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Essential oil production in rural Africa

Identifying and evaluating technologies to reduce the fossil energy needs for steam distillation

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Abstract

The goal of this study is to identify opportunities to reduce the fossil energy use for the steam distillation process of essential oils (EO) in rural Africa. Therefore, renewable energy technologies (RETs) and energy efficiency measures (EEMS) were identified, evaluated and assessed on applicability. As a results, eight technologies were found suitable to achieve this goal, these are: CSP-, biomass- and efficient boiler, an economizer, solar water heating (SWH) system, feedwater condenser, insulation and cascading heat (using a heat pump). These technologies were evaluated on fitness for rural Africa, energy reduction potential and costs. A model was constructed to assess the fitness for rural Africa for each technology. This model was based on relevant technological criteria found in a case- and literature study. In addition, a model was constructed to calculate the energy requirements for EO distillation. Moreover, this model was used to calculate the potential energy reduction and levelised costs of energy for the identified technologies. At the evaluation step, it was found that insulation, an economizer, CSP boiler and SWH system are most fit to be implemented in rural Africa. RETs (CSP- and biomass boiler), cascading of heat and an efficient boiler, respectively have the highest energy reduction potential. The most cost effective energy reduction technologies identified are insulation, feedwater condenser and an economizer, respectively. However, not all identified technologies can be implemented simultaneously, since some compete with each other or are subject to case specific factors. Therefore, the technologies were assessed on their applicability. This was done by using a reference case, an EO distillery in the Baviaanskloof, South Africa. A decision tree was constructed to identify the applicable technologies for a specific case. For the reference case it was found that an efficient boiler, insulation, SWH system and a feedwater condenser could be applied. Here a feedwater condenser is preferred over the competing SWH system technology, since it has higher energy reduction potential and lower associated costs. As a final result of this research, an extensive overview and evaluation of fossil energy reducing technologies is given, that fit the EO production process in rural Africa.

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Nomenclature and abbreviations

A	surface area, m^2
α	thermal diffusivity, m^2s^{-1}
β	volumetric coefficient of expansion, K^{-1}
C_p	specific heat, J/(kg.K)
E	energy, J
g	gravitational acceleration, m/s^2
h	heat transfer coefficient, $W/(m^2K)$
h_i	enthalpy, kJ/kg
HV	heating value, kJ/kg
k	thermal conductivity, $W/(m^2K)$
L	length, m
M	mass, kg
$\dot{m}$	mass flowrate, kg/h
η	efficiency, %
Nu	Nusselt number, no unit
P	power, W
Ra	Rayleigh number, no unit
T	temperature, K or °C
t	time, s
X	characteristic dimension, m

EEMs	Energy efficiency measures
EO	Essential oils
DS	Distillation still
GHGs	Greenhouse gasses
LCOE	Levelized cost of energy
RETs	Renewable energy technologies
SP	Steam pipe
SWH	Solar water heating

1. Introduction

1.1. Background

The essential oil market is growing and in 2022, it is expected to be an $11,5 billion market (Allied, 2016). The major factor for this increase is due to the consumer preference for natural and organic products. Essential oils (hereafter described as EO) are applied in a wide variety of products but primarily used in the cosmetic and food industry. Most EO for commercial use, are obtained by steam distillation, which is therefore the most widely applied method (about 93 percent) (Masango, 2005). This production method is an energy intensive process, which makes up for 20-40 percent of the total processing costs (Boris, 2012). In a Lifecycle analysis study into the production (using steam distillation) of EO from Spearmint, it was found that over 90 percent of the energy used comes from non-renewable energy sources (Heydari et al., 2015).

The EO industry is agro based, and EO distillation is often done near the cultivation site (Kebede & Hayelom, 2008). This is for quality- and economic reasons. Processing the plants immediately after harvesting results in higher yields and a specific chemical composition (which differs from the composition of using dried biomass material) (Baser & Buchbauer, 2010). Furthermore, the EO are a very small fraction of the mass of the bio material. Transportation from the rural area to a central facility can therefore be very costly. Therefore, it is often preferred to distil EO on site (A Munir & Hensel, 2010).

In sum, the EO market is expected to grow, and the production of EO is an energy intensive process, where most energy is often supplied by non-renewable energy. Furthermore, the distillation facility is often near the harvesting location. Hence, many distillation facilities are decentralized and located in rural areas. A case that fits the above mentioned profile is found in the Baviaanskloof (valley of the Baboons), South Africa.

The incentive for producing EO in the Baviaanskloof is the need for a more sustainable agricultural business model, to counteract land degradation on a large scale. The opportunities that occur in a growing EO market have convinced the local farmers to move from traditional goat farming to cultivating lavender and rosemary (Grounded, 2017). The rosemary and lavender are cultivated for the production of EO. On location, a distillery is constructed to produce the oils, since transporting the biomass outside the valley is not an option.

The steam distillation process is predominantly powered by a diesel boiler. The use of diesel significantly increases the carbon footprint of the facility and has high operational cost; transportation into remote area and rising diesel prices (Khadka & Shakya, 2014). A growing concern of the exhaust of greenhouse gasses and the energy cost component, drive the urge for a reduction of fossil fuel use during the production process for EO.

Therefore this study looks into opportunities for reducing the amount of fossil energy used for the production of EO. This can be done by reducing energy use by process optimization, using renewable energy sources and applying energy efficiency measures (RVO, 2013). Examples are, respectively, adequate boiler management, utilising a biomass boiler and insulation hot objects to counteract heat losses. This study specifically focuses on technologies; renewable energy technologies (hereafter described as RETs) and energy efficiency measures (hereafter described as EEMs) that suit the production process. These technologies will be evaluated on their energy saving potential and their associated costs. Additionally, to take into account the fact that the production of EO is often located in rural areas of Africa, this study will identify criteria for the implementation of technologies in rural Africa. The selected RETs and EEMs will be evaluated against these criteria. Finally, the found results are put to practice, by looking into the applicability of these technologies at the reference case in Baviaanskloof.

1.2. Research- aim and questions

The aim of this research is to identify technologies in order to make the production of EO less fossil energy consuming, in rural areas of Africa. This is done by looking into RETs and EEMs that reduce the fossil energy demand. The obtained outcomes of this study should give EO producers (e.g. farmers of the Baviaanskloof) insight in how to reduce the amount of fossil energy during their distillation process. This results in the following research question:

''How can the production of essential oils using steam distillation, by applying RETs and EEMs, become less fossil energy demanding for EO distilleries in rural Africa?''

In order to answer the main research question, sub questions are formulated:

1. What technological criteria should be considered when implementing RETs or EEMs in rural Africa?

2. What are the energy needs and losses for the production process of essential oils, using steam distillation?

3. What RETs and EEMs suit the production process of essential oils, for steam distilleries in rural Africa?

4. How do the identified technologies perform on the criteria: fitness for rural Africa, energy reduction potential and costs?

5. How can the identified energy reduction technologies be applied in the specific case of the Baviaanskloof?

Answering these sub questions, will provide insight that is required for answering the main research question. This will provide an overview of technologies that reduce the fossil fuel consumption for the production of essential oils, specified on distilleries that are located in rural Africa. Furthermore, it is assessed how the energy reduction technologies can be applied to the reference case.

1.3. Scope and boundaries

The most widely applied method for EO extraction is steam distillation, 93 percent of the EO are produced using this method (Masango, 2005). Other methods for essential oil extraction are hydro-diffusion, solvent-, critical fluid- extraction and water distillation. However, steam distillation is the most used and accepted method for commercial essential oil production (Özek, 2012). Since steam distillation is the most widely applied method, this study specifies on steam distillation, other methods are beyond the scope of this research.

The value chain of EO consists of an agricultural- and an extraction process (Heydari et al., 2015). After that, the oil is packed and distributed among manufacturers, who turn it into cosmetics, medical and food products which are sold on to retailers. In this study the focus is on the extraction process; steam distillation. Therefore, a gate-to gate approach is chosen and the agricultural process and further distribution and manufacturing of the final-product is outside the scope of this study.

The distillation of EO is often done on site. This is mainly for two reasons; it is unpractical and economically unattractive to transport the biomass over long distances, and the fact that biomass needs to be distilled as it is still fresh, for quality reasons (Baser & Buchbauer, 2010). Furthermore, this study uses a reference case, the essential oil distillery in the Baviaanskloof, South Africa. This facility is located in a rural and remote area. For the above mentioned reasons, the study specifies on the essential oil production in rural areas in Africa.

1.4. Study outline

In effort to answer the main research question, this study employs a combination of literature research and case study methods. For multiple sub questions, the results from literature study are either validated through the case study or applied to the case study. The case that is used in this study is an EO distillery located in the Baviaanskloof, South Africa.

The next chapter, Theoretical background, discusses general theory on EO production. The Method chapter elaborates on the way the sub questions were studied. The research employs the following steps that directly corresponds to the sub questions:

1. Identification of technological criteria for rural Africa, based on the case study and literature.
2. Identification of energy- needs and losses for the distillery in Baviaanskloof.
3. Identification of energy reduction technologies for steam distillation in rural Africa.
4. Evaluation of identified technologies on fitness for rural Africa, energy reduction potential and costs.
5. Assessing the applicability of the identified technologies in general and to the reference case.

Thereafter, the Results chapter discusses the findings for each research step in the research process. The Results chapter is followed by the Discussion section, which sheds light on the implications and limitations of this research. Finally, the Conclusion chapter answers the main research question.

2. Theoretical background

This chapter discusses the most important underlying theory that is needed for conducting this study. Theory on the production process of EO and its energy needs is touched upon. During this process, the boiler requires most fossil energy, therefore the theory of boiler operation and its energy needs and -losses are explained.

2.1. Production of essential oils

Essentials oils are multi-component chemicals and can be obtained from aromatic plant material. The chemical compositions of these oils differ widely. They are important ingredients for cosmetics, spices, flavour, fragrance, perfumes and the conservation of food (Kostova et al., 2010).

2.1.1. Steam distillation

Steam distillation is a well-known and relatively simple process (see Figure 1). Plant material is placed in a cylindrical still. Outside this still, steam is generated by a boiler. The steam is passed through the packed plant material. The EO are present in the cells of the plant. Increasing the temperature causes the cell walls to burst. This releases and evaporates the oils, which are then carried within the steam flow (Baser & Buchbauer, 2010). Thus, the steam has two functions; evaporating the oils by heating the biomass and act as a carrier of evaporated essential oil molecules. For most plants, distillation is done at atmospheric pressure. However, for some plants, the oils have higher boiler points, and therefore the distillation system is pressurized to increase the steam temperature (Baser & Buchbauer, 2010).

This steam- oil mixture is collected at the top of the still. This steam flow leaves the distillation still (can be referred to as DS) and enters the condenser. Here the steam is cooled down and condenses. The cooling of the steam is done by cooling water, which is pumped through the condenser and exchanges heat with the steam- oil mixture. Thereafter, the condensate flows into a separator. In the separator, the oil content is separated from the water and collected as product. The water obtained is called aromatic water or hydrosol, since it contains dissolved polar compounds of the biomaterial (Masango, 2005).

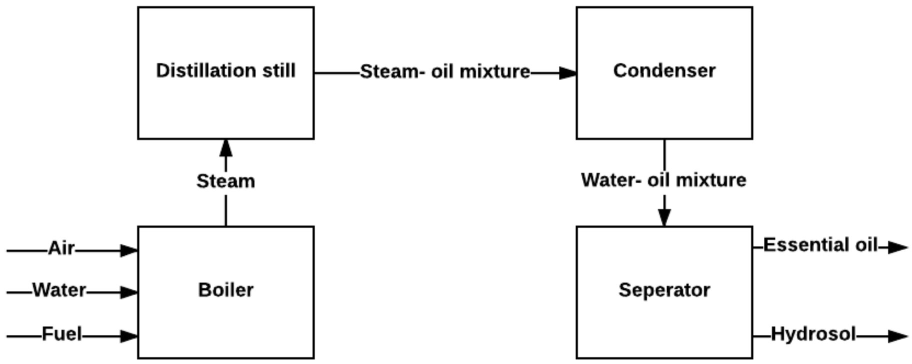

Figure 1. Steam distillation process essential oils

The main energy requirement for this process is the production of steam. Furthermore, energy is needed to pump circulate water, to produce a cooling flow. This is the general steam distillation process. However, the process parameters differ for each specific plant material and distillation facility (Özek, 2012). Therefore, the important yield optimization parameters and key performance indicators (KPIs) are briefly discussed.

2.1.2. Key performance indicators

Important yield optimization parameters are distillation time and steam flowrate (Özek, 2012). Distillation time (s) is the time that steam passes though the plant material. And steam flowrate (kg/h) is the amount of steam that passes through the material given a certain time (Özek, 2012). Important KPIs are the oil concentration, oil extraction and energy required for oil extraction. The corresponding units are: mL oil/mL condensate, mL oil/kg biomass and kWh/mL oil, respectively.

A method for determining the optimal distillation time and steam rate, is to construct oil yield curves (Masango, 2005). This is done by measuring the oil concentration (mL oil/mL condensate) over time at different steam rates. The curve will indicate the most productive steam rate and the corresponding distillation time. In Figure 2, an example of an oil yield curve is shown. This curve is constructed by using a laboratory setup and collecting samples during the distillation process at equal time intervals. This was done for three different steam flow rates. It can be seen that the highest yield was obtained with the lowest flowrate, 2.5 ml/min.

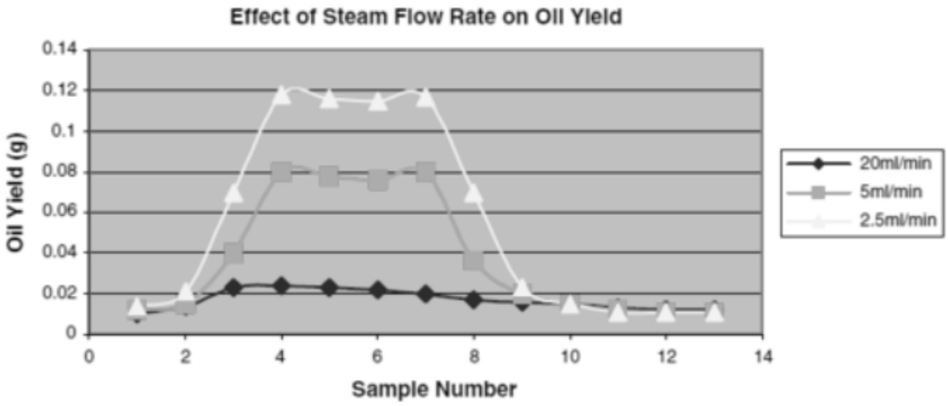

Figure 2. Yield curve; effect of steam flowrate on oil yield, Masango 2005

2.1.3. Quality of essential oils

There are many factors that influence the quality of the EO obtained. The climate, quality and the preparation of the soil, water- and insect stress, and timing of harvest. These quality factors are determined during the agricultural process (Baser & Buchbauer, 2010). However, during processing, the distillation time has a significant influence on the quality of the obtained EO In a study on the distillation time of Lavender, it was found that the oil yield is optimal after 60 minutes distilling (Zheljazkov, Cantrell, Astatkie, & Jeliazkova, 2013). However, if an oil with high camphor concentrations is desirable, the lavender should be distilled between 7,5- 15 minutes (Zheljazkov et al., 2013). Thus, distillation time is an important influencing factor for the chemical compound composition of the EO. This is due to different boiling point of these chemical compounds, the highest boiling compounds will be the last to come over (Handa, Khanuja, Longo, & Rakesh, 2008). However, as stated before, there are many factors that influence the quality of the EO. This complexity makes it challenging to deliver oils with a consistent compound composition over time.

The quality norm is set by the market. Producers send their EO samples to suppliers, who chemically analyse the quality. For the buyers, it is essential that the quality remains constant, therefore there is no 'better' quality, the compound composition is either the same or not in order (Baser & Buchbauer, 2010). For this reason and the complexity of obtaining consistent compound compositions, producers stick to traditional production methods. Since these methods have been practiced and fine-tuned over centuries, these compound compositions have been established as the quality norm. However, suppliers try to improve their processes, by adapting modern technology. But challenges are found in obtaining the same quality, in order to meet the buyers demand. There are examples were producers reverted back to traditional production methods, since the modern process did not live up to the quality norms (Baser & Buchbauer, 2010).

2.2. Steam boiler

A boiler is a vessel in which water (or other fluid) is heated. This is done by burning a fuel in a furnace. The hot gases that are produced transfer their heat to the water, consequently evaporating the water and producing steam. A distinction is made between fire- and water tube boiler. For fire tube boilers, water partially fills the boiler vessel, and a small volume is left for the steam to accommodate. The furnace is completely surrounded by water. Water tube boilers, have tubes filled with water, which are arranged in the furnace (Bahadori, 2016).

Before water enters the boiler, it needs to be treated; the impurities in the water need to be removed. This is done to keep the boiler internally clean. When water evaporates, it leaves the boiler as steam, however impurities do not evaporate, and therefore remain in the boiler. These impurities accumulate on the bottom of the boiler. When these impurities are heated, they can react inside the boiler, causing corrosion (Sate government Victoria, 2015).

There are three types of water impurities; suspended solids, dissolved solids and dissolved gasses (Kenny, Pope, & Technology, 2000). For each type of impurity, common pre-treatment methods are shown in Table 1.

Table 1. Pre-treatment methods of water impurities

Suspended solids	Dissolved solids	Dissolved gasses
Filtration	Ion exchange softening	Deaeration
Clarification	Demineralization	Degasification
	Reverse osmosis	Dealkalization

Despite the feedwater treatment, some impurities still remain on the bottom. Therefore, the boiler is periodically drained to remove impurities from the bottom of the boiler, this process is referred to as blowdown operations (Einstein, Worrell, & Khrushch, 2001).

2.2.1. Boiler thermodynamics

The thermodynamics of a boiler will be clarified by using a T-h diagram, shown in Figure 3. On the Y-axis temperature and the X-axis enthalpy.

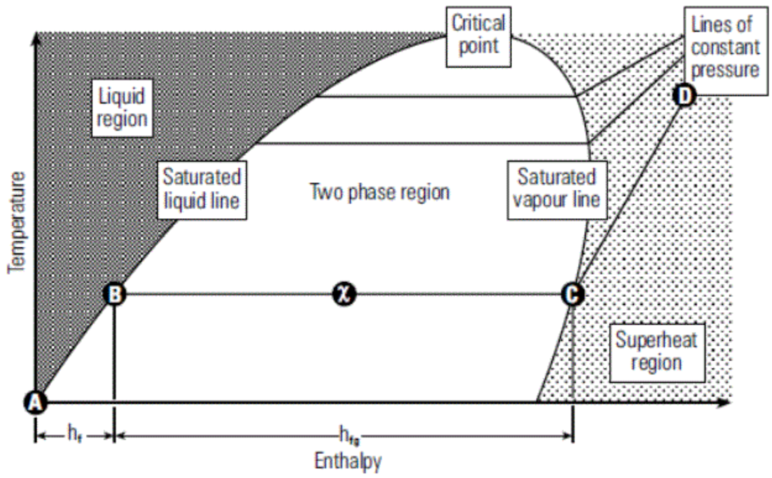

Figure 3. Enthalpy temperature diagram, Wermac.org

Water enters the boiler at a certain temperature and pressure, this is point A. The water is heated in the boiler and moves to point B. This is the boiling point of water. The actual temperature of the boiling point depends on the pressure in the boiler (Cengel & Boles, 2015). More heat is added to the water, the water evaporates and steam is produced. The temperature does not rise, but the steam fraction increases against the water fraction. At point C, all water has turned into steam, thus dry saturated steam is formed. When more heat is added, the temperature rises and superheated steam is created. Each point on the right side of the dry saturated steam line, is superheated steam, like point D.

The region between point B and C is called the two phase region, where vapour and water are in equilibrium. In this area, the steam has a certain quality, a steam quality of one means dry saturated steam (point C) and a steam quality of 0 means saturated water and no steam formation (point B). From this analysis, is can be seen that the most energy is needed to move from saturated water (at the boiling point) to a saturated steam.

2.2.2. Boiler efficiency

There are two methods to determine the efficiency of a steam boiler, the direct and indirect method. The direct method uses the energy in- and output, where the indirect method looks into the energy losses during the operation of the boiler (Raut, Kumbhare, & Thakur, 2014).

2.2.2.1. *Direct method*

The amount of input energy depends on the heating value and flowrate of the fuel. And the energy output depends on the flowrate of the steam and the steam/water properties at inlet and outlet. This relation is given in Equation 1.

Equation 1. Boiler efficiency

$$Boiler\ efficiency\ (\eta) = \frac{\dot{m}_S \cdot (h_S - h_{FW})}{\dot{m}_F \cdot HV_F}$$

$\dot{m}_S$ is mass flowrate of steam, in kg/hour
h_S is the enthalpy of the steam, in kJ/kg
h_{FW} is the enthalpy of the feed water, in kJ/kg
$\dot{m}_F$ is the mass flowrate of the fuel, in kg/hour
HV_F is the heating value of the fuel, in kJ/kg

Thus to determine a boilers efficiency, the mass flowrate of fuel and steam need to be measured. Furthermore, the enthalpy of the feedwater and the steam need to be known, which depend on the temperature and pressure. These values can be found in a steam table (Cengel & Boles, 2015).

2.2.2.2. ***Indirect method***

The efficiency of the boiler can also be determined by measuring all the losses that occur during operation. Hence, this indirect method summarizes all relative energy losses and subtracts this amount from the total energy input. The energy losses in a boiler are briefly discussed.

Flue gas heat losses – flue gasses leave the furnace at high temperatures. And thus carry away significant amount of energy, which has not been transferred to the water in the boiler. To minimize this loss, the temperature of the flue gases should be decreased. However, the temperature should not come below the acid dew point, because this will cause corrosion inside the boiler (Teir & Kulla, 2002). The amount of energy that leaves through the boiler can be calculated using Equation 2 (Faizel, Hamzah, & Navaretsnasinggam, 2014).

Equation 2. Heat loss due to flue gasses

$$\dot{Q}_{heat\ loss} = \dot{m}_{FG} \cdot c_p \cdot (T_{FG} - T_A)$$

$\dot{Q}_{heat\ loss}$ is the amount of heat lost, in kJ/s
$\dot{m}_{FG}$ is the mass flowrate of the flue gas, in kg/s
c_p is the specific heat of the flue gas for a given temperature of the flue gas, in kJ/(kg.K)
T_{FG} is the temperature of the flue gas when it leaves the chimney, in K
T_A is the temperature of the inlet air, in K

Radiation and convection losses – Heat energy is lost by heat radiation and convection of the boiler to the boiler room, the amount of losses depend on the boiler size, insulation (Faizel et al., 2014). This loss is constant for a boiler at operating temperature, and expressed as a percentage of the boiler heat output (NRcan.gc.ca, 2015). The amount of heat loss is usually not measured but estimated, using the ABMA (American Boiler Manufacture Association) convection and radiation loss curve (Faizel et al., 2014) .

Heat loss due to evaporation of water formed due to H in fuel –When a fuel is burned, the hydrogen component in the fuel, leaves the boiler as water vapour (Faizel et al., 2014). This water vapour has an enthalpy that corresponds to the temperature and pressure conditions in the boiler. The amount of energy lost depends of the H-percentage in the fuel, and the temperature difference between the flue gas and the surroundings (Raut et al., 2014).

Excess air in boiler – For combustion air is needed, to make sure all fuel is used, air is slightly in excess of the ideal stoichiometric fuel-air ratio required (Einstein et al., 2001). However, all the excess air that is not used for combustion, is heated up and leaves through the chimney, which is a loss of energy.

Moisture in air – Vapour in the form of humidity in air, enters the boiler with the inlet air flow. This vapour is superheated in the boiler and leaves through the chimney and is therefore an energy loss.

Heat loss due to moisture present in fuel – Moisture in the fuel will leave the boiler as additional water vapour. The amount of energy loss depends on the moisture percentage in the fuel, the flue gas- and ambient temperature (Raut et al., 2014).

Unburnt losses in fly ash and bottom ash – These two losses only apply for boilers that are fired with solid fuels. Unburnt fuel ends up in the bottom or fly ashes of the boiler. In order to determine the amount of energy lost, both bottom- and fly ash need to be analysed on their carbon content (Faizel et al., 2014).

2.2.3. Blowdown operations

For maintenance reasons, the boiler has to be cleaned internally to remove the accumulated impurities. These impurities cause corrosion to the boiler drum and reduce the heat transfer to the water (Einstein et al., 2001). Therefore, the water in the boiler is periodically discharged or "blown down" from the boiler, to lower the concentration of suspended solids. However, the water inside the boiler contains significant energy, which is lost (Sate government Victoria, 2015). The amount of energy lost is given Equation 3 (Teir & Kulla, 2002).

Equation 3. Heat loss due to blowdown operations

$$\dot{Q}_{heat\ loss} = \dot{m}_{BD} \cdot (h_{BW} - h_{FW})$$

$\dot{m}_{BD}$ is the mass flowrate of the blowdown water, in kg/s
h_{BW} is the enthalpy of the boiler water in the boiler drum, in kJ/kg
h_{FW} is the enthalpy of the feedwater entering the boiler, in kJ/kg

3. Method

This chapter outlines the methodology that is used to answer the research questions. This is done by first explaining the structure of the research design, which is shown in Figure 4. In this figure, specific research steps are indicated, leading to the intended final results. First, the general research approach is discussed, thereafter justification for selecting the reference case is given. Finally, the individual research steps are elaborated on in more detail.

3.1. Research design

The goal of this research is to provide an overview of technological options to reduce the fossil energy needs for EO production in rural Africa. This goal will be obtained by undertaking five research steps, as indicated in Figure 4. Research steps 1 to 5, directly correspond to the sub questions. Additionally, two models are constructed (model A and B). These models are required to address the sub questions.

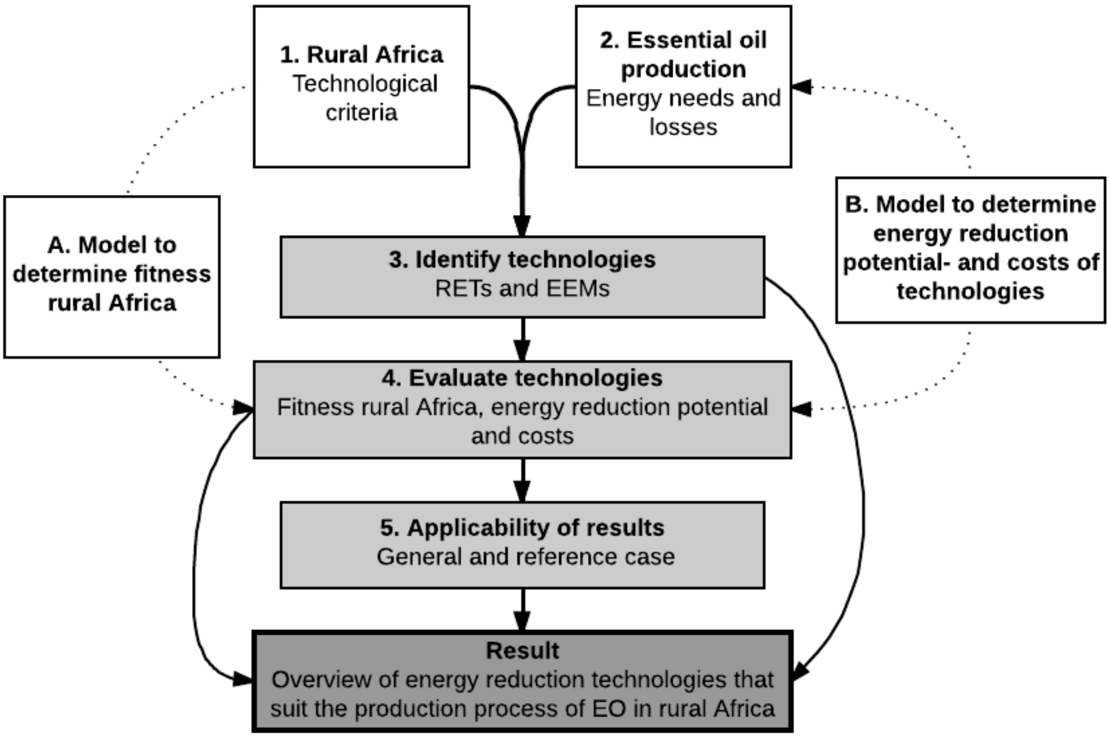

Figure 4. Visualization of research design

In step 1, the obstacles and limitations for implementing technologies in rural africa will be identified. In step 2, the EO production process and the associated energy requirements and -losses will be studied. Step 3 identifies RETs and EEMs that suit the steam distillation process in rural Africa. Step 4 evaluates the technologies identified in step 3 on their appropriateness to be implemented in an EO distillery in rural Africa. Step 5 applies the results of the former steps on the case of the Baviaanskloof in South Africa.

The answering of each subquestion relies on the results found in the former subquestions. In particular, the evaluation of technologies on their appropriateness for implementation in rural Africa (step 4) relies on both the criteria that were identified in sub question 1 (Model A), and the characteristics of the production process as identified in sub question 2 (Model B).

The next section elaborates on the relevance of the reference case for this study and gives a brief description of the reference case. Thereafter, more detail is given on how the results were obtained and what specific methodology was used for each research step.

3.2. Case: Baviaanskloof, South Africa

The EO distillery in the Baviaanskloof was selected as reference case for this study for several reasons. In this distillery, EO oils are produced using steam distillation, which is the most widely applied technique and the focus of this study (see section 1.3). Furthermore, the distillery is located in rural Africa. Finally, the project developers and -operators are incentivized to reduce the fossil fuel needs of this distillery. Therefore, this is an accessible case to research the possibilities to reduce the fossil fuel for EO production, by applying RETs and EEMs. The next section gives insight into relevant information considering the reference case.

The Baviaanskloof reserve is a World Heritage site (Livinglands, 2015), and an essential catchment area for the water supply of Port Elizabeth (Commonland, 2017). Due to overgrazing and unsustainable land management, the land absorption characteristics, soil fertility and biodiversity has decreased. In order to counteract these negative effects and secure the water supply for Port Elizabeth, multiple land restoration projects have been initiated. One of these projects is the development and implementation of a more sustainable agricultural business model. In collaboration with the local farmers a new business model was developed by Grounded; growing lavender and rosemary to produce- and sell essential oils. A company was established, Baviaanskloof DEVCO Pty Ltd, DEVCO refers to developing company. Three companies (Grounded, Livinglands and Commonland) work together with the local community on the Baviaanskloof developing company (DEVCO Pty Ltd).

For the production of essential oils, a steam distillation facility was built in the Baviaanskloof. This distillery is located near the lavender and rosemary fields, and only accessible through a three hour drive on a dirt road. A customized distillation system was constructed for this distillery which holds two distillation stills, both with a capacity for 1.3 tonne of biomass. A second-hand diesel powered boiler provides the steam for the distillation process. This boiler is from 1964, but completely refurbished and has a 500 kW capacity with an estimated thermal efficiency of 70 percent. Feedwater for the boiler is treated with sodium chloride to soften the water. The cooling water for the condenser is supplied by a water pond that is located next to the distillery. The construction and initial production operations are managed by Justin Gird, co-director at Livinglands. When the construction is finalized, the distillery will be managed by the local farmers and operated by workers from the local community. Additional information on the reference case can be found in Appendix 1A: Case report.

3.3. Research procedure and associated methods

Following sections entail the five research steps. For each step, it is discussed what is done, which method is applied and how the required data is collected.

3.3.1. Step 1: Technological criteria rural Africa

In order to identify technologies that are suited for the implementation in rural Africa, technological criteria needed to be identified. These criteria were identified by conducting interviews among stakeholders at the reference case. Furthermore, literature was consulted to validate the results from the interviews. These results were used to construct a model (model A in Figure 4). This model aims to evaluate the fitness of a technology for implementation in rural Africa.

3.3.1.1. Interviews reference case

The interviews were aimed to identify barriers for operating, and criteria for the implementation of technologies in the Baviaanskloof. Therefore, interviewees were selected that have experience with carrying out and operating projects in the Baviaanskloof. Semi- structured interviews were conducted with one interviewee and one interviewer. The interviewer asks predetermined but open questions based on an interview guide, which were asked in a conversational way. By this way, participants are free to emphasize issues and topics that they feel are important (Longhurst & Zealand, 2009).

As a result from these interviews, substantial qualitative data was collected. In order to structure and analyse this data, a method described by Gioia, Corley, & Hamilton (2012) was utilised. This method was developed to analyse qualitative data and to ground theory. This method contains three steps. As a first step, a first order of concepts is grouped, which consists of topics and quotes from the interviews. Second, these concepts are clustered under an overarching theme. The final step concerns aggregating the second order themes in an aggregated dimension.

The second order concepts and aggregated dimension are barriers and criteria for executing technology projects in the Baviaanskloof. These found criteria will be crosschecked with technology criteria that are described in literature. Results from this syntheses were applied to construct an evaluation model. The construction of this model (Model A in Figure 4) is described in the next section.

3.3.1.2. Model A

Model A is constructed to evaluate the fitness for rural Africa for each identified technology at research step 4. In order to construct this model, the principles of multi criteria analyses (hereafter MCA) were utilised. An MCA is a tool that allows to compare various (technology) options, accounting for different criteria (Wang, Jing, Zhang, & Zhao, 2009). For the comparison of these options, relevant criteria need to be identified. Each technology option is scored on the identified criteria. The scoring can be done in several ways, depending on the criterion, which can be either qualitative or quantitative (Wang et al., 2009). One method to score the technologies performance on the criteria, is to look into criteria indicators. This method was applied for constructing Model A. A questionnaire was drawn up to test the performance on specific indicators. Each indicator relates to one or more of the identified technology criteria. As a result, a score can be allocated to a technology, which indicates the fitness to be implemented in rural Africa.

3.3.2. Step 2: Essential oil production process and associated energy requirements

This research step aims to identify the energy requirements for the production of EO. In order to get insight into the energy needs, a better understanding of the production process in general is required. In effort to comprehend this process, the reference distillery was visited multiple times. Moreover, experts and literature on EO- and steam production were consulted. The next step depicts the determination of energy needs and losses for this process. At the reference case, no measurements could be done neither was there any data available on energy requirements, since the facility is not operating yet. Furthermore, no literature is available on the energy requirements of this specific process. Therefore, for this research specific, a model (model B in Figure 4) was constructed that simulates the energy requirements for EO production.

3.3.2.1. Model B

Model B was contstructed in Excel, and a Add-in was applied: Water97_v13 (Spang, 2002). This add-in provides a set of functions for calculating thermodynamic properties of water and steam. These properties are calculated by using the industrial standard IAPWS-IF97. In order to get results, parameters and properties were used based on the reference case; distiling parameters, boiler-, environmental- and distillery characteristics. As a result, the model simulates the energy requirements for the reference case.

3.3.3. Step 3: Identification energy reduction technologies

Three steps were taken in order to identify technologies that could reduce the fossil energy needs for the EO production process. First, by looking into the process dynamics and calculating the energy needs and losses (as described in section 3.3.2). This gave insight in potential energy savings. From there on, literature was consulted to find solutions for similar cases. Finally, experts on EO production and steam systems were consulted. To crosscheck whether the found technology options are feasible, and to look for other technology options.

When selecting a technology, the technology criteria identified at research step 1 were taken into account. Therefore, technologies that do not meet the technology criteria, were not taken into further consideration. This functions as a first demarcation step in selecting technology options for energy reduction.

For each technological option, a brief description of the working principle was given. Furthermore, when relevant, remarks were made about considerations before implementing the technology. These are considerations that are relevant when looking into the applicability of the identified technologies at research step 5.

3.3.4. Evaluating identified technologies

Technologies that are identified at research step 3 are suitable to be implemented in rural Africa and reduce the fossil fuel consumption for the EO production process. Also, how well these technologies fulfil the goal is assessed. This is done by looking into three criteria, fitness for rural Africa, energy reduction potential and costs. The next sections go into detail on how each specific criterion is evaluated.

3.3.4.1. Fitness of technology for implementation in rural Africa

The fitness of a technology for rural Africa is determined using Model A (as described at 3.3.1.2). Each technology option is evaluated using this model. The data required for this evaluation was found by consulting literature, manufacturers, and suppliers of the technologies.

3.3.4.2. Energy reduction potential of technology options

This criterion looks into the potential energy reduction potential of each technology. The potential energy savings for each technology are calculated using Model B. In effort to evaluate each technology on an equal base, it was assumed that the technology option is implemented at the reference case. Based on this, assumptions were made. Since the energy reduction potential of a technology highly depends on the installed capacity.

Model B is used to calculate the energy needs when a specific technology is implemented at the reference case. This is done by changing the parameters in the model, that were altered as result of utilization of a specific technology. The percentage of reduced energy, in comparison to the base case (no RETs and EEMs), is presented as the energy reduction potential of the technology.

3.3.4.3. Costs of the technology options

This criterion looks into the costs of implementing and operating the energy reduction technologies. The goal is to compare the costs of the identified technologies with each other. As a costing method, Order of Magnitude Screening is applied, because it is appropriate for preliminary assessment and is able to compare technology (de Jong, 2015). Additionally, the levelized cost of energy (hereafter referred to as LCOE) method is applied to compare the technology costing. This method is chosen since LCOE allows to compare technologies that have different capacity, lifecycles and investment costs (Short, Packey, & Holt, 1995). Furthermore, it allows to compare energy saving and -producing technologies (EEMs and RETs). When the operation costs, fuel costs and energy production (or savings) of a technology are constant over each year, the LCOE is calculated using Equation 4 (Blok & Nieuwlaar, 2017). The unit of LCOE is €/GJ, which is an indicator for the cost per unit energy produced or saved by implementing a specific technology.

Equation 4. Levelized cost of energy

$$LCOE = \frac{\alpha \cdot I + OM + F}{E}$$

α is the capital recovery factor
I are the initial investment costs of a technology
OM are the annual operating and maintenance costs
F are the annual fuel costs
E is the amount of annual energy savings or production by the technology

The capital recovery factor is calculated using the discount rate and the lifetime of a technology, this relation is shown in Equation 5 (Blok & Nieuwlaar, 2017).

Equation 5. Capital recovery factor

$$\alpha = \frac{r}{1 - (1 + r)^{-n}}$$

r is the discount rate
n is the lifetime of a technology, in years

This data required for calculating the LCOE was found by consulting literature, manufactures- and suppliers of the technologies.

3.3.5. Step 5: Applicability of identified technologies to case

In order to assess the applicability of the identified technologies to the reference case, two steps were taken. First, an overview was constructed of the compatibility of the technologies. This overview indicates which technologies compete with and exclude each other. Furthermore, it indicates the technologies that can be implemented simultaneously. Thereafter, a decision tree was constructed to find the most applicable technology for a specific case. This decision tree accounts for technology specific implementation and utilization considerations. As a final step, the applicability of the identified technologies are tested on the reference case.

4. Results

The results are discussed in the same order as presented in the method. First, criteria found for implementing technologies in rural Africa. Second, a description of the production process and the associated energy requirements for EO production. Thereafter, the identified RETs and EEMs that were found suitable are discussed. This is followed by an evaluation of these technologies on fitness for rural Africa, energy reduction potential and costs. Finally, the applicability of the results to the reference case are discussed.

4.1. Results step 1: Criteria for technologies in rural Africa

This section elaborates on the technological criteria for implementing technologies in rural Africa. First the results are presented from the case study, these are the barriers and challenges of implementing technologies in the Baviaanskloof. Thereafter, results found in literature are presented. Similarities between these results are used to construct Model A, which is presented afterwards.

4.1.1. Results case study

Four semi-structured interviews were conducted with stakeholders of the EO distillery. These stakeholders were selected on their experiences on operating (technology) projects in the Baviaanskloof. These interviews can be found in Appendix 1B: Stakeholder interviews. Qualitative data obtained from the interviews was analysed as described at method section 3.3.1.1, this result is shown in Figure 5. The next two sections elaborate on this analysis.

4.1.1.1. Barriers operating in the Baviaanskloof

Three main barriers for operating in the Baviaanskloof came forward: *low level of education of the average population*, *undeveloped infrastructure* and *remoteness.* These barriers are all characteristics for the Baviaanskloof. Following from these barriers, certain criteria were identified that are deemed important for selecting a technology that is suited to be implemented in the Baviaanskloof.

4.1.1.2. Criteria for implementing technologies in the Baviaanskloof

Based on the interviews, four relevant technology criteria were identified for operating in the Baviaanskloof: *ease of – operation and maintenance*, *ease of repair, simpleness-and robustness of technology* and *reliability of technology supplier*. These criteria are all deemed relevant to enhance the *lifecycle support of a technology*.

Because of the remoteness and undeveloped infrastructure, the project operators want to be independent of expertise and materials from outside of the Baviaanskloof. Since getting material and labour into the Baviaanskloof can be a costly, complex and prolonged operation. Thus the operators want to be able to repair the technology themselves, when necessary. Therefore, a simple technology is preferred over a complex technology. Since this allows the operators to repair it themselves. Additionally, the technologies are likely to be operated by low skilled workers. Which emphasizes the importance of a simple technology, and thus the ease of- operation and maintenance. Moreover, robust technologies are preferred over 'fragile' technologies since these tend to last longer. Finally, when selecting a technology the reliability of the supplier is deemed important. Since the supplier is seen as a back-up when a technology defects.

In Figure 5 it is indicated how the operating barriers relate to specific criteria. Statements and concepts from the interviews are indicated in the dotted boxes. These are clustered and relate to an overaching concept, show in square box. Finaly, these overarching concepts are subject to one aggregate dimension.

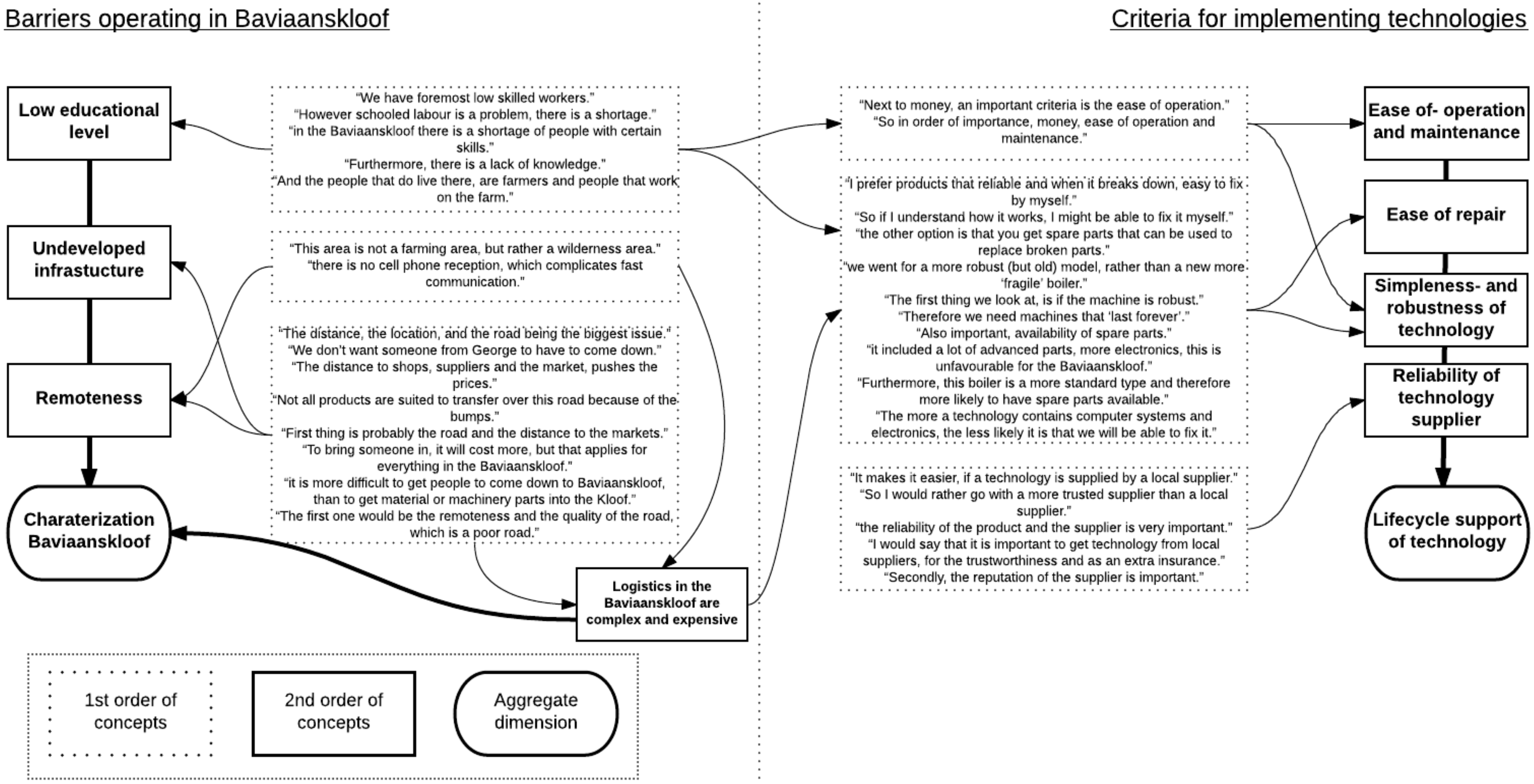

Figure 5. Analysis of stakeholder interviews

4.1.2. Results literature study

In studies on entrepreneurship in rural Africa several limitations and challenges are identified for operating businesses in these areas. It was pointed out in the literature that the distance, undeveloped-infrastructure and public transport are the cause of several limitations (Barry, Steyn, & Brent, 2011; Boohene & Agyapong, 2017; Nagler & Naudé, 2017). For entrepreneurs, trading activities tend to require higher costs due to the distance to the markets (Nagler & Naudé, 2017). Moreover, education and professional services are associated with higher costs, and are therefore less often taken advantage of. In general, the population in rural Africa have a low income- and low educational level (Boohene & Agyapong, 2017). The above mentioned characterization of rural Africa bring challenges forward, when executing technology projects in rural Africa. A study by Barry, Steyn & Brent, 2011, looked more specific into success factors and -obstacles for executing projects in Africa.

In this study, factors were identified that should be taken into account when implementing renewable energy technologies in Africa. Thirteen factors were found, which were categorized in four categories: technology-, site selection-, economic- and organisational factors. This study focuses on the technical aspects for selecting a technology for rural Africa. Therefore, the two technology factors are further discussed. The first factor is the ease of maintenance and support of life cycle of the technology. Second, ease of transfer knowledge and skills to relevant people in Africa is considered as an important factor.

In order to support the life cycle of a technology, several measures were mentioned by Barry et al. (2011), these are:

- *Good quality of the installations* – the use of poor quality will undermine the confidence in the technology of the end user.
- *Maintenance plans* – for ensuring continues maintenance to prevent breakage.
- *Training of technicians* – lack of local technical support can result in a loss of confidence by the end user. Therefore local technicians should be trained, in order to provide technical support.
- *Maintenance training for users* – this in combination with maintenance plans, will avoid minor technical problems.
- *Keeping maintenance simple* – maintenance is mostly done by untrained people or workers, therefore it must be simple and close to what people know.
- *Adapting the technology to the specific environment* – technology in Africa must be robust and easy to handle. When selecting a technology, the availability of spares and use of local materials must be taken into account. Since obtaining spare parts can be challenging in developing countries, even more in remote areas. The importance to have access to spares was also stressed by Dunmade, 2002, since this enables quick repair and thus avoiding (or reducing) downtime.

The transfer of knowledge and skills to relevant people can be enhanced by the following measures:

- *Stakeholders to train* – the right stakeholders must be identified and selected for training sessions.
- *Methods of skills transfer* – several methods can be used, depending on the target group; user manuals, formal workshops, informal training and demonstrations. It is important that the training is practical.

- *Skills to be transferred to users* – these must predominantly include operation and maintenance aspects.
- *Quality of training* – this must be high. The users often do not have the initial skills, therefore high quality is needed.
- *Formalisation of skills transfer* - this can be done by updating the school programs and academic curricula.

4.1.3. Syntheses case- and literature study

Similarities between the case study are found. In literature, for technologies in rural Africa, the lifecycle support of a technology is seen as the main challenge (Barry et al., 2011). Therefore the ease of- operation, maintenance, repair and the simpleness of a technology are deemed important (Barry et al., 2011; Boohene & Agyapong, 2017; Nagler & Naudé, 2017). This directly corresponds to the results found in the case study. Moreover, access to spare parts was stressed as important since this can be challenging in rural Africa.

A difference between the results found in literature and the case, is the importance of having a reliable supplier. This criterion is deemed important to the stakeholders in the Baviaanskloof. However, this might rather be a generic criterion when selecting a new technology, and thus not rural Africa specific. Therefore this criterion is disregarded for further analyses. Moreover, in literature the importance of training and knowledge transfer for operating and maintaining of the technologies was stressed. However, this not an intrinsic property of a technology, and therefore not taken into account when evaluating the technologies using Model A.

4.1.4. Model A: technology fitness for implementation in rural Africa

This model is constructed by combining the findings from the case- and literature study. The model aims to evaluate the fitness of a technology, for implementation in rural Africa. The four criteria are evaluated, by testing the technologies on eight indicators. These indicators came forward from the case- and literature study. Each indicator is stated as a question and relates to one or more criteria, as indicated in Figure 6.

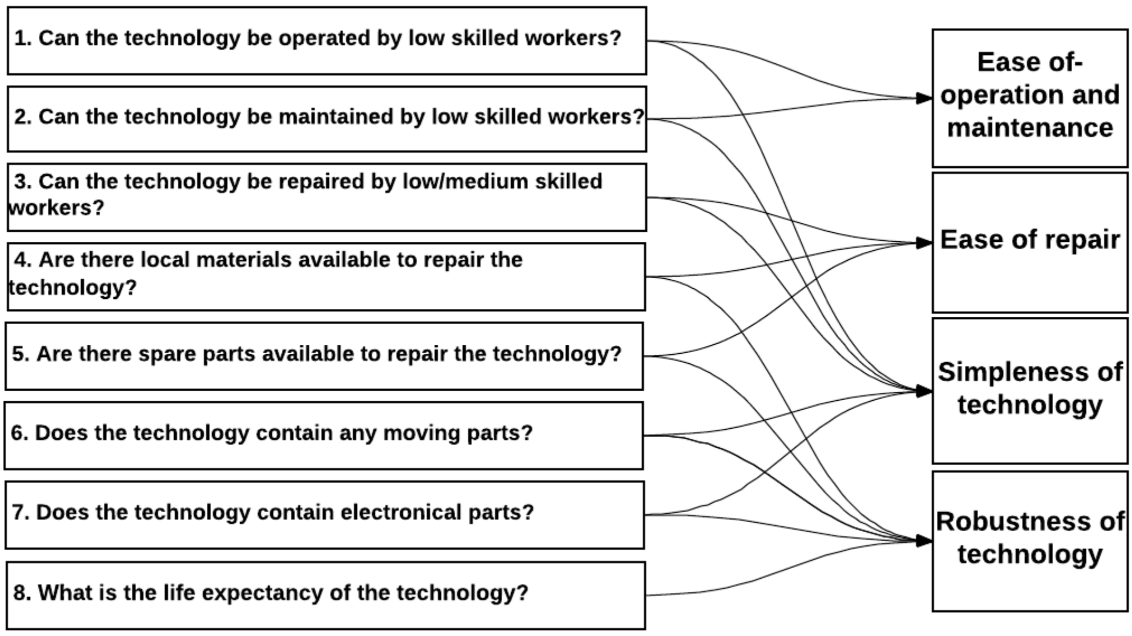

Figure 6. Model A technology fitness for rural Africa

A grading system is applied to determine the fitness of a technology. Points are allocated to a technology, depending on how the technology relates to each specific indicator. The point allocation method is shown in Table 2. Each of the eight questions is briefly discussed, on how these relate to the criteria. Using this questionnaire, the maximum score for a technology its fitness, to be implemented in rural Africa is 24 points.

Table 2. Questionnaire to determine technology fitness for rural Africa

Technology fitness rural Africa					
		Answers and associated scores			
	Questions	**-**	**1**	**2**	**3**
1	Can the technology operated by a low skilled workers?	No	After training, with supervision	After training, no supervision	Yes
2	Can the technology be maintained by low skilled workers?	No	After training, with supervision	After training, no supervision	Yes
3	Can the technology be repaired by low/medium skilled workers?	No	Supposably not	Supposably	Yes
4	Are there local materials available to repair the technology?	None	Few materials	Most materials	All
5	Are there spare parts available to repair the technology?	None	Few parts	Most parts	All
6	Does the technology contain any moving parts?	Yes, many moving parts	Yes, a few moving parts	No, supportive technologies do*	No
7	Does the technology contain any electronical parts?	Yes	Yes, a few electronical parts	No, supportive technologies do*	No
8	What is the life expectancy of the technology?	<5 years	5< years <10	10< years <20	>20 years

* Two points are allocated when the technology itself does not contain any moving or electronical parts, but when the supportive technology does contain moving or electronical parts, e.g. operating a condenser requires a water pump.

Description of relevance indicators to criteria:

1. In both literature (Barry et al., 2011) and the case study, it was found that skilled labour is a scarcity in rural Africa. Therefore, it is preferred that a technology can be operated by a low skilled worker. Furthermore, if a technology is easy to operate, it implies that the technology itself is rather simple.
2. The same argumentation as at statement 1 applies for the operation indicator.
3. The same argumentation as at statement 1 applies into certain extent. The need for a repair does not occur on a regular base. In rural areas there are workers with certain skills, however the main part is low educated. But if the repair of a technology can be done by a medium skilled worker (e.g. the stakeholder in Baviaanskloof), people in the rural area might be able to do it by themselves. Furthermore, if a low- or medium skilled worker is able to repair the technology, it indicates that the working principle of a technology is simple.

4. The availability of local materials to repair the technology, will enable workers to repair the technology themselves, instead of requiring assistance from an expert outside of the region (Dunmade, 2002). In addition, this availability of materials reduce the waiting time for materials from outside the region. This allows quicker repairs and therefore potentially reduces downtime in the event of a technology breakdown.
5. The same argumentation applies for spare parts as at statement 4.
6. If a technology contains moving parts, it is more likely to tear and break down (Dunmade, 2002). Thus, making a technology less robust. Furthermore, the presence of moving parts within a technology, makes the technology more complex.
7. The argumentation of statement 6 also applies for electronical parts.
8. The lifetime expectancy is an indicator for the robustness of a technology. Were a high lifetime expectancy indicates a more robust technology.

4.2. Results step 2: Energy requirements EO production

This section discusses the EO production process and gives insight into the associated energy requirements. First, a description of Model B is given. This model description provides an elaborate description of the distillation process. Thereafter, results on the energy needs and losses, derived from Model B are presented.

4.2.1. Structure Model B

The general model structure is shown in Figure 7, were the rectangle boxes depict a sytem component. The first component of the system is the boiler. Three material flows go into the boiler for steam production: fuel, feedwater and air. Fuel is burned in the combustion chamber producing flue gasses, which leave through the chimney. Two energy losses occur when operating the boiler; efficiency losses and blowdown operation losses (see theoretical background 2.2.2 and 2.2.3).

The steam that is produced in the boiler moves towards the distillation system. It moves through steam pipes (can be referred to as SP) before entering the DS. In both the SP and DS, energy is lost due to heat transfer to the surroundings.

In the DS, the distillation process occurs. Here the energy in the steam flow is utilised for heating the biomass to distillation temperature, evaporation of oils and the mass transfer of evaporated oils. The evaporated oils leave the DS by the steam mass transfer, and enter the condenser. In the condenser, the steam- oil mixture is cooled down to liquid phase.

In Figure 7, two flows are indicated as potential energy recovery flows: flue gass and heat of condensation. These are two heat flows that leave the system. However, these energy flows can be utilised to make the system more efficient. Therefore, the amount of energy in these flows are included and calculated in this model. Since this will be useful for assessing certain EEMs.

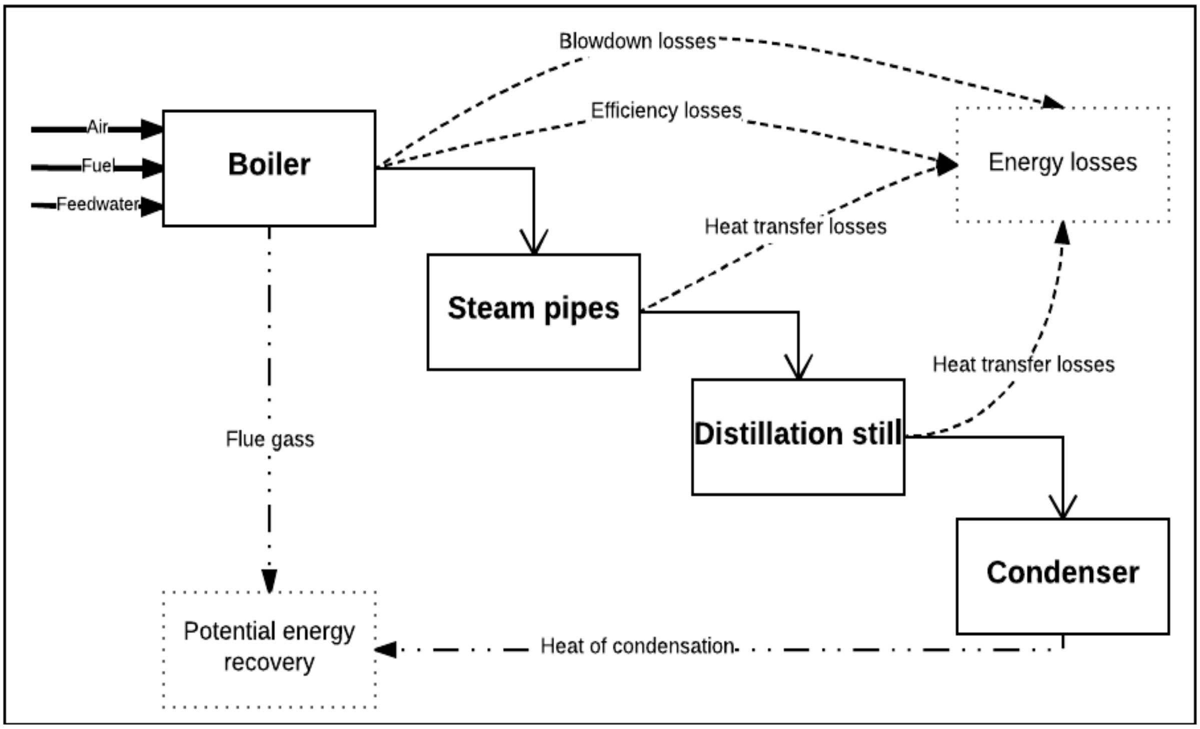

Figure 7. Model structure

This model assumes that fossil energy is only consumed by the operating the steam boiler. However this is a simplification of the reality. Since in reality, electrical pumps are required to produce the water flow for the cooling water for operating the condenser, and pump the feedwater towards the boiler. However, pumps are excluded from this model since energy consumption pumps is relativly small (5 kW versus 500 kW boiler, for the case in the Baviaanskloof).

The next sections describe each component of the model. Furthermore, it elaborates on the formulas that were used and assumptions that were made in order to calculate the energy needs and losses of the EO production process.

4.2.2. Energy needs and losses steam boiler

A steam boiler produces two flows that require energy, a steam- and blowdown flow. Energy is lost for both flows, due to the efficiency of the boiler. Furthermore, the blowdown flow is considered as an energy loss. The formulas for calculating steam- and blowdown flow are both discussed.

For calculating the energy needs for producing a steam flow, Equation 6 was applied (Cengel & Boles, 2015).

Equation 6. Energy requirements steam boiler

$$E_{fossil\ energy} = \left(\frac{\dot{m}_S \cdot (h_S - h_{FW})}{Boiler\ efficiency\ (\eta)}\right) \cdot t_{DT}$$

$\dot{m}_S$ is the mass flowrate of steam, in kg/h
h_S is the enthalpy of the steam, in kJ/kg
h_{FW} is the enthalpy of the feedwater, in kJ/kg
t_{DT} is the distillation time, in hours

Enthalpy values for feedwater and steam were found by determining the temperature and pressure. For the feedwater these were assumed to be equal to average ambient temperature in the Baviaanskloof and atmospheric pressure. The enthalpy of steam was found by looking into the operating pressure of the boiler, and the temperature was determined by looking into the corresponding boiling point. Therefore, it is assumed that the steam produced by the boiler is saturated. Steam flowrate and distillation time are parameters that are determined by the operator and depend on the crops and distillation system (see section 2.1.2 in theoretical background).

Energy losses caused by blowdown operations were calculated using Equation 7 (Teir & Kulla, 2002).

Equation 7. Energy losses due to blowdown operations

$$E_{fossil\ energy} = \left(\frac{\dot{m}_{BD} \cdot (h_{BW} - h_{FW})}{Boiler\ efficiency\ (\eta)}\right) \cdot t_{DT}$$

$\dot{m}_{BD}$ is the mass flowrate of the blowdown flow, in kg/h
h_{BW} is the enthalpy of the blowdown water, in kJ/kg

The blowdown mass flow is calculated using the blowdown rate. Where the blowdown rate is a certain percentage of the steam flowrate. Therefore, it is assumed that blowdown operations are done automatically. Furthermore, the blowdown flow is assumed to be saturated water, which has the same temperature as the boilers operating temperature. Thus the enthalpy of the blowdown water is determined by using the temperature of saturated water, at boiler operating pressure.

4.2.3. Heat flows

Several heat flows are identified during the EO production process. First the heat transfer between the SP and DS to its surroundings. Second, two heat flows leave the system, the flue gasses and the heat of condensation (through the cooling flow in the condenser). These heat flows result in a loss of energy. However, the heat from the flue gasses and condensation of steam could potentially be utilised for other appliances. The methodology of modelling and calculating the amount of energy in these heat flows is discussed in the next sections.

4.2.3.1. Heat transfer losses at distillation still and steam pipes

Heat transfer occurs between objects with a temperature difference. For calculating the heat transfer between the distillation system and its surroundings, radiation and convection losses were calculated. Only free convection occurs, since the distilling system is inside a facility. Thus, there is no forced convection due to airflow.

In order to calculate the amount of energy that is lost due to heat transfer, the total heat transfer rate was determined for both heat objects. In the facility, two heat objects were pointed out; DS and SP (as indicated in Figure 7). The total heat transfer rate, is the sum of heat transfer by convection and radiation. And the energy losses due to heat transfer are given by Equation 8, Equation 9 and Equation 10 (Twidell & Weir, 2015).

Equation 8. Energy loss due to heat transfer

$$E_{heat\ transfer\ losses} = \left((P_{Conv\ DS} + P_{Rad\ DS}) + (P_{Conv\ SP} + P_{Rad\ SP})\right) \cdot t_{DT}$$

$P_{Conv\ DS,SP}$ is the heat flow due to convection for DS/SP, in Watt
$P_{Rad\ DS,SP}$ is the heat flow due to radiation for DS/SP, in Watt

Equation 9. Heat transfer convection

$$P_{Conv\ i} = h_{conv\ i} \cdot A_{\ i} \cdot \Delta T$$

$h_{conv\ i}$ is the convective heat transfer coefficient of object i, in W/(m^2.K)
$A_{\ i}$ is the surface of object i, in m^2
ΔT is the temperature difference between object i and its surroundings, in K

Equation 10. Heat transfer by radiation

$$P_{Rad\ i} = \varepsilon_i \cdot \sigma \cdot A_{\ i}\left(T_i^4 - T_{surroundings}^4\right)$$

ε_i is the emissivity factor of object i, no unit
σ is the Stephan-Boltzmann constant which is 5.67 *10^{-8} W/m^2.K^{-4}
T_i is the temperature of object i, in K

The temperature of the object is assumed to be the same temperature as the steam (inside the DS and SP). This assumption is made based on the high thermal conductivity (16,5 W/m.K) of stainless steel (of which both SP and DS consists, at the reference case). Therefore the outer surface of the material has approximately the same temperature as the inner surface.

The convective heat transfer coefficient is calculated for a heat body using Equation 11.

Equation 11. Convective heat transfer coefficient

$$h_{convection} = Nu \cdot \frac{k}{X}$$

Nu = the Nusselt number, no unit
k = thermal conductivity of air, in W/m.K
X = characteristic dimension of heat body, in m

The Nusselt number is determined by calculating the Rayleigh number. The equation for calculating the Nusselt number depends on the geometry of the heat body and the mode of airflow; laminar or turbulent (Twidell & Weir, 2015). The geometry formulas used for horizontal-, vertical cylinder and the horizontal flat plate are described in (formulas applied can be found in Appendix 2A). The Rayleigh number is found by using Equation 12.

Equation 12. Rayleigh number

$$Ra = \frac{g \cdot \beta \cdot X^3 \cdot \Delta T}{v \cdot \alpha}$$

Ra is Rayleigh number
g is gravitational acceleration, in ms^{-2}
β is volumetric coefficient of expansion, in K^{-1}
X is characteristic dimension, in m
ΔT is temperature difference, in K
v is kinematic viscosity, in m^2s^{-1}
α is thermal diffusivity, in m^2s^{-1}

Besides that the Rayleigh number is required to calculate the Nusselt number, it also indicates if the fluid flow is turbulent or laminar. And therefore indicates which equation is needed to determine the Nusselt number (see Appendix 2A).

4.2.3.2. Heat flows at chimney and condenser

The condensation of flue gasses can cause damage to the equipment, since they contains acids which are corrosive (US Department of Energy, 2012c). Therefore, only a fraction of the energy in the heat flow can be utilised for energy recovery. The available energy in the flue gasses depend on the specific heat of the flue gasses, the mass flow rate and the temperature difference. Where there is a limit to the temperature difference, since this should not reach the condensation temperature of certain acids. The available energy for flue gasses is given by Equation 13.

Equation 13. Available energy from flue gasses

$$E_{available} = \dot{m}_{FG} \cdot c_p \cdot \Delta T$$

$\dot{m}_{FG}$ is the mass flowrate of the flue gasses, in kg/h
c_p is the specific heat of the flue gas at a given temperature, in kJ/(kg.K)
ΔT is the temperature difference, in K

The mass flowrate of the flue can determined by combining the law of mass conservation and assuming complete combustion. Following the law of mass conservation, Equation 14 applies.

Equation 14. Determining mass flowrate flue gasses

$$\dot{m}_{FG} = \dot{m}_F + \dot{m}_A$$

$\dot{m}_F$ is the mass flowrate of fuel, in kg/h
$\dot{m}_A$ is the mass flowrate of combustion air, in kg/h

In order to calculate the mass flowrate of the flue gasses, the mass flow rate of air needs to be determined. This is done by using stoichiometric air to fuel ratio between fuel and combustion air, as shown in Equation 15 (Cengel & Boles, 2015).

Equation 15. Determining mass flowrate air

$$\dot{m}_{air} = \dot{m}_{fuel} \cdot AFR$$

AFR is the stoichiometric air to fuel ratio (mass based; kg/kg)

The energy that is available at the condenser, depends on the evaporation enthalpy and mass flowrate of steam- oil mixture, as shown in Equation 16.

Equation 16. Available energy from condensation heat

$$E_{available} = \dot{m}_{So} \cdot h_{fg}$$

$\dot{m}_{So}$ is the mass flowrate of the steam- oil mixture, in kg/h
h_{fg} is the evaporation enthalpy in kJ/kg

The evaporation enthalpy is depended on the steam temperature. In the model it is assumed that this temperature is equal to the distillation temperature. Furthermore, for the steam- oil mixture it is assumed that the enthalpy for steam applies. Since the oil fraction in the steam- oil mixture is rather small, 1-5 percent of the steam- oil mixture are EO (Baser & Buchbauer, 2010).

4.2.4. Distillation process

Steam energy in the DS is utilised to heat the biomass and evaporate the oils that are inside the cells. Thereafter, the steam flow transfers the oils from the DS to the condenser, functioning as a 'mass carrier'(as described at 2.1.1). In the model a distinction is made between energy needed for- heating the biomass and energy for mass transfer. The energy to heat the biomass, is provided by condensation heat of the steam, condensing a part of the steam. However, in practice these energy needs are not distinguished. In practice, the energy usage is determined by the distillation time and steam flowrate and the amount of condensed steam is referred to as reflux.

Energy needed for heating the biomass is calculated using Equation 17.

Equation 17. Energy for heating biomass

$$E_{heat\ biomass} = c_{p\ BM} \cdot \Delta T \cdot m_{BM}$$

$c_{p\ BM}$ is the specific heat of biomaterial, in kJ/(kg.K^{-1})
m_{BM} is the mass of the biomaterial, in kg
ΔT is the difference between biomaterial- and distillation temperature, in K

The amount of energy that is used as mass carrier, is the remaining energy that was produced by the boiler minus the energy- losses and needs for heating the biomass. This relation is shown in Equation 18.

Equation 18. Energy remainder for mass transfer

$$E_{Mass\ transfer} = (\dot{m}_S \cdot\ (h_S - h_{FW}) \cdot t_{DT}) - E_{Heat\ transfer\ losses} - E_{Heat\ biomass}$$

$\dot{m}_S$ is the steam mass flowrate, in kg/h
t_{DT} is the distillation time, in s

4.2.5. Model constants and parameters

In Table 3 an overview is given of parameters and constants that were applied for constructing the model.

Table 3. Overview of parameters and constants that are utilized in the model

Parameter and constants	Value	Unit	Comments
Parameters required for model			
Specific heat flue gas	1.092[1]	J/(kg.K^{-1})	
Stoichiometric air to fuel ratio	14.7	-	Mass based, for diesel combustion (Goel & Stonecypher, 2013)
Specific heat biomass	3.49[2]	kJ/(kg.K^{-1})	
Atmospheric pressure	1	bar	
Constants			
Gravitational acceleration	9.81	ms^{-2}	
Stephan Boltzmann constant	5.67 *10^{-8}	W/m^2.K^{-4}	

4.2.6. Energy needs for the production of a batch EO

In order to generate results; parameters and properties were imported into the model. These input parameters and properties are based on the reference case in the Baviaanskloof and shown in Table 4. The functional unit of the model, is the production of one batch. Therefore, the outcomes on energy requirements are given per batch. First the outcomes of this model are discussed. Thereafter, insight is given into the energy needs for operating the facility in the Baviaanskloof on a yearly base.

[1] The flue gas is assumed to have the following composition: 13 percent CO_2, 11 percent H_2O, 76 percent N_2. Furthermore the C_p corresponds to a temperature of 200 °C. This information was retrieved from: http://www.pipeflowcalculations.com/tables/flue-gas.php, on November 18th 2017.
[2] The specific heat for biomass was calculated by assuming 75 percent moisture content. The specific heat of dry wheat straw was assumed to be representative for lavender and rosemary. At a temperature of 333 K, the specific heat was found to be 1.43 kJ/(kg.K^{-1}) (Dupont, Chiriac, Gauthier, & Toche, 2014).

Table 4. Input parameters and properties for model

Parameters/properties	Value	Unit
Distilling process parameters		
Steam flowrate	600	kg/hour
Distillation time	0.75	hour
Amount of biomass	1.3	tonne
Operating pressure boiler	2	bar
Boiler characteristics		
Efficiency	70 %*	
Blowdown rate	7 %	Of steam flow
Fuel required	Diesel	
Distillery characteristics Baviaanskloof		
Length distillation still	2.5	m
Diameter distillation still**	1.75	m
Length steam pipes	10.8	m
Diameter steam pipes	0.1	m
Emissivity factor stainless steel	0.9	
Temperature distillery	25	°C
Temperature feedwater	20	°C

* The efficiency of the boiler was estimated in consultation with an expert from the company that supplied the boiler to the reference distillery. This efficiency is HHV based.
** It was assumed that no insulation was applied to the DS. This assumption deviates from the reference case. However, this assumption was made to get insight into the energy losses (and potential savings) due the heat transfer at the DS.

The outcomes, as a result from the model using the mentioned parameters, are shown in Table 5 and further discussed. A distinction is made between the energy requirements for operating the boiler and the distillation system. By operating the boiler, two losses occur: efficiency losses and blowdown operations. The remaining energy is transferred to the water, producing the steam flow, which is injected into the distillation system. In the distillation system, not all energy is utilised for the distillation process, since some energy is lost due to heat transfer at the SP and DS. The total amount of fossil energy that is required to produce one batch of EO is *1705.0 MJ*. A breakdown of the total energy need is given in a pie chart (Figure 8).

Table 5. Energy requirements steam distillation

EO production, energy needs and losses for boiler and distillation system in MJ per batch		
Boiler operations		
Energy to steam flow	1180.2	
Energy to blowdown operations	19.0	
Efficiency losses	505.8	
Distillation system		
Energy utilised during distillation process		925.9
Heat transfer losses		
Distillation still		229.9
Steam pipes		24.4
Total amount of fossil energy used	**1705.0**	

In the energy breakdown (Figure 8), the left pie chart indicates the energy breakdown of the steam boiler. Here 69 percent of the total energy is transferred to the steam flow, which goes into the distillation system (right pie chart). Due to heat losses in the distillation system, 54 percent of the total used energy, is utilised for the actual distillation process. For the distillation process energy is needed to heat the biomass, evaporate the oils and transfer these oils to the condenser (see section 2.1.1).

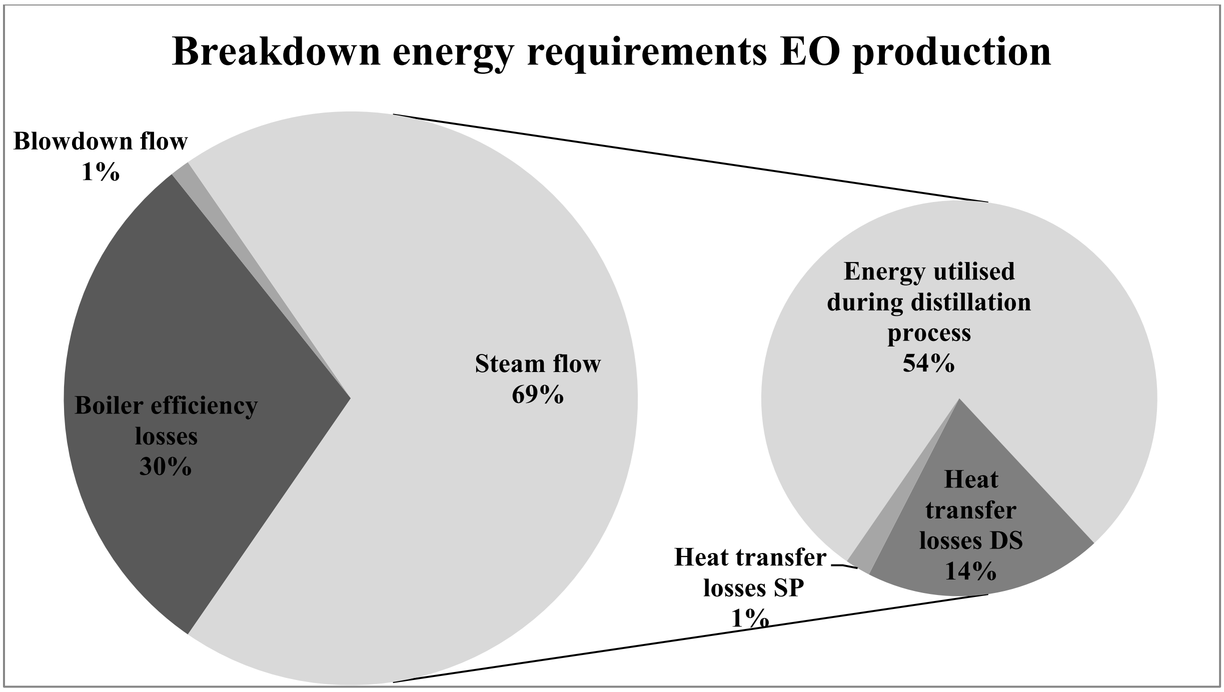

Figure 8. Breakdown of energy requirements for EO production

4.2.7. Energy needs yearly production

For the reference case in the Baviaanskloof, 99 hectares are available to grow crops for EO production. It was estimated by DEVCO Pty Ltd, that these 99 hectares of arable land will produce 710 tonne of biomass (lavender and rosemary). Per batch, 1.3 tonne of biomass can be processed. Therefore, processing 710 tonne of biomass corresponds to the production of 547 batches. Based on these production predictions and the energy needs per batch, it is expected that the yearly energy needs are *932.6 GJ*. This corresponds to 20.8 tonne diesel fuel on a yearly base (using HHV of 44.8 MJ/kg).

4.3. Results step 3: Technologies for fossil energy reduction

Ten technologies (RETs and EEMs) were identified that could reduce the fossil fuel needs of the production process. This was done by literature study and consulting experts. First, the RETs are discussed, thereafter the EEMs. The working principle of each technology is briefly discussed. Furthermore, some insight in given for the most important considerations when implementing a specific technology.

4.3.1. Concentrated solar power

The production of steam using CSP is already applied for the process industry. In India, CSP is applied for industrial laundry and milk processing (Jayasimha, 2004). The production of EO, using CSP has been researched by Munir & Hensel (2014). This experimental setup is shown in Figure 9, and further discussed.

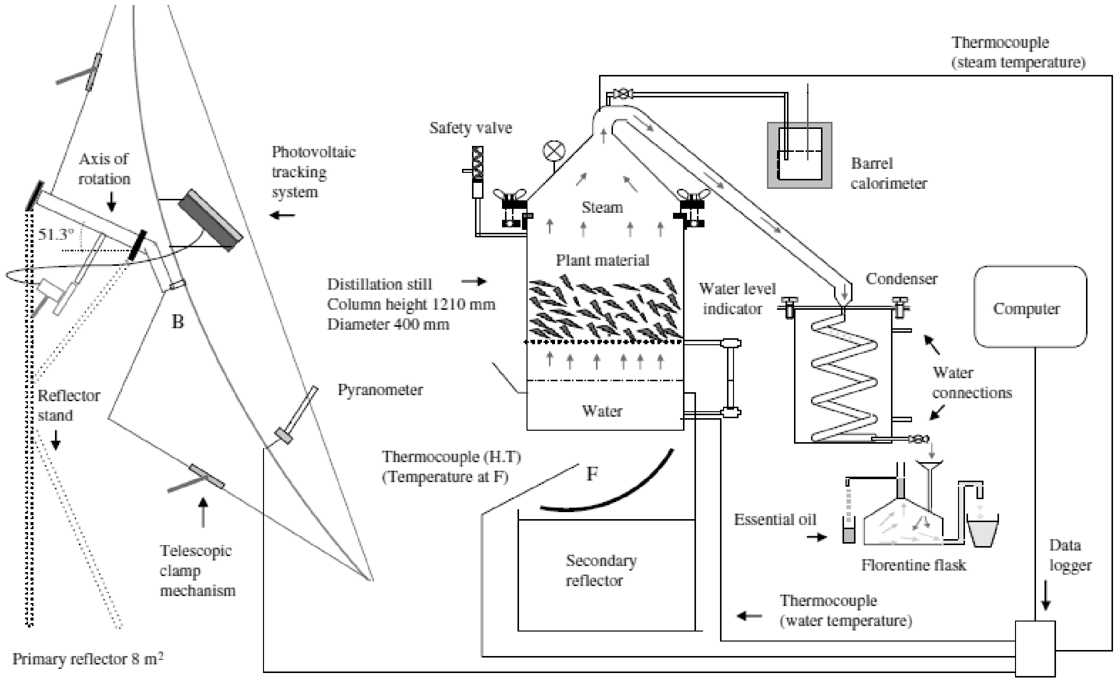

Figure 9. CSP distillation setup by Munir et al., 2010

In this setup a Scheffler reflector was used with a surface of 8 m^2. This reflector concentrated and directed the solar radiation to a secondary reflector. The secondary reflector directed the radiation towards the DS. This caused the water to boil and produce steam, and thus powering the distillation process.

The average power and efficiency of this setup was found to be 1.548 kW and 33.21 percent. During a sunny day, this setup operated for 10-12 hour, producing 18.58 kWh. Several aromatic plans were processed successfully using solar power, these were: Peppermint, Rosemary, Cumin and Cloves. This study gives a clear proof of concept. It is possible to produce EO using CSP, given the correct (sunny) conditions.

Considerations CSP boiler

An important consideration before implementing CSP as renewable energy source, is the capacity fit. The setup from the study by Munir & Hensel, the average power output was 1.55 kW and an daily power output of 18.58 kWh. Comparing this power output with the reference case, this is a really small distillery setup (1.55 kW versus 500 kW).

Furthermore, the power production is purely dependent on the sun. Therefore the annual power output should be assessed, to see if the production of EO can fully powered by CSP. This should include the power generation by CSP for a year. This assessment should include the intermitting characteristics of CSP and the (daily and seasonal) solar cycle. Furthermore, it should be checked, if there is sufficient solar power 'available' during harvest and production season.

4.3.2. Biomass steam boiler

The production of steam using biomass boilers is a widely applied technology. The applications of steam produced by biomass boilers range from electricity generation to district heating (van Loo & Koppejan, 2008). Generating steam for the distillation of EO with a biomass boiler has been proven successful (Kebede & Hayelom, 2008). Another example is found in Madagascar, here the company Bionexx produces EO by using a biomass boiler which is powered by the spent biomass[3].

The working principle is similar to a conventional, fossil fuel powered steam boiler and the power output of a biomass boiler ranges from 200 kW to 10 MW (Binder, n.d.). Therefore, biomass steam boiler can be used for relatively small distilleries and larger facilities. However, not all biomass is suited as fuel and if the biomass meets the fuel requirements, some considerations need to be taken into account; availability, storage and pre-treatment (van Loo & Koppejan, 2008).

Considerations biomass boiler

Before implementing a biomass steam boiler, the biomass that is intended to be used as fuel, needs to be assessed; suitability as fuel and availability to meet energy demand.

In order to determine whether a biomaterial can be handled as a fuel, a fuel analysis needs to be done. In this analysis the fuel is assessed on: minimal and nominal LHV, granulometry, volatile matter, ash-, moisture-, S-, Cl-, N-, F- and dust content[4]. For instance, a biomass with high Cl content is not suitable as fuel, since Cl is corrosive and causes degradation of steel boiler elements (Król & Poskrobko, 2015). The same applies for a high Sulphur- of Fluorine content (van Loo & Koppejan, 2008). Information on the LHV is needed, to asses if the biomass supply can meet the energy demand.

For essential oil production, it would be ideal if the spent biomass material contains sufficient energy to power the production of the next batch. In this scenario, the production process can be self-sufficient since no additional energy source is needed. Therefore, the energy content and -availability of biomass, and energy demand for the production of EO should be mapped on a yearly base. This has to be on a yearly base, since energy supply and demand differ over the seasons. In the case that there is insufficient energy in the spent biomass to power the production on a yearly basis, an additional energy source needs to be found. This a biomass material must be suited for co-fire with the spent biomaterial and preferably locally available. The mismatch between energy- demand and needs over time, requires the storage of biomaterial.

Biomass has a lower energy density than most fossil fuels, therefore the design of storage facilities is important for keeping fuel cost low (van Loo & Koppejan, 2008). For long term storage of biomass with moisture content over 20-30 percent, biological and biochemical degradation should be considered, since this can lead to heat development and self-ignition (van Loo & Koppejan, 2008). Furthermore, changes in moisture content and the growth of fungi and bacteria (which can be a health risk) should be taken into account. Drying the biomaterial before storing on the long term, reduces the above mentioned risks. Furthermore, drying of biomass is often necessary to sustain the combustion in

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[3] C. Zebrowski, project manager at Bionexx, Personal communication, June 17 2017.
[4] D. van Ryckeghem, project sales manager at VYNCKE, personal communication, June 13 2017

the boiler (van Loo & Koppejan, 2008). Additionally, the combustion of dry biomass increases the boiler efficiency and adiabatic flame temperature (Amos, 1998).

The drying process of the biomass is important to take into account, since this is an energy-intensive (and thus costly) process (Li et al., 2001). There are several drying methods: rotary-, flash-, disk-, cascade- and superheated steam dryer. Of which the rotary drying is the most common technique used for biomass drying (Amos, 1998). This method is briefly discussed.

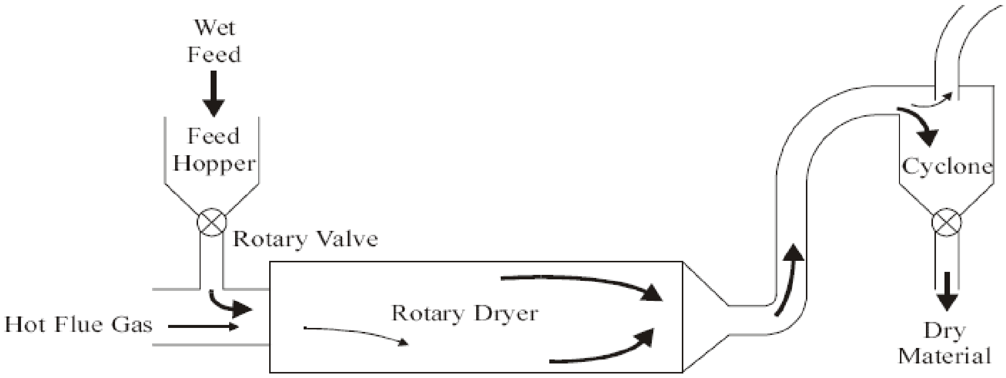

Figure 10. Working principle rotary drum dryer, Amos 1998

Figure 10 shows the working principle of a rotary drum dryer. Wet biomass is fed into a rotating drum. A flow of hot gases is blown into this drum. The rotating movement of the drum promotes a better heat and mass transfer. In the drum, biomaterial and the hot gasses are in direct contact. If the contamination of the biomaterial is not a concern, hot flue gasses (from the boiler) can be used directly. When contamination of the biomass is a matter of concern, a burner can be used, to raise the temperature of the incoming air.

Summarizing the above mentioned, the implementation of a biomass boiler requires additional research and investments. A fuel analysis and assessment is needed to be done, in order to see if the fuel is suitable and if the biomass supply can meet the energy demands. Furthermore, a storage facility is likely to be constructed. And a drying installation is needed to put in place for pre-treating the biomaterial.

4.3.3. Efficient steam boiler

When looking at the energy losses for the production process, it is seen that most energy losses are due to the efficiency of the boiler. Fossil energy is lost because not all heat is transferred to the water. When utilising a boiler with 60 percent efficiency, 40 percent of the fossil energy is lost, per definition. In Figure 8 it can be seen that most part of the energy losses, are due to boiler efficiency losses. Therefore, utilising a more efficient boiler will save significant energy.

Considerations s efficient steam boiler

This is foremost a monetary consideration. Whether the energy savings (and thus cost savings) outweigh the extra cost of procuring a more efficient boiler, over time.

4.3.4. Economizer

When a boiler is operating, hot flue gasses leave through the chimney, which is part of the boilers efficiency losses (see 2.2.2 and 4.2.3). This flow of hot flue gasses can be utilised to increase the boilers efficiency. This is done by applying an economizer, which is a common practice for steam systems[5].

An economizer is a heat exchanger that uses the heat from the flue gasses, to pre-heat the feedwater or air that enters the boiler. The flue gasses and the feedwater are led through the economizer, here heat is exchanged (A. D. Patil, Baviskar, Sable, & Barve, 2015). Utilising the heat from the flue gasses, reduces the amount of heat needed in the boiler to heat up the feed- water or air. An economizer can either be a gas-to-gas or liquid-to-gas heat exchanger. Furthermore a distinction is made between a condensing and non-condensing economizer (US Department of Energy, 2012a). Where in a non-condensing economizer only the sensible heat from the flue gasses is used. In a condensing economizer both sensible and latent heat are utilised to pre-heat the feedwater.

Considerations

There is a limit to what extent a flue gas can be cooled down. This limit is determined by the sulphur content of the fuel. When sulphur condenses in the economizer, it causes corrosion. These minimum temperatures are: for high sulphur content this is 175°C, for low sulphur content 150°C and 120°C for natural gas. Therefore, the sulphur content and flue gas temperature should be known, in order to assess the energy saving potential.

4.3.5. Feedwater condenser

The steam flow with the distillate contains a significant amount of energy (as described in 4.2.3). This energy can be utilised for pre-heating the feedwater. Heat from the steam flow is transferred to the feedwater, consequently cooling down and thus condensing the steam flow. This method has been put into practice for increasing the efficiency of EO production in a distillery in Madagascar[6].

However, the feedwater flow has not enough "cooling power" to condensate the entire steam flow, because of the heat of condensation is approximately seven times higher than the feedwater heating capacity (Cengel & Boles, 2015). Therefore this condenser should be placed in series, in front of the condenser that runs with cooling water.

Considerations feed water condenser

The pre-heating of the feedwater starts as soon as the steam mixture leaves the DS and enters the condenser. This takes time, since the biomass needs to be heated up to distillation temperature, before the steam leaves the DS. Therefore, at the start of the process, feedwater is not pre-heated by this measure.

4.3.6. Solar water heating system

Heating water using solar energy is estimated to be used in 200 million households, and is thus a widely applied application (Twidell & Weir, 2015). There is a wide range of solar water heating (hereafter described as SWH) designs, in this analyses the focus is on non-focusing collectors, because of their ease of operations (Twidell & Weir, 2015). For non-focusing collectors, beam- and diffuse solar radiation is absorbed, heating the fluid that is inside the collector tubes. A distinction can be made between direct and indirect SWH systems. In an indirect system, solar heat is absorbed by a heat transfer fluid and this fluid transfers the heat to the water in a heat exchanger (Homola, n.d.). Direct systems are applied in climates were it rarely freezes, this system is further analysed for the Baviaanskloof. Direct collectors generally heat the water up to 80 °C. Pre-heating the feedwater up to 80 °C, will reduce the quantity of energy that needs to be delivered by the boiler.

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[5] R. van den Berg, project engineer at Kleijn energy consultants, May 30th 2017.
[6] C. Zebrowski, project manager at Bionexx, Personal communication, June 17th 2017.

Considerations SWH system
If production planning requires to operate the facility during night hours, there will be no energy savings from the SWH system. However, this problem can be overcome by placing a storage tank. Moreover, some additional collectors may be needed to be installed, to provide for the extra processing capacity.

4.3.7. Distillation still with steam jacket
In a study by Masango (2005), a new design of distillation still was proposed in order to make the production of EO by steam distillation more clean. This DS has a steam jacket that surround the packed bed of biomass material. This steam jacket ensures that the distillation occurs on a constant, elevated temperature. Furthermore, by applying the steam jacket, the biomass is pre- heated before steam enters the DS. As result, the amount of steam that condenses during the distillation process is minimized. This increases yield, since less EO end up in the condensate in the DS. Hence, it was found that by applying this steam jacket, the oil yield was higher and energy use lower, compared to an old distillation design without steam jacket.

This technology is left out for further analyses. Since there is no further information available on the energy reduction potential and the associated costs of implementing this technology. Furthermore, the energy reduction potential of this technique could not be confirmed by an expert[7].

4.3.8. Insulation
For the DS and SP, it is important that no heat is transferred to its surroundings. This heat transfer can be counteracted by insulating the heat objects. This increases the thermal resistance and therefore reduces the heat transfer from DS and SP to its surroundings. Insulation of SP typically reduce energy losses by 90 percent (US Department of Energy, 2012d).

4.3.9. Cascade heat
Another energy efficiency measure is to cascade the heat that is available in the heat flows (heat energy is available as flue gas and heat of condensation, as described at 4.2.3) to other applications. Utilizing the available heat in the flue gasses can be done by using a economizer, as described at 4.3.4. The heat of condensation can be cascaded, using a heat pump.

When heat flows between 70 °C to 105 °C are sent to the drain, heat pumps can be applied to utilize this heat. Moreover, a steam flow that is vented or condensed is well suited for heat pump technology (US Department of Energy, 2003). Therefore, the heat of condensation from the steam- oil mixture could be utilised, using a heat pump. A suitable heat pump technology for this temperature range would be a mechanical vapor compressor (RVO, 2015).

The heat of condensation is transferred to a refrigerant. This refrigerant evaporates and is transferred towards a compressor. Here the refrigerant, with the absorbed waste heat, is pressurized. This increases the temperature of the refrigerant. Thereafter, the high temperature refrigerant, is pumped to a condenser, were it transfers condensation heat to the other appliance, e.g. a drying process (De Kleijn Energy Consultants, n.d.).

Considerations cascade heat
The main consideration or requirement for this technology option, is an application for the heat near the facility. Furthermore, the heat requirements of this application, need to match the supply of the

[7] W. Bester, owner of EDE (Essential oil distillation equipment) South Africa, personal communication, November 22nd 2017.

distillation process (RVO, 2015). For the distillation process, a lot of heat is available in a short time period (distillation time). This heat is not suited for e.g. residential heating.

4.3.10. Biomass drying before distillation

The water content in a plant ranges from 50 percent to over 80 percent (Baser & Buchbauer, 2010). As described in section 2.1.1, energy is required to heat the bio material. Depending on the water content, a part of the energy is needed to heat the water content in the biomaterial. Drying the biomass reduces the water content of the biomass. Therefore, less energy is needed to heat up the biomass during distillation, when the biomass is dry.

There are multiple ways to dry the biomass: direct sun drying, rotary drum dryers, superheated steam dryers and more (Li et al., 2001). To dry biomass using a technology (for instance rotary drum dryer), energy is required is to produce hot air and power the system. Therefore, there will be no net energy reduction for the whole process (drying and distilling biomass). For this reason, drying biomass using a technology, is not a valid technology option for this research, since the aim of this study is to identify technologies to reduce the energy needs for the whole EO production process. However, direct sun drying of the biomass is a valid method to reduce the fossil fuel consumption for the EO production process. This is a straightforward and simple method. However, this study focuses on technologies for energy reduction. Direct sun drying does not rely on technology and can rather be seen as an action within the process. Therefore, this energy reduction option is left out from further analyses.

Considerations drying biomass

The drying of the biomass does influence the quality of the EO. Resulting in different chemical compositions of the essential oil when extracted from dry or wet biomass (Baser & Buchbauer, 2010). In Appendix 2B: Composition essential oils, an overview of the differences in essential composition of fresh and dry biomass distillation.

4.4. Results step 4: Evaluating identified technologies

The identified RETs and EEMs were evaluated on three criteria: fitness for rural Africa, energy reduction potential and costs (by determining the LCOE). The results of this evaluation for each technology are presented in Table 6. Each identified technology option was assumed to be implemented at the reference case. Based on this, further assumptions on the implementation and utilization of these technologies were made. The elaboration (and underlying assumptions) of the results can be found in in Appendix 3: Evaluation of technologies.

Table 6. Evaluation technologies on fitness rural Africa, energy reduction potential and LCOE

Technology	**Fitness rural Africa**	**Energy reduction potential**	**LCOE**
	Score on Model A	Fossil energy decrease %	€/GJ
CSP boiler*	**17**	**100**	**195.5**
Biomass Boiler	**7**	**100**	**31.8**
Efficient boiler	**8**	**17.6**	**29.5**
Economizer	**18**	**1.8**	**21.4**
Feedwater condenser	**12**	**7.0**	**5.1**
SWH	**16**	**3.7**	**71.3**
Insulation	**24**	**13.4 / 1.5****	**1.9/5.5****
Cascade heat	**6**	**37.7*****	**44.5**

* Not feasible to use this technology for a 500 kW essential oil distillery, only applicable at 3kW or smaller distilleries (Anjum Munir et al., 2014).
** The results on energy reduction potential and LCOE goes under the assumption that the DS and SP are not insulated. For the Baviaanskloof, the DS is already insulated. For the Baviaanskloof, SP could still be insulated, the energy reduction potential would be 1.5 percent and LCOE 5.5 €/GJ.
*** This measure does not reduce the fossil fuel consumption of the distillation process. However, energy is saved by reducing the energy needs of other heat applications.

The results indicate how each technology performs on each of the three criteria. However, no statements can be made on which is the 'most suitable' technology. Because it is not specified what the relative importance of each specific criterion is.

Technologies that are most fit to be implemented in rural Africa are, insulation, an economizer, a CSP boiler and a SWH system. Utilizing a CSP-, biomass boiler or heat pump will results in the highest fossil energy reduction.

In order to put the technology results of the LCOE in context, the LCOE for the base case was calculated. This is the cost per unit of energy to operate the distillery in the Baviaanskloof without any RETs or EEMs in place, which was found to be *32.9 €/GJ (*see LCOE base case *page 64)*. Hence, when the LCOE of a technology is found to be lower than LCOE of the base case, it indicates that implementing this technology will result in cost savings. This is because the costs for an unit energy saved or produced by a technology, is lower than the costs of an unit energy produced by the boiler at the base case. For implementing technologies with a higher LCOE, it indicates that additional costs are made, to reduce fossil fuel consumption. Thus, implementing a biomass boiler, efficient boiler, economizer, feedwater condenser or insulation, will result in energy and cost savings over the technology its lifetime.

4.5. Results step 5: Applicability of identified technologies to case

This chapter looks into the applicability of the identified technologies. Since the implementation of specific technologies require certain conditions (as indicated as technology considerations in section 4.3). For instance, the implementation of SWH requires sufficient solar irradiation. Moreover, not all technologies can be implemented simultaneously, since some technologies compete with- or exclude each other. In section 4.5.1 an overview is given of compatibility of the technologies; technologies which can and which cannot be implemented simultaneously and technologies that ‘compete’ with one another.

In order to find the best suited energy reduction technologies for a specific distillery, certain considerations need to be taken into account. In section 4.5.2 a decision tree is constructed for selecting the most suitable technology for a specific case. This decision tree is briefly discussed. Thereafter, this decision tree is applied to the reference case. In order to find the most suitable technologies to implement at the EO distillery in the Baviaanskloof (section 4.5.3).

4.5.1. Compatibility of technologies

In Table 7, an overview is shown of the technologies which can and which cannot be implemented simultaneously. Technologies that exclude each other are indicated with an X. In case technologies compete with each other, it is indicated with an O. When these technologies are implemented simultaneously, their energy reduction potential will be influenced negatively by one another.

Table 7. Overview compatibility of technologies

	CSP	Biomass boiler	Efficient boiler	Economizer	Feedwater condens	SWH	Insulation	Cascade heat
CSP	x	x	x	x		x**		x***
Biomass Boiler	x	x	x	x*				
Efficient boiler	x	x	x					
Economizer	x	x*		x	O	O		
Feedwater condenser				O	x	O		O
SWH	x**			O	O	x		
Insulation							x	
Cascade heat	x***				O			x

*Economizers cannot be applied for biomass boilers, this is due to the sulphur content in biomass (van Loo & Koppejan, 2008).
**Using SWH to pre-heat the feedwater for a CSP is circuitous, since both technologies rely on solar irradiation.
***A CSP boiler does not produce any flue gasses. Furthermore, a CSP boiler has a maximum capacity of 3 kW, however the minimum capacity of mechanical vapor compressor heat pumps are 200 kW (RVO, 2015).

4.5.2. Selecting suitable energy reduction technologies for specific case

In Figure 11 the decision tree, for selecting energy reduction technologies for a specific case is shown.

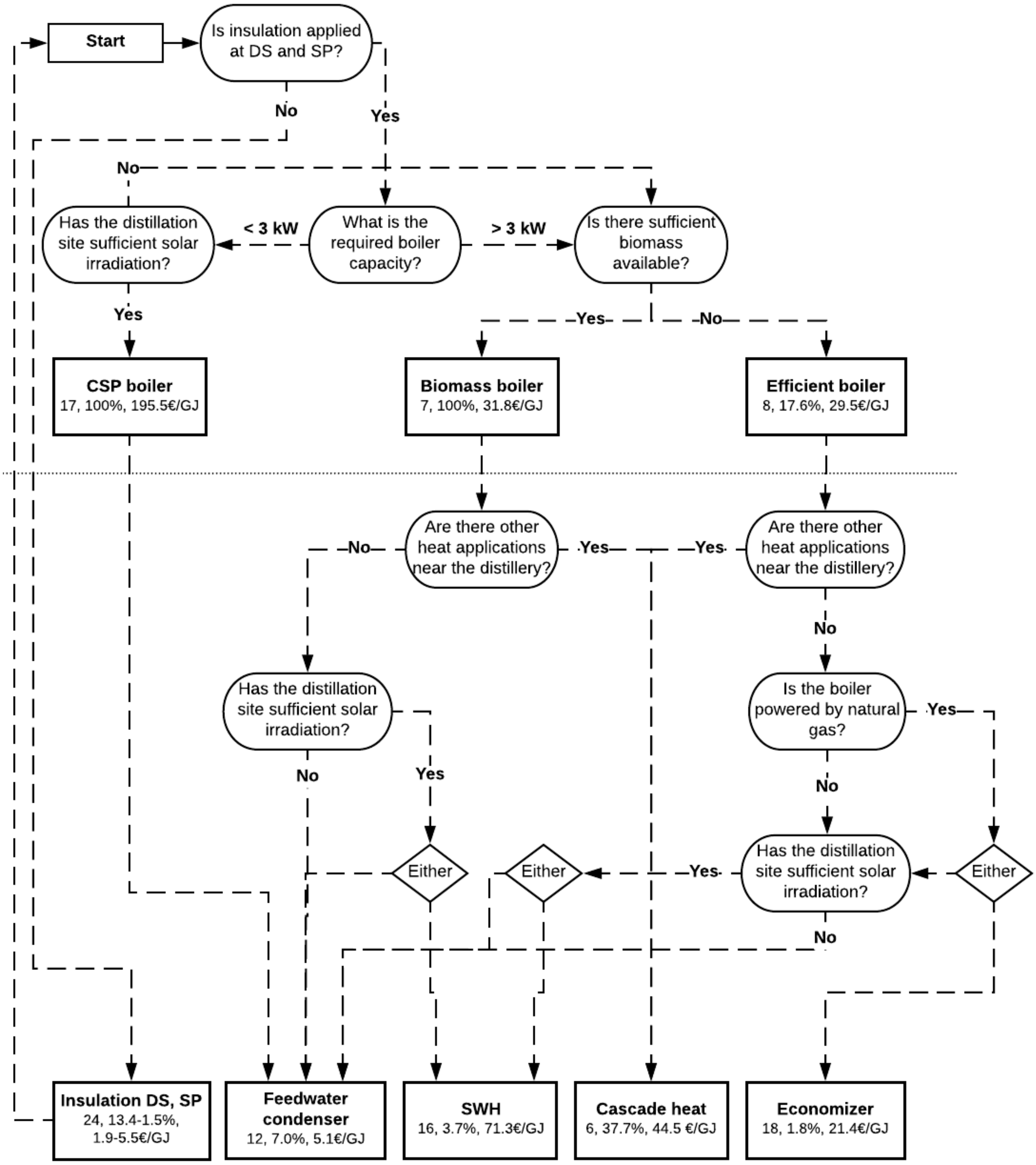

Figure 11. Decision tree to select suitable fossil energy reduction technology for specific case

The first step is to check if the SP and DS are insulated. Thereafter, a distinction is made between the required capacity of the boiler. Since only low capacity CSP boilers are available. When a boiler capacity higher than 3 kW is required, a biomass- and conventional boiler are suitable to produce steam for the production process. However, a biomass boiler can only be utilised if there is sufficient biomass available (see section 4.3.2). Otherwise, a conventional (efficient) fossil fuel boiler should be utilised. After selecting a suitable boiler, EEMs that fit the case specific conditions should be selected.

Since there is a heat surplus for the EO production process, the first step is to check if there are other heat appliances near the distillery to utilise this heat surplus. Moreover, cascading heat has the highest energy reduction potential, thus options to cascade heat should be assessed first. Thereafter, depending on the type of boiler in place, multiple EEMs are feasible. Furthermore, the EEMs insulation and a feedwater condeser can be implemented for any case.The evaluation results on the criteria are indicated in the boxes with technology options. These values are based on the reference case and therefore will differ for other distilleries. The next section goes into the applicability of identified technologies for the reference case.

4.5.3. Applicability technologies to reference case

The applicability of the technologies to the reference case are assessed by going through the steps of the decision tree. At the reference case, insulation is applied to the DS but not to the SP. Thus as a first EEM, insulation should be applied to the SP. The required boiler capacity is 500 kW and thus a CSP boiler is not a valid option. A biomass boiler is also not a valid option, since no sufficient biomass is available as fuel. The Baviaanskloof area is a very dry area with little vegetation[8]. Therefore no other biomass than the spent bio material after distillation is available. For the spent biomass it is uncertain if it is suitable to be used as fuel for a biomass boiler[8]. Moreover, the spent biomaterial is of great value for the area, since it can be utilised as compost in order to restore the vegetation in the area (see interview Justin Gird, Appendix 1B: Stakeholder interviews). Restoring vegetation in the area is one of the main goals for the Baviaans DEVCO project. Thus spent biomass is preferred to be utilized as compost rather than as fuel for a biomass boiler. Thus for steam production at the reference case, two options remain; an efficient boiler or remain with the boiler that is in place.

Cascading heat is not an option for the reference case. Since no other heat applications are available near the distillery. The boiler in place uses diesel fuel, and thus an economizer is not suitable for this process. An economizer would only be an option in the case that an alternative boiler would be implemented, that uses natural gas. The two remaining EEMs for the reference case are a feedwater condenser and SWH system. In the Baviaanskloof area 2000 kWh/m^2 solar irradiation is available. Based on this it was found that SWH had an energy reduction potential of 3.7 percent and LCOE 71.3 €/GJ. Since SWH system and feedwater condenser are competing technologies, they should not be implemented simultaneously. A feedwater condenser has higher energy reduction potential and a lower LCOE compared to a SWH system. Based on this, a feedwater condenser is the most suitable technology for the reference case.

Concluding, the technologies that are applicable to the reference case are: insulation, efficient boiler, feedwater condenser and SWH system. Here a feedwater condenser is preferred over a SWH system. Insulation should be applied to the SP since this is a cost efficient energy reduction measure. Replacing the current boiler for a more efficient boiler is a valid option. However, remaining with the current boiler does not exclude the applicable technology options.

[8] T. Teunis, director Grounded South Africa, personal communication, 28th November 2017.

5. Discussion

This chapter elaborates on the implications and limitations of the results found in this study. Furthermore, opportunity and needs for further research are touched upon. The discussion is structured according to research design and associated results.

5.1. Identification of criteria and Model A

The results on technological criteria for rural Africa are likely to be more directed to the Baviaanskloof than rural Africa in general. This is because the reference case was taken as a starting point for the identification of technology criteria for rural Africa. Therefore, literature study was done in order to validate these criteria. If another case was taken as a starting point, it could be that other technology criteria were identified and deemed important. A different approach to identify technological criteria for rural Africa would be to conduct interviews among multiple technology projects in rural Africa. When the sample of technology projects is representative for rural Africa, the results can be generalized for entire rural Africa (Marshall, 1996).

Model A was constructed using the technology criteria found in the case- and literature study. Because of this, the results on technology fitness for rural Africa are specialized on the Baviaanskloof and thus less generalizable for other cases. Therefore these results should not directly be projected onto another case. Care should be taken when interpreting these findings. However, this model can function as a framework that can be extended and customized for case specific interests. Furthermore, Model A was constructed to evaluate each technology its fitness for implementation in rural Africa. As a result, the model graded each technology on a scale from 0 to 24, using a questionnaire consisting out of eight questions. Each indicator was of equal importance. However, it would be more accurate to allocate weights to the specific indicators, according to importance (Wang et al., 2009). For instance, the lifetime expectancy of a technology could be deemed more important than a technology containing electronical parts. Allocating weights would make the final score more accurate on predicting a technology its fitness for rural Africa. Therefore, when applying Model A to a specific case, it is advised to review this model, customize it, and allocate weights according to the case necessities.

5.2. Energy requirements EO production and Model B

Model B was constructed to calculate the energy requirements for EO production in the Baviaanskloof. This was done, since there was insufficient literature and data available that goes into the energy requirements of the EO production process. The model was based on (thermodynamic engineering) theory. However, this model was subject to simplifications, neglecting certain energy cost, which results in uncertainties in the results on energy requirements.

The functional unit of this model is the production of one batch. Due to this simplification, start-up- and standby energy costs are neglected. A fire tube boiler (as in place at the reference case) has significant higher start-up energy costs than a flash- boiler (efficient boiler alternative) (Kellermann, 2013). The same applies for a CSP boiler, which directly delivers heat when it is operated. When accounting for the start-up and standby time for specific boilers, the results on the energy requirements will be altered and more accurate to real practice. Moreover, alternative boilers (e.g. Vapomat- of CSP boiler) are likely to have a higher energy reduction potential and lower LCOE, when accounting for start-up and standby energy costs. For further research, start-up and standby boiler operations should be taken into account.

Since the functional unit is the production of one batch, seasonal change was not taken into account. However, the energy requirements are indeed subject to change over environmental factors and thus seasons. For instance, if the average temperature drops because of winter, the feedwater temperature and distillery temperature will drop as well. When the feedwater- and distillery temperature are 12 °C and 18 °C, respectively. The total energy needs will be 1728 MJ and 287.0 MJ will be lost due to heat transfer, these are increases to the base case of, 0.06 percent and 13 percent, respectively. Based on this, it can be stated that a drop in feedwater temperature does not influence the energy needs substantial. Decrease of the distillery temperature does substantially influence the heat transfer losses, however, this can be counteracted by applying insulation. A factor that does have substantial influence on the energy needs, is the forced convection caused by wind. For this model it was assumed that the distillation is not subject to forced convection, since it is done in a closed facility. However, a forced airflow can significantly influences the energy requirements. An example was found, were the same distillation unit had a reflux of 2 percent of the steam flow, when operated inside a facility and a 20 percent reflux when utilised in an open field, being subject to forced airflows[9].

In line with these simplifications, certain distillery operating energy costs were neglected. These energy costs are: energy to, pump the cooling and feedwater, to pressurize the feedwater, electricity for operating the boiler and energy to power the overhead cranes to load the biomaterial into the DS.

5.3. Identification of energy reduction technologies

One general limitation of this research is the fact that it only looked into energy reduction technologies. Reduction of fossil energy could also be achieved by looking into optimization steps and other measures. For instance, the measure of drying biomass before distillation. Moreover, energy could be saved by improved process control, boiler- and steam system maintenance (Einstein et al., 2001). As an example, for industrial boilers 10 percent and 3 percent of the total fuel needs can be saved by boiler maintenance and improved process control, respectively (Einstein et al., 2001). The importance of periodically maintenance plans was also stressed in the literature on technologies in rural Africa (Barry et al., 2011). However, due to time constraints, the focus of this study is the utilization of technologies for fossil energy reduction.

Ten technologies were identified as suitable options for energy reduction, of which eight were further evaluated. These technologies were identified based on literature on EO- and steam production. Thereafter, these technologies were discussed with experts, in order to verify the applicability to the EO production process. Therefore, it can be stated that the eight technologies are certain to achieve the goal of energy reduction for the EO production process. In line with this, the steam jacket technology was left out further analyses. Since only one article was available that described this method. Moreover, experts could not validate this method. When more information on this method is available, this can be a relevant technology for further research.

Cascade heat was identified as a technology, and for this research it was assumed that heat is cascaded by utilising a heat pump. This technology was further analysed. However, there are multiple technologies that can be applied in order to cascade heat. For instance, direct heat use, air coolers and heat exchangers (Energydesignresources, 2017). The cascading of heat has a high energy reduction

[9] W. Bester, owner of EDE (Essential oil distillation equipment) South Africa, personal communication, November 22nd 2017.

potential, since there is a heat surplus for the EO production process. Therefore, further research is needed into other technologies that cascade heat, to be implemented for EO production process.

5.4. Evaluation of technologies

The implications and limitations of the results found on the evaluation of technologies are separately discussed for each evaluation criterion.

5.4.1. Fitness rural Africa

Data for the evaluation on the criterion fitness for rural Africa was obtained by consulting literature, manufacturers, and suppliers of the technologies. However, within the technology classification, there is a broad range of specific technology models. As an example, different types of SWH collectors are available; flat plate-, evacuated tube- collectors and open-, closed systems (Twidell & Weir, 2015). This broad range of technology models applies for each identified technology, excluding insulation and CSP boiler. Due to this variation within technology classification, a variation on the score for a technology its fitness for rural Africa is inevitable. For this study technology models were chosen for evaluation, that are likely most fit for rural Africa. For instance, economizers are available with and without electronical parts. Thus for this study, the score was based on models without electronical parts. However, the score on fitness for rural Africa is not generalizable for each technology model. Thus care should be taken when interpreting these scores.

5.4.2. Energy reduction potential

In order to calculate the energy reduction potential for each technology, it was assumed that the technologies would be implemented at the reference case. Based on this, further assumptions were made. Due to this, the results on energy reduction potential are only relevant to the reference case and not generalizable for other specific cases. However, these values do give insight into the order of the energy reduction potential. Moreover, some demarcation and simplifications steps were made in order to conduct this calculations within the time constraints.

The first simplification step was to not account for the energy needs to operate a RET or EEM. For instance, electricity is needed to operate the pumps for the SWH system and feedwater condenser. Which results in an increase of energy needs for the whole system. For a biomass boiler energy is needed to pre-treat the biomass (drying and chipping). Second, it was assumed that the technology would only be operating during the distillation process. This assumption does not correspond to a SWH system in practice, this technology operates during daytime. Thermal energy produced during the day by a SWH system could be stored, and utilized when needed (Twidell & Weir, 2015). Thus increasing the energy savings. Storage of thermal energy was not accounted for when calculating the energy reduction potential. The same applies for a feedwater condenser. Here, a surplus of heat is available in the steam flow, of which the feedwater condenser only a fraction. If the other heat fraction could be stored, and utilized for another batch, energy can be saved. For further research, the option of energy storage is an interesting option to take into further consideration.

5.4.3. LCOE

To calculate the LCOE for the identified technology options, it was assumed that the technologies would be implemented at the reference case. Based on this, assumptions on investment, operating and maintenance and fuel cost were made. Due to these assumptions, the LCOE values only apply to the reference case. Moreover, order of magnitude screening method was applied for calculating the LCOE. Associated accuracy of this method is ± 40 percent (de Jong, 2015). The uncertainty of the LCOE values limits the representativeness to reality.

A shortcoming of the LCOE method, is that it does not account for the magnitude of the upfront investment costs of a technology (Short et al., 1995). For technologies with high upfront investment cost, a loan may be required when insufficient capital is available. A loan is subject to interest and will result into higher costs of the technology. However, the additional costs due to the interest rate on a loan can be included when calculating LCOE. As an example in this study, a biomass boiler has a lower LCOE than the base case. But the initial investment cost of a biomass boiler is more than six times the initial investment cost of the boiler in place at the Baviaanskloof. Based on the LCOE, the biomass boiler is a more favourable option. However, this might change in case the upfront investment costs and the (possibly) associated loan interest costs are included.

Based on the above mentioned, before selecting a fossil energy reduction technology, a more accurate calculation for the LCOE should be made, using detailed budgeting method (± 5 percent accurate) (de Jong, 2015). Furthermore, the initial investment costs should be taken into account for decision making. Nevertheless, for this study the aim was to get insight into the order of magnitude of the technology costs and be able to compare the different technologies on associated costs. Therefore, the applied method was sufficient for this study.

A simplification step was made when calculating the LCOE for the technologies; the price for (fossil) energy was assumed to be constant over time. However, fossil energy price are expected to rise (UK Department for Business, 2017). Therefore, the LCOE values for technologies that rely on fossil energy are expected to rise. Technologies that rely on fossil fuel are: the base case, efficient boiler, and cascade heat (heat pump).

The cumulative produced or saved energy over the lifetime of the technology, is a highly influential parameter. In line with this, the load factor of a technology determinative for the LCOE value. An example is found were the (financial) feasibility of a heat pump highly depends on yearly load factor of the technology (RVO, 2015). For the reference case, the load factor was expected to be relatively low (410 production hours vs 8760 hours in a year, which corresponds to a load factor of ~ 0.05). This yearly operation load for the reference case, was estimated on the financial model and forecast of the DEVCO Pty Ltd. Thus, the load factor was based on a forecast, rather than historical data. Therefore the estimation on yearly production is highly uncertain.

If the yearly production increases, the LCOE for technologies (with lower variable cost than the base case) will decrease in respect to the base case. For example, when production is doubled (1094 batches and 810 load hours) the LCOE of heat pump, SWH, and biomass boiler would be 23.2 €/GJ, 35.7 €/GJ and 18.7 €/GJ, respectively.

However, for this study the LCOE values functioned purely to compare the technologies among each other and give an indication of the associated costs. Despite the uncertainty to the LCOE values, these goals were achieved. However, due to the uncertainty in the LCOE figures, these should not be interpret as set in stone.

5.5. Applicability of technologies

In order to assess the applicability of technologies to the reference case, a decision tree was constructed. For the decision making, limitations and considerations of the implementation of the technologies were accounted for. Therefore, decisions were made, based on the distillery- and distillery site characteristics, combined with the limitations of the technologies. However, the decision tree does not account for budget limitations. The cost of a technology plays a significant role in decision making for technology selection for a project, this was also stressed by the stakeholders during the interviews. For further research it is recommended to account for budget limitations and to further asses the costs of the technologies. The results of this study on LCOE can function as a starting point for further research into the financial feasibility of technologies.

6. Conclusion

The aim of this research was to identify opportunities to reduce the fossil energy needs for the production of EO, in rural Africa. This was done by looking into RETs and EEMs that fit the EO production process. Additionally, the fact that the production of EO often is located in rural areas was taken into account when identifying RETs and EEMs. Technologies that were identified as suitable for the EO production process and implementation in rural Africa were further assessed. This was done by evaluating each technology on three criteria: fitness for rural Africa, energy reduction potential and costs. As a final step, the results were put into practice by looking into the applicability of these technologies at the reference case in the Baviaanskloof.

The production of EO in rural Africa can become less fossil energy demanding by implementing (a combination of) RETs and EEMs. These energy reduction technologies are: *CSP-, biomass-* and *efficient boiler*, *economizer, feedwater condenser*, *SWH system*, *insulation* and *cascading of heat* (using a heat pump). Insulation, an economizer, CSP boiler and SWH system, were found to be most suitable for implementation in rural Africa, respectively. RETs (CSP- and biomass boiler), cascading of heat and an efficient boiler, respectively have the highest energy reduction potential. However, a CSP boiler can only be utilised at distilleries with a capacity lower than 3 kW. The most cost effective energy reduction technologies identified are insulation, feedwater condenser and an economizer, respectively. Since these technologies were found to have the lowest LCOE. However, not all identified technologies can be implemented simultaneously. Because some technologies compete with each other, for instance, an economizer and feedwater condenser both pre-heat the boiler feedwater. Furthermore, the operating performance of technologies are subject to case specific factors. For instance, the availability of sufficient biomass, required boiler capacity and solar irradiation. Therefore, the applicability of these technologies need to be further assessed in the context of a specific case. In line with this, the applicability of technologies for the reference case were assessed. It was found that insulation, SWH system and a feedwater condenser could be applied at the distillery in the Baviaanskloof. Here a feedwater condenser is preferred over a SWH system, since it has higher energy reduction potential and lower associated costs. Furthermore, replacing the diesel boiler with a more efficient boiler is a valid option as well, to reduce fossil energy use at the Baviaanskloof distillery.

In the effort of answering the main research question, additional findings came forward. As a first result, technological criteria were identified for rural Africa. These criteria were used to construct a model. The aim of this model was to assess technologies on their fitness for implementation in rural Africa. This model can be used for similar studies, that also look into technology fitness for rural Africa. However, it is advised to review this model and customize to the research goals. Since this model was constructed in order to fulfil the research aim of this study. Moreover, this study proposes a model to calculate the energy requirements for EO production. Based on the results fiound by this model, it can be stated that there is a general heat surplus for the production of EO. Furthermore, the most significant energy losses are due to boiler efficiency and heat transfer at the DS. Additionally, this model can be used to calculate the approximate energy- needs and losses for EO production of different cases. Because the dynamics of this model apply to the steam distillation process in general. In order to do this, the distillery parameters and properties should be adjusted the case specifications.

This research is subject to two main limitations. First, it only looked into energy reduction technologies. Thereby, process optimization steps and other efficiency measures were left out of the scope of this research. However, there are opportunities to reduce the energy needs for this process by undertaking optimization steps, such as improving- process control and boiler maintenance. Further research into these methods is needed in order to give a broader range of energy reduction opportunities for EO production in rural Africa. Second, technologies were evaluated in the context of the reference case. Therefore, the potential energy reduction and LCOE of technologies were calculated based on assumptions that these are implemented at the reference case. In line with this, the results on energy reduction potential and LCOE, cannot be directly projected to other cases. However, the results do give an indication of the identified technology their energy reduction potential and associated costs. This information is useful for assessing other cases. Consequently, an important implication of this research is that it provides a starting point for research into energy reduction for EO production in rural Africa. Furthermore, it gives insight into technological opportunities and limitations to reduce fossil fuel consumption for the distillery in the Baviaanskloof.

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Appendices

In the Appendix, background information that was needed for this study, is provided. In Appendix 1, a report on the case study can be found and the interviews that were conducted with stakeholders. In Appendix 2, background information on convective heat transfer and EO compound compositions are given. Appendix 3 contains the elaboration of the evaluation of the identified energy reduction technologies.

Appendix 1: Case study

This case study was conducted by visiting the project site, and staying in the area for a month. The main findings from this case study are documented in a case report. Furthermore, four semi- structured interviews were conducted with stakeholders of the project. First, a summary of these interview is given.

Appendix 1A: Case report

The case report gives insight into the DEVCO Baviaanskloof project. The incentive for initiating the project is described. Furthermore, some information is given on the EO production facility that was constructed in the Baviaanskloof. At last, insight is given into the Baviaanskloof area and the community that lives here.

Baviaanskloof land restoration project

Baviaanskloof DEVCO Pty Ltd is the name of the essential oil production company. DEVCO is an abbreviation for developing company. The name captures the essence of the project, create sustainable development in the Baviaanskloof.

Decades of goat farming has led to massive land degradation in the Baviaanskloof. If the farmers continue to rely on an income from goat farming, the land could become a desert (Grounded, 2017). Therefore, a new economic model needed to be found. Which allows the transition from traditional goat farming to a more sustainable business model. Moreover, this new business model needs to aid in restoring the soil quality, increase the vegetation cover and increase the water table.

In collaboration with the local farmers, Livinglands, Commonland and Grounded, a solution was found. A business model was developed with the farmers, where essential oils would be the new source of income. The cultivation of lavender and rosemary requires little water and 100 times less space than goats. Furthermore, cultivating lavender and rosemary will aid to maintain water and minerals in the soil, increasing the soil quality.

This initiative raised enough funds through several investors and the company was established in June 2015. Currently, 80 hectares of rosemary and lavender have been established. The distillation facility is nearly finished, the first crops have been harvested and test batches have been produced.

Essential oils production facility

A steam distillation facility was constructed in the Baviaanskloof, as part of the DEVCO project. The facility holds two distillation columns with each a capacity of 1.3 ton of biomass intake. Two distillation pots were placed, to alternate each other in order to enhance constant production. A 500 kW diesel fire tube (with an estimated thermal efficiency of 70 percent[10]) steam boiler produces the steam that is required for the process. This boiler is second-hand (from 1964) but completely

[10] Estimations made by the boiler supplier, Cyclotherm South Africa.

refurbished and provided by Cyclotherm, a South African boiler supplier. The boiler feedwater is softened by pre-treating the feedwater with sodium chloride. A customized distillation system was built for this facility, supplied by Herb-Alplenty (South African company), and fully consist out of stainless steel.

Outside of the factory a water basin was laid out. This water basin supplies the cooling water, which runs through the condenser with a flowrate of approximately 10,000 l/h. Biomass material is harvested near the distillery and transported to the distillery on a truck loader. Roller doors in the facility allow the truck loader to move into the distillery. Here the trucks are unloaded onto an overhead crane. On the overhead crane the biomaterial is weighted and loaded into one of the two stills. In the distillery a separate room is available to run tests on the obtained oils. Furthermore, in this room the oils are distributed in flasks samples, and the bulk is stored in drums in the facility for further distribution.

The construction costs of the facility were 1,600,000 ZAR, the distillation installation costed 2,793,000 ZAR and the boiler costed 210,000 ZAR.

Baviaanskloof area

The Baviaanskloof is a valley that crosses the boarders of the Western- and Eastern Cape. The majority of the land has been established as a wilderness area. And the Baviaanskloof reserve is a World Heritage site. Within the park, there is private land, here the landowners farm livestock and run tourism activities (Livinglands, 2015).

There are two access routes to go into the Baviaanskloof. The west entrance goes from Willowmore or Uniondale, and is an approximately three hour drive along a gravel road. The eastern entrance, goes from Cambria, and requires a 4x4. This road goes through the nature reserve and is therefore kept rugged.

Baviaanskloof community

In the Baviaanskloof there are approximately 510 households, with an average household size of 4.6. This comes to a population around 2300 persons, and the population density is 0.87 person per square kilometre. In the Baviaanskloof there is a low employment rate, 37 percent and a high poverty rate (Livinglands, 2015).

Appendix 1B: Stakeholder interviews

Interviewee	Relevance	Location	Date
Justin Gird	Project development manager	Padstal, Baviaanskloof	25-08-2017

Interviewer: What are, in your opinion and by your experience, the biggest barriers or challenges when you want to execute a project in the Baviaanskloof?

Justin Gird: The distance, the location, and the road being the biggest issue. Another issue is the fact that we are doing an alternative farming system. We don't have any support. The area around us, Baviaanskloof Uniondale, Willowmore and bigger, George. These areas are al into other types of farming, largely stock farming. So we don't get support from these industries. Not that they don't want to per se, more that they are not familiar with our ways, and so cannot help us. Therefore we have to do anything by ourselves.

Interviewer: What are important criteria to consider, when selecting a technology for implementing in Baviaanskloof?

Justin Gird: First of all, budget. We are in a development phase, and there are always things to do, room for improvement. But on this moment, we don't even make money out of it. Therefore budget is the most important criteria at the moment.

Next to money, an important criteria is the ease of operation. How easy is a technology to run? And what sort of maintenance do you look at? We have foremost low skilled workers, and for maintenance or when something breaks down. We don't want someone from George to have to come down. So in order of importance, money, ease of operation and maintenance.

Interviewer: On a scale from one to ten, how important will it be that the technology is delivered by a local supplier?

Justin Gird: It makes it easier, if a technology is supplied by a local supplier. But if that includes that they will deliver service. If something break down, and they will come and fix it, perfect. However, I am a bit sceptical about local suppliers. Because we are at this point that we don't know enough about the matter. Therefore in some cases we can't tell if people are being honest with us. So I would rather go with a more trusted supplier than a local supplier. But, a local and trusted supplier would be ideal. For instance, if you look at the distillation technology. I trust technology coming out of France, more than I trust the local guys.

Prior the questions on EEMs and RETs background information was given on the technology. After background information was given, questions were raised on feasibility of installing the technologies in the Baviaanskloof.

Economizer

Justin Gird: So taking one step back, as we discussed, in the Baviaanskloof there is a shortage of people with certain skills. But you should also know, there is a shortage of people that want to be trained into certain skills. However, a welder is something that we earmark, that quit a few people would like to become. And so we could provide this training. A welder could link very nicely to other areas where we work and where we could use the this skill. Furthermore, would link into our goals of empowering the local community.

So one option is that you get a skilled welder and the other option is that you get spare parts that can be used to replace broken parts. I like that, and think that would be a feasible option for the distillery. And I am sure that these economizers are supplied ‘locally’. You should look into our industrial towns, Port-Elizabeth for instance

Side note, there are a couple of things that I would like to do, before looking into all these energy saving technologies. I would like the optimize the system, for instance blowdown. Therefore, we need some systems in place to monitor certain parameters. Which will enable us to maximize the energy efficiency. I would like that you will also look into these optimization issues

Pre-heating feedwater with condenser

Justin Gird: I like this option, and should be relatively simple. Yes this should be possible, since it is the same principle as the condenser and that works.

Side note: Would you put into your report/thesis where you recommend, to have monitoring certain values, in order to optimize the system.

Biomass boiler

Justin Gird: My only concern about a biomass boiler, when looking at a greater scheme of things. Is that the biomass that we produce, its more valuable I would assume. I think it’s more valuable to have the biomass here and use is for as compost. And rather bring in more ‘refined’ product such as diesel. We need this biomass for are land restoration projects. So we rather bring in diesel than biomass, purely looking to the transport costs. The value of biomass in these area is quits high. It might be interesting to put a monetary value to it and see. On this moment the focus in this area is to get back a fertile topsoil. Therefore it would not make sense to use biomass as a fuel.

That being said, I think on the long run, say 5 to 10 years. The fertility of the topsoil will be alright, and we don’t need that biomass for compost anymore. So if we utilize the biomass now, there might come a time that we don’t need that compost anymore. Than it might become more feasible and interesting to look at biomass boilers. So it is interesting to consider this as an option for making the production of essential oils more clean.

And what about creating your own bio-diesel? I say this because we are reducing stock in this area. Therefore, in the future we will need to grow another crop, to fill up this gap. And it might be worthwhile to look into crops that can be used to produce bio-diesel.

- Part interview omitted; no further relevance for this research-

Interviewer: Any final remarks?

Justin Gird: If you could put something along the line about blowdown rate and where we should measure to monitor the process. That would be really helpful. These might be cheap solutions that can improve a lot.

Interviewee	Relevance	Location	Date
Willie van Rensburg	Farmer Baviaanskloof, future facility manager	Verloren Rivier, Baviaanskloof	01-09-2017

Interviewer: What are, in your opinion and by your experience, the biggest barriers or challenges when you want to execute a project in the Baviaanskloof?

Willie van Rensburg: My personal opinion and experience, Baviaanskloof is not the best place for farming in South- Africa. This area is not a farming area, but rather a wilderness area, and people aren't supposed to farm here. Big barrier in Baviaanskloof is the distance to the market. And the cost that goes along with this distance. The distance to shops, suppliers and the market, pushes the prices. I think because of the distance, Baviaanskloof is still a 'raw' place and we lack a bit behind on other farming places.

We are here in the Baviaanskloof with eight farmers. Beginning a new project asks a lot of time from us. We have to do this besides the other projects that are going on and the daily farming. So we can't give a hundred percent. It is a big step to take up another project besides the farming.

Interviewer: What are important criteria to consider, when selecting a technology for implementing in Baviaanskloof?

Willie van Rensburg: First of all, it has to make money or save money, be a better option that you had before. Second, I find it important that it is responsible, and does not go by the expenses of something/somebody else.

I am not that afraid of complicated technology. For example, if we take boilers, you got a choice between four or five types. It doesn't matter which you choice, everything that works will break down eventually. When it can be fixed by us, we will do it. To bring someone in, it will cost more, but that applies for everything in the Baviaanskloof. But off course, I prefer products that reliable and when it breaks down, easy to fix by myself.

Interviewer: On a scale from one to ten, how important will it be that the technology is delivered by a local supplier?

Willie van Rensburg: As long it is in South- Africa, I think it is fine. If something breaks down, or we need a new part for replacement. Everything in South- Africa, can be in George within a day. Only to get the parts from George to the Baviaankloof can be tricky. If you need a qualified worker to replace this new part. It will take him a whole day, instead of an hour. Because it takes three hours to go in, and another three hours to go out the Baviaankloof. Even if you only need 30 minutes of his time, it will cost him a whole day. Therefore, it is more difficult to get people to come down to Baviaanskloof, than to get material or machinery parts into the Kloof.

- Part interview omitted; no further relevance for this research-

Interviewer: What do you think deserves most priority, in order to make the distillery more efficient?

Willie van Rensburg: First of all, qualified and educated workers. Next to that, we need to monitor the process. We need to measure the steam flow and water flow. Ideally have everything on a big screen, or run the distillery from behind your laptop for instance. In my opinion, this will save you the most money, because you will directly identify problem. For instance if a pipe is leaking, you will lose more water in ten minutes time, then in a year with for instance you save water with windbreakers.

For my irrigation system, an alarm goes off when there is 0,5 bar pressure drop. Then I immediately know that there is something wrong. This saves me a lot of money and trouble. I think the same principle will apply to the distillery

Because this is all new for us, we need to monitor it, so we can optimize it and see when things aren't running as they supposed to do. By measuring we can also find our optimum, which is important since this facility is new. The optimum parameters are unknown.

Furthermore, from my experience as a farmer. I realized that the most costs by damage is because of human error. We have leopards, jackals and other animals that will kill and eat my goats. But these losses are nothing in comparison to those of human error. For instance, not spotting sickness at the animals early enough. Or being too late with vaccinating. Therefore, the changes of human error should be minimized, also in the distillery.

Interviewer: Any final remarks?

Willy van Rensburg: I think you got all the key elements and you are doing a great job. The power supply is coming next week, and I want to see the distillery working again. Furthermore, I think we should do something with the hydrosol.

Interviewee	Relevance	Location	Date
Runé van Rensburg	Farmer Baviaanskloof, growing crops for distillation	Damsedrift, Baviaanskloof	04-09-2017

Interviewer: What are, in your opinion and by your experience, the biggest barriers or challenges when you want to execute a project in the Baviaanskloof?

Runé van Rensburg: First thing is probably the road and the distance to the markets. Not all products are suited to transfer over this road because of the bumps. And more general, to get funding. Commercial bank, won't help farmers anymore, you must be a mega farmer before you get funding from commercial banks. Labour is not a big issue here, there is enough. However schooled labour is a problem, there is a shortage.

Interviewer: What are important criteria to consider, when selecting a technology for implementing in Baviaanskloof?

Runé van Rensburg: I find it important that I have some knowledge about the technology and how it works. So if I understand how it works, I might be able to fix it myself, or see what's wrong. Furthermore, the reliability of the product and the supplier is very important. I rather spend more money on a tractor, from a reliable brand than go for the cheapest option. We have a saying: a machine or truck is as good as its backup. Therefore, the suppliers and there trustworthiness is very important to us. You want to rely on the supplier, that he will come down to fix problems if there are any.

In the context of this project, we are involved in a lot of new things. For instance, we are importing a harvester from Bulgaria, since no rosemary harvester is available in South Africa. So for the decision making of these purchases, we have to go on the trustworthiness of the suppliers. This also applied for the purchase of the boiler. Here, we went for a more robust (but old) model, rather than a new more 'fragile' boiler. As this was advised by the supplier, who came with straightforward arguments, which seemed trustworthy.

Important feature of the boiler, it is simple. No unnecessary equipment, just a few buttons. That important for the Baviaanskloof, to just keep it simple and understandable for the people who have to work with it. Furthermore, the boiler supplier is located in South-Africa, so if part breaks down, we can easily get new parts. Well, more easy than to get it, for instance, from China.

Interviewer: On a scale from one to ten, how important will it be that the technology is delivered by a local supplier?

Runé van Rensburg: Well, nowadays the world is small, so shouldn't make much difference. But the supplier is your backup, so if the supplier is in George for instance. You can walk into his shop and meet him face to face quiet easily. This gives some extra insurance. This does not apply for companies overseas.

I would say that it is important to get technology from local suppliers, for the trustworthiness and as an extra insurance. But with local I would say South Africa is local.

- Part interview omitted; no further relevance for this research-

Interviewer: What do you think deserves most priority, in order to make the distillery more efficient?

Runé van Rensburg: I would like to see the facility run, to see where improvement is needed. Get some more measurements and figures. We need to learn more about this facility and how to operate it. So it will be important to place enough measurement equipment. Cause we don't want to learn it by trial and error, as we have did on this farm for a few generations. Better get measurements and analyse them, to bring science and practice together.

So I would like to place some more measurement equipment, this isn't even that expensive. But we can learn a lot from this, prevent mistakes and optimize our process. On this moment we are doing the must by our 'gut feeling'. Furthermore, better insulation of the pipes and other hot parts, this is easy and cheap.

Interviewer: Any final remarks?

Runé van Rensburg: No not really. I looking forward to have the facility up and running. And well, we still need to harvest the plants off course, first things first. It is good the be pioneering, but sometimes is hard as well, but we will see where it get us!

Interviewee	Relevance	Location	Date
Thekla Teunis	Project manager DEVCO	Albert road 66, Cape Town	14-11-2017

Interviewer: What are, in your opinion and by your experience, the biggest barriers or challenges when you want to execute a project in the Baviaanskloof?

Thekla Teunis: There are several aspects. The first one would be the remoteness and the quality of the road, which is a poor road. Therefore, it takes a long time for people to come into the Baviaanskloof. This can result in the situation that, when you miss a machine part or need a tool, you sometimes have to wait for several days before it will be in the Baviaanskloof.

Second, there is no cell phone reception, which complicates fast communication. For instance, a supplier comes into the Baviaanskloof, but gets lost. Than he has to go back to the main road, or the nearest place with reception/internet. This actually happened, a took another day before the supplier, and the parts came in. And in the meantime, we are waiting for the supplier, without knowing anything, quiet frustrating.

Furthermore, there is a lack of knowledge. Because in the first place, there are not that many people living in the Baviaanskloof. And the people that do live there, are farmers and people that work on the farm. These people are not necessarily specialized technicians. This makes it hard to execute projects, because everything comes down to yourself. You will have to figure everything out yourself. I think that those three are the main barriers.

Interviewer: What are important criteria to consider, when selecting a technology for implementing in Baviaanskloof?

Thekla Teunis: The first thing we look at, is if the machine is robust. If a machine is likely to breakdown with one or two years, it will breakdown within half a year in the Baviaanskloof. Because it is such a poor road. Therefore we need machines that 'last forever'.

Second, the reputation of the supplier is important. Did we hear positive sound from third parties or not. Did other parties have positive experiences with these suppliers or not. So we always consult other parties, before purchasing a new technology. This helps us to predict the robustness of the machine.

Also important, availability of spare parts. For instance, when purchasing the boiler, we looked at a more fancy model. However, some spare parts were only manufactured in Johannesburg. Moreover, it included a lot of advanced parts, more electronics, this is unfavourable for the Baviaanskloof. If something breaks down, than we rely on one small part, all the wat from Johannesburg. And to only rely on that, can become quiet problematic. Since we cannot afford downtime during peak production. Since this can cost a lot of money. So we went for a supplier that is located in George and Port Elizabeth. This supplier also goes into the Baviaanskloof, also for service checks. Furthermore, this boiler is a more standard type and therefore more likely to have spare parts available. Besides, the fact that the boiler is more simple, allows us to do maintenance.

The more a technology contains computer systems and electronics, the less likely it is that we will be able to fix it. For instance, a farmer in the Baviaanskloof would never purchase a 4x4 that has a lot of computers in it. They can afford it, but they won't be able to fix it. A getting out of the Baviaanskloof with a broken car is not an option. Getting someone in, to fix it, gets really expensive. So less fancy, but more easy to understand.

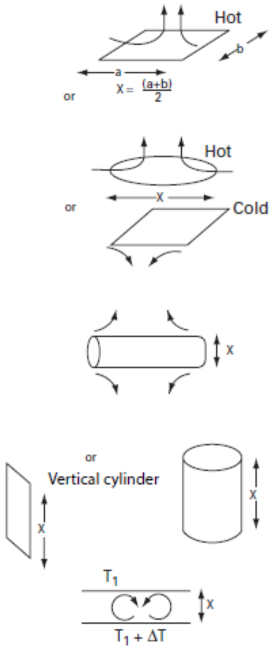
The cost play a major role. When doing an investment, you are bound on the available capital. We get funds, and therefore we have always work between budgets. It is always a balance between upfront investment and operation costs.

Another consideration is off course the safety of a technology. Therefore, simpleness is preferred. I would prefer a boiler that can only be switched on and off (assuming it works properly). Than having a boiler, of which you can alter al the settings, which might lead to unsafe operating (especially when it done be somebody with insufficient know-how). The boiler we got on this moment is a bit tricky on that aspect. Since we did not (yet) get a lot of instructions on how to exactly to operate the boiler. You don't want accidents, but especially not in this remote area. Because medical care etc. is at least a three hour drive.

When looking into new technologies, we always try to take the environmental aspect into considerations. Since, this is one of the pillars of the four return methodology. For instance we looked into solar and biomass. However, due to time and budget constraints (and a lot more factors), we could not go to much in depth with this. And left it open for the long-term. First, prove of concept, thereafter improve the process. So we will see on the long term how we can improve this, hopefully the results of your study will help us with that.

Appendix 2: Background information

Appendix 2A: Free convection



Shape	*Case*	*Overall Nusselt number*
Horizontal flat plate	Laminar ($10^2 < \mathcal{A} < 10^5$)	$\mathcal{N} = 0.54\,\mathcal{A}^{0.25}$
	Turbulent ($\mathcal{A} > 10^5$)	$\mathcal{N} = 0.14\,\mathcal{A}^{0.33}$
Horizontal cylinder	Laminar ($10^4 < \mathcal{A} < 10^9$)	$\mathcal{N} = 0.47\,\mathcal{A}^{0.25}$
	Turbulent ($\mathcal{A} > 10^9$)	$\mathcal{N} = 0.10\,\mathcal{A}^{0.33}$
Vertical flat plate	If laminar, ($10^4 < \mathcal{A} < 10^9$)	$\mathcal{N} = 0.56\,\mathcal{A}^{0.25}$
	If turbulent, ($10^9 < \mathcal{A} < 10^{12}$)	$\mathcal{N} = 0.20\,\mathcal{A}^{0.40}$
Parallel plates (slope <50°)	Turbulent ($\mathcal{A} > 10^5$)	$\mathcal{N} = 0.062\,\mathcal{A}^{0.33}$

Figure 12. Free convection formula's, Twidell & Weir, 2015.

Appendix 2B: Composition essential oils

Component	"Vert Broyee" (%)	Traditional (%)
Myrcene	0.9–1.0	0.9–1.1
Limonene	0.2–0.4	0.3–0.5
Ocimene cis	0.3–0.5	0.4–0.6
Ocimene trans	0.5–0.7	0.8–1.0
Copaene alpha	0.5–0.7	1.4–1.6
Linalool	13.0–24.0	6.5–13.5
Linalyl acetate	56.0–70.5	62.0–78.0
Caryophyllene beta	1.5–1.8	2.5–3.0
Terpineol alpha	1.0–5.0	Max. 2.1
Neryl acetate	0.6–0.8	0.7–1.0
Germacrene d	1.1–7.5	1.5–12
Geranyl acetate	1.4–1.7	2.2–2.5
Geraniol	1.4–1.7	1.2–1.5
Sclareol	0.4–1.8	0.6–2.8

Figure 13. Difference in EO composition; wet- vs dry biomass Buchbauer, 2010.

Appendix 3: Evaluation of technologies

This appendix chapter goes into detail on how the evaluation of the identified technologies is done. For each separate technology, the fitness for rural Africa, energy reduction potential and costs is assessed. In order to make calculations on the energy reduction potential and estimate the LCOE of a technology, it was assumed that each specific technology would be implemented at the reference case. As a consequence, assumptions on implementing the technologies, were based on the conditions in the Baviaanskloof.

For each technology, the technology setup is first described. Next, the model of assessing the fitness for rural Africa is applied (see section 4.1.4). This is followed by a method of calculating the technology its energy reduction potential. Finally, the LCOE of the technology is calculated. However, first the LCOE for the reference case is calculated. This functions as a base case, in order to compare the LCOE of the other identified technologies. Furthermore, values that are used in this calculation will also be utilised to determine the LCOE of the other technologies, for example the discount rate, fuel prices and currency converting factors.

LCOE base case

The LCOE for the reference case is calculated by determining the annual- costs and energy output for the boiler. For the steam boiler at the reference case, the costs consist out of: initial investment costs (I), operating and maintenance costs (OM) and fuel costs (F). The annual energy output (E), is the amount of energy that is delivered to the distillation system as steam. In Table 8, an overview is given of the values that were used to calculate the LCOE. The yearly expenses for OM were assumed to be 10 percent of the initial investment. Furthermore, it was assumed that the production per year would be constant over the technology its lifetime. Lastly, the lifetime of the boiler was is assumed to be 15 years, since it is a second-hand boiler.

Table 8. LCOE for base case

	Value	Unit	Comments/references
Conversion rate Euro to ZAR	16		http://www.xe.com/currencyconverter/, retrieved on December 10th 2017
Batches per year	547		See section 4.2.7
Fossil energy per batch	1705.0	MJ	See section 4.2.6
Fossil energy per year	932.6	GJ	
Energy delivered to distillation system per batch	1180.2	MJ	See section 4.2.6
Energy delivered to distillation system per year	645.6	GJ	Based on yearly production and energy needs per batch
Fuel needed per year (diesel)	20.8	tonne	See section 4.2.7
Fuel costs (diesel)	14	ZAR	http://www.globalpetrolprices.com/South-Africa/diesel_prices/
Initial investment costs	13,068.0	€	Quotation from boiler supplier converted from ZAR to Euro
Yearly OM costs	1306.0	€	Assumed to be 10 % of initial investment
Yearly fuel costs	18,215.3	€	
Lifetime technology	15	year	Second-hand boiler
Discount rate South Africa	10 %		Recommended discount rate for industry projects that lack investment specific data (Short et al., 1995).
Capital recovery factor	0.131		
LCOE	**32.9**	**€/GJ**	

CSP boiler

CSP boilers are only available with small heating capacity, between 1,5 and 3 kW (Munir et al., 2014; R. J. Patil, Awari, & Singh, 2011). Therefore, this technology option is not applicable to the reference case. Nevertheless, this technology is evaluated on the three criteria, since it might be a relevant option for distilleries that require a low heating capacity.

Fitness rural Africa CSP boiler

1. Two studies were found that developed a CSP boiler that intended to be operated in rural areas (Anjum Munir et al., 2014; R. J. Patil et al., 2011). Additionally, the working principle of a solar boiler is rather simple; track the sun, concentrate and direct the sunlight to a water containing vessel. Therefore, it is assumed that a CSP boiler can be operated by a low skilled worker.
2. In the study by R. J. Patil, Awari, & Singh, 2011 a Scheffler reflector was chosen for the water heating system for heating applications in rural India; low cost, easy in operation and maintenance. Following from this, it is likely that a CSP boiler (using a Scheffler reflector) can be maintained by low skilled workers.
3. A solar tracking system moves the reflector in order to increase the efficiency (Rapp & Schwartz, 2010). This is powered by an electric motor and battery. Furthermore, the system contains moving parts. Based on this, it is assumed that a medium skilled worker is required to repair the reflector system.
4. These systems were designed to be constructed out of materials that are available in rural areas (SolareBrücke.org, n.d.). Based on this, it is assumed that there are local material available to repair the technology.
5. The solar reflector system consists out of: reflective plates, a steel framework and a tracking mechanism consists out of a mechanical and electric design (Rapp & Schwartz, 2010). These are commonplace materials, and therefore spare parts are likely to be available.
6. The system does contain moving parts.
7. The technology includes electronical parts.
8. There are Scheffler reflectors that have been operating over 20 years[11]. Therefore, the lifetime expectancy is over 20 years.

Table 9. Fitness rural Africa CSP boiler

Technology evaluation fitness rural Africa					
		Answers and associated scores			
	Questions	**-**	**1**	**2**	**3**
1	Can the technology operated by a low skilled workers?				Yes
2	Can the technology be maintained by low skilled workers?				Yes
3	Can the technology be repaired by low/medium skilled workers?			Supposably	
4	Are there local materials available to repair the technology?				All
5	Are there spare parts available to repair the technology?				All
6	Does the technology contain any moving parts?	Yes, many moving			

[11] H. Hoedt, project manager at Solare Brücke, personal communication, November 20th, 2017.

		parts	
7	Does the technology contain any electronical parts?	Yes	
8	What is the life expectancy of the technology?		>20 years
	Total score	**17**	

Energy reduction potential CSP boiler
RETs will replace the (fossil fuel) boiler. Therefore, for this analysis it is assumed that a CSP boiler reduces the fossil energy need with 100 percent. However, this is based on the assumption that the boiler is the only energy consumer during the process. In reality there are other appliances that use fossil energy, for instance water pumps.

LCOE CSP boiler
In the study by Munir et al. the investment cost were \$ 2000 for the development of the Scheffler reflector and accessories. These cost apply for a CSP boiler with an average system capacity of 1.548 kW. In order to compare this technology, with the other identified technologies, it is assumed that the yearly operating time of the CSP boiler is similar to the operating time of the other technologies. Following from this, the operation time of the CSP boiler is 410.3 h/year (batcher per year divided by distillation time of reference case). This operation time corresponds to a yearly energy production of 2333.5 MJ (assuming an average capacity of 1.548 kW). Furthermore, the OM cost were assumed to be 15 percent of the initial investment. The results are shown in Table 10.

Table 10. LCOE CSP boiler

	Value	Unit	Comments/reference
Produced energy per year	2.3	GJ	
Initial investment costs	1706.0	€	0.853 conversion factor, retrieved from xrates.com, 12th December, 2017
Yearly OM costs	255.9	€	Assumed to be 15 % of initial investment costs
Lifetime technology	20	year	See results Table 9
Capital recovery factor	0.117		
LCOE	**195.5**	**€/GJ**	

Biomass boiler
For the biomass boiler technology it is assumed that a boiler of 500 kW is utilised (similar capacity to the boiler in place at the reference case).

Fitness rural Africa biomass boiler

1. The operation between an biomass boiler does not differ from operating a fossil fuel boiler. However, there is some knowledge and training required before a low skilled worker is able to operate a (biomass) boiler. Therefore, two points are allocated.
2. A biomass boiler requires additional operation and maintenance in comparison to a conventional boiler. This is mainly due to the extra ash production and fuel pre-treatment[12]. These operations are not complex, and therefore it is assumed that it can be done by low skilled workers after training.
3. A biomass boiler is a complex technology of which some parts are pressurized. In order to repair pressurized parts, ASME certified welder are required[13]. Thus a biomass boiler cannot be repaired by low skilled workers.
4. It is not likely that there are local material available for repair. Furthermore, it will remain questionable if workers in rural Africa are capable of using these materials in order to repair the biomass boiler. Therefore, no points allocated.
5. The availability of spare parts depend on the model type- and the supplier of the biomass boiler. Thus, it is possible to obtain spare parts[14]. However, it remain questionable if workers in rural Africa are capable of replacing the spare parts and repairing the biomass boiler. Therefore, one point is allocated.
6. There are multiple moving parts in a biomass boiler: biomass feeding system, combustion air supply van and an ash scraper (BERC, 2011; Binder, n.d.).
7. There are multiple electronical parts in a biomass boiler: burner, electrical motor driving fuel the supply, control- and measurement equipment (BERC, 2011; Binder, n.d.).
8. The lifetime expectancy of a biomass boiler is between 15-20 years (Zengzhou Boilers, 2017).

Table 11. Fitness for rural Africa, biomass boiler

Technology evaluation fitness rural Africa					
		Answers and associated scores			
	Questions	**-**	**1**	**2**	**3**
1	Can the technology operated by a low skilled workers?			After training, no supervision	
2	Can the technology be maintained by low skilled workers?			After training, no supervision	
3	Can the technology be repaired by low/medium skilled workers?	No			
4	Are there local materials available to repair the technology?	None			
5	Are there spare parts available to repair the technology?		Few parts		
6	Does the technology contain any moving parts?	Yes, many			

[12] https://www.theenergysmartgroup.co.uk/2017/03/07/biomass-boiler-maintenance/, retrieved December 13th, 2017.
[13] W. Bester, owner of EDE (Essential oil distillation equipment) South Africa, personal communication, November 22nd 2017.
[14] Biomass boiler supplier, that also supplies spares: https://cochran.co.uk/spares .

7	Does the technology contain any electronical parts?	Yes, many	
8	What is the life expectancy of the technology?		10< years <20
	Total score	**7**	

Energy reduction potential biomass boiler

The same argumentation at CSP, a biomass boiler is a RET and thus 100 percent effective.

LCOE biomass boiler

The specific cost for a biomass combustion system are approximately 160 €/kW and fuel costs between 15 – 25 €/MWh (van Loo & Koppejan, 2008). Based on these values, the initial investment for a biomass boiler system would be € 80,000. For the fuel price, is assumed to be 20 €/MWh. Moreover, the lifetime expectancy of this boiler is assumed to be 18 year (this assumption is based on the findings at fitness for rural Africa, here the average life expectancy is chosen, see Table 11). In order to calculate the required fuel on a yearly basis, it was assumed that this boiler has a thermal efficiency of 80 percent. It is expected that the OM cost are higher for a biomass boiler than a conventional boiler. Since, additional work is needed for the biomass pre-treatment. Moreover, additional cleaning and maintenance is required due to the generation of ashes (Saidur, Abdelaziz, Demirbas, Hossain, & Mekhilef, 2011). Therefore, the OM costs are assumed to be 9 percent of the initial investment. This is substantially higher than the OM for a conventional boiler (7,200 vs 1,306). These values, interim- and final results are shown in Table 12.

Table 12. LCOE biomass boiler

	Value	Unit	Comments/reference
Required energy per batch	1591.3	MJ	As result of the 80 p% efficiency
Required energy per year	870.4	GJ	
Energy delivered to distillation system per batch	1180.2	MJ	See section 4.2.6
Energy delivered to distillation system per year	645.6	GJ	
Fuel needed per year	179.3	MWh	
Fuel costs per year	3586.5	€	
Initial investment costs	80,000	€	
Yearly OM costs	7,200	€	Assumed to be 9 % of initial investment
Yearly fuel costs	3586.5	€	Diesel fuel used to operate boiler
Lifetime technology	18	year	
Capital recovery factor	0.122		
LCOE	**31.8**	**€/GJ**	

Efficient boiler

For this technology option it was assumed that a flash boiler is applied. This assumption is based on an alternative boiler option, that was considered to be implemented at distillation facility in the Baviaanskloof. This is a Vapomat boiler, which produces 600 kg/h steam at a 85 percent thermal efficiency[15].

Fitness rural Africa efficient boiler

1. Same argumentation as for the biomass boiler, thus two points allocated.
2. After training, the Vapomat boiler can be maintained by low skilled workers. However, supervision is recommended[15].
3. Same argumentation as for the biomass boiler. Boilers in general contain pressurized parts, and only certified workers are allowed to repair these parts.
4. Same argumentation as for the biomass boiler.
5. Same argumentation as for the biomass boiler, some spare parts can be obtained from the supplier. However, a specialist is required to repair the boiler.
6. A steam boiler contains moving parts: air blower, feedwater- and fuel pumps
7. A steam boiler contains electronical parts: electronic pumps, controlling panel and measuring equipment.
8. The lifespan of a boiler is expected to be over 20 years[15].

Table 13. Fitness rural Africa efficient boiler

Technology evaluation fitness rural Africa					
		Answers and associated scores			
	Questions	**-**	**1**	**2**	**3**
1	Can the technology operated by a low skilled workers?			After training, no supervision	
2	Can the technology be maintained by low skilled workers?			After training, no supervision	
3	Can the technology be repaired by low/medium skilled workers?	No			
4	Are there local materials available to repair the technology?	None			
5	Are there spare parts available to repair the technology?		Few parts		
6	Does the technology contain any moving parts?	Yes, many moving parts			
7	Does the technology contain any electronical parts?	Yes, many electronical parts			
8	What is the life expectancy of the technology?				>20 years
	Total score	**8**			

Energy reduction potential efficient boiler

The energy reduction potential was calculated using the model, by changing the efficiency parameter. By utilizing a boiler with higher efficiency, less fossil energy is required as shown in Table 14.

[15] A. Bouiliart, Applied heat South Africa, personal communication on, November 20th 2017.

Table 14. Energy reduction potential efficient boiler

	Value	Unit
Energy needs base case	1705.0	MJ
Energy needs with efficient boiler	1404.1	MJ
Energy reduction potential	**17.6 %**	

LCOE efficient boiler

The initial investment costs are based on a quotation of the Vapomat boiler supplier, which is 260,000 ZAR, this corresponds to € 16237.9 (using same conversion rate as at the base case). Since the boiler is more efficient than the base case boiler, less fossil energy is needed to deliver the same amount of energy to the distillation system. Per batch 1404.1 MJ fossil energy is required. This boiler runs on diesel fuel and thus the HHV and price of diesel are used to determine the yearly fuel costs, which are € 15,000.9. The OM costs are expected to be higher than the boiler in the base case, since workers with more training are required to operate and maintain the boiler. Therefore, the yearly OM costs are assumed to be 13 percent of the initial investment costs. In Table 15 the interim and final results are shown.

Table 15. LCOE efficient boiler

	Value	Unit	Comments/reference
Fossil energy per batch	1404.1	MJ	See Table 14
Fossil energy per year	768.0	GJ	
Energy delivered to distillation system per batch	1180.2	MJ	See section 4.2.6
Energy delivered to distillation system per year	645.6	GJ	Based on yearly production and energy needs per batch
Fuel needed per year	17.1	tonne	Using diesel fuel (HHV 44.8 MJ/kg)
Fuel costs per year	1,8215.3	€	
Initial investment costs	16,237.9	€	Quotation from Vapomat boiler supplier converted from ZAR to Euro
Yearly OM costs	2110.9	€	Assumed to be 13 % of initial investment
Yearly fuel costs	15,000.9	€	Diesel fuel used to operate boiler
Lifetime technology	20	year	New boiler, see Table 13
Capital recovery factor	0.117		
LCOE	**29.5**	**€/GJ**	

Economizer

For this technology option it is assumed that an economizer is implemented at a distillery with similar characteristics as the facility in the Baviaanskloof. One deviation from the reference case, is that the boiler is assumed to be powered by natural gas. Since the high sulphur content in diesel fuel, makes it unfit to utilize an economizer (see section 4.3.4).

Fitness rural Africa economizer

1. There is very little to operating an economizer, and thus can be done by a low skilled worker [16].
2. Removal of soot, is the only maintenance required, this is a simple procedure and can be done be low skilled workers[16].
3. The coils in an economizer are fabricated to ASME (American Society of Mechanical engineers) standards. Therefore, the repair must be performed by a ASME certified welder, to work on the pressure containing coils. Thus, an economizer can only be repaired by a high skilled worker.
4. An economizer consists out of coils, metal housing and a piping system. Materials to repair the metal housing and piping system are likely to be available. However, the coils are pressurized and cannot be repaired using local materials.
5. For specific types of economizers, there is an option to make repairs easier. By fabricating the economizer with removable coils and providing spare coils. When a coil break down, it can simply be replaced (Cannon Boiler Works, 2002). Moreover, coils are the parts that are most likely to break down first. Therefore, two points are allocated.
6. This depends on the type of economizer. Some types will have a temperature controller, which regulates the inlet of flue gas, by measuring the feedwater temperature (US Department of Energy, 2012b). However, there are models available that do not contain any moving parts (Cannon Boiler Works, 2002). Therefore, an economizer is rated three points, since the option of a more simple model (without moving parts) is available.
7. The results found at question 6, also apply for electronical parts. Thus, economizers without electronical parts are available.
8. The lifespan of an economizer is expected to be over 25 years (Farthing, n.d.).

Table 16. Fitness rural Africa of an economizer

Technology evaluation fitness rural Africa					
		Answers and associated scores			
	Questions	**-**	**1**	**2**	**3**
1	Can the technology operated by a low skilled workers?				Yes
2	Can the technology be maintained by low skilled workers?				Yes
3	Can the technology be repaired by low/medium skilled workers?	No			
4	Are there local materials available to repair the technology?		Few materials		
5	Are there spare parts available to repair the technology?			Most parts	
6	Does the technology contain any moving parts?				No

[16] R. Trinka, sales manager E-tech, personal communication, August 17th, 2017.

7	Does the technology contain any electronical parts?		No
8	What is the life expectancy of the technology?		>20 years
	Total score	**18**	

Energy reduction potential economizer
In order to determine the effectiveness of an economizer, the following calculation steps are made:

- Calculate the mass flow rate of the flue gasses.
- Determine the available energy in the flue gasses.
- Calculate the feedwater temperature increase by utilizing heat form flue gasses.
- Calculate energy reduction (compared to base case) by pre-heating the feedwater.

Mass flowrate flue gasses – this flowrate is calculated by using the stoichiometric air-fuel ratio, using Equation 14 (page 28). Therefore, the mass flowrate of the fuel needs to be determined first. This is done by using Equation 1 (page 10). In this scenario natural gas is utilised, which has stoichiometric air-fuel ratio is 17.2 for natural gas (Goel & Stonecypher, 2013) and the HHV is 50.0 MJ/kg (Cengel & Boles, 2015).

Available energy in flue gasses – this depends on the specific heat of the flue gas and the temperature difference before entering and leaving the economizer. The flue gas temperature is assumed to be 60 °C higher than the water temperature in the boiler drum at operating pressure[17]. Flue gas of natural gas can be cooled down to 120 °C (US Department of Energy, 2012b). Furthermore, it is assumed that the energy transfer efficiency of the economizer is 70 percent.

Temperature increase feedwater – the temperature increase of the feedwater is calculated using Equation 19.

Equation 19. Energy requirements pre-heat feedwater

$$\Delta T = \frac{\dot{Q}}{\dot{m}_{fw} \cdot c_{p\,FW}}$$

$\dot{Q}$ is the heat flow from the flue gasses to the feedwater, in MJ/h

Energy use reduction – the fossil energy needs are calculated for a feedwater temperature of 40.3 °C (feedwater is 20 °C at the base case, plus 20.3 °C increase as result of the economizer), using the model. The interim- and final results are shown in Table 17.

Table 17. Energy reduction potential economizer

	Value	Unit
Mass flowrate air	827.5	kg/h
$\Delta \boldsymbol{T}$ economizer	60.4	°C
C_p flue gas	1.01[18]	kJ/(kg.K)

[17] R. van den Berg, project engineer at Kleijn energy consultants, May 30th 2017.
[18] The flue gas is assumed to have the following composition: 13% CO_2, 11% H_2O, 76% N_2. Furthermore the C_p corresponds to a temperature of 200 °C. This information was retrieved from: http://www.pipeflowcalculations.com/tables/flue-gas.php, on November 18th 2017.

Heat flow flue gasses	61.2	MJ/h
Heat flow flue gasses per batch	45.9	MJ/batch
Heat transferred to FW	32.1	MJ/batch
Temperature increase feedwater	15.9	°C
Energy needs base case	1705.0	MJ
Energy needs with economizer	1673.6	MJ
Energy reduction potential	**1.8 %**	

LCOE economizer

The cost of a ~450 kW economizer was found to be approximately $ 36,800, including the installation costs (Farthing, n.d.). For the reference case, a 17 kW economizer is required (this is determined using Equation 19, here $\dot{Q}$ per second gives the economizer power). An estimation for the initial investment of an economizer is made, using the Equation 20, for economies of scale.

Equation 20. Economies of scale

$$\frac{Costs_{size2}}{Costs_{size1}} = \left(\frac{Size_2}{Size_1}\right)^R$$

$Costs_{size1,2}$ are the costs for purchasing a specific capacity
$Size_{1,2}$ are the capacities for each specific economizer, in kW
R is the scaling factor

When assuming a scaling factor of 0.8, the initial investment cost of an economizer suited for the reference case would be $ 26889, or € 2294. Economizers require little OM (see Table 16) and therefore the yearly OM costs are assumed to be 5 percent of the initial investment. Therefore, the OM costs are € 115 on a yearly base. Applying an economizer results in 31.4 MJ energy saving per batch (see Table 17, energy needs base case vs energy need with economizer). The interim- and final results are shown in Table 18.

Table 18. LCOE economizer

	Value	Unit	Comments/reference
Energy delivered to distillation system per batch	31.4	MJ	
Energy delivered to distillation system per year	17.2	GJ	
Initial investment costs	2294	€	
Yearly OM costs	115	€	
Lifetime technology	25	year	
Capital recovery factor	0.110		
LCOE	**21.4**	**€/GJ**	

Feedwater condenser

To utilise the technology a (smaller) condenser is placed in front of the condenser that is already in place. This condenser is designed to have a minimum temperature difference between to liquid- and vapour flow of 20 °C. Therefore, the feedwater is pre-heated to 80 °C.

Fitness rural Africa feedwater condenser

1. Operating a condenser is rather simple. It is a matter of gradually introducing the fluid flows into the condenser, starting with the cold flow. This has to be done gradually to prevent a thermal shock (Dmimfg.net, n.d.). Therefore, it is assumed that a condenser can be operated by a low skilled worker.
2. To determine when maintenance is required, the condenser needs to be monitored frequently, a decrease of heat exchanging performance indicates that maintenance is required. Monitoring can be done be measuring the in- and out let temperature of both fluids. Maintenance is predominantly required, for the removal of fouling from the inner tube side and therefore, the condenser needs to be partly disassembled. The maintenance procedure requires lifting of the condenser, dissembling, replacing of gaskets, cleaning with rotary wire brushes and inspection of the heat exchanging surface (Dmimfg.net, n.d.).This indicates that a medium skilled worker s required for maintenance operations.
3. A common defect is a split tube, which results in mixing of fluids[19]. To repair this defect, the split tube must be identified and replaced by a new tube. Finding the split tube is a time consuming- and two man’s job. Furthermore, specialized equipment is required (Dmimfg.net, n.d.). And so, it is concluded that high level workers are required to repair a condenser.
4. A condenser consist out of heat exchanging tubes, metal casing and a piping system. Materials to repair the casing and piping system are likely to be available in rural Africa.
5. Tubes can be obtained as spare part. However, a specialized technician is required to replace the tube. Therefore, there is no reason to have spare parts, and thus are no points allocated.
6. A condenser itself does not contain any moving parts[19]. However, the cooling flow needs to be pumped through the condenser. Therefore a water pump is needed, and so the system does contain moving parts. However, since this can be seen as separate machines, and a pump is easy to replace, two points are allocated.
7. A condenser has an heat probe, the measure the in- and outlet temperature of the fluids[19]. However, a condenser will still function without this heat probe. Furthermore, a water pump is (often) an electrical device. Same argumentation as for moving parts applies here, thus 1 point granted.
8. A condenser is expected to have a lifespan between 20-40 years (CDW Engineering, n.d.).

Table 19. Fitness rural Africa feedwater condenser

Technology evaluation fitness rural Africa					
		Answers and associated scores			
	Questions	**-**	**1**	**2**	**3**
1	Can the technology operated by a low skilled workers?				Yes
2	Can the technology be maintained by low skilled workers?		After training, with supervision		
3	Can the technology be repaired by low/medium skilled workers?	No			

[19] J. Huisamen, Technician at Segel SWH system, personal communication, November 16th 2017.

4	Are there local materials available to repair the technology?		Few materials		
5	Are there spare parts available to repair the technology?	None			
6	Does the technology contain any moving parts?			No, supportive technologies do	
7	Does the technology contain any electronical parts?			No, supportive technologies do	
8	What is the life expectancy of the technology?				>20 years
	Total score	**12**			

Energy reduction potential feedwater condenser

The condensation energy of steam at 100 °C is approximately 2258 kJ/kg steam. To heat feed water from 20 °C to 80 °C, approximately 251 kJ/kg is needed. The steam flowrate is 600 kg/h and the feedwater flowrate 645.2 kg/h. Therefore, there is sufficient energy in the steam flow to pre-heat the feedwater. Furthermore, a second condenser need the be placed in series, to absorb the remaining condensation heat, to condensate the steam- oil mixture flow.

However, it takes time before the steam flow reaches the feedwater condenser. Since the steam flow first heats up the biomass in the DS. When the biomass is heated by the steam, the steam condenses and does not leave the DS. Thus, at the beginning of the distillation process, the feedwater is not pre-heated. In order to calculate the effectiveness of this technology, the following steps were taken:

- Calculate the time to heat up the biomass to distillation temperature.
- Determine time fraction that the feedwater condenser is operating.
- Calculate the average temperature of the feedwater.
- Calculate energy reduction due to increased feedwater temperature.
- Determine energy reduction in by applying a feedwater condenser in comparison to the base case.

Time to heat biomass – this time is calculated by determining the power delivered by the steam flow, through transferring the condensation heat to the biomass. The required energy to heat the biomass is calculated using Equation 17 (page 28) and is 339.5 MJ. Dividing this amount of energy, by the power of the steam flow, gives the time that is required to heat the biomass.

Operating time feedwater condenser – the time that the feedwater condenser is operating, is the time to heat biomass subtracted from the distillation time. For both operating- and down time, the fractions were calculated, by dividing these values by the distillation time.

Average temperature – The average temperature of the feedwater, as a result from this technology, is calculated by multiplying the temperature of operating and non- operating with the corresponding temperature. Which is 20 °C when the condenser is not operating and 80 °C when operating.

Energy use reduction – the fossil energy needs are calculated, using the model, for average feedwater temperature when the feedwater condenser is in place. The results are shown in Table 20.

Table 20. Energy reduction potential feedwater condenser

	Value	Unit
Time to heat biomass	15	min
Down time fraction	0.33	
Operating time fraction	0.67	
Average feedwater temperature	61.6	°C
Energy needs base case	1705.0	MJ
Energy needs with feedwater condenser	1565.4	MJ
Energy reduction potential	**7.0 %**	

LCOE feedwater condenser

The initial investment cost of a feedwater condenser is estimated to be between 25,000 and 30,000 ZAR[20]. For the LCOE calculations, 30,000 ZAR is assumed, which corresponds to €1,875. Furthermore, operation and maintenance cost are low, thorough cleaning of the heat exchanging surface is required on a yearly base[20]. Yearly OM costs, is assumed to be 10 percent of the initial investment, which corresponds to €188. The energy savings as result of applying a feedwater condenser are 139.6 MJ per batch, this results in 76.4 GJ savings on a yearly base. No operating fuel or energy costs are taken into consideration for calculating the LCOE of a feedwater condenser. The lifetime expectancy is assumed to be 30 years. Interim and final results are in Table 21.

Table 21. LCOE feedwater condenser

	Value	Unit	Comments/reference
Energy delivered to distillation system per batch	139.6	MJ	
Energy delivered to distillation system per year	76.4	GJ	
Initial investment costs	1,875	€	
Yearly OM costs	188	€	
Lifetime technology	30	year	
Capital recovery factor	0.106		
LCOE	**5.1**	**€/GJ**	

[20] W. Bester, owner of EDE (Essential oil distillation equipment) South Africa, personal communication, December 18th 2017.

Solar water heating system

For utilising this technology at the reference case, it is assumed that 60 m^2 of thermal solar collectors are placed on the roof of the EO distillery in Baviaanskloof.

Fitness rural Africa SWH system

1. SWH systems are widely applied in South Africa, including rural areas (Eskom, 2009). Therefore, it is assumed that a SWH system can be operated by a low skilled worker
2. Two factors affect the performance of al SWH system; scaling and corrosion (Energy.gov, n.d.). Water with high mineral content can cause the scaling of calcium deposits. In order to prevent scaling and corrosion, periodically inspection is required. This inspection several aspect, a few examples are: collector glazing, seals, plumbing, ductwork, wiring- connections and insulation. Based on this, it is expected that some level of expertise or training is required and a medium skilled worker would be able to do maintenance, therefore point.
3. This depends on the kind of repair required, on the piping system or the panel itself. When it depict the panel, it is likely that an specialist is required to repair it[21]. Thus, it is assumed that a SWH can probably not be repaired by a low skilled worker.
4. A SWH system consists out of a supportive framework thermal solar panels, piping- and pumping system. Materials, other than the solar panels, are likely to be available.
5. SWH is at mature technology, with an extensive offer of different models (Twidell & Weir, 2015). Spare parts are provided by several suppliers[22], however the availability of spare parts might depend on the model type.
6. The water is pumped through the system using pumps which contains moving parts. However, the solar collector itself does not contain any moving parts.
7. Argumentation at question six also applies for electronical parts and thus, two points allocated.
8. The lifetime expectancy of a SWH system is between 25 to 35 years (Twidell & Weir, 2015).

Table 22. Fitness rural Africa SWH system

Technology evaluation fitness rural Africa					
		Answers and associated scores			
	Questions	**-**	**1**	**2**	**3**
1	Can the technology operated by a low skilled workers?				Yes
2	Can the technology be maintained by low skilled workers?			After training, no supervision	
3	Can the technology be repaired by low/medium skilled workers?		Supposably not		
4	Are there local materials available to repair the technology?			Most materials	
5	Are there spare parts available to repair the technology?		Few parts		
6	Does the technology contain any moving parts?			No, supportive technologies do	
7	Does the technology contain any electronical parts?			No, supportive technologies do	
8	What is the life expectancy of the technology?				>20 years
	Total score	**16**			

[21] Q. Duplessis, project manager at Franke South Africa, personal communication, November 15th 2017.
[22] http://www.solardirect.com/, http://www.solarhotwaterparts.com.au/.

Energy reduction potential SWH system
These collectors are assumed to have a collector efficiency of 65 percent[23]. The average annual solar irradiation was found to be 2000 kWh/m^2, for the Baviaanskloof area (Department of Energy South Africa, 2015). This corresponds to an average irradiation of 228 W/m^2. However, for this scenario it is assumed that production is done during the daytime. Thus is the average annual irradiation doubled, 456 W/m^2. In order to calculate the effectiveness of implementing a SWH system, the following calculations were done:

- Calculate the thermal power output of the 60 m^2 SWH system, during daytime operations.
- Determine the temperature increase of the feedwater flow as a result from this heat input.
- Calculate the energy reduction due to the increased feed water temperature.

Thermal power output – this is determined by using Equation 21 (Twidell & Weir, 2015).

Equation 21. Thermal output solar collector

$$P = \eta_{swh} \cdot A \cdot G$$

η_{swh} is the collector efficiency of the SWH system
A is the surface of the SWH system, in m^2
G is the average solar irradiation, in W/m^2

Temperature increase – the temperature increase is calculated, by assessing the amount of energy that is added to the feedwater flow, for a given time.

Energy use reduction – the fossil energy needs are calculated for a feedwater temperature of 34.6 °C, using the model. The results are shown in Table 23.

Table 23. Energy reduction potential SWH system

	Value	**Unit**
Power SWH system	16.4	kW
Energy delivered by system per hour	59.2	MJ
Increase of feedwater temperature	21.9	°C
Energy needs base case	1705.0	MJ
Energy needs with feedwater condenser	1642.0	MJ
Effectiveness	**3.7 %**	

LCOE SWH system
The initial investment cost of a SWH system was found to be between 760-820 $/kW for South Africa (IRENA, 2015). For this technology, 60 m^2 was assumed to be installed, which corresponds to a capacity of 16.4 kW, for the conditions in Baviaanskloof (see Table 23).When assuming 790 $/kW, the initial investment cost for the reference case would be approximately € 11,091. A SWH system requires very little service costs and has a life expectancy between 25-35 years (Twidell & Weir, 2015). Based on this, the yearly OM cost are assumed to be 5 percent of the initial investment and the lifetime expectancy is set at 30 years. Yearly energy production is based on the calculations at section

[23] This assumption is based on the typical efficiency curves of single-glazed flat-plate collectors, Twidell & Weir 2015, page 88.

energy reduction potential. The yearly energy production of the SWH system is approximately 24.3 GJ (44.4 MJ per batch, 547 batches per year). No fuel or energy needs (and associated costs) for operation costs were taken into account for calculating the LCOE. The interim- and final results are shown in Table 24.

Table 24. LCOE SWH system

	Value	Unit	Comments/reference
Energy delivered to distillation system per batch	44.4	MJ	
Energy delivered to distillation system per year	24.3	GJ	
Initial investment costs	11,091	€	
Yearly OM costs	554.6	€	
Lifetime technology	30	year	
Capital recovery factor	0.106		
LCOE	**71.3**	**€/GJ**	

Insulation

For this technology option it was assumed that the DS and SP are insulated. However, at the reference case, insulation is already applied at the DS, but not at the SP. Thus, the energy savings are calculated for the case that both DS and SP are insulated. Thereafter, the potential energy savings for the Baviaanskloof are calculated by insulating the SP.

Fitness rural Africa insulation

1. This statement is inapplicable to insulation, insulation does not require any operation thus this statement is rated with three points.
2. This statement is inapplicable to insulation, insulation does not require maintenance. Insulation can (partly) be replaced, when degraded. This can be done by low skilled workers.
3. For insulation, repairing means replacing a unit of insulation with a new layer of insulation material. This is rather simple and can be done by a low skilled worker.
4. When procuring insulation material, some extra material should be bought, as spare material.
5. Same argumentation as question 4 applies.
6. This technology does not contain any moving parts.
7. This technology does not contain any electronical parts.
8. There is a divers scale of insulating material, however, these al have a lifetime expectancy over twenty years (Diez, 2014).

Table 25. Fitness rural Africa insulation

Technology evaluation fitness rural Africa					
		Answers and associated scores			
	Questions	**-**	**1**	**2**	**3**
1	Can the technology operated by a low skilled workers?				Yes
2	Can the technology be maintained by low skilled workers?				Yes
3	Can the technology be repaired by low/medium skilled workers?				Yes
4	Are there local materials available to repair the technology?				All
5	Are there spare parts available to repair the technology?				All
6	Does the technology contain any moving parts?				No
7	Does the technology contain any electronical parts?				No
8	What is the life expectancy of the technology?				>20 years
	Total score	**24**			

Energy reduction potential insulation

Applying insulation, reduces the energy losses due to heat transfer from the DS and SP. Insulation of SP typically reduce energy losses by 90 percent (US Department of Energy, 2012d). In order to calculate the effectiveness of applying insulation the next steps are taken.

- Calculate energy savings by applying insulation.
- Subtract the amount of energy saved from the energy needs for the base case, and calculate the energy reduction

The potential energy savings for insulation the DS and SP are shown in Table 26.

Table 26. Potential energy reduction insulation (DS and SP)

	Value	Unit
Energy needs base case	1705.0	MJ
Energy needs with insulation	1476.1	MJ
Energy saving potential	**13.4 %**	

In order to calculate the potential energy savings for the distillery in the Baviaanskloof, by insulating the SP, the following calculations are made.

- Calculate the total energy consumption for the distillery, with insulation at the DS. Assuming that this insulation reduces heat transfer losses with 90 percent.
- Calculate the energy savings by applying insulation to the SP, and subtract this amount of the total energy needs.

The results are shown in Table 27.

Table 27. Potential energy reduction insulation (SP)

	Value	Unit
Energy needs reference case	1490.1	MJ
Energy needs with additional steam pipe insulation	1476.1	MJ
Energy saving potential	**1.5 %**	

LCOE insulation

In order to determine the LCOE of insulation the DS and SP, an educated guess was made by an expert (W. Bester, owner EDE South Africa) on costs of applying insulation to the reference case. The DS is insulated with thick rock wool and cladded with stainless steel plates, this costs approximately 1500 ZAR/m^2. For SP insulation, thick rock wool with a metal cladding is applied, which cost around 1800 ZAR/m^2. The surface of the DS and SP are 19.2 m^2 and 3.4 m^2, respectively. Therefore, the initial investment cost for insulating the DS and SP are € 2182.5. Furthermore, no operation and maintenance cost is assumed to be required. The saved energy per batch is 228.8 MJ, which corresponds to 125.2 GJ on yearly base. The lifetime of the insulation is expected to be 25 years. The interim- and final results are shown in Table 28**.**

At the reference case, insulation is already in place at the DS. However, insulation could be applied at the SP, therefore the LCOE for insulating SP is calculated. The initial investment for insulating the SP corresponds to € 328.5. Energy saving per batch will be 14 MJ (see Table 27), this corresponds to 7.7 GJ yearly savings. The LCOE for only insulating the SP are shown in Table 29.

Table 28. LCOE insulation at DS and SP

	Value	Unit	Comments/reference
Energy saved per batch	228.8	MJ	
Energy saved per year	125.2	GJ	
Initial investment costs	2182.5	€	
Yearly OM costs	0	€	
Lifetime technology	25	year	
Capital recovery factor	0.110		
LCOE	**1.9**	**€/GJ**	

Table 29. LCOE insulation at SP

	Value	Unit	Comments/reference
Energy saved per batch	14.0	MJ	
Energy saved per year	7.7	GJ	
Initial investment costs	328.5	€	
Yearly OM costs	0	€	
Lifetime technology	25	year	
Capital recovery factor	0.110		
LCOE	**5.5**	**€/GJ**	

Cascade heat

A mechanical vapor compressor heat pump is suited to utilise heat from 70 °C to 105 °C (RVO, 2015). These requirements are suited for the EO distillation process. Therefore, for further analysis, it is assumed that a mechanical vapor compressor is utilised.

Fitness rural Africa cascade heat

1. Heat pumps are standalone machines and simple to operate [24]. The operating principle relies on the same principle as a refrigerator. Thus it is likely that a heat pump can be operated by a low skilled worker.
2. Maintenance of a heat pump depicts replacement and cleaning of oil filters, visual inspection, replacement of gaskets and other parts. In general, more intensive maintenance service is provided by specialized companies[24]. After training it might be possible that workers can do maintenance, Therefore it is assumed that maintenance can be done by low skilled workers after training and with supervision.
3. The same applies for repair of a heat pump, it is often done by specialized companies. Therefore it is assumed that repairs cannot be done by workers in the Baviaanskloof.
4. The parts for a heat pump are specialized parts, and therefore not likely to be locally available.
5. Spare parts are available, however to repair the technology using these parts, training is required. Therefore one point is allocated to this criterion.
6. The driving force behind a heat pump is a compressor (De Kleijn Energy Consultants, n.d.).
7. The compressor is powered by electricity, furthermore electronical measurement equipment is in place.
8. A heat pump has a minimum life expectancy of 15 years, however it longer lifespans are not uncommon (Emerson Climate Technologies, 2012).

Table 30. Fitness rural Africa heat pump

Technology evaluation fitness rural Africa					
		Answers and associated scores			
	Questions	**-**	**1**	**2**	**3**
1	Can the technology operated by a low skilled workers?				Yes
2	Can the technology be maintained by low skilled workers?		After training, with supervision		
3	Can the technology be repaired by low/medium skilled workers?	No			
4	Are there local materials available to repair the technology?	None			
5	Are there spare parts available to repair the technology?	None			
6	Does the technology contain any moving parts?	Yes, many moving parts			
7	Does the technology contain any electronical parts?	Yes			
8	What is the life expectancy of the technology?			10< years <20	
	Total score	**6**			

[24] R. vd Berg, Energy consultant at de Kleijn consulting, personal communication, December 14th 2017.

Energy reduction potential heat pump

In this case it is assumed that a heat pump is utilised to cascade the condensation heat to other appliances. The steam- oil mixture is cooled down by circulating a coolant through the condenser. This coolant absorbs the waste heat from the steam- oil mixture. In the heat pump, the waste heat is upgraded by pressurizing the coolant, using a motor. This upgraded heat can be used for other appliances. Energy is required to power the motor, for this case it is assumed that an electrical motor is applied.

At the condenser, approximately 376 kW heat is available from the condensation heat. This power is determined by multiplying the steam flowrate (600 kg/h) with the condensation enthalpy (~2257,5 kJ/kg at 100 °C). The power of a heat pump is given by Equation 1 (Twidell & Weir, 2015).

Equation 22. Thermal power of heat pump

$$P_{out} = C_{cop} \cdot P_m = P_g + P_m$$

P_{out} is the thermal output by the heat pump, in kW
P_m is the power of the pressurizing motor, in kW
P_g is the power delivered by the 'waste' heat source, in kW
C_{cop} is the coefficient of performance, this factor is characteristic for each specific heat pump and indicates the ratio between delivered- and invested energy. A higher COP value indicates a more effective heat pump

Mechanical vapor compressor heat pumps have a COP between 10 and 30 (RVO, 2015). When assuming that the heat pump in place has a COP of 15[25], the corresponding power for the motor and heat output will be 25 kW and 401 kW, respectively. As mentioned before, this technology indirectly saves fossil energy, however no energy is saved during the distillation process. However, to compare this technology to the other identified technologies, the energy 'saving' potential will be determined. The energy 'saving' potential is determined using the following calculation steps.

- Determine operation time
- Determine amount of energy cascaded during operation
- Determine amount of energy used by electric motor during operation
- Determine net energy gain by operating the heat pump
- Compare energy cascading potential to energy needs in base case

The same principle as at the feedwater condenser, applies to the heat pump. A heat pump can only operate when the steam- oil mixture enters the condenser. The results of these calculation steps are shown in

Table 31. Results energy saving potential heat pump

	Value	Unit
Operation time	0,5 (67 % of 45 min)	h
Cascaded heat	720.9	MJ
Electricity to power motor	44.9	MJ

[25] The influence of the COP on the thermal power output is relatively small. With COP 30, the total power output would be 389 kW and with COP 10 it would be 414 kW.

Net energy gain	676.0	MJ
Energy needs base case	1705.0	MJ
Energy needs with heat pump	1029.0	MJ
Energy 'saving' potential	**39.7 %**	

LCOE heat pump

The initial investment for mechanical vapor compressor heat pumps is approximately 250 €/kW (RVO, 2015). Using this figure, the initial investment for the heat pump for this analysis (with 401 kW) would be € 100,250. The yearly OM costs are assumed to be 5 percent of the initial investment, which corresponds to € 5012.5. Fuel costs depend on the yearly electricity- needs and price. To power the electric motor, 24.6 GJ electricity is need per year, and the price of electricity is 1,8 ZAR/kWh[26]. In Table 32 the interim- and final results are shown.

Table 32. LCOE cascading heat using a heat pump

	Value	Unit	Comments/reference
Electricity per batch	44.9	MJ	See Table 31
Electricity per year	24.6	GJ	
Energy cascaded per batch	720.9	MJ	See Table 31
Energy cascaded per year	394.3	GJ	
Electricity costs per kWh	1.8	ZAR	
Electricity costs per year	768.2	€	
Initial investment costs	100,250	€	
Yearly OM costs	5012.5	€	Assumed to be 5 % of initial investment
Lifetime technology	20	year	
Capital recovery factor	0.117		
LCOE	**44.5**	**€/GJ**	

[26]https://businesstech.co.za/news/energy/88524/how-much-electricity-costs-in-south-africas-biggest-cities/, retrieved on December 12th, 2017.