 Capital Costs of AD

Various metrics have been used to generate simple rule-of-thumbs for estimating the capital cost of AD. This can either be a typical investment cost per unit of kW electricity generated, or an investment cost per tonne of annual material processed. The choice of which metric is used to determine the investment cost of an AD plant depends on which feedstock is being processed. If one were to design a plant that used low-energy feed-stocks such as farm slurries and manures, then using an investment cost per kW output may be misleading as the electrical output of the plant would be small compared to the size required to process the feedstock. If on the other hand one were to base an investment cost for a high-energy yielding feedstock

2 This chapter has been written by Dr. William Mezullo, Biogas expert based in the United Kingdom.

AD plant, such as crops for example, it would then not be appropriate to use the tonnage throughput of the plant as a guide to the investment cost. Rather, the kW rating of the combined heat and power (CHP) should be used.

Capital costs within literature have been reported to be £2,500 to £6,000 per kW of installed electricity generating capacity[3]. Capital costs from a study of 60 German AD plants showed an average of around €3,000 per kW of electrical capacity. This equates to a capital cost per unit of methane output to be, on average, around £500/m^3 of methane per day[4].

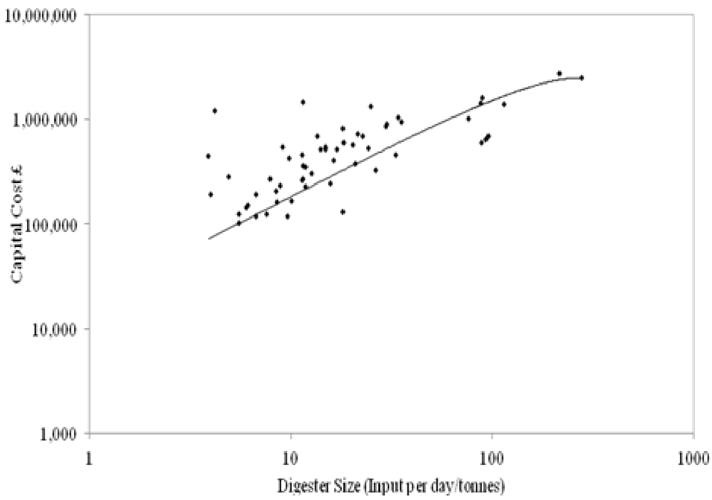


Figure 15. Capital costs of AD plants vs. daily feedstock input capacity- Data from 60 operational AD plants (FNR 2005)

3 Redman, G. 2008. A Detailed Economic Assessment of Anaerobic Digestion Technology and its Suitability to UK Farming and Waste Systems, The Anderson Centre, Leicestershire.

4 Exchange rate at the time of reporting costs in this chapter are as follows; 1 Euro = 1.3 US Dollars, 1 British Sterling = 1.63 US Dollars.

An analysis of 60 operational AD plants in Germany using a range of co-substrates, interestingly, showed that there was little correlation between the daily biogas output (and methane output) and the capital costs of the plants. A much closer correlation was obtained when the capital costs of a plant against the daily input of feedstock was examined. The results in the graph above show a near linear correlation of increase in capital costs versus the increase in daily input of feedstock into the plant. The capital cost for these plants averaged around €25,000/tonne of daily feedstock input.

The reason for the close correlation of CAPEX versus the daily input is that this measurement essentially dictates the size of digester and digestate storage tanks, the number of tanks and the size of the feeding equipment. It also dictates to some extent the size of the CHP.

The costs associated with AD set-up are primarily associated with the digester tank manufacture and installation. The digester cost is typically in the region of €50/m^3 and €30/m^3 for a digestate tank[5]. The installation costs for CHP units are typically between €360/kW to €1,200/kW installation capacity. Consequently, the CHP unit could account for 12-40% of the total capital investment.

The setup costs can vary significantly depending on the equipment and requirements adopted. For example, a simple animal waste AD plant would not require the use of a pasteurization facility. Other plant equipment, which may or may not be adopted for biogas production include hydrogen sulphide reduction systems, post-digestion solid separation systems which separate the fibrous fraction of the waste (used as P-fertiliser) from the liquid fraction of the waste (used as N-fertiliser) and other gas cleaning equipment.

Depending on the national environmental and farming regulations, further post AD treatments may also be required, which can ultimately increase the capital costs of a plant. This includes pasteurization equipment to remove pathogens from the process, or waste sorting reception halls which are required to have suitable biofilters and odour suppression equipment. This can add significant costs to an AD plant installation, however it is intrinsically dependant on the regulations of the country where the plant is installed and operated.

Given the basic materials and construction techniques used in AD plants, economies of scale play a crucial role. In simple terms, the specific costs per unit energy production (e.g. €/MW) for biogas production and utilisation increased significantly with decreasing plant size. A UK consultancy funded by the UK Government developed a set of equations to define CAPEX costs for biogas production and utilisation (e.g. digester, gas engine, upgrading etc.). The consultancy developed the equation to fit the majority of real costs gathered during data collection and analysis. The following has been extracted from their findings[6]:

The equations are based on a known cost for a known scale of plant (A) and a constant (N) that gives a non-linear change in cost with change in scale (B) to reflect economies of scale. An example is provided below:

CAPEX = CAPEX of plant A x (scale of plant B/scale of plant A)^N

For example, if the CAPEX of a known AD plant (excluding gas engine) is €7m for a plant with a capacity of 10,000 tonnes of dry matter per year, then a plant with a capacity of 20,000 tonnes of dry matter per year will cost:

CAPEX = €7m x $(20000/10000)^{0.6} = 7 \times 2^{0.6} = 7 \times 1.5 =$ €10.6m

Similarly, if a the CAPEX of a known AD plant (excluding gas engine) is €7m for a plant with a capacity of 10000 tonnes of dry matter per year, then a plant with a capacity of 5000 tonnes of dry matter per year will cost:

CAPEX = €7m x $(5000/10000)^{0.6} = 7 \times 0.5^{0.6} = 7 \times 0.66 =$ €4.6m

For other plant items different units depicting scale were used as appropriate (e.g. CAPEX for gas engines based on electrical output - €/MWe; CAPEX for boilers based on heat output - €/MWth; biogas upgrading equipment based on biogas input - €/m^3/h).

Given the favorable economies of scale, the financial output of biogas production at larger AD setups tends to be more favorable than smaller installations. Although this may be true for the setup costs, greater biogas production would ultimately require a greater availability of daily feedstock. This could result in increased feedstock collection and transport costs during operation. Therefore, there is a trade-off between the setup and operational costs and the expected biogas output of the plant.

For the purpose of this study a capital cost of €25,000/tonne of daily feedstock input was used for sludge AD installations given that this factor dominated the electricity output of the plant (in other words the

5 Ecofys 2005. Planning and Installing Bioenergy Systems - A guide for Installers, Architects and Engineers, 1st ed. Earthscan Publications Ltd, London.

6 SKM Enviros 2011 - Analysis of characteristics and growth assumptions regarding ad biogas combustion for heat, electricity and transport and biomethane production and injection to the grid.

sludge has relatively low energy output). The biogas output is dependant on the efficiency and feedstock of the plant. For high energy feed-stocks, such as crops for example, the assumptions used above would be misleading given that one would require minimal feedstock to produce the same amount of biogas (and electricity) than the feedstock required from sludge to make an equivalent amount of biogas. As sludge waste has a considerably lower energy output compared to the co-substrates, it is more appropriate to associate the CAPEX to the daily throughput of the plant.

7.2.2 Operational Costs of AD

Costs

The two most significant operating costs of an AD plant are the feed-stocks costs (positive or negative) and the actual site operation and maintenance costs. The use of slurry and farm waste will effectively provide "free" biogas, but given its low gas yield per wet tonne of feedstock, the size of the plant will need to be much larger. As more slurry and farm waste needs to be handled to produce a respectable amount of energy, the transport costs will then also rise. In addition to this, the increased digestate will also increase the transport costs to remove it from site. Therefore although slurries and manures may appear to be a good choice as a feedstock for AD, one should be careful not to over rely on these feedstocks and eliminate any energy benefits by having to transport from greater distances. The typical sources of operational costs for AD installations have been broken down below in the following sections:

Feedstocks: The cost of feedstock acquisition can either be a burden for an AD developer or an additional source of income. If co-substrates such as energy crops, maize, sugar cane or wheat are used in order to increase the energy performance of the plant, these in turn will have an acquisition cost associated to them. Typically the higher energy yielding feedstocks will have an associated acquisition cost for producing them.

On the other hand waste feedstocks, such as the co-substrates mentioned in this report, would ultimately end in landfill sites if a suitable waste treatment technology was not available. In some countries such as Germany where there is a total ban of organic material entering landfill, these feedstocks become an attractive opportunity for AD. Landfill sites typically charge a "gate-fee". This gate-fee can then be charged by the AD operator if the material is avoiding the need to enter landfill. Typically, for example in the UK, the value of this gate-fee has reached up to €87/ton. As a result of this, the financial viability of waste-AD plants in the UK is dependant on the income from gate-fees and not just the electricity generation.

The UK (and many other European countries) are now experiencing much lower gate-fees, typically around €30/ton due to a high demand for these wastes. In some cases investors are assuming a zero gate-fee value to increase the robustness of the project viability.

Transport: Transport costs of feedstocks and the return of digestate to the land can be an extremely significant cost and if the transport distance increases, the costs can escalate significantly. A recent experience in the UK, for example, estimated a net cost of the digestate from a particular AD plant to be €15 per ton. Although the digestate can provide valuable nutrients to farmland, including N, P and K (these are the most common agricultural fertilizers used) it has a very low dry matter content (often as low as 3-7% DM) making it very expensive to transport.

This is also true for low energy yielding feedstocks such as manures and slurries. From UK experience, it is not recommended that manures are transported more than 5-6 km from source to site. Higher energy yielding co-substrates such as grease and fat can be transported much greater distances as the energy (and cost) of transport becomes more marginal.

The sludge from WWTP in this report is assumed to have a 10% Dry Matter (DM) concentration. Consequently the energy density of sludge for AD is extremely low and transport distances should be minimised as much as possible.

On-site energy costs: If the AD plant is running successfully, the onsite electrical and heat demand should be zero. The electrical demand of a well-run AD plant should be between 2-5% of the total electrical output. This will vary depending on:

- The agitation technology adopted;
- The dry matter concentration within the fermenter;
- The type of pre-treatment and post-treatment technologies adopted;
- The overall efficiency of the plant.

Heat will also be required for the fermenter and this is typically in the range of 5-60% of total heat output from the plant. This energy is effectively free as it can be taken from the CHP cooling jacket. The heat demand will be dependent on a number of variables such as the dry matter and whether the plant is operated at mesophylic or thermophylic temperatures.

Although waste heat from the engine can be considered as a "free" source of energy, it can displace the opportunity of using and selling the heat for alternative demands. For example, if the plant is situated close to a high industrial energy user, the waste heat could be sold and become an additional revenue stream. Consequently, it is important to reduce the heat demand from the plant.

Maintenance and Repairs: Typically, the cost of maintaining an AD plant is around 2-3% of its capital value. The German industry believes these costs can be as high 4% of the total capital cost**4**. The maintenance of the CHP generator should be accounted for separately. Engine suppliers will often sell O&M (Operation and Maintenance) contracts with performance guarantees calculated as a cost per kW electrical generation. Larger, more efficient engines should cost around 1-1.23 Eurocent/kWh of electricity generated, whilst smaller or less efficient units can cost as much as 1.7 Eurocent/kWh. CHP will have a typical design life of 50-60,000 hours and require a major rebuild after that time. This might either be built into the support package provided or at separate cost. The replacement of a CHP generator every 6-8 years should be factored in when carrying out financial modeling for AD projects.

An analysis of 60 operational AD plants showed that maintenance costs (including spare parts and labor) can vary significantly[7]. These costs were found to be between €4,000/year on a capital cost of just under €500,000 up to €72,000 on a capital cost of just below €1million.

7.3 Revenue from AD

There are four possible sources of revenue from AD plants. These include the revenue from electricity production, heat generation, biogas as a transport fuel and the fertilizer properties of the digestate. Revenues from selling the energy part of the AD process are at present heavily dependent on national financial incentives available.

7.3.1 Electricity

For countries where AD deployment is common, the selling of electricity generated from the biogas can often be broken down into two parts. These include the revenue from a guaranteed Government financial subsidy (often called a Feed-in Tariff) and the revenue from selling the electricity on the wholesale market. The latter will often be a lower value compared to the electricity price paid by end-user customers as the generated electricity will be treated similarly to any other form of electricity generation (such as nuclear or coal for example).

In common practice, feed in tariff (FIT) guarantees a payment per unit of electricity produced for a number of years (as long the producers continue to produce the electricity). These tariffs can vary according to plant size and in the case of AD vary depending on the feedstock used for biogas production, as is the case in Germany and the UK.

The use of feed in tariffs is widely used across Europe. Of the 27 EU member states, 70% operate using FITs. Although FITs appears to be an attractive proposition, there are risks and uncertainties associated with this policy support scheme. The issue of a fixed price over a number of years could result in a deceleration of technology development and efficiency improvement, as financial income is secured.

7.3.2 Heat

There are very few cases where countries are currently incentivising the production of renewable heat. However this is now changing and more countries are introducing a "bonus" incentive for heat production. Data from German AD plants showed that heat energy in Germany was rewarded financially under certain circumstances. These included plants that were solely fed by either manures or energy crops. The cost of renewable heat in these cases was found to be between 4-6 €c/kWh depending on the plant scale. The percentage of the income derived from heat was found to vary between 3-26% of total annual revenue.

7.3.3 Transport Fuel

Selling biogas as a transport fuel is extremely common in Sweden where the number of biogas vehicles outnumbers the population of natural gas vehicles. There are, however, significant complexities and additional capital investment to convert biogas into a useable transport fuel. This technique can only work with considerable government incentives and a relatively high cost of gasoline.

7.3.4 Displacement of Artificial Fertilizer (Via Digestate)

The financial value of digestate as a valuable fertilizer can vary significantly depending on the farming demand for this product. A study carried out in the UK in 2006, for example, calculated a value of digestate compared with the application of slurry and inorganic fertilizer that would have been applied to the field if there was no AD facility. This value was around €1.5/ton of digestate. This value only represented the difference

7 FNR 2005 Ergebnisse des Biogas-Messprogramms (Scientific measurement programme for the evaluation of AD plants in the agricultural sector) Fachagentu Nachwachsende Rohstoffe e.V. (Government Agency for Renewable Energy Resources), Gülzow, Germany in nitrogen, potassium and phosphate composition (N, P2O5, K2O respectively) between the digestate and standard fertilizer techniques.

7.4 Economics assessment on identified WWTP options

Project 1

It is suggested that the Tripoli AD plant will also treat the additional wastes from Jbeil, Batroun and Chekka. However as the Tripoli plant is already operating it is not possible to retrofit an expansion to accommodate the additional feedstock. It is also understood that current plans are to treat the sludge through an incinerator.
If an additional standalone AD plant was installed on the Tripoli WWTP site which took in all the feedstock from the three smaller sources it would require a design annual capacity of 2,694 DM tons/year. In order to operate within an AD system the DM concentration would be a maximum of 10%. Therefore the design annual capacity would be around 27,000 tons of sludge per year. Based on this assumption the capital costs are estimated to be around €1.85million. The calculated electrical output of the plant would be 250kW.

Conclusion: co-digestion is not recommended. No further assessment required.

Project 2

The suggested improvement for this project would be to transport the sludge from Tebnin & Chaqra to the planned AD plant at Sour. As the Sour WWTP is already under construction it has not been recommended to retrofit an expansion to this plant.

Given this information, a standalone additional AD plant situation nearby to the Sour WWTP has been assessed. The design annual input for this plant would be around 24,000 tons per year with calculated electrical output of 200kW. The estimated capital cost of this plant would be approximately €1.6million.

Conclusion: The extension of Sour AD plant would be fed using additional sludge feedstock. The introduction of co-digestion at this stage is not possible. No further assessment required.

Project 3

The recommendation for this site is to design an AD plant using local substrates and add the sewage sludge from the WWTP – the total sewage sludge available from these three plants would be around 80,000 tons per year (fresh feedstock). The co-substrate feedstock would equate to around 20,000 tons per year. The calculated electrical output of a co-digestion AD plant is approximately 730kW; this is also the same size CHP rating for the sludge digestion AD plant. This example highlights very clearly the energy benefits of adding co-substrate due to the higher energy yields.

The recommended scenario for this project is to plan a co-digestion AD plant and then add the sludge from the nearby WWTP. The estimated capital cost of a 100% sludge fed AD plant would be approximately €5.5 million. Following the same calculation method the estimated capital cost of a co-substrate only fed AD plant would be between €1-2 million. However if the two feedstock streams were taken to a single AD plant the total annual throughput would be around 100,000 tons capable of generating around 1.5MW of electricity through CHP. The capital cost would be in the region €6.3 million following the formula for economies of scale.

Conclusion: The addition of co-substrate would increase biogas yields with nominal increase in capital costs. It is recommended to add co-substrate as a feedstock to the plant.

Project 4

It is recommended to plan an AD plant Sarafand where there is an available feedstock of just under 10,000 tons per year of dry sludge (equivalent to a feed of 93,000 tons per year assuming a 10% DM concentration). As the neighboring WWTP are too small it is recommended to transport the sludge feedstocks from these two plants to the main AD plant. This would require a total annual throughput of just under 120,000 tons per year. This would equate to an estimated capital cost of €7.9 million.

The addition of co-substrate feedstocks is relatively limited at around 9,100 tons per year. However, given the high energy output of this feedstock it is estimated that it should generate around 450kW of electricity through a CHP. The estimated capital cost of this plant as a standalone would be approximately €2 million. The additional of 9,000 tons per year is very small compared to the sludge feedstock availability. Therefore by using the economies of scale formula the expected capital cost of co-digestion would be €8.3 million.

Conclusion: Given the limited sizes of Yahmor and Nabatiyeh it is recommended that a centralised AD plant is installed at Sarafand capable of taking all the available feedstocks. Given the high energy output of the co-substrates it is recommended that co-digestion is preferred.

Project 5

It is recommended to install an AD plant at the Saida WWTP with the supplement of local co-substrates and sludge produced at nearby WWTP. The total annual throughput of the WWTP is calculated to be approximately 140,000 tons per year. Given the amount of feedstock required it is calculated that the capital cost of this plant would be around €9.3 million.

The co-substrate addition is very limited on this project compared to the amount of sludge that is expected to be treated. Consequently, using the economies of scale method the estimated capital expenditure with co-digestion would be around €9.6 million. The estimated co-substrate feedstock is approximately 7,000 tons per year. However as the co-substrate feedstock contains slaughterhouse waste, grease, wheat and other oil residues, its energy output per ton of feedstock is extremely high (in fact the highest per ton of material for any of the projects). A useful metric for comparing the performance of co-substrate is to divide the CHP rating by the daily tonnage throughput giving a kW/ton efficiency. The co-substrate for this project could generate around 22 kW/ton of daily material fed. The other projects in this report have been calculated to be between 13-17 kW/ton.
For this reason it would be favorable to simply add this feedstock into the total sludge available from the WWTPs. This would equate to an annual throughput of around 150,000 tons with a total electrical rating of 1.7MW. Given the large capital cost associated with treating all the sludge through an AD plant it is not expected that the addition of another 7,000 tons per year of feedstock would require any more significant investment.

Conclusion: It is recommended that co-digestion is included to this AD plant given the extremely high energy output of the co-substrate.

Project 6

The recommendations put forward for this project are very similar to the prior project. It is therefore suggested to treat all the sludge from the two WWTPs under a single AD plant installation (treating a total of 110,000 tons per year) with calculated capital investment of €7.4 million.

The availability of co-substrate means there is approximately 18,000 tons per year at the disposal of AD treatment. Installing a standalone AD plant for this quantity of material, producing around 770kW of electrical output, would require a capital investment in the region of €5.65 million. However it is recommended that this material is added to the sludge from the WWTP, in which case the fermenter size, the digestate storage tank and the CHP size would need to increase. These additions would pose a minimal increase to capital investment and using the economies of scale method the expected total capital expenditure would be around €8.1 million.

Conclusion: It is recommended that the use of co-digestion is implemented to this project.

Project 7

It is recommended to introduce co-substrates to the existing sludge availability from the proposed WWTPs. The total capacity from the WWTP sludge is approximately 60,000 tons per year capable of generating just under 500kW of electricity through a CHP. The estimated capital cost of this plant would be approximately €3.9 million.

The introduction of co-substrates in the other projects above were found to be extremely favorable in terms of maximizing energy output from the plant with minimal capital cost additional investment. This was due to the relatively high performance metric of the co-substrate of up to 22kW/ton of daily loaded material in some cases.

The issue identified with this particular project is that the low energy output of the co-substrate per ton of co-substrate added (the metric in this example is as low as 10 kW/ton of daily material added. Adding this amount of co-substrate would require around 65% more fermenter and digestate storage and an additional CHP unit rated at 1,000kW.

The total estimated capital cost of a combined co-substrate fed plant would require an annual throughput of approximately 260/tons per day (or just under 100,000 tons per year). This would equate to an estimated capital cost of €5.3 million.

Conclusion: It is recommended that certain co-substrates are introduced to this project. It is not recommended to use liquid cattle manure as a co-substrate due to its low energy potential and considerable daily tonnage availability.

7.5 Operating Costs and Returns from electricity displacement

At this preliminary stage it is difficult to ascertain the exact operational costs associated with these projects. However a rule of thumb technique should be used allowing around 2-4% of the total capital cost to be allocated to maintenance costs4. Assuming an average life of 20 years, the operation and maintenance costs as a percentage of capital costs was around 8-14%.

The revenue from electricity sales on the wholesale market alone is usually not enough to offer an attractive return for investment opportunities for renewable technologies. In countries where AD is being highly deployed it is evident that the payback of this technology is made attractive by the introduction of incentives such as an electrical feed-in tariff (FIT). Germany for example has a FIT ranging between 8-22 Eurocent/kWh, whilst the UK has FIT ranging from 9-15p/kWh (11-17 Eurocent/kWh). A country which has recently experienced a boom of AD installation (around 500MW installed over the past 2 years) has been Italy where the Government incentivised the production of electricity from AD with 28 Eurocent/kWh for up to 1MW plants.

These incentive levels are significantly higher than current electricity wholesale prices which are, for example, around 5-7 Eurocent/kWh in the UK. Yet the average cost of energy in Lebanon is $c26/kWh, and therefore these sources are relatively competitive using current values.

7.5.1 Expected simple payback of projects

The current industrial electricity prices for Lebanon have been obtained from Electricité du Liban[8] and have been used to assess the basic payback of the capital investment from the annual returns (gross will be used for simplicity). This will be applied to the projects that have been earmarked for co-digestion.

What can be deduced is that by adding a co-substrate to the sludge AD system will reduce the payback period significantly ranging from 20-60% reduction. All of the projects suggested to have co-digestion improved their payback period dramatically. Interestingly however, Project 7, where it was suggested that only part of the co-substrate were used for co-digestion purposes (i.e. to remove the liquid manure as a substrate) performed the best in terms of lowering the payback period time. This was due to the amount of co-digestion being more than the sludge itself. As a result it is still recommended to remove the lower performing feedstocks from the co-substrate feedstock list in order to maximize the efficiency of the plant.

The economics of the energy valorization from the WWTPs can also be presented in terms of the levelised costs of electricity, assuming a zero value for heat generated (therefore adopting a conservative assumption). Adopting an 8% interest rate and an assumed lifetime of 15 years, Table 43 presents the results.

PROJECT	CAPEX	Electricity Generation kWh	Revenue/year	Payback (yrs)
Project 3 WWTP	€ 5,535,000	5,961,592	€ 344,640	16
Project 3 Co-dig	€ 6,320,530	11,809,720	€ 682,720	9
Project 4 WWTP	€ 7,925,244	8,840,598	€ 511,075	16
Project 4 Co-dig	€ 8,287,734	12,340,056	€ 713,379	12
Project 5 WWTP	€ 9,273,863	10,652,801	€ 615,838	15
Project 5 Co-dig	€ 9,550,153	13,984,145	€ 808,423	12
Project 6 WWTP	€ 7,396,849	8,240,278	€ 476,370	16
Project 6 Co-dig	€ 8,079,675	14,374,669	€ 831,000	10
Project 7 WWTP	€ 3,939,370	3,919,844	€ 226,606	17
Project 7 Co-dig	€ 5,320,316	12,642,687	€ 730,874	7

Table 42. Simple payback period of the projects

As can be seen from the Table 42 above, without a financial incentive to generate clean renewable energy from AD in Lebanon the payback periods are not favorable. These payback periods are calculated using gross revenue from the AD plant.

8 Electricité du Liban: http://www.edl.gov.lb/AboutEDL.htm#5

Project 3		Project 4		Project 5	
Without Co-digestion	With Co-digestion	Without Co-digestion	With Co-digestion	Without Co-digestion	With Co-digestion
19.7	8.7	16.1	10.6	15.6	10.7

Project 6		Project 7	
Without Co-digestion	With Co-digestion	Without Co-digestion	With Co-digestion
16.2	9.0	7.7	7.1

Table 43. Levelised electricity costs of energy from 5 WWTPS in Lebanon

Table 43 shows that all scenarios are below the current average generation costs of the Lebanese electricity system. However, combining co-digestion delivers a much better levelised cost estimate.

7.6 Concluding Remarks on Economics

The capital cost of AD installations is dominated by the basic consumption of primary materials such as concrete and steel and civil engineering construction costs. As these costs are very well established and unlikely to reduce over time, AD as a renewable technology is different from other technologies such as PV, solar thermal or even wind, where the costs of materials and labor have gradually reduced over the past years.

Government placed financial incentives for generating renewable energy dominates the European market. In many cases the capital cost of these technologies are intrinsically linked to these incentives and there have been cases in Europe where, for example, the cost for the same 1MW AD plant is different from one country to another. Consequently, it is very difficult to determine the true cost of deployment for this technology in a country where there are at present no financial incentives.

What is clear is that due to the low energy output of sludge from WWTPs it is vital that AD plants using this as a primary feedstock need to be supplemented with co-substrates such as food and farming wastes. Co-substrate selection should however be limited to only high-energy yielding materials such as oily residues, wheat residues, agro-food products, grease, slaughterhouse waste and some manure. Feedstocks such as liquid cattle manure which are only able to generate around 25m^3/ton of feedstock should not be considered suitable as a co-substrate feedstock for AD.

CONCLUSION

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8. Conclusion

Through the available data collected, this study has identified five WWTPs that meet the condition to implement at least a sludge AD, i.e., Sour, Aabde, Sarafand, Saida and Majdal Anjar. An AD unit has already been implemented in Tripoli.

Altogether, the total primary energy expected from these six plants is estimated at 143,000 MWh, for an installed electrical power of 5.9 MW, split as follows (depending on the valorization method):

- Energy production through co-generation:
  - Electricity: 56,000 MWh/year
  - Heat: 58,700 MWh/year.
- Electricity production only: 56,000 MWh/year
- Heat production only: 121,800 MWh/year

The anaerobic digestion of sludge allows the production, on average, of 75% of the WWTP's electrical consumption. Heat production can be added to this in case of co-generation engines.
The sludge AD of these six WWTPs allows the reduction of greenhouse gas emissions by approximately 20,500 tons of CO_2 equivalent, compared to the use of natural gas.

To increase the energy production and enable WWTPs to reduce their fossil fuel energy consumption, co-digestion scenarios, with local co-substrates and sludge produced in nearby WWTPs, have been developed.

The implementation of Sludge Anaerobic Digestion in small to medium WWTP is not economically viable. The final disposal of the sludge is currently planned to go for landfilling. Therefore it is recommended to treat this sludge in a large scale WWTP equipped with AD.

Additionally, a co-digestion platform scenario in the Bekaa region has been developed based on the sludge produced in three WTTPs and co-substrates, mainly from the main Lebanese milk processing facility. The feasibility of collection and transport of these co-substrates in the region needs to be studied and evaluated.
Based on the National Bioenergy Strategy, co-substrates, such as manure, agricultural residues and agro-food industries co-products, have been selected according to the regional production and the estimated availability.

The addition of sludge from small to medium WWTP and co-substrates allows an average increase in energy production of 70% compared to the digestion of sludge only, for an installed electrical power of 11.6 MW. The total primary energy is estimated at 237,700 MWh, split as follows (depending on the valorization method):

Energy production through co-generation:
Electricity: 92,700 MWh/year
Heat: 97,400 MWh/year.
Electricity production only: 92,700 MWh/year
Heat production only: 202 100 MWh/year

	Primary Energy	Energy production through CHP		Electricity production onlyproduction only	Heat production only MWh/year	Electrical Power
	kWh/year	Electricity MWh/year	Heat MWh/year	MWh/year	MWh/year	MWel
Tripoli WWTP	56,197,532	21,917	23,041	21,917	47,768	2.74
Sour WWTP	14,305,358	5,579	5,865	5,579	12,160	0.70
Aabde WWTP	10,585,965	4,129	4,340	4,129	8,998	0.52
Sarafand WWTP	18,596,966	7,253	7,625	7,253	15,807	0.91
Saida WWTP	22,316,359	8,703	9,150	8,703	18,969	1.09
Majdal Anjar WWTP	17,166,430	6,695	7,038	6,695	14,591	0.84
TOTAL	139,168,610	54,276	57,059	54,276	118,293	6,78

Table 44: Total energy production from sludge AD projects

	Primary Energy	Energy production through CHP		Electricity production only	Heat production only	Electrical Power
	kWh/year	Electricity MWh/year	Heat MWh/year	MWh/year	MWh/year	MWel
Tripoli Project	61,455,882	23,968	25,197	23,968	52,238	3.00
Sour Project	18,505,290	7,217	7,587	7,217	15,729	0.90
Aabde Project	28,232,775	11,011	11,575	11,011	23,998	1.38
Sarafand Project	30,567,253	11,921	12,533	11,921	25,982	1.49
Saida Project	34,898,904	13,611	14,309	13,611	29,664	1.70
Majdal Anjar Project	34,898,904	13,611	14,309	13,611	29,664	1.70
Bekaa Project	29,218,369	11,395	11,980	11,395	24,836	1.42
TOTAL	237,777,377	92,733	97,489	92,733	202,111	11.59

Table 45: Total energy production from co-digestion projects

Altogether, these seven projects allow the reduction of greenhouse gas emissions by approximately **35,000 tons of CO_2 equivalent**, compared to the use of natural gas.
As shown in Table 44, the increase in energy production will permit the WWTPs to be self-sufficient in terms of electricity and even produce it in excess.

	Electricity consumption estimate	Co-digestion project
	MWh/year	% of electricity consumption produced
Tripoli WWTP	28,800	83
Sour WWTP	7,250	100
Aabde WWTP	5,365	205
Sarafand WWTP	9,425	126
Saida WWTP	11,310	120
Majdal Anjar WWTP	8,700	156

Table 46: Percentage of WWTPs electricity consumption produced through co-digestion

THE ENERGY PRODUCTION OF THESE SEVEN PROJECTS COULD REPRESENT 3% TO 4% OF THE NATIONAL BIOENERGY POTENTIAL IDENTIFIED IN THE BIOENERGY STRATEGY PLAN.

The economics of the energy valorization from the WWTPs have been presented in terms of payback period and the levelised costs of electricity, assuming a zero value for heat generated (therefore adopting a conservative assumption). Adopting an 8% interest rate and an assumed lifetime of 15 years, the levelised costs resulted in favorable values relative to the current average generation costs for electricity in Lebanon. In terms of payback period, only when co-digestion is included would the payback periods of the various projects be acceptable.

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