Master's degree thesis

LOG953 Logistics

The concept of energy efficiency technologies in the upstream petroleum industry: A literature review

Sahab Ali

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Preface

My interest in this research stemmed in a conversation with my supervisor. It sparked my thoughts towards better use of resources especially in a highly resource dependent industries. The need for energy is inevitable for the progress of todays World and there will be an increased need to use the energy in a way which does not compromises the needs of our future generations. This Master's Thesis is written as a general requirement in the master's program in Petroleum Logistics at Molde University College – Specialized University in logistics.

All thanks and praise is for the Almighty Allah for this achievement. I would like to thank my wife and family for their resilient support and love. I would like to give special thanks to my supervisor Yury Redutskiy for sharing his time and knowledge.

Molde, August 2020
Sahab Ali

Abstract

The extracted hydrocarbons from wells undergo complex and energy-intensive technological processes until they are transformed into the form of marketable products. These processes are often unsustainable in their economic and environmental performance, and lead to substantial CO2 emissions and energy loss. Energy efficiency is presented as a viable solution to reduce emissions, costs, and energy use. Achieving energy efficiency in upstream processes requires the reuse and integration of energy within the processing operations, thereby diminishing energy waste, costs, and the associated CO2 emissions. Achieving energy efficiency involves adopting a life-cycle view of how energy flows throughout the whole energy system. The purpose of this thesis is to study the concept of energy efficiency in the upstream petroleum sector from the most general perspective. It conducts a literature review to reveal the characteristic attributes of energy efficient technologies, as well as how such technologies are organized and implemented. The literature review will also draw out general research trends and highlight the empirical evidence for energy efficiency benefits. A few notable marketed solutions are analyzed as examples for practical implementation. The model of an integrated energy system will be proposed as a viable energy source for upstream processes, and this study will also consider its practical implications. This study further addresses theories that either supplement or oppose arguments in favour of energy efficiency in the upstream petroleum industry. Finally, the role of governmental regulations in the implementation of energy efficient technologies is also reviewed, and this review reveals the practical implications for policy-makers when promoting energy efficiency practices in the upstream OG industry.

This study finds that the general and characteristic features of technologies like the organic Rankine cycle, waste heat recovery, and carbon capture systems are the economic, environmental, and operational aspects of implementing them in upstream petroleum operations. Understanding these aspects is essential to comprehend the complete effects of energy efficiency implementation. These considerations should be at the core of decision-making about energy efficient technologies. It is observed that governmental regulations can have a key role in adopting energy efficiency, and that they can increase the competitiveness of the upstream petroleum industry.

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1.0 Introduction

1.1 Problem background

1.1.1 The need for energy efficiency in the oil and gas sector

Hydrocarbons are the largest source of primary energy in the world (BP 2019). They have played a central role in fueling the rapid growth of industrialization and globalization. Despite growing concerns over the degradation of the environment, global energy consumption increased by 2.9% in 2018, with the demands of oil and gas reaching up to 8000 mtoe (BP 2019). As well as being the largest source of global energy, oil and gas contribute the largest share of global CO2 emissions, i.e., 55.9% in 2018 (IEA 2020).

Hydrocarbons cause considerable environmental degradation, even though they fuel rapid globalization and industrialization. Environmental degradation is the exhaustion of the world's resources, such as land, water, air, soil, etc. (El-Haggar 2007). The UN (1994) defines environmental degradation as "[the] depletion of renewable and non-renewable resources and pollution of air, water and soils," and it is mainly caused by human activities. In the course of the present study, the focus will be on air pollution and the greenhouse effect, which causes increases in global temperature. According to the (EPA 2017), greenhouse gases (GHG) such as such as carbon dioxide, methane, nitrous oxide, and certain synthetic chemicals, cause outgoing heat energy to become trapped within the atmosphere. This leads to changes in radiative balance of the Earth (that is, the balance between the energy received from the sun and that emitted from the Earth), which results in changing climate and weather patterns both regionally and globally. This phenomenon is known as the greenhouse effect. While there are various natural causes that contribute to the greenhouse effect, such as volcanic eruptions, the carbon cycle, changes in the Earth's orbit, etc., these are only natural causes and cannot therefore be regulated. Yet CO2 remains the most important gas among all the GHGs, and it accounts for the greatest contributor to global warming that is associated with human activities (EPA 2017). Regulatory emphasis should therefore be placed upon adopting sustainable development practices for those human activities that cause environmental degradation—especially in those sectors that contribute the most to such degradation, like the petroleum industry.

Sustainability is a viable way to tackle environmental degradation. The term has various interpretations and definitions, and it first came to prominence in the UN World Commission for Environment and Development. In the report called "Our Common Future," sustainability is defined as "development that meets the need of the present without compromising the ability of the future generations to meet their needs" (Asefa 2005). Energy (including hydrocarbons) has a complex relationship with sustainability. On the one hand, the services provided by energy promote sustainable development (e.g., an improved economy), but, on the other hand, the production of energy pollutes the environment by emitting GHG, and the exploitation of energy sources can cause environment degradation if it is not carefully planned (OECD 2007). For example, a study into the major environmental effects caused by the upstream oil and gas (OG) operations in western Libya revealed that combustion and flaring were the highest risks to the environment (Irhoma et al. 2016). In addition to that, gas flaring during upstream OG operations produces around 35 million metric tons of CO2, methane, hydrocarbons, and other GHG annually in the Niger delta atmosphere. Evidently, these emissions increase the concentration of GHG in the atmosphere and contribute to global warming, and they also cause possible reactions in the photochemical smog in the region (Ite and Ibok 2013). Despite the harmful effects of OG/hydrocarbon usage, human dependence on this energy source continues, and at current rates of increase in its use, it is only a matter of time until this non-renewable resource is exhausted from our planet.

Hydrocarbons are a non-renewable resource whose exploitation requires a careful balancing act. In order to minimize the risk of harm to the environment (and its inhabitants), and thereby reduce the degree of environmental degradation, the use of this resource should be energy efficient: that is, use of the minimum amount of the resource to obtain the maximum amount of energy output (Firat et al. 2017). Because any approach to development that does not compromise the ability of future generations to meet their needs and also reduces adverse environmental effects is, by definition, sustainable, energy efficiency can therefore be termed as a sustainable development approach. In support of this point, CO2 emissions remained fairly stable between the economic growth period of 2014 to 2016, and the main reason for this was strong improvements in energy efficiency (IEA 2019). Figure 1 represents the relative decrease in global CO2 emissions after 2014, correlated with the rate of population growth and with GDP PPP (GDP converted to international dollars using purchasing power parity rates). One of the vertical axes represents the change in CO2 emissions indexed at 100 million tons in the year 2000 (on the horizontal axis). The other vertical axis (the histograms displayed below the graph) represents the change in millions of tons of CO2 emissions due to the growth of GDP PPP and population. Figure 2 then depicts the actual primary energy related GHG emissions compared to the emissions without developments in energy efficiency. The notable illustration is in Figure 2 which shows an average reduction of 4.4 gigatons (Gt CO2 on the vertical axis) of CO2 emissions due to efficiency gains from the year 2015 until 2018 (years in the horizontal axis) (IEA 2019).

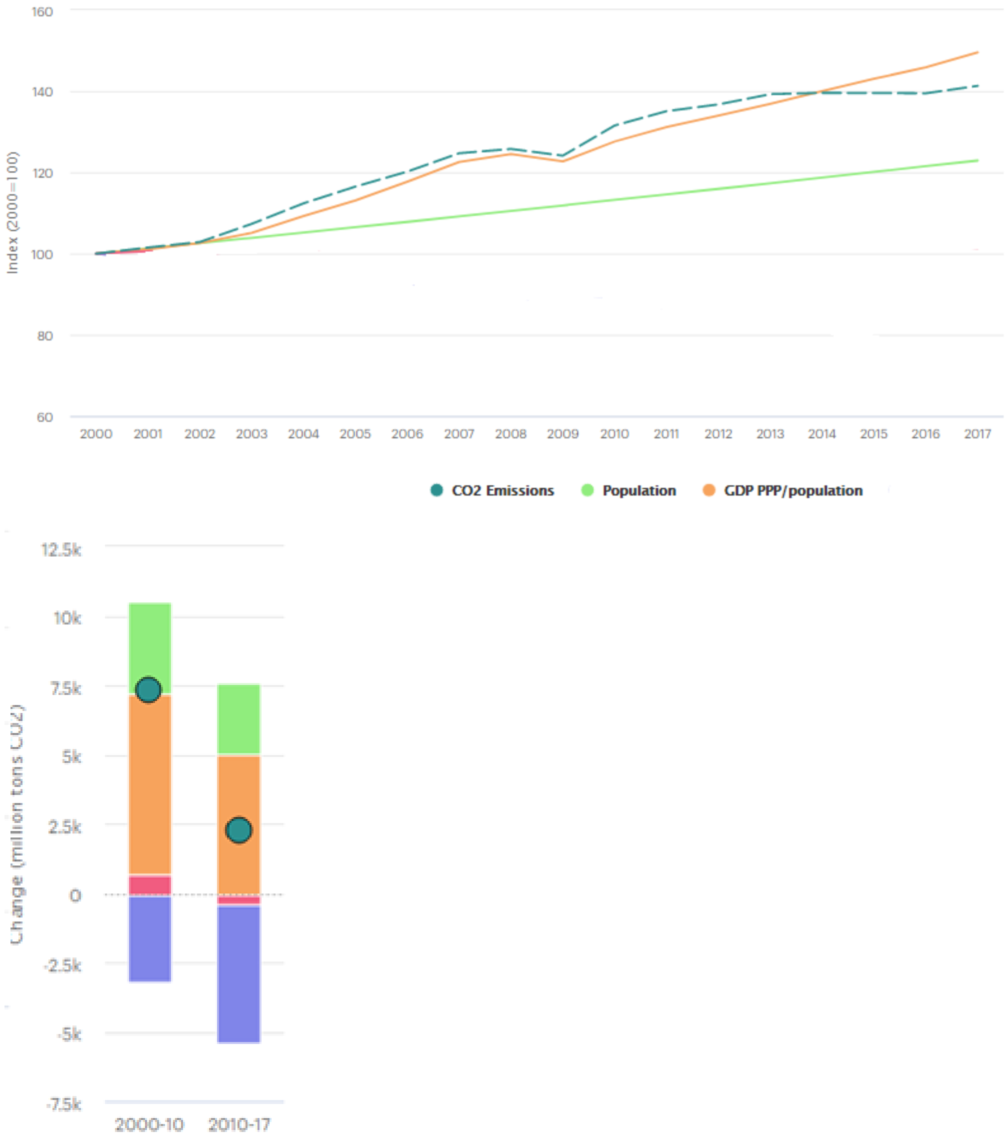

Figure 1: CO2 emissions and drivers. Source: (IEA 2019)

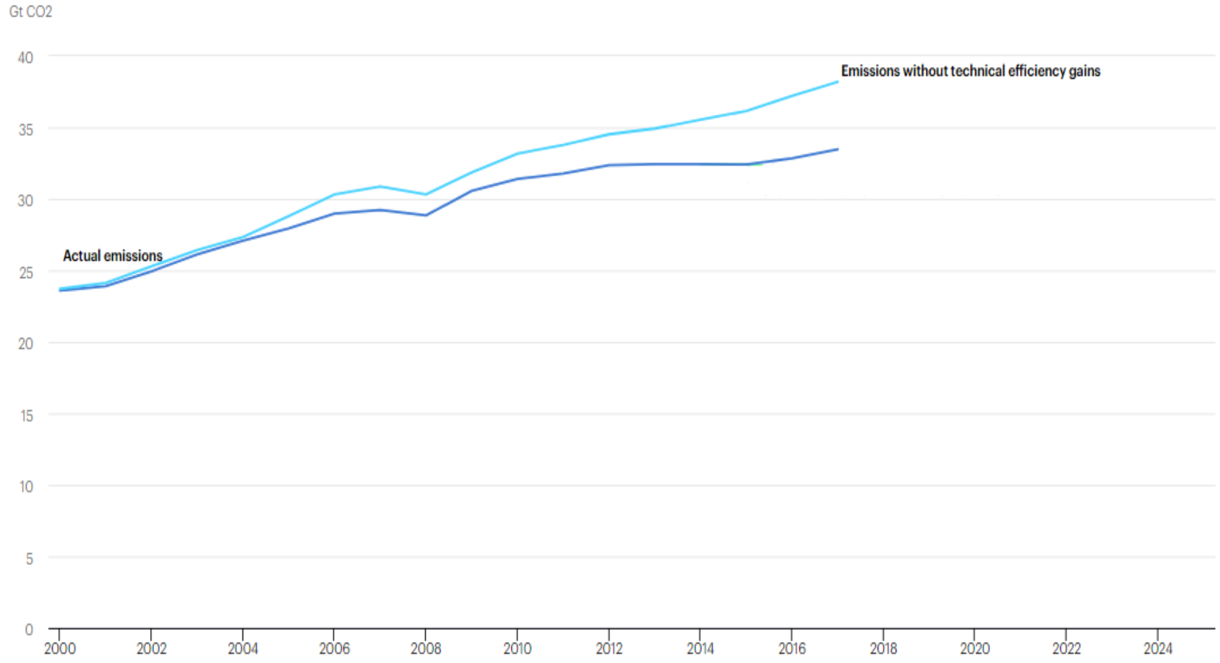

Figure 2: Energy-related greenhouse gas emissions, with and without technical efficiency gains, 2000–2025.

Source: (IEA 2019)

There is a pressing need to shift towards more sustainable forms of energy production and to preserve better the already degrading environment. For this purpose, energy efficiency represents the most viable strategy to achieve sustainability and to allow for inclusive economic growth (i.e., economic growth that is distributed fairly across society and creates opportunities for all). It is also the most cost-effective way to enhance the security of the world's energy supply, while also reducing the environmental footprint of the energy systems that are in use (IEA 2020). Such an approach is evidently also of relevance for the oil and gas (OG) industry because this industry involves the most energy intensive processes during production. Additionally, an energy efficient approach would also advance the UN's sustainable development goals of affordable and clean energy. Apart from the sustainability element, there is also a cost-related aspect underlying the energy efficiency approach. The tools of this approach can be a valuable way to reduce costs for the upstream industry, especially since energy-related costs form a major part of the overall cost of upstream operations (Grassian et al. 2017). Energy efficiency tools can thus aid the upstream industry in its efforts to reduce both its environmental footprint and its costs.

Furthermore, the legislative bodies of the developed world are actively looking into ways to curb the environmental footprints of the oil and gas industry. In this respect, Norway was the first country to impose a carbon tax on emissions produced by the oil and gas industry, and it also imposed a ban on all flaring activities. In 2020, the tax rate in the national budget is

NOK 1.15 per standard cubic meter of gas or per liter of oil or condensate (Norwegian Petroleum 2020). For the combustion of natural gas, this is equivalent to NOK 491 per ton of CO2. For the emission of natural gas, the tax rate is NOK 7.93 per standard cubic meter. Initiatives such as this are an important factor in driving the OG industry to adopt energy efficiency measures in order to avoid penalty costs on CO2 emissions (Norwegian Petroleum 2020).

1.1.2 Energy efficiency technologies to abate CO2 emissions

As stated earlier, oil and gas operations are highly energy intensive, and amongst all of their operations, 80% of emissions come from the gas turbines used to generate electricity for the production operations (Mazzetti et al. 2014). These gas turbines use natural gas/oil—or both—from the reservoirs and the combustible waste from the processing systems as input fuels to generate electricity. A detailed description of upstream operations and their power demands is included later in this work.

According to Mazzetti et al. (2014), the vital element necessary to achieve energy efficiency is to be found in new and compact technologies that are designed to reorganize gas-fired power production and which will therefore help achieve greater efficiency in the operations of gas turbines, gas compression, and well-stream energy. The most effective way to do so is by using compact bottoming cycles applied to the waste heat produced by gas turbines. This approach has the potential to reduce CO2 emissions by 25%. Also important here are the use of dual bottoming cycles, the use of alternative working fluids, and the replacement of existing gas turbines with smaller turbines that run at higher loads. Finally, the use of co-fired gas/oil turbines, the organic Rankine cycle, exhaust-fired boilers, and pre-/post-carbon capture and storage systems has also been proven to yield significant energy efficiency in upstream operations (Zhang et al. 2019b).

1.1.3 Catalyzing energy efficiency in the petroleum industry

Government regulations and policies can play an instrumental role in encouraging the industry to adopt energy efficient methods of production. Due to the carbon tax policy initiative by the Norwegian government, the carbon footprint of the petroleum sector has remained fairly stable for a number of years (Norwegian Petroleum 2020). Various other countries have also regulated to control emissions and encourage energy efficiency. For instance, the Canadian government imposed regulations to reduce methane and certain volatile organic compounds from the upstream oil and gas sector (Government of Canada 2020). Likewise, the European Union (EU) GHG emission monitoring and reporting legislation requires EU counties to monitor their GHG emissions according to internationally-agreed upon obligations and to report levels of emission of GHG gases produced by various industrial sectors. The EU also has several low-carbon development strategies, and additional policies to reduce emissions (EU 2020). Equally, the U.K.'s combustion installation (prevention and control of pollution) regulations allows for offshore combustion plants (such as an offshore OG platform) to operate only in accordance with a permit issued under pollution prevention and control regulations. These regulations are designed to control the GHG emission and to promote energy efficiency of the offshore plants (Legislation UK 2013). Finally, Australia's Offshore Petroleum and Greenhouse Gas Storage (Environment) Regulations 2009 obligates any petroleum activity to adhere to the Environment Protection and Biodiversity Conservation Act 1999 (Australian Government 2009).

Increased governmental regulations can make the industry respond in two complementary ways: by mitigating its own greenhouse gas emissions and by developing new, lower GHG-emitting products and services. This could result in significant energy savings and have long-term effects, such as the reduction of barriers towards innovation and technology adoption (Worrell et al. 2008). Therefore, policy-makers and governments can adopt certain measures to promote energy efficiency (Farrell and Remes 2009). First, they can provide finance to upgrade to energy efficient technologies. Secondly, they can provide incentives, such as revenue incentives and certification programs, that measure and reward an industry's progress towards energy efficiency. Thirdly, they can implement and enforce energy efficiency standards. As discussed above, this measure can help the industry gain a competitive advantage by cost reduction and by stimulating greater innovation (Farrell and Remes 2009).

1.2 Research questions

1. What are the main methods and engineering solutions to achieve energy efficiency during upstream OG operations?
2. How do governmental regulations for the environment and energy efficiency influence the implementation of energy efficiency in the upstream OG industry?

3. What are the core concepts in energy efficiency implementation and organization according to the literature?
    3.1. What are the general motives driving the implementation and organization of energy efficiency technology?
    3.2. What are the major costs and complementing concepts of these technologies?
    3.3. Is there enough evidence in the literature to prove the benefits of energy efficient technology implementation?
    3.4. How does the concept of platform electrification relate to energy efficiency?
    3.5. What are the main considerations and temporal horizons for energy efficiency planning in the quantitative literature?
    3.6. What are the main contrasting concepts regarding the efficient use of energy?
    3.7. What are the barriers and drivers faced by organizations in energy efficiency implementation?
4. How to integrate energy efficiency methods/technologies for the upstream energy system design?

1.3 Structure of the thesis

The thesis is structured as follows. The first chapter includes an introduction of the problem describing the role of the oil and gas sector in the increasing environmental degradation. It goes on to introduce the concept of sustainability and lays the groundwork of energy efficiency as the most sustainable method in the production of petroleum in upstream processes. Furthermore, it discusses the energy efficient technologies that can reduce CO2 emissions, as well as some governmental regulations that can help achieve the goal of energy efficiency to make the upstream operations more sustainable.

The second chapter then includes a detailed write-up about the upstream petroleum processes and their general energy requirements, which provides important background for this study. The chapter goes on to describe the scientific concept of energy integration and waste heat recovery that can help achieve energy efficiency in upstream operations. It also discusses the contemporary energy efficient technologies based on these efficiency concepts that are/can be used by the upstream OG industry to enhance overall energy efficiency. Chapter 2 ends with a review of some of the major engineering solutions provided by notable engineering solution providers to conceptualize the characteristic aspects of the technological solutions in the market, and their association with the literature. The third chapter is dedicated to highlighting the effects of governmental regulations on the OG sector and their possible externalities.

The fourth chapter includes a detailed probe into the literature regarding energy efficiency and it is structured in the following manner. First, to answer research question 3 (Section 1.2), a review of the literature regarding energy efficient processes will be presented. In this, the scope of the literature review relevant to this work is specified and the main ideas of interest and implementation are presented. Furthermore, contrasting arguments against energy efficiency are also considered in order to assess their relevance to the implementation of energy efficient technologies. Finally, the literature review illustrates the barriers and drivers to energy efficiency adoption and implementation.

Chapters 5 and 6—the final two chapters—will highlight the major findings of the literature review and conclude the thesis respectively. The document ends with the list of references used in this study.

2.0 Upstream OG processes and energy efficiency

2.1 Offshore upstream oil and gas processes and their energy needs

Upstream oil and gas (OG) processes involve the use of equipment that ranges from the processing equipment that takes the product from the wells to the equipment that transforms and delivers oil and gas as stabilized, marketable products. These processes unfold over many steps which include running the oil or gas through manifolds to gather it for processing on the upstream facility (e.g., gas treatment and compression as illustrated in Figure 3), after which it is then stored and loaded for transportation to the refineries where it will be further processed. The processing system requires considerable electrical and heat energy to work. To start with the example of the pipelines and risers of an offshore upstream facility: the risers are channels that connect an offshore facility with the wells on the sea floor. The risers contain various sensors to regulate the well pressure, and these include sensors to desludge choke, along with those to shutdown valves, check valves, etc. These sensors and risers require electric power to operate (Devold 2013).

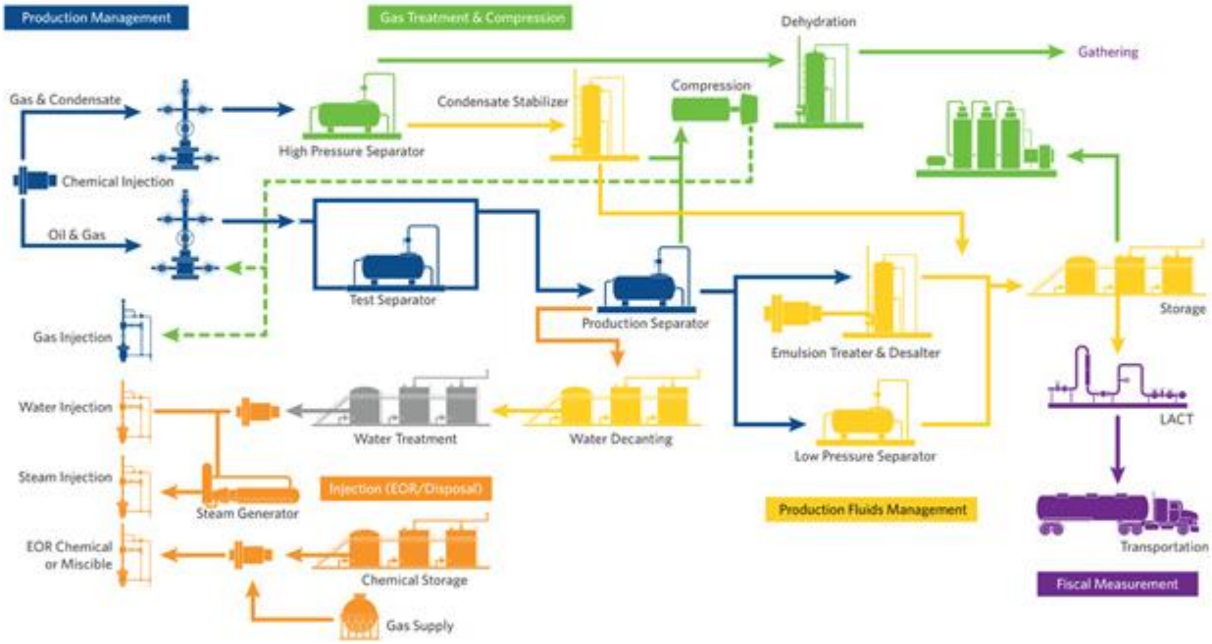

Figure 3: Schematic representation of preliminary oil and gas processing at an upstream facility. Source: (Emerson 2020)

The risers then transmit the flow onto the next stage of the process, which is separation, since the hydrocarbon flow from the wellhead consists of a mixed stream that contains oil, gas, and water (the exact proportions depend on the particular stage in the well's life-cycle). The separator works to separate the stream into distinct phases, and it requires power input in order to operate (Figure 4). In the production separator, electric power is mainly required to perform its various functions, such as regulating the flow of separated and unseparated streams. In addition, a control system operates the separated streams of the oil, gas, and water, and one of its functions is to hold back the separated stream. The control system has another function in that it prevents gas-blow-by, which is done by the pressure control valve in the separator, which is controlled by this control system when it senses the pressure in the separator and opens the valve if the pressure inside is too high, and vice versa. This control system consists of various sensors that require electrical energy in order to operate. Moreover, energy for heating is also needed when the flow moves from the first separator and enters the second and the third. The flow from the first-stage separator is usually heated before it enters the second-stage separator, and this is to ease the separation of water when the water cut is high but at a low temperature. Similarly, in the final separator, the liquid may have to be heated in a heat exchanger in order to achieve a good separation of the heavy components. The pressure reducers in this separator also require electrical energy (Devold 2013).

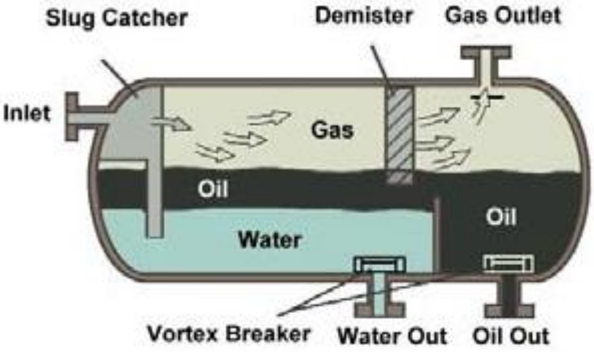

Figure 4: Visual representation of a separator. Source: (Devold 2013)

After the liquid stream has been through the separator, the next stage comprises the final removal of the water in a coalescer. The coalescer also uses electrical energy to power the electrodes used to form an electric field (field strength of 0.2 to 2 kV/cm) which breaks the surface bonds between the conductive water, and isolates the oil in an oil-water emulsion that fills the coalescer (refer to Figure 5). Furthermore, the separated oil may contain salts in amounts that render the oil unacceptable commercially; these salts, therefore, are removed by an electrostatic desalter. This desalter also requires electrical energy to operate because it too creates an electrostatic field, which removes salts like sodium, calcium, and magnesium from the oil (Devold 2013).

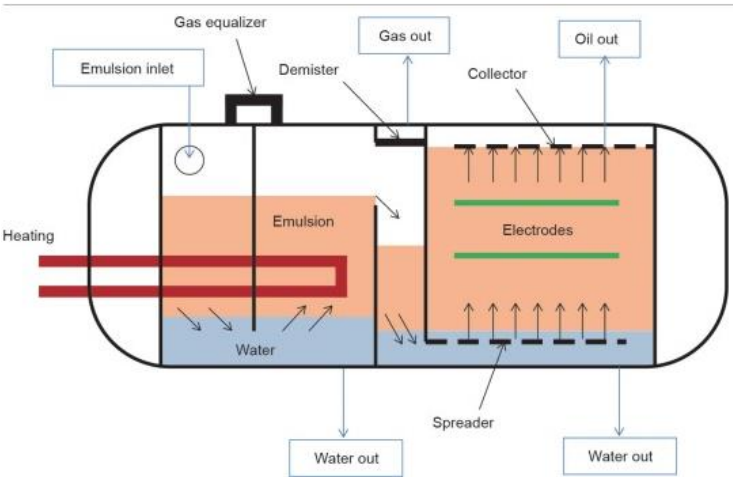

Figure 5: Visual representation of an electrostatic coalescer. Source: (Rossi et al. 2017)

In some upstream installations, the hydrocarbons extracted from the reservoir may contain a high water cut, especially because water is present in almost all the reservoir and it is extracted along with the hydrocarbons. This water contains oil content and other dissolved contaminants. In most countries, there are restrictions in place to limit the level of oil content in water before the water can safely be discharged. For example, the OSPAR convention (an action plan between the Oslo and Paris Commissions for the Protection of the Marine Environment of the North-East Atlantic) sets limits of 40 mg/liter (ppm) for the oil to water ratio. Therefore, in order to comply with these regulations, upstream facilities usually use a water treatment system (Figure 6). A typical such system consists of a sand cyclone, a hydro cyclone, and a water degassing drum (refer to Figure 6). The water treatment facility also requires electrical energy to operate, and it treats the water before finally discharging it into the sea or into a geological formation (Devold 2013).

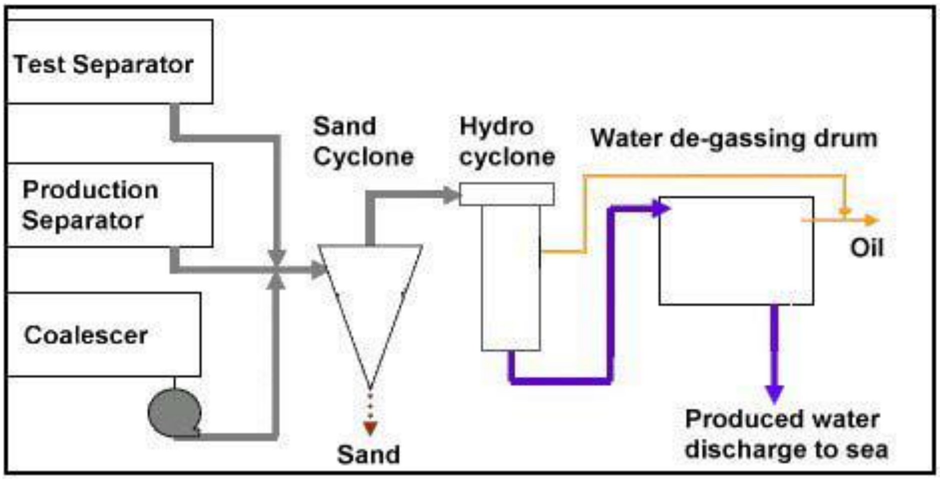

Figure 6: Visual representation of a water treatment system. Source: (Devold 2013)

As mentioned previously, the production separator breaks apart a singular hydrocarbon stream into three distinct streams of gas, oil, and water. Each of them needs at least some processing before the final product can be obtained. The gas stream from the production separator goes through various stages before it can be used as a final product. Typically, the first step is to cool the gas that is extracted from the production separator's gas outlet. A heat exchanger is used for this cooling process, and the cooled gas stream then passes through a scrubber to remove any liquids, before it enters the compressor. The scrubber contains glycol to absorb the liquids present in the gas stream, and then this glycol is heated in order to boil out the absorbed liquids from the gas (the process of glycol regeneration is represented in Figure 7). Such a process ordinarily utilizes heat energy produced by the integrated energy system IES (though in some designs, electric heaters are used). During this process, an anti-surge loop allows the gas to recirculate in the system. The purpose of the heat exchanger is to lower the temperature of the gas, so that the compressor may operate efficiently. The heat exchanger, as well as the compressor, naturally require electricity to operate. In addition, the pressure and temperature sensors within the compressors also run on electricity: these sensors maintain the thermodynamic balance of the compressed gas. The compressors themselves are powered by gas turbines that form part of the IES, and are used for various oil and gas processes, ranging from upstream production to gas plants, pipelines, and petrochemical plants (Devold 2013).

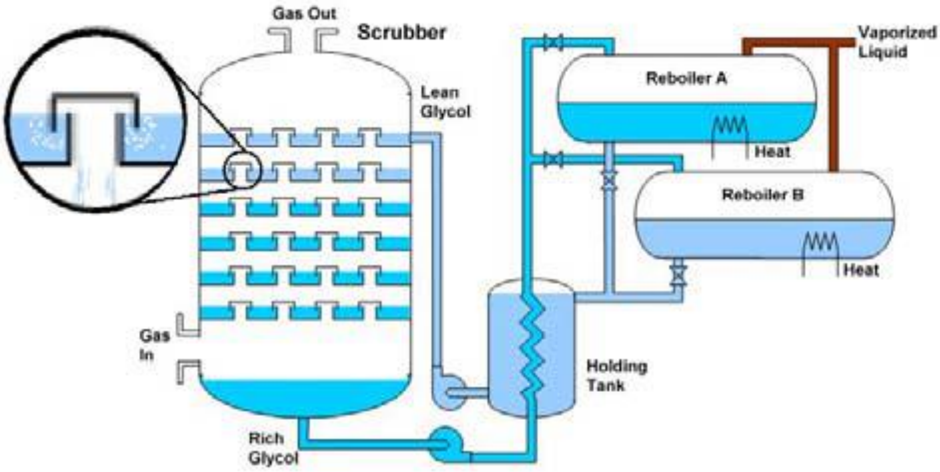

Figure 7: Glycol regeneration in gas treatment. Source: (Devold 2013)

Finally, it is essential to meter the final product before the product can be passed from producer to consumer. Installations therefore have analysis and metering systems that provide product data, such as its density, viscosity, and water content. In order to maintain the accuracy of the measurements, the metering process is split across several runs. Each run employs one meter and several instruments to provide temperature and pressure correction. An open/close valve system allows runs to be selected, and control valves are used to balance the flow between runs. The instrument and actuators are monitored and controlled by a flow computer (Devold 2013).

2.1.1 Energy needs and the energy flow in the upstream processes

The energy needs for upstream processing can be divided into electrical energy demands and heat energy demands. These remain the primary energy types required for OG upstream processes. While energy is required all along upstream processing and production operations, the focus of the present discussion will remain on the processing operations, as opposed to production operations, not least because electrical energy is also required for production operations like well logging, well monitoring, production control, etc. and this electric energy is provided by the same IES which powers the processing operations. Integrating the production operations to achieve greater energy efficiency is a whole other topic, and is beyond the scope of the present study. In upstream processing operations, the main electrical energy demands are those of the sensors that are used in various processes, such as separators, risers, etc. These sensors control the processes as well as the energy that those processes require. For example, the separator sensors control the amount of energy required to power the electrodes, and this is based on the water content of the well stream. Another example concerns the riser sensors: these control the level of hydrocarbon material that is allowed into the manifolds, and regulates its pressure. The main heat energy demands come from the gas and water treatment systems, and are devoted to the heating of the gas and water streams.

Keeping in view the upstream OG processing systems specifically, Figure 8 illustrates the generalized energy flow of an upstream OG facility. The general energy flow of the processing operations begins when the fuel first enters the gas turbine for internal combustion. This produces electrical energy that powers the energy requirements of the processing systems. The input fuel can be gas, oil, or some other combustible waste produced by the processing operations themselves (discussed in detail in Section 2.3). This power source (gas turbine) generates electrical energy that is primarily stored in a storage capacitor, and then distributed to the demand points as needed in the upstream facility. The heat demands are met either by powering a heat source with the generated electricity, or by harnessing the waste heat from the gas turbine operation (i.e. cogeneration, which is discussed in detail in Section 2.2.1). In Figure 8, waste heat meets the heating demands of the processing operations.

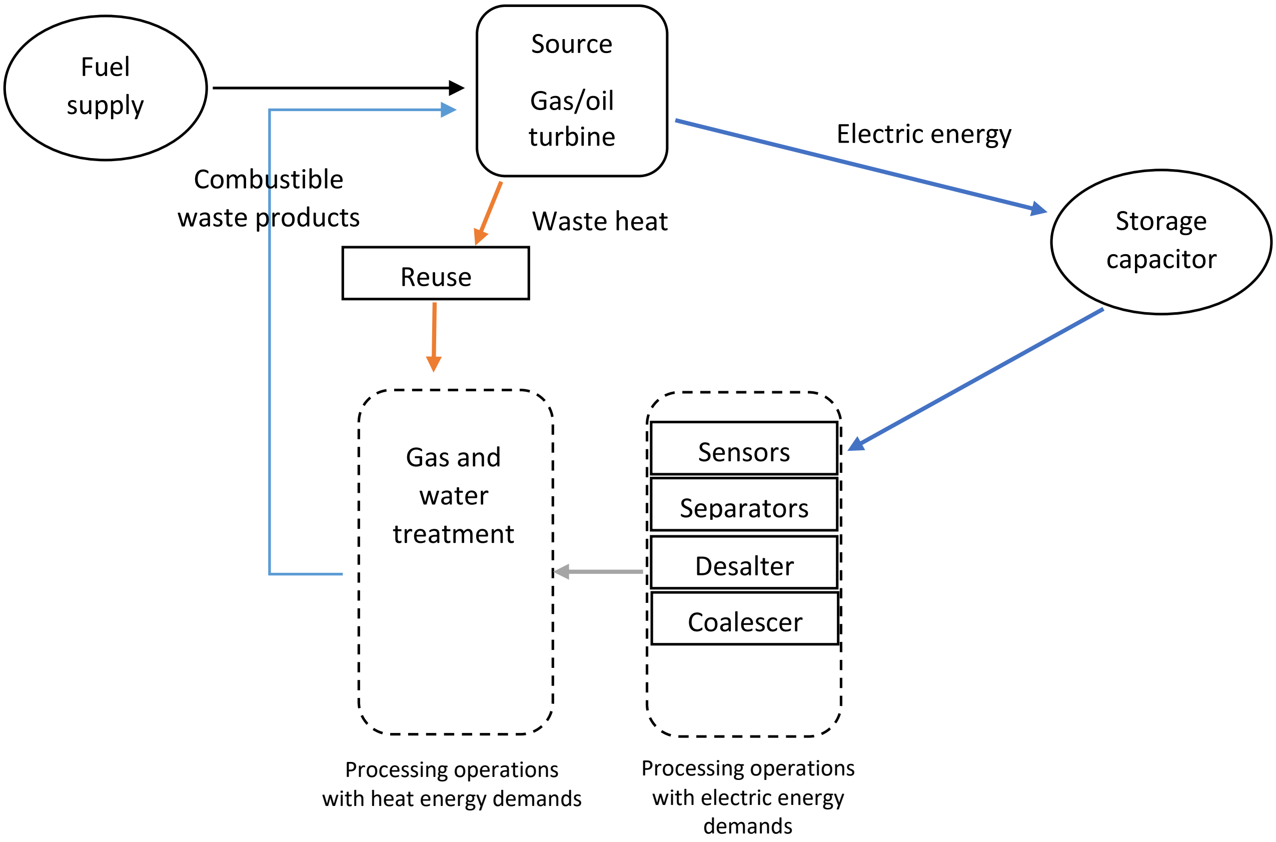

Figure 8: Generalized energy flow of an upstream OG facility

2.2 Achieving energy efficiency in upstream petroleum processes

Upstream petroleum processes are complex chemical-technological systems that consume heat and electrical energy resources in significant quantities. The energy component in the final product cost reaches up to 11–15%, and this amount is trending to increase (Kulbyakina and Ozerov 2018). What this means is that in the cost of the produced hydrocarbon, 11–15% of that cost comes from the energy spent on producing it. Kulbyakina and Ozerov (2018), in their analysis of the energy savings potential in Russian OG enterprises, found the potential for up to 30.2 GWh in energy savings. This clearly demonstrates the potential for significant energy savings in the upstream OG processes. But in order to identify energy savings potential in large-scale operations such as those of the OG industry, one needs to bring a systematic approach to the analysis and synthesis of complex systems.

Because the main functions of any upstream facility are raw hydrocarbon production and preliminary processing (as discussed in detail above), the operation of these functions consume the bulk of facility’s energy demands. The main fuel users within such facilities are as follows: equipment for processing operations (e.g., separation, gas treatment, etc.), the furnaces, thermal waste treatment plants, flaring systems, and boilers. The main fuels that feed the supply systems are, in general, hydrocarbon gases (associated gas, liquid fuels) and gas from the commercial gas network (used to handle the excess demands sometimes made of the fuel system). Therefore, the main way to promote energy and fuel efficiency involves the use of the facility’s own fuel and the comprehensive utilization of the combustible waste that arises from the processing system itself, i.e., preliminary treatment of the produced hydrocarbons like gas treatment, oil and gas separation, etc. Nevertheless, an integrated approach to energy and fuel efficiency that is based on the principles of system analysis and mathematical modeling is needed to improve efficiency (Kulbyakina and Ozerov 2018). Put differently, to understand overall energy use, it is necessary to trace the complex chains of energy flow from fuel to final product (Cullen and Allwood 2010).

Every upstream OG facility implements the production and processing of the OG extracted from the well streams in a different way. These differences are largely down to the following reasons. First, an offshore OG facility can produce either stabilized market product (the OG products that match sales specifications) or an unstabilized market product (crude oil/natural gas, which requires further processing before handing it to the customers which may be a refinery or a downstream distributor depending on the type of marketable product that the upstream facility produces). For example, in the Gulf of Mexico, the common strategy is to make stabilized market products; conversely, in the North Sea, crude oil/natural gas tends to be exported in its unstabilized form and is then further processed at another onshore crude oil/gas terminal (e.g., Bacton Gas Plant in the eastern U.K.) before it is injected into the local gas grid. These differences arise from differences in the export specifications from facility to facility. Additionally, export specifications can also vary because of different separator specifications in use at any given upstream facility. These separators govern the throughput of the OG to be exported, which is itself an export specification (i.e., at what pressure crude oil/natural gas must be transmitted through the pipeline to the customer). Generally, purity and pressure requirements constitute the main differences across export specifications for crude oil/gas. Secondly, each upstream facility has different specifications for the OG that comes from the well streams, and this causes variations in processing requirements and energy demands across facilities. For instance, the field that produces low-API (the index specifying the viscosity of crude oil) crude oil often has a low gas-to-oil ratio (i.e., less gas compared to oil in the incoming well stream). This type of crude oil requires low-pressure stage separation because the stage separation process separates the oil and gas while also recovering the maximum amount of hydrocarbons in the liquid phase; a low oil-to-gas ratio and low-API crude oil thus requires relatively less separation because it remains more liquid than gas. It also stabilizes the resulting separated oil and gas in a way that allows each to retain its gaseous or liquid phase when exposed to atmospheric pressure. On the other hand, the fields producing high gas volumes relative to oil (i.e., a high gas-to-oil ratio) will require high-pressure stage separation and this will increase the scale and cost of the separation processes by creating greater energy demands. Thirdly, the temperature of the crude oil as it comes from the well streams naturally differs. Differences in temperature have effects on the various processing steps: for example, in wells that produce relatively cool crude oil, much more heating is needed to reduce the viscosity of this crude oil and to separate it into gas and oil (Bothamley 2004). All the foregoing reasons mean that the specific energy use requirements and level of CO2 emissions vary across upstream OG facilities.

Keeping with the differences in energy use across upstream OG facilities, the work of Nguyen et al. (2016) analyzed and compared the different energy efficiency measures that can be used to improve energy use. This study looked at the following: the promotion of energy and process integration, the exploitation of low-temperature heat from the gas cooling steps, the use of the waste heat from the power plant, as well as several other measures. The efficiency measures just mentioned can yield significant energy and CO2 emission savings. Later sections (2.2.1 and 2.2.2) will elaborate on these different measures.

2.2.1 What is energy integration? And what are the benefits of it?

Energy integration refers to the ways in which energy systems can work more efficiently at both an individual level and within the energy system as a whole (Torres 2020). The overriding goal of process integration is to minimize the use of energy within a given system. This can be achieved by promoting internal heat exchanges and by improving the integration of each individual process that has heating and cooling values as inputs/outputs. In other words, recovering the energy produced from some processes can be used as valuable input energy for other processes. Energy recovery could reduce the demand for external cooling, thereby decreasing overall levels of power consumption (e.g., fewer cooling operations in an offshore platform would require fewer seawater lift processes). Additionally, balancing the temperature profile of the utility and processing plants could allow for cogeneration possibilities. For example, if the exhaust temperature of a gas turbine equals the input temperature of an exhaust-fired turbine, this will result in the cogeneration of two forms of energy (electrical and heat energy) from a single source (Nguyen et al. 2016). Further, in a simple gas turbine cogeneration system (Figure 9), the hot exhaust gases from the gas turbine provide the source for process heat production (that is, energy in the form of steam). As exhaust gases from a gas turbine are utilized by a heat recovery system to produce steam, the produced steam can then be used as process heat (i.e., an ancillary heat source) and to produce electric power through a steam turbine, thereby generating electric and heat energy from a single source (Bilgen 2000). Not only, therefore, does system integration allow for reduced fuel consumption, it also leads to reduced costs, energy use, and environmental effects, especially if the heating and cooling processes are matched (Nguyen et al. 2016).

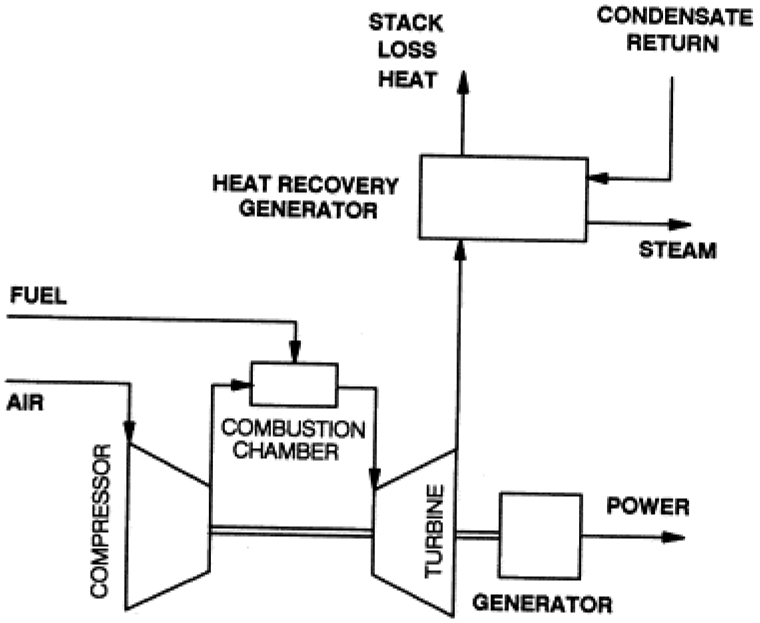

Figure 9: Schematic representing a cycle of gas turbine electric power and process heat cogeneration. Source: (Bilgen 2000)

To take an example, consider a trigeneration system (a type of a cogeneration system). Such a system utilizes the waste heat produced by the exhaust gases from the gas turbine to generate process steam in a waste heat recovery steam generator (WHRSG); this system also powers absorption chillers for gas turbine inlet air-cooling, and supplements the plant's electrical power. As a result, this type of system produces a combined cooling, heating, and power scheme through absorption cooling, and leads to power generation through a regenerative bottoming cycle. On the other hand, a bottoming cycle produces thermal energy directly from fuel and utilizes the recovered waste heat to generate electrical and mechanical power. But in a trigeneration system (Figure 10), a heat recovery steam generator uses the waste heat recovered from exhaust gases produced by gas turbines to generate steam. This steam can then be used either to produce lean gas (i.e., a form of natural gas that can be used for burning) in a heat exchanger, or, if the steam is high pressured, it can be used to drive a steam turbine in a combined cycle mode to produce electrical and thermal energy. Additionally, this steam can also be used in a thermal absorption refrigeration system (ARS), which utilizes heat content from the steam to provide refrigeration at 5^{o} C. This refrigeration also relies on the phase transformation (evaporation) of lithium-bromide, which is used as a refrigerant. The results of using this system suggest the potential for recovery of up to 79.7 MW of gas turbine waste heat (Popli et al. 2012). However, without an energy integration approach, large amounts of produced steam would be lost, and separate energy sources would be required for heating one stream and for cooling another.

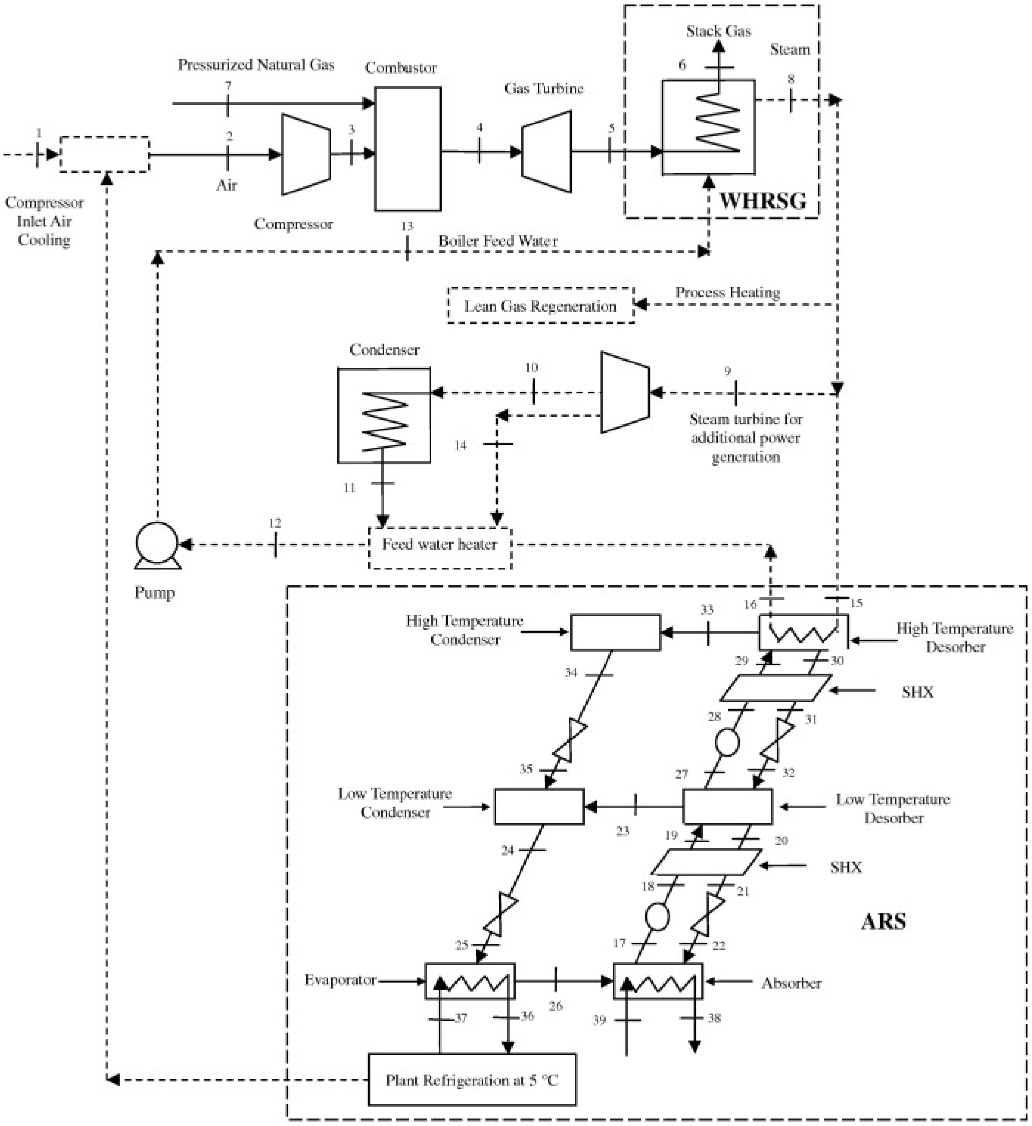

Figure 10: Schematic of a trigeneration system. Source: (Popli et al. 2012)

2.2.2 What is waste heat recovery? What are the benefits of it?

In an upstream OG facility, gas recompression and treatment sections produce waste heat at high and low temperatures. Low-temperature waste heat is produced when the gas is cooled at the required processing stages and/or before the export process of the final product. The gas is cooled in order to reduce the power demands made by the processing plant, to improve the dehydration process, and to ensure that moderate-temperature gas enters the pipeline inlets when that gas is exported away from the upstream facility. The organic Rankine cycle (ORC) has been proven to be useful in recovering low-temperature exhaust gases, but it requires proper design and a control strategy prior to its installation (Pierobon et al. 2014).

The medium- to high-temperature exhaust gases from the gas turbines can also be used to produce both heat and electricity. The use of Rankine cycles or exhaust-fired boilers may prove effective here. Such technologies can result in increased efficiency of the power system whilst also providing greater flexibility, and, in the event that the upstream facility is connected to an electricity grid, they can also potentially enable the export of power to that grid. Most importantly, however, and beyond the higher capacity for the facility's power system, these technologies can lead to lower fuel-gas consumption and lower CO2 emissions. Implementing these waste heat recovery technologies would require proper design and integration within the existing energy system of the upstream facility (Nguyen et al. 2016).

A conventional natural gas boiler emits flue gases directly into the atmosphere at temperatures ranging from between 150º to 200º C; however, wasting flue gas at such high temperatures causes significant heat loss. Exhaust-fired boilers that simultaneously generate power while utilizing the high-temperature exhaust gas can further increase the thermal efficiency of the gas turbine (Qu et al. 2014).

Looking further at the upstream OG processes and the methods of heat recovery and energy integration to achieve energy efficiency, a case study of Anguil (an environmental and energy solution provider) has highlighted the benefits of heat recovery and energy integration in an upstream OG facility. A conventional thermal oxidizer used by an upstream OG company heats the amine solution (i.e., the solution used to absorb acidic gases from the produced natural gas to meet export specifications) in order to oxidize hazardous byproducts, such as sulfur and other volatile organic compounds from the amine solution, before venting the oxidized byproducts into the atmosphere to meet emission regulations. The oxidization of hazardous byproducts in natural gas renders them as benign products that do not pollute the environment. Once the amine solution is free from such byproducts, it can be reused in the gas treatment process. The existing thermal oxidizer maintains a temperature of 815º C to heat the amine solution, a process which requires a considerable amount of fuel for heating, thereby leading to increased operating costs and GHG emissions. To reduce operating costs and increase efficiency, Anguil developed a Regenerative Thermal Oxidizer that recovers the waste heat as it exits the system in the form of the vented gases from the treated amine solution (no energy wastage). This waste heat is recovered by heat exchangers in a Regenerative Thermal Oxidizer which absorbs the heat energy, and this recovered heat is then used within the system itself—such as for the purpose of heating the thermal oxidizer—and/or for meeting the other heating requirements of the upstream facility. This technology therefore reduces overall fuel demand.

As a result of this energy integration strategy and waste heat recovery system, the OG operator improved efficiency by 99%, while saving $500,000/year in natural gas costs (Anguil 2020). In other words, the Anguil example demonstrates the considerable savings in operating costs for an upstream OG company that develops strategies for increased energy efficiency. The operating costs that are saved by using less fuel correspond to reduced GHG emissions.

2.3 The integrated energy system

Upstream operations are powered by a complex, structured, and integrated internal energy supply system, which continuously processes raw materials and consumes/generates energy. The internal energy supply system contains the following: a fuel supply system, an electrical supply system, and a heat supply system. Of these, the fuel supply system requires the highest number of interactions with both the process system and with the external energy supply system. Figure 11 shows several of these interactions (Kulbyakina and Ozerov 2018).

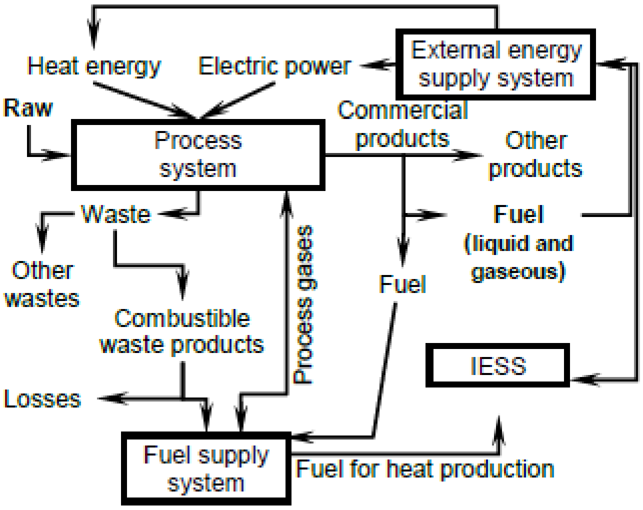

Figure 11: Relationships between the fuel supply system, the process system, and the internal energy supply system.

Source: (Kulbyakina and Ozerov 2018)

The upstream facilities are powered by integrated energy systems (IES). The example of this IES is taken from the work of Zhang et al. (2019b), which combines the approaches that were mentioned in Section 2.2, along with a carbon capture and storage system to plan an optimal IES for offshore upstream application. The IES they have presented has been proven to reduce operating costs, CO2 emissions, and energy use. The IES mentioned in this research is currently in use at an upstream offshore platform, and later, the present study (in Sections 2.3.1, 2.3.2, 2.3.3 and 2.3.4) will come to a description of the technologies used in this IES. Additionally, waste heat recovery and carbon capture and storage have also been considered as an appropriate means to reduce CO2 emissions in upstream OG operations (Nguyen et al. 2016).

2.3.1 Gas turbine

Gas turbines are, in essence, rotary engines that extract energy from a flow of combustion gas. Gas turbines offer flexibility because they can use a range of liquid or gaseous fuels, and they are comparatively small in size and weight when compared to conventional steam power plants (Sarkar 2015). The power output of industrial gas turbines can be up to 593 MW (Siemens 2020).

A simple gas turbine consists of three main sections: a compressor, a combustor, and a turbine. Working on the principle of the Brayton cycle, the gas turbine uses compressed air, mixes it with fuel, and burns it under constant pressure conditions. The result is a hot gas mixture which can then be expanded by using a turbine (Pathirathna 2013). Moreover, gas turbines operate on the Brayton cycle and utilize a working fluid (typically air). The Brayton cycle can be a closed or an open cycle. In an open Brayton cycle (Figure 12), the air is drawn into the compressor where its temperature and its pressure are increased. The combustion of a fuel, such as hydrogen, diesel, or natural gas, then further increases the temperature of the air. This produces a working fluid, one which includes air but excludes oxygen, which reacts with the fuel, whereby carbon dioxide and steam emerge as the products of the combustion. The high-temperature and high-pressure working fluid is next fed to the turbine, and here the working fluid is expanded and its temperature and pressure are decreased. This turbine drives the compressor and also drives the generator to produce electric power. Finally, the working fluid is then exhausted from the turbine (Viteri and Anderson 2005).

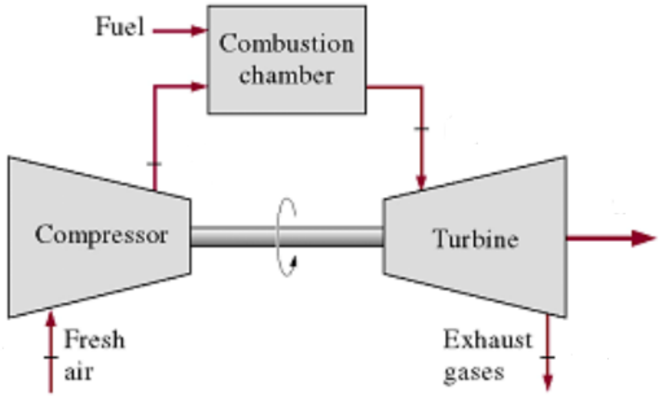

Figure 12: Schematic representation of an open Brayton cycle. Source: (Al-Hadhrami et al. 2011)

In most cases, stationary gas turbine power systems consist of an open Brayton cycle, which functions as merely one part of a more elaborate, combined cycle. The reason for this is because of the high temperature of the working fluid as it exits the turbine: this heat can be used to generate steam in a heat recovery steam generator before it is finally exhausted. The steam heated within the heat recovery system can then be used to drive a steam turbine, such as that found in a typical closed Rankine cycle steam power plant. This system of operation has a combined cycle of the open Brayton cycle gas turbine and closed Rankine steam turbine in order to extract power most efficiently from the fuel when it is combusted within the gas turbine (Viteri and Anderson 2005).

Furthermore, in a closed Brayton cycle, the working fluid (typically helium) remains separate from the heat source and it is recirculated from the turbine exhaust back into the compressor without being formally exhausted. Because the working fluid is not exhausted, it cannot contribute to environmental pollution. However, if hydrocarbon fuel with air is utilized to heat the working fluid between the compressor and the turbine (as in our case), the closed Brayton cycle gas turbine will still have an exhaust stream which will include CO2 and NO2. Therefore, there is a need for a Brayton cycle gas turbine that heats the working fluid by the combustion of a hydrocarbon fuel but which also avoids the emission of pollutants into the atmosphere (Viteri and Anderson 2005).

2.3.2 Organic Rankine cycle (ORC)

The Rankine cycle converts heat energy into mechanical work by means of a thermodynamic cycle. A circulating working fluid evaporates and condenses continuously during the process. A simple Rankine cycle consists of a vapor generator (boiler + super heater), expansion device (turbine), condenser, and feed pump. Figure 13 shows a schematic representation of a simple Rankine cycle. The Rankine cycle does not strictly use a certain working fluid or a temperature range; instead, it uses different variants. Some common variants of a Rankine Cycle plant are the following: a steam Rankine cycle, an organic Rankine cycle, and a super critical Rankine cycle (Singh and Pedersen 2016).

ORC differs from the Rankine cycle only in the type of working fluid that the system uses. An ORC uses organic fluids, such as hydrocarbon gases, refrigerants, etc. Moreover, an ORC plant layout is similar to that of a Rankine plant because it contains the same basic components. At moderate heat sources (232° to 649° C), an organic working fluid is best suited to attain the best levels of efficiency and the highest power outputs. The reason for this is because organic fluids have a much lower specific vaporization heat when compared to water. Accordingly, the configuration of an ORC can be arranged in many different ways, as can be seen in the work of Lecompte et al. (2015).

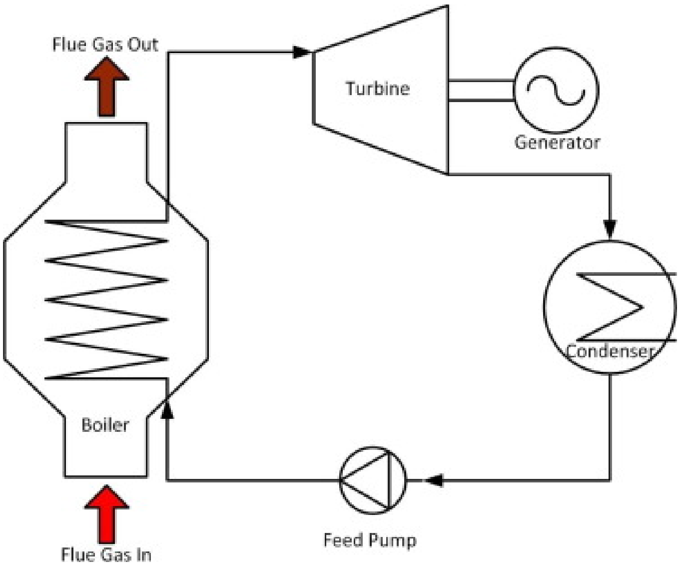

Figure 13: Schematic representation of a simple Rankine cycle. Source: (Singh and Pedersen 2016)

2.3.3 Heat recovery steam generator (HRSG)

Gas turbines with heat recovery systems can be operated both in cogeneration and combined cycle modes—a schematic of both modes is shown in Figure 14. In the former, the steam produced by the HRSG is directly used for application to other process. Conversely, in the latter mode, power is generated by a steam turbine generator, where the HRSG generates steam by utilizing the exhaust from the gas turbine. However, some plants can also generate steam while the gas turbine is off. This is done by using a separate forced-draft fan, along with a burner, to generate hot gases which are then used to generate steam (Ganpathy 1996).

HRSG design can also include multiple-pressure units for maximum energy recovery. These multi-pressure units treat the input feed of exhaust gases as two or three separate flows (high, medium, and low pressure) for the purpose of generating steam. Each section of the multi-pressure unit contains a steam drum and an evaporator section. The evaporator section consists of numerous pipes containing high-pressure water, which is heated by the incoming exhaust gases to produce steam. The steam produced will have the same pressure level as the input feed (that is, low-pressure or high-pressure steam) and is mostly saturated, meaning that the steam is produced at the same temperature as the water from which it comes. This saturated steam is then fed into a super heater to raise the temperature beyond the saturation point, thus making it ready for use in the steam turbine (PEI 2008). Evidently, the multi-pressure units allow for higher work outputs because no input feed is lost, but these units are usually more costly. Moreover, the essential starting-point in the engineering of an HRSG is the evaluation of its steam generation capacity and its gas and steam temperature profiles because the HRSG will behave differently based on the low inlet gas temperature and a large gas/steam ratio (Ganpathy 1996).

The steam production and the gas and steam temperature profiles of an HRSG are affected by two main variables: pinch point and approach point. The pinch point refers to the difference between the temperature of the gas leaving the evaporator and the temperature of the saturated steam. The approach point is the temperature difference between the saturated steam and the temperature of the water that enters the evaporator. Additionally, these variables also influence the size of the super heaters, the evaporator, and the economizer. Pinch and approach points are selected for each particular exhaust gas condition (design case); unlike a conventional steam generator, HRSG steam production is influenced by the specific conditions of the exhaust that leaves the gas turbine and enters the HRSG. The operating parameters can vary based on ambient conditions, elevation, gas turbine load, and fuel. Therefore, the design case could be any acceptable parameters for gas inlet. By using the exhaust gas parameters, it is possible to determine the design temperature profile, which forms the basis for sizing the HRSG. Moreover, the selected pinch and approach points can vary due to different ambient conditions and gas turbine loads, thereby resulting in different exhaust gas parameters (Ganpathy 1996).

Furthermore, it has been established that the HRSG generates steam, the quality and quantity of which depends on the flow and temperature of the exhaust gas that enters the unit. Large cogeneration and combined cycle plants generate high pressure and temperature super-heated steam (4137-10342 kPa at 343-510° C). In order to control this superheated steam spray, desuperheaters are used, just as is the case for conventional boilers. Moreover, HRSG units are ordinarily classified into three different types: unfired, supplementary-fired, and exhaust-fired (Ganpathy 1996).

In our case, an exhaust-fired HRSG is used. This type of HRSG uses firing temperature ranges from 927° to 1649° C, and it employs a furnace that is completely water-cooled in order to contain the flame. The burner used is typically a register burner with a windbox, although a duct burner may also be used for temperatures up to 1316° C. The exhaust gas from the gas turbine is used for combustion (Ganpathy 1996).

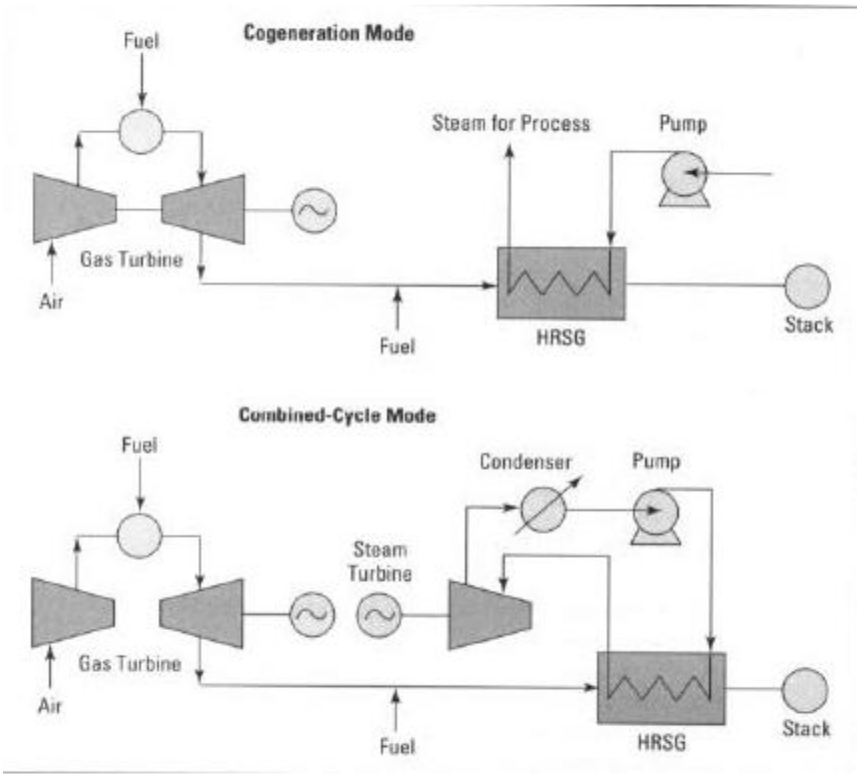

Figure 14: Schematic representation of heat recovery steam generations. Source: (Ganpathy 1996)

2.3.4 Carbon capture system (CCS)

A carbon capture system is an energy intensive system, and over twenty technologies have been proposed for the CCS. Because they are pertinent to our case, only pre-combustion and post-combustion capture systems will be described. Figure 15 illustrates the working principle of both CCS types. In post-combustion capture, most of the CO2 is processed in the final stage and is extracted from the exhaust gases before it is released into the atmosphere. In order to extract CO2, a wet scrubbing method is used in conjunction with aqueous amine solutions. At a low temperature (50° C), the amine solvent removes the CO2 from the waste gas. The solvent is then repurposed for reuse by heating it to around 120° C: the solvent is thus cooled and recycled continuously. The removed CO2 from the regeneration process is dried, compressed, and transported for storage underground in a safe geological storage facility (Gibbins and Chalmers 2008).

Because CO2 tends not to be readily available for removal before combustion occurs, the pre-combustion capture system of CO2 can be termed as an oxymoron. Nonetheless, all types of fossil fuel can be partially combusted or reformed with sub-stoichiometric amounts of oxygen (i.e., an amount of reactants that do not completely react with each other, and hence leave an excess of either of the reactants) at elevated pressures (30-70 atmospheres) to yield a synthetic gas mixture that contains mainly carbon monoxide (CO) and hydrogen (H2). Water (steam) is then added and the mixture is passed through a series of catalyst beds for the water-gas shift reaction to bring the mixture to equilibrium: CO+H2O⇔CO2+H2. The CO2 is captured and treated before sending it to be stored in a geological formation, while the hydrogen is used as a low-carbon fuel for power generation. Further, the energy requirements for CO2 capture and combustion in pre-combustion capture systems can be half the amount required by post-combustion capture. The reason for this is because no heat is needed to regenerate the solvent, and CO2 can be released at pressure levels higher than atmospheric pressure. Moreover, the CO2 produced by pre-combustion capture can be separated by using a physical solvent in order to leave a hydrogen-rich fuel gas. This CO2 is dissolved at a higher pressure, and then released for treatment and storage as the pressure is reduced (Gibbins and Chalmers 2008).

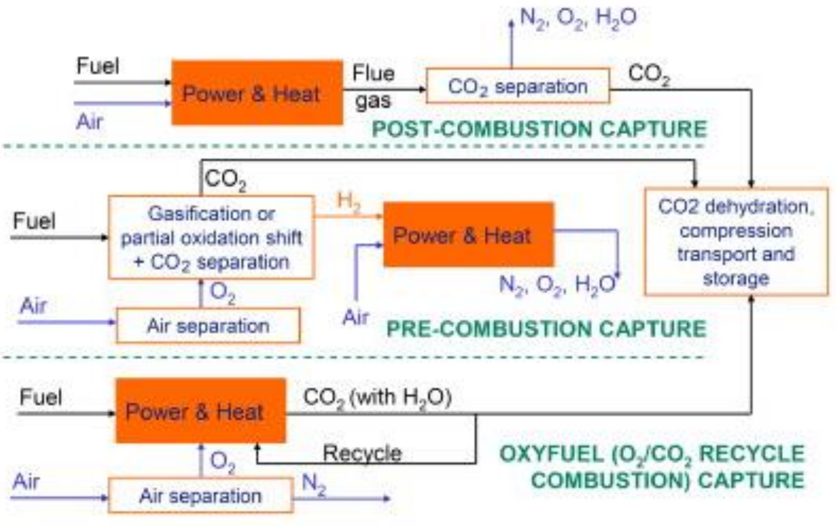

Figure 15: Carbon capture and storage process. Source: (Gibbins and Chalmers 2008)

2.4 Energy efficiency engineering solutions for the OG industry

The companies that offer energy efficient engineering solutions have played a major role in the development of the technology underpinning these solutions. Market competition, moreover, drives these companies to improve continuously the technology that they offer. Companies such as Baker Hughes, General Electric, Turboden, Techouse, Thermax, Parat, Sigma Thermal, and others all offer WHR solutions to the upstream OG industry. Conversely, CCS engineering solutions are provided by companies like General Electric, Aker Solutions, Mitsubishi Heavy Industries, among others. This present section will consider examples of a few of the WHR and CCS technologies on offer. By providing illustrated engineering examples, managers will be able to form an outline of the major engineering solutions currently available on the market. This discussion can also serve as a starting-point for later discussion about the implementation and organization of energy efficient technologies in practice. Most importantly, the present discussion will highlight how the links between the literature and practice can mutually reinforce the general concept of energy efficient technologies.

The number of companies that offer WHR solutions far exceeds the number of those that offer CCS solutions. The literature on the subject reflects this fact as well, not least because CCS is a relatively new energy efficiency technology for the upstream OG industry. The existing literature also reinforces industry-led practice in its emphasis on the facility- or case-specific application of any given energy efficient technology. The engineering companies generally offer tailor-made solutions according to the customer’s needs, and do not employ a one-size-fits-all approach to the problem. In other words, each upstream OG facility has unique requirements for the application of a particular engineering solution, and these requirements depend on the specific waste heat profile, the gas turbine specifications, power demands, carbon emission quantities, etc. Therefore, it is necessary to conduct an in-depth analysis of each facility with an eye for looking at its case-specific requirements before selecting the specific energy efficient engineering solution to be adopted in such-and-such a facility. This means that the responsibility for the selection and adoption of the most suitable technology falls to the operating company of the OG facility in question. It is therefore paramount that decision-makers and managers have an exhaustive understanding of the concept of energy efficiency.

The companies providing energy efficient technologies tend to emphasize on their websites the efficiency enhancement and environmental aspects of their technologies: that is, they advertise the improvement in a plant’s energy efficiency alongside the decrease in CO2 emissions. Describing energy efficient solutions in this way represents the perspective of the

OG industry towards energy efficient technologies. However, all of the environmental, economic, and efficiency effects provided by the technologies should be considered together, in order to provide a holistic image of the complete potential of these energy efficient technologies.

To mention a few examples of engineering solutions. Baker Hughes, for instance, offers ORegen, which is an ORC system containing an organic working fluid. ORegen's efficiency is thought to lead to gains of up to 24%, and can provide power output of up to 16MW per unit (Baker Hughes 2020). Techouse offers custom-made WHR units that are mainly intended for offshore OG application, and are designed according to the specific requirements of the upstream facility in question. The WHR are robust when it comes to handling extreme energy loads and the offshore environment more generally (Techouse 2020). Parat WHR units are more compact; they have an innovative heat exchanger design that complements offshore OG facility implementation, taking into account the weight and space constraints of such environments. This engineering solution is believed to reduce the heating energy demands by 30%, and requires relatively low levels of maintenance (Parat 2020). Further, Turboden—which is a Mitsubishi Heavy Industries group company—provides ORC units capable of power production of up to 20MW per turbine for waste heat recovery and which is applicable to OG processes. The ORC is tailored for each site according to the specific characteristics of the project, such as number of gas turbines, etc. Turboden has provided a 1MWe ORC to a gas compressor station in Canada, and a 1.8MWe ORC in Russia for the purpose of waste heat recovery from flare gas. In addition, it has two ORC solution projects in development for gas compressor stations in Uzbekistan (Turboden 2020). Besides the above-mentioned ORC solutions, other companies like Siemens, Exergy, Orcan, ENOGIA, and GEA also provide ORC engineering solutions that are applicable to the upstream OG facilities.

General Electric is one of world's largest manufacturers and suppliers of gas turbine technology. It offers a wide range of solutions (including simple and combined cycle operation), based on the energy demands of the prospective site. The output of this company's gas turbines ranges from 34MW to 571MW (GE 2020a). Combined cycle gas turbines are considered to be the most environmentally friendly solution for power generation if reliability, maintenance, and GHG emissions are considered (Faraoni et al. 2015b).

As established earlier, CCS technologies can also be adopted in OG facilities in order to reduce CO2 emissions. Aker Solutions offers services, products, and solutions for the entire carbon capture process, including its utilization and its safe storage. It also offers enhanced oil recovery solutions from the captured carbon (Aker 2020). Mitsubishi Heavy Industries commercialized its first post-combustion carbon capture system in 2019, and has since installed it in thirteen commercial plants. The carbon capture technology is also offered with an enhanced oil recovery option for upstream OG application, and can capture up to 90% of carbon from the flue gas (Mitsubishi 2020). General Electric also offers CCS engineering solutions, both new and retrofit solutions based on a plant’s specific requirements. Both pre- and post-combustion CCS technologies are offered by GE, along with a complete service from product design to implementation and installation of the CCS technology. Additionally, GE offers operation and management training to use the technology (GE 2020b).

3.0 Effects of governmental regulations on OG industry

3.1 Outline of governmental regulations

Governments of various countries are becoming increasingly aware of the pressing need to manage better the world's energy resources. Energy efficiency policies play a central role in addressing energy security, climate change, and different countries' economic objectives. To take an example: the G8 countries' energy officials issued a statement that the "promotion of energy efficiency in both the energy supply and demand chains in a cost-effective manner is a necessary prerequisite for addressing energy security and climate change while supporting economic growth" (Jollands et al. 2010). As mentioned earlier, one of the core objectives behind energy efficiency policies is to address environmental issues, and environmental regulations treat the improvement of efficiency as an intrinsic value (Dirckinck-Holmfeld 2015). These terms can therefore be used inter-changeably. This section discusses the effects of governmental regulations on the OG industry, and will consider the effects produced by both environmental and efficiency regulations.

There are two main policy models regarding energy use or GHG reduction: the bottom-up approach and the top-down approach. The former approach argues that it is possible to achieve a considerable reduction in emissions by promoting higher efficiency (market incentive regulations), and while this approach is considered to be slow and non-interventionist, it is nevertheless also considered to be more efficient, and can minimize the negative impact of energy policies on economic growth. On the other hand, the top-down approach posits direct intervention by means of energy taxes, energy input restrictions, etc. (i.e., command-control regulations). Many industrialized countries have, however, strongly favored the bottom-up approach of efficient energy use at various international conferences on climate (Feijoó et al. 2002; EPA 2018; OpenStax Economics 2016). In other words, market-based mechanisms allow firms themselves to explore the best paths toward efficiency, whereas command-control mechanisms encourage process and technology development to comply with governmental regulations (Managi et al. 2005).

Market-based mechanisms such as subsidies, information programs, etc. have the potential to encourage firms to undertake pollution control efforts that serve their own interests and meet policy goals. This is because these types of regulation provide incentives (e.g., tradeable licenses, subsidies, etc.) to those firms that exceed the limits set by regulations if a low-cost process or technology can be identified and used by such firms. Conversely, command-control mechanisms establish uniform standards on firms which are based primarily on performance and technology. Regardless of the specific costs incurred, firms have to share the pollution-control burden equally. Therefore, in some cases this can be expensive and even counter-productive, not least because these standards could mean very high costs for some firms (e.g., small or less productive firms) by forcing them to adopt pollution abatement methods (Jaffe et al. 2002). However, in the wake of environmental regulations, the firms that proactively manage their environmental performance (for example, by redesigning pollution producing processes, adopting energy conservation, and waste management, etc.) tend to reap greater benefits from sustainability practices (Ramanathan et al. 2017).

Environmental regulations can encourage firms to invest in the development of new technologies that can enhance energy efficiency. Yet in the absence of such regulations, firms may underinvest in these technologies and, as a result, they may not capture all the benefits that the new technologies offer. As the Porter hypothesis suggests (Porter and van der Linde 1995), environmental regulations spur innovation, which in turn leads to increased productivity of market outputs. With stringent environmental regulations, firms may develop innovative methods to comply with them, and these methods may increase market production as well as reducing environmental emissions. Supporting this hypothesis, a study led by Managi et al. (2005) found that the adoption of environmental technology in the offshore OG industry in the Gulf of Mexico led to an increase in productivity along with an increase in market products (oil and gas). Therefore, environmental regulations increase the productivity of both market and environmental outputs. However, this same study suggested that the productivity of environmental outputs lagged behind that of the market-based outputs. The reason for this was because the environmental regulations under study were of a command-control design, and these types of regulation provide neither scope nor much incentive to surpass the environmental goals as set out by the regulations. Thus the effects on productivity are likely to differ depending on the type of regulatory framework used in any given context (Managi et al. 2005).

Regardless of the types of regulation, however, the possibility to induce technological change is inevitable. The nature of the regulations, no matter their type, will force firms to initiate endeavors that they would not have otherwise done. Moreover, stricter environmental regulations ensure that firms increase their expenditure on abatement practices (i.e., pollution control). Additionally, external pressures from stakeholders may also force a firm to spend more on abatement so that it can maintain positive environmental reputation. Therefore, an increase in pollution abatement expenditures is proven to be associated with an increase in environmental innovation. Environmental innovation is typically measured as an increase in the number of successful patent applications (Brunnermeier and Cohen 2003). Furthermore, the achievement of greater technological efficiency (i.e., by means of innovation, energy efficiency practices etc.) acts as an intermediary between environmental regulations and CO2 emission reduction, especially for energy intensive industries like the OG industry (Pei et al. 2019). For instance, the increase in patent activity in carbon capture and storage technology is principally affiliated with an increase in spending designed to maintain lower levels of CO2 emissions (discussed in more depth in Section 4.1.2).

Consider, in this respect, a study looking into the effects of environmental regulations on the Australian upstream OG industry. In this study, it was revealed that firms faced with high levels of regulation were more likely to introduce product and service innovation. With less prescriptive regulations in place (in contrast to command-control regulations), the firms were found to adopt innovative approaches and technologies, and to ensure over-compliance with the regulations. The reason for the over-compliance was for the firm to gain a competitive advantage and to maintain its image as a socially acceptable company to its active and well-informed stakeholders. Innovation in response to regulations was also found to be related to the internal capabilities of the firms (research and development, and collaboration). In the wake of governmental regulations, firms tend to collaborate externally in order to innovate and comply with the regulations (Ford et al. 2014).

An example of a command-control regulation is provided by the CO2 tax imposed on the Norwegian offshore OG sector. Likewise, permits for the venting of flared gases represent another such administrative regulation. The purpose of the CO2 tax was to provide incentives for OG companies to reduce their emissions. In response to the CO2 tax, the largest operator on the Norwegian continental shelf has quantified an emission reduction of 8% in three years (1996–1999). Additionally, this operator also implemented various technologies like waste heat recovery, flaring and venting, process optimization, etc. on the Norwegian continental shelf upstream OG operations. This represents one of the benefits provided by government regulations, whereby innovation in the sector can be stimulated through regulatory intervention (Svalheim 2002). Another study which aimed to identify the gains from the CO2 tax revealed that innovation in the Norwegian petroleum sector is not just related to the regulations, but also to the company’s resources, capabilities, and some market-specific factors (Christiansen 2001).

Besides regulations, the US Department of Energy (US DOE) facilitated energy efficiency in another way, though still relying on governmental intervention. This method was to fund the research, development, and demonstration of energy efficiency research (a market-based mechanism). This research was targeted primarily at nine energy-intensive sectors, including the petroleum sector. Further, US DOE provided technical support in the advancement of energy efficiency of motors, compressed air, and steam systems. As a result, a reduction of 1.2% in energy use was observed, as of 2001, collectively across the whole sector (Geller et al. 2006).

Another example is the U.K. government's energy efficiency obligation. In April 2002, the U.K. government adopted a scheme to create a regulatory framework that would obligate major energy supplying/producing companies to adopt energy efficiency programs. In response, Centrica (also involved in OG exploration and production) and Scottish Power cited this regulation as the major driver towards their better use of energy, and they targeted savings of 154 million tons of CO2. In addition, Centrica reportedly invested $150 million to meet the obligation of energy efficiency imposed by this regulation (Okereke and Russel 2010).

The examples of Norway, Australia, the U.S. and the U.K. all illustrate the effects of government regulation on the OG industry; these countries are known OG producers of the developed world, and, moreover, they are all good performers on the Environmental Regulatory Regime Index (ERRI). This index is a performance measure of the quality of the environmental regulatory system in any given country; a high ERRI therefore indicates greater levels of enforcement and implementation of a country's environmental regulations. Some major OG producers, such as Saudi Arabia, Iran, China and Russia, do not perform well on this index because of the more interventionist approaches and economic traditions that exist in these countries (Esty and Porter 2011).

3.2 Some negative consequences of governmental regulations

Yet environmental regulation also comes with some unintended negative consequences. It can lead to an indirect increase in energy use caused by following environmentally friendly techniques. Further, regulations may have positive environmental effects in one region while introducing adverse effects in other regions. There are also additional regulations that are trying to tackle the problem of the huge volumes of environmentally hazardous waste material and short product life cycles. An example of one such regulation is the vehicle recycling regulation, aimed at the promotion of the reuse and recycling of end-of-life vehicles (Smink 2007). However, such regulations can end-up influencing the design of the product as firms and industries replace various materials with eco-friendly ones, and modify elements of their processes in order to reuse certain materials. This has an indirect environmental consequence because sometimes inefficient technologies are used in processing such material, which then leads to an increased use of energy, thereby reducing the environmental gains supposedly achieved from the regulation (Gurtoo and Antony 2007). For instance, Goosey (2004) states that the Waste Electrical and Electronic Equipment (WEEE) legislation in the U.K. will encourage the reuse and recycling of end-of-life electronics; nonetheless, while some products such as precious metals produce a positive environmental effect, at the same time, recycling metal-dominated products as a whole does not constitute a significant positive effect. Similarly, Knight (2005) determined the effects on the environmental when using steel doors instead of wooden doors in an attempt to save wood (an environmentally friendly policy). It was determined that the processing of steel doors required more energy and produced more emissions when compared to the use of wood. In this case, if it were mandatory to use the environmentally friendly method—i.e., to use steel doors instead of wood—energy usage levels could actually increase as a result. Further, as to the point that regulations may have positive consequences in one region while having adverse consequences in another, consider as an example the MARPOL Annex VI regulation, which controls the sulfur content of ship fuels in order to limit environmental emissions (IMO 2020). This regulation is more stringent in four emission control areas (ECAs, with a sulfur content limit of 0.1%, compared to the global limit of 0.5%). Due to these stricter limits, ship operators tend to sail longer distances in order to avoid sailing through the ECAs, and they sail at higher speeds while outside the ECA. They avoid these ECAs to minimize their operating costs because the low-sulfur fuels tend to be more expensive than their higher-sulfur counterparts. The consequence of this is higher fuel consumption (due to high sailing speeds) and CO2 emissions (due to using high-sulfur fuels) (Fagerholt et al. 2015).

Additionally, environmental regulations can create unwanted discrimination and trade barriers for governments. Discrimination is evident when governments lower their standards to manufacture export products, while also harming the environment in the process. Another potential consequence of environmental regulation is the increased logistical complexity for businesses to operate (Gurtoo and Antony 2007). To take an example of trade barriers raised by environmental regulations, one can turn to the stringent wastewater discharge regulation in

China, which has been observed to deter entry for new firms into the export market, meaning that more productive firms occupy a greater market share, which results in imperfect competition. This means a loss of competitiveness in the global market due to fewer export options for the low-producing firms that are held back from entering the market (Zhang et al. 2020). Stringent environmental standards tend to be forced on low-income countries by their more developed counterparts in order to control imports (Bhagwati 2000). Likewise, considering the matter of logistical issues, various environmental regulations in the U.S., Japan, and Europe place responsibility for the recovery of end-of-life waste material for purposes of reuse, remanufacturing, etc. on the manufacturers themselves, and this requires reverse logistics (i.e., the return flow of manufactured goods from purchasers into the manufacturer's logistics network) (Kumar and Putnam 2008). However, reverse logistics is a challenge on its own and has considerable barriers when it comes to its implementation, such as management barriers, capital barriers, infrastructure barriers, and the lack of government-supported economic policies (Abdulrahman et al. 2014).

4.0 Literature review

Energy efficiency is at the center of the policy agendas of various countries (World Energy Council 2008). The importance of energy efficiency is manifold, and is linked to commercial/industrial competitiveness, to energy security, and, most importantly, to environmental benefits. As the International Energy Agency (IEA) executive director stated, "Energy efficiency is key to ensuring a safe, reliable, affordable and sustainable energy system for the future" (IEA 2018). However, the term "energy efficiency" is generic, and diverse measures exist in order to quantify it. In general terms, it refers to "using less energy to produce the same amount of services or useful output" (Patterson 1996).

To improve energy efficiency, energy efficient technologies have been the subject of extensive research, and the discussion of this research will form the starting-point for the present literature review. The aims and objectives of the literature review can be formulated as follows:

- Because energy efficient technologies have widespread applications in various sectors, the major findings from the energy efficiency literature from disparate streams will be reviewed and then generalized in the form of a concept matrix. The goal here is to assess the generalized motives for the implementation of energy efficient technology in the upstream OG industry. In addition, this concept matrix can identify the most general trends of the research based on the aspects of energy efficient technologies that each study focuses on.
- This review will also survey how the literature has approached the birth, development, interest areas, and cost aspects of energy efficient technologies. However, the overall aim remains that of assessing the applicability and integration of these technologies within upstream petroleum operations.
- This review also discusses literature that addresses the role of energy efficiency in reducing the harmful environmental effects of OG operations, and the objective is to survey the evidence of whether energy efficiency represents a viable way to decrease environmental emissions by reducing energy use in upstream petroleum activity.
- This review explores alternative methods of reducing environmental emissions by looking at the electrification of upstream activities.

- Since the organization and practical implementation of energy efficient technologies involves various objectives and temporal horizons, another concept matrix which outlines the use of mathematical models for the purposes of energy efficiency planning as discussed within the literature will be presented, and this is in order to produce generalizations about the organization and planning of energy efficient technologies. These generalizations aim to provide useful insights that can facilitate more effective decision-making.
- A review of how the literature addresses some of the more challenging concepts questioning the principles of energy efficiency will be presented in order to evaluate substantive challenges to the idea that energy efficiency is the most viable method to reduce energy use and adverse environmental effects. The relevance of these concepts in practice will also be discussed.
- Lastly, this study deems it vital to understand the barriers and drivers that exist in the adoption of energy efficiency; therefore the relevant literature in this context will also be reviewed. Since driving forces and barriers have a significant influence on the practical workings of energy efficiency, consideration of them should therefore play a vital role in decision-making. The aim here is to pinpoint the factors (barriers/drivers) that promote or hinder decisions to implement energy efficient solutions in the upstream petroleum sector, and to identify the effects of environmental regulations. It remains important to analyze the factors that underpin decision-making either for or against adopting policies of energy efficiency. The major findings of the review will be generalized in the form of a concept matrix, allowing one to identify the sources of the various barriers and drivers.

This literature review primarily considers research published in academic journals. The reviewed academic literature has been found in the following online databases: Science Direct, OnePetro, Springer Link, ABI Inform, Research Gate, Energies, and ASC online publications. The bulk of the reviewed research articles come from the Science Direct database. Additionally, the references used within the research that has been studied, along with the articles cited within these research outputs, have been included in order to broaden the scope of this review. Unpublished research and textbooks have not been considered for the purposes of this literature review. With only a few exceptions, the majority of the research considered here dates from after 2000. These exceptions are comprised of papers that explain pioneering research developments or that propose a taxonomy; nevertheless, the temporal scope of the concept matrices covers post-2000 literature, and mainly concerns the last decade of research in order to engage with the most recent ideas. Furthermore, to search for relevant literature, searches were run through the platform “Google Scholar.” Specific searches were conducted with the following search terms: “energy efficiency technology,” “energy saving technology,” “upstream petroleum energy efficiency,” “energy efficiency barriers,” “platform electrification,” “energy efficiency optimization,” “energy efficiency analysis,” “emission reduction technologies,” “CO2 mitigation petroleum industry,” “sustainability upstream petroleum,” “sustainable energy solution,” “energy efficiency decision support,” “barriers and drivers energy efficiency,” “energy efficiency implementation,” “energy efficiency case study,” and “energy saving solution.” Since research into energy efficiency in the upstream petroleum sector is relatively young, and is often oriented towards divergent practical applications, it has been important for this study that the scope of the studied literature is confined to the petroleum industry (upstream and refining) and process industries.

4.1 Interest in energy efficient technologies

Energy efficient technologies are of the utmost importance in achieving energy efficiency, especially for energy intensive operations such as those of the upstream petroleum sector. It has been established that an interest in such technologies is actively growing due to the increasing concerns of companies, stakeholders, and governments over environmental degradation. Table 1 simplifies the concept of energy efficiency in the upstream petroleum sector by grouping the literature studied here and by presenting the characteristic features concerning the implementation and organization of energy efficient technology as identified in the extant literature. This table does not contain any research that is more than ten years old. The chronological parameters for this concept matrix have been confined to the last decade in order to include the most contemporary research.

After reviewing more than thirty research articles on energy efficient technologies, it is clear that the interest in energy efficient technologies largely revolves around three main themes: environmental, economic, and operational. Put differently, the benefits of energy efficiency mainly concern the environmental, economic, and operational aspects of any project. The subdivisions of these aspects in Table 1 further includes CO2 and CH4 emission reduction, which are also considered as environmental aspects of the implementation of energy efficient technology. Energy savings and cost reduction form a subdivision of the economic aspects, and they represent the energy saved due to energy integration and reuse processes that are an integral component of energy efficient technologies. This energy saving, along with other economic factors such as reduced fuel use, etc., also leads to cost reduction for the entire project; this represents the second subdivision of energy efficiency's economic aspects. Finally, the relationship between the weight of technology and its efficiency are regarded as energy efficiency's operational aspect. The subdivision of weight is not an effect per se of energy efficiency implementation, but rather an aspect of it that must be considered prior to any decision over which energy efficiency technology to use in those cases where weight constraints are present. Efficiency, on the other hand, represents the overall efficiency benefits in the operation of the project that are gained from the use of energy efficient technologies.

The literature does not always consider collectively the results of the use of energy efficient technologies of all three aspects—i.e., the environmental, economic and operational. For instance, one strand of the literature only studies the environmental aspects of incorporating energy efficiency in OG operations, whereas some literature considers both the environmental and operational aspects of adopting energy efficiency, and so on. In order to classify the research according to these three main concepts, the check marks in Table 1 identify the aspect studied in the respective article, while the absence of a check mark indicates the absence of that aspect. The categories in Table 1 are not wholly explicit, but instead they represent a simplification of the aspects under consideration. To explain this, consider the economic aspects of energy savings. Here, energy savings can also be taken to include other implicit meanings and factors of saving energy, such as increased revenue, decreased energy consumption (which equates to a decrease in operating costs), etc. Thus, the divisions within the concept matrix presented in Table 1 cover the general, rather than specific, ideas of the aspects as they have been addressed in the literature. Similarly, the operational aspects of energy efficiency concern the functioning of energy efficiency technologies, and these aspects are further sub-divided into weight and efficiency. Weight refers to the weight of the energy efficient technology, and this is of interest in cases where weight and space constraints exist. This column in the concept matrix identifies the research that studies the weight of energy efficiency technologies in their implementation and organization. Yet the efficiency benefits of the energy efficient technologies are also generalized and cover various implicit meanings, such as efficient fuel use, overall improvement in power consumption, better energy conversion, increased exploitation of waste heat, improved energy conversion, etc., all of which are studied in various articles. Generally speaking, the column "efficiency" indicates the literature that considers the efficiency improvements allowed for by energy efficient technologies. It is important to note that all three aspects under consideration are interrelated and influence each other. For example, operational benefits gained from the incorporation of energy efficient technologies such as

Table 1: Concept matrix of the aspects of energy efficient technology studied in the literature

Article	**Technology**	**Environmental Aspects**		**Economic Aspects**		**Operational Aspects**	
		CO2	**CH4**	**Cost reduction**	**Energy Saving**	**Weight**	**Efficiency**
(Mazzetti et al. 2014)	WHR	✓		✓		✓	
(Morrow et al. 2015)	CHP/process improvement	✓		✓			
(Johansson et al. 2012)	CCS/other	✓					
(Pierobon et al. 2014)	WHR/ORC	✓		✓		✓	
(Campana et al. 2013)	WHR/ORC	✓		✓	✓		
(Karellas et al. 2013)	WHR/ORC			✓	✓		
(Nguyen et al. 2016)	Multiple	✓			✓		
(Villar et al. 2012)	WHR & other	✓			✓		✓
(Hasanbeigi et al. 2013)	WHR & others			✓	✓		
(Nord and Bolland 2012)	WHR/HRSG			✓		✓	✓
(Oluleye et al. 2016)	WHR						✓
(Hasanbeigi et al. 2012)	CCS & other	✓		✓			
(Negri et al. 2011)	WHR	✓			✓		✓
(Faraoni et al. 2015a)	WHR/ORC & other	✓					✓
(Basile et al. 2013)	WHR			✓			✓
(Zhang et al. 2013)	WHR	✓			✓		
(Olajire 2010)	CCS	✓					
(Sun et al. 2018)	WHR & other	✓		✓			
(Kuramochi et al. 2012)	CCS	✓					
(Bains et al. 2017)	CCS	✓					
(Volkart et al. 2013)	CCS	✓					
(Rochedo et al. 2016)	CCS				✓		
(Seifert et al. 2019)	ORC			✓	✓		✓

(Kwak et al. 2014)	ORC			✓			✓
(Yao et al. 2018)	CCS	✓					
(Song et al. 2014)	ORC						✓
(Chen et al. 2015)	WHR	✓		✓	✓		✓
(Chan et al. 2016)	CCS	✓		✓			✓
(Talaei et al. 2020)	WHR	✓	✓		✓		

better energy consumption in an OG upstream facility will lead to reduced costs (i.e., an economic aspect) and will reduce the CO2 emissions of the facility. Thus all three aspects are directly or indirectly affected by the use of energy efficient technologies. Efficiency benefits include operational, environmental, and economic, though different studies consider these benefits in varying combinations.

4.1.1 Waste heat recovery

Birth and development

The concept of waste heat recovery emerged when Emmet (1925), building on the work of Charles Bradley on the basic principle of the combined cycle, laid out research on a mercury steam plant in a seminal ASME paper, and called the system the "Emmet steam plant." The early development of the gas/steam combined turbine then appeared in the work of Seippel and Bereuter (1960), where they presented seven configurations of a gas turbine and steam turbine plant. Then in the 1970s, companies like General Electric, Westinghouse, and Brown Boveri established a higher-level gas turbine whose exhaust went to a heat recovery steam generator, which then supplied steam to a lower-level steam turbine, with no additional heating of the exhaust required (Horlock 1995).

Over time, various heat recovery technologies were developed. Waste heat recovery (WHR) methods use the captured heat from a process and transfer it, either as a gas or liquid, back to the system as an extra energy source. Waste heat can also be conducted directly from the system by using thermodynamic cycles, like an organic Rankine cycle. In general, WHR systems can be categorized according to the ranges of usable waste heat that they produce. High-temperature WHRs recover waste heat at temperatures greater than 400° C; medium-temperature WHRs recover at temperatures ranging from 100° to 400° C; and low-temperature

WHRs recover waste heat at temperatures below 100° C. Current research provides descriptions of the various waste heat recovery technologies presently available, including regenerative and recuperative burners, economizers, waste heat boilers, air preheaters, recuperators, regenerators, heat recovery steam generators, etc. Moreover, different industrial processes require different energies and produce different types of waste heat. Therefore, different WHR methods would be suitable depending on the specific processes (Jouhara et al. 2018).

Applicability

One of the earlier attempts to promote WHR opportunities and benefits (Sternlicht 1982) identified ORC as a suitable method to harness waste heat into power, while also being cost-effective. To find a suitable waste heat recovery technology for offshore OG facilities, the work of Pierobon et al. (2014) shows that despite its high cost, ORC remains the most viable option for offshore OG facilities when thinking of CO2 emissions, weight, and economic revenue. Further, estimates were made concerning the application of ORC in cement, steel, glass, and OG industries in 27 EU countries, and found to be up to 20TW of thermal energy saving per year, all the while eliminating 7.6 tons in CO2 emissions (Campana et al. 2013). For the cement industry, a water/steam Rankine cycle is found to be more efficient, and it clearly reduced electrical consumption and operating costs. This was because of the low efficiency of the cement plant that was under study, and because its flue gas had a higher temperature; the authors suggest that ORC might still be the most viable option for higher-efficient cement plants with lower-temperature flue gases (Karellas et al. 2013). However, in cases where there are different qualities in waste heat, a combined thermodynamic cycle may be applicable. In the study of He et al. (2011), the authors performed an energy analysis of an internal combustion engine which had different waste heat characteristics, and they proposed a combined thermodynamic ORC cycle (for comparatively higher temperature exhaust gas) and a Kalina cycle (for low temperature exhaust gas).

WHR technologies are applicable to wide range of industries. This can also be seen in a techno-economic analysis where Ma et al. (2016) discovered huge consumption and cost saving benefits that could be gained in a coal-fired power plant by incorporating three WHR technologies, namely, a low-temperature economizer, segmented air heating, and a bypass flue. Terhan and Comakli (2016) conducted an economic analysis of WHR applications in a university's heating system, and they found significant cost savings were achieved by its application. The study of Singh and Pedersen (2016) provides a comprehensive review of WHR options that can be applied in the maritime sector. These authors investigate options that address the peculiar property whereby maritime waste heat is low-temperature waste heat, and they reveal that the Rankine cycle, organic Rankine cycle, supercritical Rankine cycle, Kalina cycle, exhaust gas turbine systems, and thermo-electric generators are all the most viable options.

Complementing concept

The efficiency of an ORC depends on the type of working fluid used in it (Badr et al. 1985). Badr et al. (1985) studied the thermodynamic and thermophysical properties of different organic working fluids. A study by Liu et al. (2004) conducted a thermal efficiency and heat recovery analysis of various fluids, and found that hydrogen bonds in certain molecules of working fluids, thermal efficiencies of the working fluids, and the critical temperatures of the working fluids all have a significant influence on efficiency. Upon comparing the energy efficiency of an ORC when using different working fluids, another study found that a working fluid with lower critical temperature (the maximum temperature at which a liquid can maintain its state) provides better overall efficiency to the ORC (Long et al. 2014). Similarly, Wang et al. (2011) analyzed the performance of different working fluids on an ORC and their results reveal that some fluids allow for higher thermodynamic performances than do others with stable net power outputs.

Cost aspects

The study of Gutiérrez-Arriaga et al. (2015) reveals that the annual operating costs of WHR technology differs depending on the type of working fluid used. Some working fluids are therefore more efficient than others, yielding greater output and thereby rendering them less costly. The operating costs concerned here include heating costs, costs of the cooling/refrigeration of the waste heat stream within the WHR unit, and expenses on the energy required for these operations. The capital costs of WHR technologies depend on the size of the technology unit and on the different components of that technology. For example, heat exchangers have been found to contribute to about 90% of the capital cost of an ORC, and larger WHR units are more expensive than those used in smaller plants (Varga et al. 2012). Furthermore, the study of Ali et al. (2018) posits that installation of the pipeline installation that is used to collect the steam from the exhaust gas source represents a potential significant capital cost of WHR technology. Other cost aspects concerns the pressure of the steam, the operating hours of the unit, and its installation costs. Steam pressure affects the cost because the higher the steam pressure the greater the surface area that will be required to utilize that heat, thus bigger and more expensive equipment (bigger heat exchangers) will be required. Further, maintenance costs contribute up to 40% of the operational costs of such units; finally, other running costs include utilities, salaries, etc., and maintenance costs, operational costs, and running costs are also part of the fixed costs associated with WHR technologies.

4.1.2 Carbon capture and storage (CCS)

Carbon capture and storage is a feasible option for CO2 emission reduction and should be considered for tackling climate change as well as for purposes of energy efficiency. Although CCS technology faces environmental, technical, political, and economic challenges in its implementation, it nevertheless has considerable prospects in many industries. CCS is a relatively high-cost technology and must be supported by some stringent carbon policy (Anderson and Newell 2004).

Development of the technology

Quintella et al. (2011) have studied the development in CO2 capture technologies by looking at patents and articles, and they have found that the influence of regulations looms large in the technological development of CO2 capture technologies. The work of Leung et al. (2014) examined CCS technology and the accompanying issues such as carbon capture, storage, transportation, leakage, monitoring, and life-cycle analysis in order to identify the best available practices. Li et al. (2013) studied the progress in carbon capture technology by examining patent reviews; they outlined the pros and cons of some of the major technologies available, while also identifying potential remedies for improvement. A study into growing research trends in CCS technologies covering the years 1980 to 2013 showed that research in this field was largely governed by the pace of international negotiations on climate change mitigation. For example, research intensity peaked after the Kyoto protocol (which sets binding emission targets) (Karimi and Khalilpour 2015). The work of Luis Míguez et al. (2018) explored the development of CCS technologies by evaluating patent activity from 2007 to 2017. This research offers useful knowledge concerning the trends in technological development and further areas to investigate in the working of CCS systems. The authors indicate that the leading patent contributions originate in the U.S., Japan, China, and Korea, which suggests the importance of global research institutions in the development of these technologies. This study also suggests that the integration of CCS technologies can lead towards the achievement of sustainability in the current industries.

Applicability

The relatively new CCS technology is costly and bears uncertainty in its performance on large scale projects. Yet a study of similar technologies and the challenges in implementation at their inception can help draw important conclusions that may be relevant for CCS technology (Rai et al. 2010). The work of de Coninck et al. (2009) concluded that the measures to better understand the applicability and the capacity of CCS, such as global cooperation, information and cost sharing, and transparency, were vital and should be deployed soon in order to uncover the potential of CCS technology in reducing emissions. However, governments must play a decisive role in promoting this technology through the promulgation of regulations, funding, and so on; the development of novel technologies with the help of governmental intervention certainly has historical precedents (Scott et al. 2013). Moreover, CCS requires a great deal of capital to be established at any given plant. This capital can be difficult to source from governments, and in order to elicit it from the private sector, one needs to develop the necessary frameworks. Large-scale deployment of CCS technology can be promoted through international coordination to learn more from the projects involving CCS use that have already been deployed (Reiner 2016). To give an example of just such a demonstration project, Xiuzhang (2014) presented the implementation of a CCS system within one of the world's largest coal-based integrated energy suppliers, illustrating the CO2 savings, costs, storage, major technological breakthroughs, and the overall CCS chain. This work has been valued by the industries and by academia because it provides usable insights into the operation of CCS technology.

Complementing concepts

Carbon storage is a major factor that impedes the adoption of CCS, and studying the relationship between CCS technological and geological storage capacities is therefore essential. Szulczewski et al. (2012) considered the duration in the lifespan of a CCS system that was needed to elapse until the storage capacity could handle the system's carbon outputs. Likewise, Viebahn et al. (2015) suggested that in order to assess the viability of CCS technology for a project, a thorough storage capacity assessment is a prerequisite. Selosse and Ricci (2017) have evaluated the role played by geological carbon storage potential upon the development of a CCS option.

Another important factor in the implementation of CCS technology is the transportation of the captured CO2 to either onshore or offshore storage sites. Gale and Davison (2004) thus studied the risks associated with the transportation of CO2 through existing pipeline infrastructure, as well as the costs associated with it. Svensson et al. (2004) presented feasible options for CO2 transportation, and revealed that transportation costs may vary depending on the storage type and the transportation method. Transportation costs have also been studied by McCoy and Rubin (2008); they evaluated the cost per metric ton of transporting different amounts of CO2, and came to the conclusion that the pipeline was the most viable option for transporting liquid CO2. From their analysis, the main factors that affect CO2 transportation pipeline costs are those of pipeline capacity and capital recovery. Morbee et al. (2011) developed a model that facilitates in the design of an optimal pipeline based on CO2 transport infrastructure. Middleton and Bielicki (2009) also presented a model that they suggest can generate a complete CCS system by determining the amount of CO2 to capture and store and the location to build pipelines of varying sizes; and the result of their model would produce a solution based on the lowest possible costs. And the costs of CCS technology are also discussed in some other studies (e.g., Rubin and Zhai 2012; Hu and Zhai 2017).

Cost aspects

The operating costs of CCS technology include the cost of the electricity, heat, and water that are used during the operation of the CCS system. Steam or heat energy is used to boil and regenerate the absorbent (i.e., the liquid used to absorb the captured CO2). This cost can be nullified if a heat recovery steam generator is used, where the steam is provided by a steam generator. Moreover, electricity is required by the pumps that are used to maintain CO2 flow or pump water in the cooling operations, and by the cooling operations that are used to cool the flue gas prior to CO2 capture (Kim et al. 2013). The capital costs of deploying CCS technology depend on the target plant and on the size of the technology. Other cost aspects of the CCS system include CO2 transport and geological storage. The overall cost of CCS technology can be reduced if the captured CO2 can be used for enhanced oil recovery by injecting CO2 into the reservoirs to recover maximum hydrocarbons (Rubin et al. 2015). The study of Rubin et al. (2013) suggests a methodology to report the costs of CCS, and identifies dissimilarities in the different costing methodologies.

4.2 Energy efficiency for GHG emissions reduction in the petroleum sector

Energy efficiency measures and carbon capture and storage can significantly reduce the CO2 emissions in the European petroleum refining industry (Johansson et al. 2012). In another study, Sun et al. (2018) investigated the energy efficiency, market penetration rate, and emission reduction cost of each energy efficiency solution (i.e., by changing the production process, energy efficient technology, alternative fuels, and recycling technology) in order to evaluate the CO2 reduction potential in the Chinese OG industry. The results indicate that the bulk of emission reduction is due to the improvement in energy efficiency. While designing and testing integrated methods to evaluate deployment strategies for GHG emission reduction in industrial plants, energy efficiency measures were deemed to be effective across all four strategies under investigation based on their avoidance cost and GHG reduction potential (Berghout et al. 2019).

Yáñez et al. (2018) group various energy efficiency measures into four categories based on the aim and level of complexity of the technology involved: process optimization, gas recovery, power generation, and process upgrading. These efficiency measures, when applied to a Colombian OG value chain case, revealed an energy saving potential and GHG reduction potential of 25% and 19% of the total energy consumption respectively.

4.2.1 Energy efficiency is sustainability for petroleum industry

According to the chief economist of ADNOC (Abu Dhabi National Oil Corporation), Kamel Bennaceur, carbon capture and storage offers the largest potential for the decarbonization of petroleum activities. Further, incorporating energy efficiency in petroleum production represents the major contribution that the OG industry can make towards sustainability (Bennaceur 2019). Increasing energy efficiency in the production and transformation of hydrocarbons is a key sustainable development goal for the OG industry (UNDP 2017).

In this regard, the work of Abdulrahman et al. (2015) has revealed a significant improvement in reducing emissions through the adoption of flare gas recovery. Farajzadeh et al. (2020) also discuss the sustainability aspects of carbon capture and storage, and suggest methods whereby CCS technology can be efficient at reducing CO2 levels: the energetic cost of CO2 separation must be reduced, and no emissions should be produced in the carbon capture process. In the natural resource based view of OG supply chains, Kwak et al. (2019) argue that the adoption of clean technologies is a major factor in achieving sustainability. According to Hart and Dowell (2011), “Reduced material and energy consumption occurs through the pursuit of clean technologies that provide for human needs without straining the planet’s resources”. Clift (1997) also discusses clean technology, and looks at the materials that are systematically used and reused in order to increase the resource productivity, which will lead to greater sustainability in human activities. Energy efficient technologies therefore fall under the broader rubric of clean technology. Essential for the sustainability practices of the OG industry is the recycling of the waste products generated during petroleum industry operations (Small 2017). Energy efficiency and CCS technology has also been considered as a risk management method to mitigate the sustainability risks posed by OG companies (Anis and Siddiqui 2015).

4.2.2 Platform electrification to reduce CO2 emissions

Electrification means to supply electricity to an offshore OG installation from a power source onshore, either in whole or in part. The electrification of offshore platforms has been proven to reduce CO2 emissions, but its efficacy depends on whether the electricity is generated by a gas-fired power plant or by hydroelectric facilities (Nguyen et al. 2016). There are nevertheless certain limitations to onshore power supplies, including onshore power availability, energy price, etc. The use of renewable wind power therefore offers a competitive source of power for platform electrification (Devold et al. 2016). Moreover, offshore wind power has been found to be the more economically and environmentally feasible option for platform electrification, though this depends on wind farm size and operational strategy (Korpås et al. 2012).

The incorporation of renewable wind farms in OG operations can increase voltage and frequency stability (Marvik et al. 2013). Numerous studies have looked at how to integrate offshore wind farms into the OG platform (Gang et al. 2012; Svendsen et al. 2011; Årdal et al. 2014; He et al. 2013). Further, Riboldi et al. (2019) assessed the environmental and economic effects of platform electrification in the Norwegian continental shelf, and revealed that:

- The total reduction in the levels of CO2 emissions enabled by electrification depends on how the additional power demands made on the entire power system are evaluated.
- When considering the marginal effects of platform electrification, the lifetime CO2 emissions increase because of the utilization of coal plants to meet the marginal increases in power demand. In other words, electrification equates to more energy use in Norway, which means less energy export to other markets (mainly to Germany, the U.K. and the Netherlands). The importing countries would then have to increase their own energy production, or import from other countries (e.g., Poland, the Czech Republic). Additional power demands may lead to importing countries relying more on coal and natural gas power plants for their energy sources.
- The average level of CO2 emissions related to platform electrification decreases, though this depends on the selected geographic scope upon which one concentrates.

4.3 Energy Efficiency models

Understanding the scientific approach behind the design and operation of energy efficient technologies is necessary to comprehend the concept of energy efficiency in the upstream OG sector. The literature has considered the models underlying energy efficient technology in a generalized way and from varying angles, but here only a few notable characteristics have been used to classify the literature. Table 2 presents a concept matrix of this literature, and groups it based on the mathematical models behind the technologies. These are divided into groups according to the planning horizons and the phenomenon (i.e., environmental, operational, and economic) under consideration in the given mathematical model. A check mark indicates that the study includes discussion of the respective planning horizon, phenomenon, or model type, and vice versa. Further, Table 2 also identifies the specific model type. The synthesis of the literature on mathematical models helps us to glean useful insights about the general organization of energy efficiency in the upstream OG industry. Similar to Table 1, dividing the topics discussed in the existing literature into different phenomena—namely, environmental, economic, and operational—covers both explicit and implicit ways of framing any given concept. Thus, studies marked as interested in economic phenomena may discuss the heat exchange plates of the ORC, which represents a major cost, but they may also consider subjects such as the wider objective of reducing fuel consumption. To elaborate further on each grouping phenomenon is beyond the scope of this research. The main trends regarding the mathematical models as suggested by this literature review will be presented in the subsections of Section 4.3. Additionally, several case studies provided by the literature will be reviewed in order to explore evidence of energy efficiency benefits in the upstream OG industry.

Table 2: Concept matrix of the mathematical models used in the energy efficiency literature

Article	**Planning horizon**			**Phenomenon**			**Model type**	**Descriptive model**	**Decision-making**
	Strategic	**Tactical**	**Oper.**	**Env.**	**Econ.**	**Oper.**			
(Lin et al. 2018)	✓			✓	✓		NLP	✓	
(Stijepovic and Linke 2011)	✓				✓		MINLP	✓	
(Gotelip Correa Veloso et al. 2018)	✓			✓	✓		MINLP	✓	
(Maddaloni et al. 2015)	✓			✓		✓	MINLP		✓

(Vidoza et al. 2019)	✓			✓	✓	✓	MINLP	✓	
(Al Dhaheri and Diabat 2010)	✓			✓			MINLP		✓
(Kang et al. 2011)			✓		✓		NLP	✓	
(Liu et al. 2013)	✓				✓		NLP		✓
(Pierobon et al. 2013)	✓				✓	✓	MILP		✓
(Hu and Cho 2014)			✓	✓	✓	✓	LP	✓	
(Pękala et al. 2010)	✓				✓	✓	MILP	✓	
(Mete and Turkay 2018)			✓		✓		MILP		✓
(Lu et al. 2016)		✓				✓	LP	✓	
(Nguyen et al. 2019)	✓			✓		✓	MINLP	✓	
(Ugalde-Salas et al. 2018)		✓		✓		✓	MINLP	✓	
(Attia et al. 2019)		✓		✓	✓		LP		✓
(Wu et al. 2017)		✓				✓	LP		
(Gessa-Perera et al. 2017)			✓	✓	✓		LP	✓	
(Khalilpour 2014)	✓				✓		MINLP		✓
(Hadidi et al. 2016)	✓			✓	✓		MINLP		✓
(Hu and Cho 2014)			✓	✓	✓	✓	MINLP		✓

4.3.1 Energy efficiency optimization models

Energy efficient technology optimization/incorporation

Lin et al. (2018) designed a system to optimize ORC incorporation in order to recover medium- and low-temperature waste heat. For this purpose, they developed a non-linear mathematical model (NLP) to generate maximum profits. The optimal generator configuration with the ORC presented in this study considered the economic and environmental aspects. Another approach to design waste heat recovery in multiple plants has been presented in the work of Stijepovic and Linke (2011). These authors considered the costs associated with WHR technology (i.e., capital costs) and developed a mixed-integer non-linear programming model (MINLP) to present the design optimization problem. The research of Gotelip Correa Veloso et al. (2018) used a multi-objective optimization model to determine the optimal ORC configuration for a floating production storage and offload (FPSO) petroleum platform. They determined the optimal configuration by maximizing power generation and minimizing the heat exchanger surface area of the equipment (cost aspect). The work of Pierobon et al. (2013) presented a multi-objective optimization model for the design of an ORC to recover waste heat from an offshore platform gas turbine. The technological and economical aspects of the ORC were used as decision variables in this particular model. The output of the model provided an optimal design configuration for an ORC with an option for the selection of the optimal working fluid.

Optimal energy use

In an attempt to increase energy efficiency and reduce CO2 emissions, Maddaloni et al. (2015) proposed an MILP model to design optimal gas use in the steel production process. The objectives here are to reduce energy consumption and CO2 emissions. Vidoza et al. (2019) propose a multi-objective MINLP model for the design of an offshore petroleum production power hub. Their model considers the objectives of minimizing the cost (purchasing cost of WHR equipment), minimizing the total weight of the equipment, and maximizing the thermal efficiency (leading to reduced fuel usage and CO2 emissions). The output of their model suggests a design solution of a gas turbine with WHR technology for the offshore production power hub that they studied. The research Lu et al. (2016) optimizes the energy intensity of the ironmaking process with the objective of minimizing the energy consumption levels of the production processes. The LP optimization model will yield solutions that have lower energy intensities, which provide energy savings. In their work, Nguyen et al. (2019) develop an MINLP model for the optimization and design of offshore petroleum platforms. The objective of their model is to maximize hydrocarbon production and minimize the energy requirements of the entire energy system. The results produced by their model reveal better energy consumption in the offshore plants that amounts to a reduction in CO2 emissions. Wu et al. (2017) develop a linear programming model to minimize the energy consumption when transporting oil from storage to charging tanks, and thereby optimizing energy efficiency of the oil refinery.

Optimal CO2 emission

The work of Ugalde-Salas et al. (2018) presents a model to optimize the scheduling operations of crude oil while reducing CO2 emissions. The objective of this model is to maximize profits and minimize CO2 emissions. The results reveal that if the goal of reducing CO2 emissions is considered alongside efforts to maximize profits (conventional objectives), then refinery production schedules will be greatly affected. In addition, a suitable carbon-pricing scheme (i.e., a regulation that penalizes CO2 emissions) can further induce CO2 emission abatement efforts by the refineries. In another study, Gessa-Perera et al. (2017) present an optimal production planning LP model for the cement industry. They focused on the objectives of maximizing operational profit while also minimizing CO2 emissions (up to to a specified target) by using WHR technology. The results of the model reveal that utilizing waste heat can replace the use of fuels and increase the overall efficiency of the plant. Additionally, the type of cement produced also affects the environmental and operational performance of the plant.

4.3.2 Decision support models

The work of Mete and Turkay (2018) presents an MILP optimization model to determine the optimum operational conditions of the process system of an oil refinery with the stated objective of minimizing production costs. These optimal conditions require the lowest possible energy costs, which equates to less energy consumed, and therefore this model can also be regarded as an energy efficiency improvement. The results of this decision-support model revealed a reduction in CO2 emissions and operational costs. In the research of Attia et al. (2019), a multi-objective decision-making model is discussed for the upstream petroleum supply chain. The objective of the model is to minimize total costs and the rate of depletion of the hydrocarbon reserves, while also maximizing total profits. The model is limited only to certain feasible regions because it assumes that CO2 emissions will be kept under a certain limit at the gas processing plants. This model can assist decision-making because it can create various production plans for upstream operations that produce minimal environmental degradation and maximum profits. As a result, the decision-makers can select or change the production plans by changing the parameters in play (i.e., demand of OG, selling price of OG, etc.). The work of Khalilpour (2014), presents a decision-support model to decide whether to adopt post-combustion carbon capture technology for a coal-fired power plant, or instead to pay the emission penalty. The MINLP model considers the objective of maximizing the net present value of investment in the technology. The output of the model can point towards the best investment decision by incorporating dynamic electricity and market prices over the duration of the planning horizon.

The work of Hadidi et al. (2016) presents an optimization model to decide the best GHG emission mitigation technology at the minimum cost for an oil refinery. The MINLP model considers the objectives of maximizing overall refinery profits. The net profit includes revenues from the sales of the refined hydrocarbons, the costs of the crude oil to be refined, and the costs of using mitigation technologies. In addition, the model imposes limits on the solution space by establishing GHG emission targets. This model can help management decide on different mitigation options and their respective influence on profitability under certain emission targets.

A decision support system to optimize the energy consumption of petrochemical plants is presented by Monedero et al. (2012). Their optimization algorithm searches the historical data of the plant's working environment and combines it with an artificial neural network module for interpolating operation points. The research of Hu and Cho (2014) develops a stochastic multi-objective optimization model to minimize operational costs, CO2 emissions, and primary energy consumption. To support in decision analysis, this study also presents an incentive-based model for primary energy consumption and CO2 emissions.

4.3.3 Energy efficiency improvement cases

The effects of efficiency measures are not limited to energy efficiency improvements and energy savings.; they can also be key drivers for social and economic growth (Ryan and Campbell 2012). In this regard, various studies have addressed the evidence for and potentials of energy efficiency improvement through case studies. One such example is Yáñez et al. (2018), where the authors identify twenty different energy efficient measures, including WHR, ORC, etc., and study how they affect the case of the Colombian oil industry. These technologies and measures generated savings of 19% and 25% of the total GHG emissions and energy consumption respectively. In another study, Barrera et al. (2015) found fuel savings of up to 15% when ORC was incorporated into production process for the purpose of utilizing waste heat in a floating production storage and offloading unit. Similarly, Arriola-Medellín et al. (2019) researched the case of including process integration methods, such as waste heat recovery, etc., in a Mexican OG processing center, and they found reductions of up to 75% and 95% in the use of natural gas and electricity respectively.

The study of Worrell et al. (2000) investigated the case of the U.S. cement industry, and analyzed thirty different energy efficiency technologies and measures in order to evaluate those technologies' potential energy savings, carbon savings, investment costs, and operation and maintenance costs. In another study of a coal-fired power sector in Henan (China), Wang et al. (2016) used energy conservation supply curves along with pollutant discharge and health benefits to examine the environmental co-benefits of energy efficiency improvements. Talaei et al. (2019) developed a case study of Canada's cement industry in order to evaluate the improvement potential of GHG reduction by conducting a bottom-up scenario analysis. Finally, Morrow et al. (2015) studied the case of the U.S. petroleum refinery sector to suggest efficiency improvement measures designed to reduce emissions and they quantified the potential energy savings made possible by adopting these measures. To provide an example of the efficiency gains made possible by CO2 capture, one can turn to the study by Castelo Branco et al. (2013) which found that a coal fired power plant that captures 90% of its CO2 is projected to reduce up to 72% of its emissions, thereby proving the advantage in using carbon capture technologies.

4.4 Contrasting concepts of energy efficiency

4.4.1 Rebound effect

The rebound effect describes a phenomenon that results from the increased consumption of energy services. Increased consumption follows the efficiency improvements in the production of those services because the efficiency improvements make it easier to fulfil demand (and this is because energy efficiency improvements means performing the same task as before but now with lower levels of energy use). For example, an increase in the energy efficiency of a power plant can reduce energy prices and thus can result in increased energy usage. Therefore the energy savings gained by the efficiency improvement is quickly offset by increased energy consumption. There are three types of rebound effect: direct, indirect, and economy-wide rebound effects. Direct rebound effects mean that improved energy efficiency of a particular energy service will reduce the price and will therefore lead to an increase in consumption of that energy service. Conversely, indirect rebound effects occur when the reduced price of the energy service leads to changes in the demand for other goods or services (e.g., the cost savings obtained from an energy efficient domestic heating system may be put towards an extra vacation). The last type of rebound effect—the economy wide effect—means that the real price of energy services can reduce the price of intermediate and final goods throughout the economy. This will lead to a series of price and quantity adjustments in which energy intensive industries are more likely to gain at the expense of less energy intensive ones (Sorrell and Dimitropoulos 2008).

The extant literature does take into account the rebound effect by considering any given energy efficiency improvement, and then comparing the actual energy savings to those that had been forecast without any consumer or market responses to the energy efficiency improvement. Consumer or market responses occur because energy efficiency improvements themselves change prices. Thus, the rebound effect is expressed as the percentage of the forecasted reduction in energy use that is lost as a result of the sum of the consumer and market responses (Gillingham et al. 2015). In other words, “Technological progress makes equipment more energy efficient. The cost per unit of services of the equipment falls. A price decrease normally leads to increased consumption” (Berkhout et al. 2000).

Improved energy efficiency in the OG sector owing to the usage of energy efficient technology will likely increase the overall consumption of OG energy (end-use). For example, Frondel and Vance (2009) revealed that increased fuel efficiency in automobiles resulted in greater use of the cars and, as a result, the desired emission reductions from the increased efficiency standard were not achieved. The authors suggest that fuel taxes (which will cause increased fuel prices) remain a better option to reduce emissions or to reduce fuel usage. Thus, price is more likely to influence the end-use. Lu et al. (2017) observed that efficiency improvements in the OG industry resulted in improved outputs, which, as a result, decreased prices. It can be argued that reduced prices due to the increased efficiency (use of energy efficient technologies) may cause petroleum prices to decrease, resulting in increased usage of petroleum products, i.e., the rebound effect.

4.4.2 Jevons’ paradox

William Stanley Jevons (1865) was the first to posit the idea that gains in technological efficiency—thinking specifically of the more economical use of coal engines—actually increased the overall consumption of coal, rather than decreasing it (Alcott 2005). Jevons’ paradox can be seen as a subgroup of the implications following from the rebound effect (Greening et al. 2000). Additionally, many other authors have also supported the idea that economically justified energy efficiency improvements will also increase energy consumption. Although the empirical evidence in support of the Jevons’ paradox is weak and inconsistent, the subject nevertheless requires more attention that it has received (Sorrell 2009).

Moreover, Jevons’ paradox consists of a variety of processes, rather than a single phenomenon, and it must therefore be approached with subtlety (York and McGee 2016). In their case study of six countries, Polimeni and Polimeni (2006) found evidence for the Jevons’ paradox, and argued that technological improvement does not provide the answer to reduce energy consumption, but rather that reducing such consumption requires changes in the behavior of those who demand energy.

4.4.3 Energy efficiency gap

Despite the increased attention from policy-makers towards energy efficiency, there remains an energy efficiency gap between current and future energy use as well as between current and future *optimal* energy use. Discussion on the energy efficiency gap centers on the different ways of interpreting the energy paradox (namely that energy efficient technologies are not as widely used despite their efficiency advantages) (Jaffe and Stavins 1994). “[The] energy efficiency gap is the wedge between the cost-minimizing energy level of energy efficiency and the level actually realized,” and the disinvestment of consumers and firms in energy efficiency measures can be a cause of this gap (Allcott and Greenstone 2012). Moreover, studies by Gerarden et al. (2017) and Gillingham and Palmer (2014), upon their reviews of the economic literature on energy efficiency gap, have revealed that market failures, behavioral explanations, and modeling flaws account for the underinvestment in energy efficient technologies. Market failures such as environmental externalities, inefficient energy pricing, and information deficiency can lead to underinvestment in energy efficient technologies (Gillingham et al. 2009). Crucially, the most important aspect of the debate surrounding the energy efficiency gap is the issue of energy efficiency barriers (Lee 2015).

4.5 Barriers and drivers of energy efficiency

The literature on barriers and drivers of energy efficiency is diverse. The concept of barriers is correlative because there are implicit interactions and overlaps between their disparate elements (Cagno et al. 2013). The interrelationships amongst various barriers serves to make the precise characteristics of any one barrier itself rather vague. One barrier may lead to other barriers, or it may weigh heavily on them, thereby influencing wider elements in the decision-making process. Similarly, it can be argued that different drivers also have the same levels of correlation amongst their elements. At any rate, the barriers and drivers to energy efficiency implementation both influence the decision-making process over whether to implement such measure (Trianni et al. 2016; Cagno et al. 2013). In order to simplify these ideas, Table 3 categorizes the barriers and drivers into external and internal ones at an organizational level. Table 3 also identifies the research that considers aspects of governmental regulations as pertinent alongside the concepts of barriers and drivers. This can allow for informed decision-making over the implementation of energy efficiency, and aids in the assessment of the role of environmental regulations and policies when it comes to barriers and drivers. The grouping criteria, i.e., internal and external factors, are largely hypothetical. Factors that can be controlled or managed by the organization are considered to be internal while, on the other hand, external factors are those that influence the firm's decision-making but cannot be managed or controlled directly by the organization. The following subsections of Section 4.5 include detailed discussion regarding the barriers and drivers of energy efficiency.

Table 3: Concept matrix of barriers and drivers in the literature. (B) = Barriers; (D) = Drivers

Article	**Barriers and drivers**		**Government regulations**
	Internal	**External**	
(Rohdin et al. 2007)	B, D		
(Ren 2009)	B		
(Walsh and Thornley 2012)	B		
(Backlund et al. 2012)	D		✓
(Brunke et al. 2014)	B, D		
(Cagno et al. 2015)	B		✓
(Apeaning and Thollander 2013)	B		✓
(Chai and Yeo 2012)	B	B	✓
(Johansson and Thollander 2018)	D		✓
(Martin et al. 2012)	B, D		
(Sa et al. 2017)	D	B	
(Soepardi and Thollander 2018)	B		
(Hasan et al. 2018)	B	B	
(de Mello Santana and Bajay 2016)	B, D		✓

4.5.1 Barriers

A barrier to energy efficiency is a mechanism that inhibits investment in technologies that are both energy efficient and apparently cost-effective for the potential investor (Sorrell et al. 2004). To analyze the barriers of energy efficiency one must adopt a multiplicity of perspectives, including those from economics, social psychology, organizational theory, and system analysis. As a result, comparison between different studies can be rather tricky (Sorell et al. 2011). It is important to note that research assessing the barriers to energy efficiency in the upstream petroleum industry in particular remains insufficient. To study the barriers to energy efficiency in this sector, therefore, it seems pertinent to review the literature that addresses barriers in supply chains and different industries in a more general way. The upstream petroleum sector in itself forms part of a supply chain, or stands as an independent supply chain in some cases. Equally, the barriers to the implementation of energy efficiency are not unique to any one industry; rather they only differ in degree depending on the context or industry in question. The general barriers and drivers to energy efficiency thus presented can, therefore, be considered as pertinent to the upstream petroleum industry too.

Figure 16 shows the taxonomy of barriers to energy efficiency as presented by Sorrell et al. (2004). This taxonomy divides the barriers into three broad perspectives: economic, behavioral, and organizational theory. Each of these perspectives is further divided whereby each division accounts for a specific barrier. For example, reviewing the general rubric of economic barriers reveals that some such barriers are caused by market failures, others are not. The final column summarizes the claim made regarding each barrier and provides a brief explanation of it. It is important to note that the barriers mentioned in Figure 16 are not mutually exclusive, but rather they overlap considerably. For example, imperfect information represents a barrier itself, but it also can produce other barriers like adverse selection.

Perspective	**Sub-division**	**Barrier**	**Claim**
Economic	Non market failure	Heterogeneity	While a particular technology or measure may be cost effective on average, it may not be so in all cases. This may explain the non-adoption of some technologies at some of the organisations studied.
		Hidden Costs	Engineering-economic analyses fail to account for either the reduction in benefits associated with energy efficient technologies, or the additional costs associated with them. As a consequence, the studies tend to overestimate efficiency potential. Examples of hidden costs include overhead costs for management, disruption, inconvenience, staff replacement and training, and the costs associated with gathering, analysing and applying information.
		Access to Capital	If an organisation has insufficient capital through either internal funds or borrowing, energy efficient investments may be prevented from going ahead. In the public sector, additional borrowing may be inhibited by public sector rules. In the private sector, companies may be reluctant to borrow due to concerns about the risk of increased gearing. Where internal funds are available, other priorities may take precedence, thereby also preventing the energy efficient investment.
		Risk	The short paybacks required for energy efficiency investments may represent a rational response to risk. This could be because efficiency investments represent a higher technical or financial risk than other types of investment, or that business and market uncertainty encourages adoption of short time horizons.
Economic	Market failure	Imperfect Information	Lack of information may lead to cost-effective energy efficiency opportunities being missed. This may be considered a market failure in that information has public good aspects, which make it likely that it will be under-supplied by markets. Furthermore, unlike energy supply, energy efficiency consists of a wide range of complex technologies and services, which are purchased infrequently and for which it is difficult to determine their quality either before or after purchase. As a consequence, the transaction costs for obtaining and processing information on energy efficiency are higher than for energy supply. Over-consumption of energy may be the result.
		Split Incentives	Energy efficiency opportunities are likely to be foregone if the party cannot appropriate the benefits of that investment. For example, individual departments in an organisation may not be accountable for their energy use and, therefore, have no incentive to improve efficiency.
		Adverse Selection	Suppliers know more about the energy performance of a good than purchasers. The latter face difficulties in both obtaining information prior to purchase and verifying performance subsequent to purchase. As a result, purchasers will tend to select goods on the basis of visible aspects such as price, and be reluctant to pay the price premium for high-efficiency products. In some cases, inefficient products will drive efficient products out of the market.
		Principal-agent Relationships	Principal-agent relationships occur when the interests of one party (the principal) depend on the actions of another (the agent). This type of relationship is pervasive in hierarchical firms. It is characterised by information asymmetry, since the principal lacks detailed information about the activities and performance of the agent – and in particular about the merits of individual investment projects proposed by the agent. Such monitoring and control problems can lead principals to impose stringent investment criteria to ensure that only unambiguously high value projects are undertaken.
Behavioural	Bounded Rationality	Bounded Rationality	Actors do not make optimising decisions in the manner assumed in standard economic models. Instead, constraints on time, attention, and the ability to process information lead to reliance on imprecise routines and rules of thumb. These economise on scarce cognitive resources. A consequence of this type of decision-making is that actors may not maximise utility, even when given good information and appropriate incentives. Hence, bounded rationality may be considered as an additional barrier that does not fit into conventional economic models.
	The Human Dimension	Form of information	The cost of acquiring information is only one aspect of decision-making. Research demonstrates that the *form* of information is critical. To be effective, information must be specific, personalised, vivid, simple and available close in time to the relevant decision.
		Credibility and Trust	Also critical is the *credibility* of the source and the *trust* placed in the source. Trust is particularly encouraged through interpersonal contacts. If these factors are absent from information on energy efficiency, inefficient choices will be made.
		Inertia	Agents resist change because they are committed to what they are doing and justify inertia by downgrading contrary information. Individuals also treat gains differently from losses, thereby undervaluing opportunity costs; give greater weighting to certain outcomes than uncertain outcomes; and have a strong desire to minimise regret. All these factors cause individuals to favour the status quo. Inertia creates a bias against energy efficiency since (unlike energy purchasing) this involves investing in hardware with uncertain outcomes and represents a departure from the status quo.
		Values	*Energy efficiency has clear environmental benefits. Individuals motivated by environmental values may, therefore, give a higher priority to efficiency improvements than those that are not. Efficiency improvements are most likely to be successful if "championed" by a key individual within top management. Hence, the environmental values of key individuals is a relevant variable in explaining organisational performance on energy efficiency.*
Organisation Theory		Power or Status	Organisations can be viewed as political systems, characterised by conflicts between groups with divergent interests. The influence of a particular group depends upon its formal authority, the control it has of scarce resources (particularly finance) and its access to information. It is commonly the case that energy management has a relatively low status and is viewed as a peripheral issue by top management. Lacking power, funds and top management support, the scope for effective action by energy management may be circumscribed. This may constitute an organisational barrier to efficiency improvement.
		Culture	*Organisations may encourage efficiency investment by developing a culture (values, norms and routines) that emphasises environmental improvement. This is more likely to be successful if "championed" by a key individual within top management. Hence, organisational culture is a relevant variable in explaining*

Figure 16: Taxonomy of barriers of energy efficiency. Source: (Sorrell et al. 2004)

The following provides the description of the barriers as mentioned in Figure 16.

Access to capital is a barrier that arises when the firm lacks the capital to invest in energy efficiency. This barrier can take the form of a budget deficit or a limitation in the form of allocating the budget to invest in energy efficiency.

Hidden costs represent the costs that accrue from the time spent on managing the energy efficient investment. Evidently, management will require time to evaluate the technical information regarding the prospective energy efficiency project.

Imperfect information means that companies providing energy efficiency solutions provide insufficient information about the energy performance of different technologies, and this leads to suboptimal decisions and underinvestment in energy efficiency. In addition, if the information on energy efficient technologies comes with a cost, the investing companies may make their decisions on the basis of insufficient information, in an attempt to avoid this cost. The unavailability of accurate information can be due to the exaggeration of performance data on the part of the energy efficiency technology providers.

Asymmetric information means that parties involved in a transaction may have different levels of information. For example, a buyer of an ORC will have comparatively less information than does the seller of that technology. This asymmetry can lead to adverse selection, moral hazard, or split incentives.

Adverse selection implies that one party in a transaction may have information that is not easily available to the other. For instance, the energy efficiency of an ORC may depend on the working fluid used in it, but this information can be overwhelmed by other easily understood information like cost, payback times, etc. This can result in the buyer of the ORC selecting an inefficient technology.

Moral hazard can occur in situations where the action of one party is unobservable or difficult to observe for the other party. In such cases, because of the different interests of each party, either of them may act in an opportunistic manner in order to serve its own interest. The barriers of “principal agent relation” and “split incentives” arise from moral hazard.

Principal agent relation is related to moral hazard. The agent (e.g., a services company) is the party who acts, while the principal (e.g., a client company) is the party that is affected by that action. This relationship brings risks of opportunism because the interests of the principal and those of the agent naturally vary: for example, the principal may want to promote a new solution that requires extra costs (as a learning cost) for the agent, and the agent, therefore, can be opportunistic and prevent this solution from being adopted.

Split incentives are present in those situation when one party possesses the relevant information as to the costs and benefits of the energy efficiency investment, but may withhold this information from the other party. This information might be withheld because the party withholding it may not reap the full benefits of the investment. For example, a well engineer who is responsible only for operations may not share the benefits of a certain energy efficient technology if there is not incentive for the engineer to do so.

Heterogeneity refers to the idea that the cost-effectiveness of a certain technology is based on a variety of characteristics thought to typify the average user within a particular category. This can act as a barrier in choosing an energy efficient solution. For example, a certain gas turbine can be a proven cost-effective solution for some upstream facilities (i.e., particular category of users), yet the same gas turbine would not yield similar cost-effectiveness due to the variation in the well stream quality (i.e., the varied characteristic) of another upstream facility. As such, the quality of the well stream affects the load (directly related to fuel consumption, and hence costs) at which the gas turbine operates. Heavier oil streams need more power to pump and process, which leads to an increased load on the gas turbine, and vice versa.

Risk comes in various forms, such as a fall in crude oil prices, the reaction of the capital market due to increase financing, technical performance, the uncertainty of technologies, etc. These risks can also hinder investment in energy efficiency.

Bounded rationality suggests that decision-making often results from imprecise routines and rules of thumb owing to constraints of time, attention, resources, and an inability to process information. For the upstream petroleum sector, this could mean that decisions on new technology would be influenced by the sector’s core interest—i.e., maximum petroleum production—rather than considerations of energy efficiency.

Form of information means that information regarding the energy efficiency investment should be in a suitable form, otherwise it may be overlooked. Suitable forms of information tend to be those where the information is customized, personalized, and clear for the reader. In addition, the information must come from a credible and trustworthy source.

Inertia is the behavior when firms resist adopting new energy efficient technologies and prefer to continue with conventional practices.

Values can be institutional or personal, and they represent attitudes towards energy efficiency. Decisions are driven not only by economic consideration, but also by environmental and global climate concerns. These institutional values are rooted in the wider organizational structure of a company: for example, environmental considerations will be more highly regarded by an OG firm in Norway compared to one in Angola.

Furthermore, organizational theory focuses on barriers that originate from the very structure of the organization. Since an organization constitutes a group of individuals with varying interests and power, any investment decision therefore goes through a set of procedures that requires hierarchical acceptance. The barrier of *power and status* indicates that the group of individuals responsible for the energy efficient decision might not have the requisite power within the organization to ensure that the best solution is accepted. Finally, *culture* is analogous to values, and an organization's culture can just as well explain a firm's decision in favor of energy efficiency as it can act as a barrier to that decision (Sorrell et al. 2004).

One of the pioneering studies on energy efficiency barriers (Reddy 1991) maintained that barriers to energy efficiency are closely related to governments, consumers, equipment manufacturers, the utility of energy efficiency more widely, and financial institutions. Evidently, adapting energy efficiency requires investment and the investment decisions of a firm are deeply influenced by internal factors (e.g., financial performance) as well as factors that are external to the firm (e.g., regulations, etc.) (Cooremans 2007). External barriers are those that are external to the decision-maker and depend on institutional settings (Schleich et al. 2016). The research of Gillingham et al. (2009) describes capital market failure as one such important external barrier standing in the way of adopting energy efficiency technologies. This represents a considerable potential barrier for the upstream petroleum sector, because the lack of available capital for adopting energy efficient technologies is highly probable. Most of the major OG companies rely on capital markets to finance their upstream projects, and if these markets are not performing well due to liquidity constraint (i.e., caused by capital market failure whereby limits are placed on the amount of money that an individual can borrow, or interest rates are changed), then the lack of capital may have profound consequences. Moreover, factors such as imperfect information and split incentives between the principal and agent are also considered to be external barriers (Gillingham and Palmer 2014). It can be argued that imperfect information about the actual cost-saving and GHG-emission reduction potential of energy efficiency constitutes a major barrier to adopt energy efficiency in the OG industry. Additionally, split incentives also represent a barrier at play in upstream petroleum operations, particularly in the case of OG companies that outsource upstream operations, such as Oil and Gas Development Company Ltd. Pakistan (OGDCL). Because of this barrier, the agent (i.e., the upstream operator) may not find energy efficiency to be in its best interests, despite considerable interest in energy efficiency on the part of the principal agent (OGDCL).

In the Swedish iron and steel industry, internal economic barriers and behavioral barriers have been found to be especially prominent (Brunke et al. 2014). The internal barriers of the firms in investing in energy efficiency have been identified in the main as follows: bounded rationality, principal agent problem, and moral hazard. The authors argue that any firm is a collection of individuals, and to reach a decision the combined efforts of the group may not necessarily lead to the best-case scenario. This may be due to a clash of interest between the private interests of some individuals and the collective good of the firm, or, conversely, the bounded rationality of the individuals or managers may prevent energy efficient decisions. Also, energy efficient decisions are usually small cost-cutting projects and, for this reason, they do not receive much attention when the focus of corporate management mostly lies in major profitable projects (DeCanio 1993). Arguments suggesting that energy efficient decisions are only minor cost-cutting projects may, however, not be that relevant in the case of upstream petroleum. Research (Zhang et al. 2019a) indicates an 18.9% reduction in total cost as a result of adopting an integrated energy efficient system on an offshore platform. This reduction cannot be considered as a minor cost-cutting project, especially in light of the scale of costs involved in an upstream project. Furthermore, Schleich and Gruber (2008) conducted an econometric analysis of nineteen subsectors in German commercial and service sectors, and revealed that the investor/user dilemma and lack of information were the most significant barriers in the adoption of energy efficient technologies. The authors separated the barriers into organizational, market, and behavioral barriers. Furthermore, Sudhakara and Reddy (2013) distinguished between micro-barriers (project/end-user), meso-barriers (organizational), and macro-barriers (state, market) when they adopted an actor-oriented approach. They also presented a methodology to analyze the underlying relationships between the barriers and respective measures to address them. In another study, Lee (2015) maintained that market factors and organizational/individual factors are the most important barriers that hinder investment in energy efficiency. However, these barriers include "technical risk, capital budgets, lack of an energy manager's influence, costs of identification and analysis of business opportunities for energy management and efficiency." It is worth mentioning that technical risk can be a major barrier for the upstream petroleum sector if the impact of the energy efficient technology is not studied nor evaluated thoroughly. Cagno and Trianni (2014) propose that in order to address better these barriers, it is necessary to consider them at a smaller scale, that is, at the scale of each energy efficiency measure. To overcome these barriers, it is vital to understand whether the drivers are internal, if external motivation is required to improve energy efficiency, and the inter-relation between these driving forces. In order to achieve maximum energy efficiency in the Chinese healthcare industry, the major barriers that have been identified (and need to be overcome) are economic incentives, technology, and lack of government-supported regulations (Wang et al. 2016). It can be argued that lack of governmental regulations is also a major barrier towards achieving energy efficiency in the upstream petroleum sector. As stated earlier in the discussion, the effect of government regulations to promote energy efficient decisions for the OG industry has been emphasized throughout the literature.

4.5.2 Drivers

In contrast to a barrier, “a driving force might be seen as the opposite of a barrier, in other words different types of factors that stress investments in technologies that are both energy efficient and cost-effective” (Thollander and Ottosson 2008). Figure 17 represents the classification of firm-level drivers contributing to the adoption of energy efficiency. The classification aggregates the drivers that yield the same output and have the same meaning together; for example, research and development, education, and training all lead to competitiveness. It also aggregates the origin of the drivers considered and mentioned as internal and external drivers. Internal drivers are those that originate from within the firm, and external drivers are those that do not. A similar procedure has been followed to aggregate various subcategories into main drivers: for instance, technology, operating costs, and finances all belong to the same group of economic drivers. The reason that firm size and industrial sector are control drivers is because they have a mediating influence on other drivers: most larger firms have greater energy efficiency efforts than their smaller counterparts (Solnørdal and Foss 2018). The following, therefore, offers a brief description of each subcategory of driver.

Technology is a driver whose origins come from the additional non-energy benefits associated with using energy efficient technologies and that induce investment in such technologies. A non-energy benefit like increased productivity is the most notable in the case of upstream energy efficient technologies.

Operating costs tend to decrease with an increase in energy efficiency, and therefore operating costs represent a great driver towards adapting efficiency. For example, an upstream facility with cogeneration of heat and power will consume less energy than will a facility without this energy efficient measure. The energy savings equate to less expenditure on energy and reduced operating costs.

Financial drivers like investment cost and payback times can also influence the efficiency initiative. For example, if certain energy efficient technology has a short payback time, it is more likely to be adopted.

Management suggests that the role of managers' personal engagement and managerial practices plays a vital role in a firm's policy towards energy efficiency. For example, if the top-tier manager of an upstream petroleum company is inclined towards energy efficiency due to his or her awareness of environmental issues, and if this inclination is combined with a good energy strategy i.e. (a management practice), then that firm's move towards energy efficiency may receive a considerable stimulus.

Competence is the ability and willingness of the firm to be energy efficient and innovative. A firm's competence in innovation directly influences energy efficiency because adopting energy efficiency requires process and product innovation. For example, any firm will be more inclined to adopt energy efficiency if they consider the environmental impact as the core objective for innovation and possess experience with energy efficient technologies (e.g., Equinor).

Organizational structure is analogous to the organizational theory barriers. It can act as a driver if the energy efficiency manager is positioned nearer to the top management.

Market forces are external drivers which may originate from competition and external stakeholders. For example, firms may be inclined to adopt energy efficiency in order to gain a competitive advantage or to maintain a social image in response to pressure from external stakeholders.

Ownership can act as a driver if a firm is owned mostly by international owners (especially in the case of developing countries), and in situations when foreign investment can push the firm to adopt energy efficient measures in order to increase competitiveness and reduce GHG emissions.

Network and information mean that cooperation and information sharing between companies concerning energy efficiency can act as a significant driver. This driver can also counteract the barrier of "form of information."

Policy and regulation can coerce energy efficiency by energy taxes, emission taxes, subsidies on energy efficient technologies, etc.

Firm size can control the level of energy efficiency adapted by a firm. Large firms have a larger workforce, greater technical and financial means, more legal restrictions, higher energy cost concerns, etc., and therefore, they are more likely to adopt energy efficiency when compared to smaller firms.

Industrial sector also controls the energy efficiency in firms because different sectors have differing energy intensities and potential yields from energy efficiency. For example, the upstream petroleum sector is more likely to adopt energy efficiency since the benefits this sector can gain are greater compared to energy firms from other sectors.

Cagno and Trianni (2013) have studied the drivers behind the adoption of energy efficiency by looking at firm size, firm sector, and the complexity of the firm's supply chain. These authors suggest that complex supply chains adopt energy efficiency in order to gain a competitive advantage. This can hold true for the case of the upstream petroleum sector as well. Complementing this is Shrivastava's study (1995) in which the author suggests that environmental technologies (energy efficient technologies) can provide a tool for a firm to gain a competitive advantage. Cagno et al. (2017) also point out that, in addition to information and economic drivers, the support of external stakeholders is important to achieve energy efficiency investment, and that external and internal drivers are of equal importance. Similarly, Lee (2015) indicates that cost savings, energy tax, and energy prices are all important drivers of energy efficiency. All these findings that point towards the importance of external stakeholders, energy taxes, energy prices, and cost savings as major drivers in adopting energy efficiency are also applicable in the case of the upstream petroleum sector.

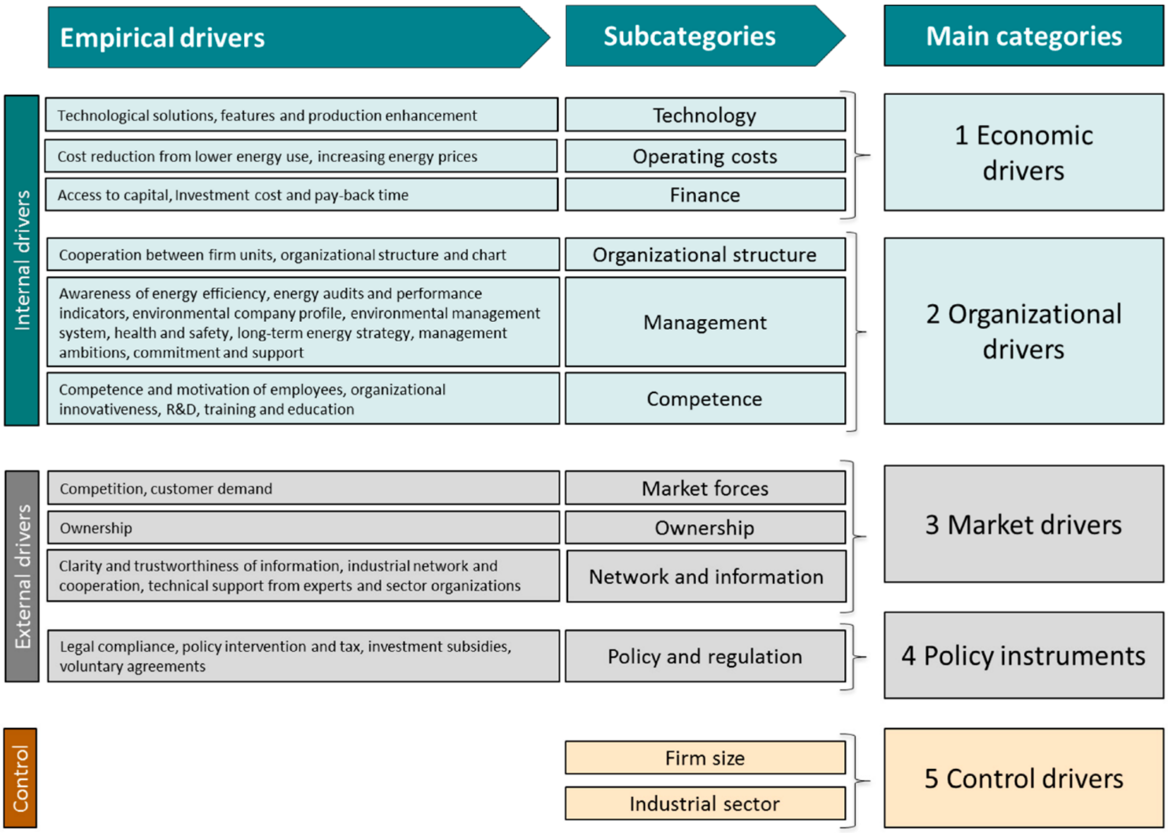

Figure 17: Classification of energy efficiency drivers. Source: (Solnørdal and Foss 2018)

5.0 Findings

The categorization of the research under review here reveals that there are significant commonalities across the literature. These common focal points aid in producing a more generalized theory about energy efficient technology, its organization, and its implementation. Further, the more general trends and interests displayed by existing research towards energy efficient technologies provides a springboard to evaluate the practical applications and consequences of such technologies in the upstream OG sector in particular. The major findings to emerge from the literature review are that waste heat recovery (WHR) technology and CCS technology are especially valuable.

Despite the value of WHR and CCS technologies, there is no one-size-fits-all approach as to how to implement them. Put differently, not all engineering solutions providing energy efficient technology can be applied universally to every OG upstream facility; rather, implementation of such technologies requires the detailed analysis of each facility in order to design the best possible engineering solution based on the specific needs of any given facility. Table 1 presented the general interests within the literature concerning energy efficient technologies. The major interests centered on these technologies' environmental, economic, and operational aspects. From the literature, the main considerations as to the effects of energy efficient technologies concern CO2 reduction impact, cost reduction, or efficiency improvement. Other aspects of these technologies, such as the weight of the units needed to operate energy efficient technology, are, conversely, only of relevance for the offshore upstream OG industry because of the weight and size constraints of offshore platforms. Comparing the aspects that have been studied in the literature allows us to identify such aspects as the main motives for why a company might pursue the application of energy efficient technology. It seems that environmental, economic, and operational benefits are intrinsic to energy efficient technologies. The decision-makers and managers must therefore consider the tradeoffs among these different aspects when deliberating on whether to incorporate energy efficiency in their firms. Further research should focus on studying collectively the economic, environmental, and operational effects of energy efficient technologies as such a research is quite scarce.

The rudimentary form of WHR application was first developed almost a century ago. This means that WHR technology is mature and well-developed. There are various types of

WHR technology whose application is context-specific, depending on the particular industrial processes and its unique requirements. In other words, different WHR technologies are available for different uses, and their application will depend on the waste heat temperatures and output requirements of the target industrial process (e.g., a coal-fired power plant may require a different WHR unit than will a gas-fired power plant). WHR has a wide application, and has been adopted in various industries—especially in energy intensive industries—with proven results of energy and cost savings. Moreover, central to WHR technology is its working fluid, and differences in working fluid can profoundly influence the costs and efficiency of the technology. Therefore, the specifications of a working fluid must be a vital consideration for firms when selecting which of the available WHR technologies to implement. The operating costs of WHR technology tend to be governed by the following characteristics: its working fluid and its energy demands. The major factor that drives up capital costs when implementing this technology is obviously the magnitude of its application. The magnitude of application represents a catch-all phrase that generalizes the application specific requirements. Capital costs depend on the technology's hardware requirements, such as unit components including the heat exchange plates and the pipelines used to collect waste heat.

CCS technology, in contrast, is at a relatively young stage, and is considered to be a developing technology whose utility remains uncertain for large-scale projects. The literature reveals that external forces, such as regulation, research institutes, etc., are important drivers underpinning the development of CCS technology. Such forces trigger technological development and the implementation of CCS technology. In addition, the high capital cost and limited applicability of CCS technology necessitates cooperation at an international level. This cooperation should involve sharing knowledge about its cost-benefits, utility, compatibility, integration, emission-saving aspects, etc., which will facilitate further discoveries into the potential of CCS systems for prospective users. An implication of this is that managers and decision-makers should make use of any demonstration project as the basis upon which they can evaluate the application and integration of CCS technology in their specific case. Such an evaluation based on a demonstration project also enables them to consider the emission reduction potential, size, and performance of the technology. Moreover, the transport and storage of captured carbon is a cardinal factor in the practical use CCS technology, and transportation and storage represent a major portion of the technology's operational and capital costs. The main operating costs for the technology come in the form of the energy requirements that such units need. Similar to WHR, the capital costs vary based on the magnitude of application (i.e., the size and specifications of the CCS units, and CO2 transport and storage). In the case of the upstream OG industry, captured CO2 also allows for the option of enhanced oil recovery, which can increase efficiency and reduce the costs of CO2 transport. There are however risks associated with CO2 transportation and storage, not least the potential for leakage from transmission pipelines or the storage site, and the capacity of the geological storage site. Finally, storage costs increase with the increase in CO2 concentration in the exhaust gas.

The main goal of this literature review on energy efficient technologies has been to assess the applicability of such technologies in the upstream OG industry. Figure 19 provides an abstract illustration of an upstream facility design that uses energy efficient technologies. Upstream petroleum activities require electric and heat energy for various operations (refer to Chapter 2). An upstream facility design that incorporates waste heat recovery options, such as waste heat boilers and an ORC, to salvage the excess heat from the turbine, along with a CCS system, can definitely be more energy efficient and reduce emissions. Figure 19 illustrates a gas turbine fitted with an exhaust boiler, an ORC, and CCS, and thereby constitutes the energy system of an upstream facility that provides heat and electric energy to the processing system. Consequently, as the input stream of OG enters the processing system through the manifolds it goes through various processing steps before it can be exported, and all these upstream operations have varying levels of energy demand. These energy demands can be met by the suggested energy system. This energy system can prove to be more energy efficient and can provide cost and environmental benefits to upstream operations.

The literature reveals sufficient evidence regarding the role of energy efficiency in the reduction of energy use and GHG emissions. Adoption of energy efficiency is proven to reduce cost and energy use and, therefore, to reduce emissions. Energy efficient technologies can be termed as a pathway to achieve sustainability in the upstream petroleum sector. The evidence presented in the literature can serve as a benchmark by decision-makers for future strategies of implementing energy efficient technologies. This evidence can also aid in the detailed organization of any such decision to incorporate energy efficient technologies within a firm’s operations. Electrification has been found to be an alternative method to reduce emissions, but it seems to depend on how any given platform is electrified (power from shore or offshore by using renewable sources like wind turbines) and the way that the electricity is produced. The impact of electrification in reducing CO2 thus largely depends on the how the additional power demands (due to electrification) of the system are measured. Some types of platform electrification may produce lower emissions locally, but these emissions could conversely increase at a global scale. However, when electricity is generated by hydropower, the average CO2 emissions may indeed experience a reduction. Platform electrification also requires significant capital costs, but these are offset by low maintenance and operating costs. Incorporating wind turbines as source of electrification for offshore platforms is both technically and economically feasible. The capital costs of electrification are directly related to the distance between the platform that is to be electrified and the power source. Most importantly, electrification does not complement the concept of energy efficient technologies; it cannot be applied to support the energy efficiency of the energy system because electrification does not use or support the energy that is generated by the energy system itself. Rather, it presents a way to reduce the facility's dependence on the offshore energy system, and a way to power the upstream facility with an alternative electrical source, whether that be an onshore grid or a renewable energy source. At any rate, the overall purpose of electrification remains to reduce the harmful emissions that are generated by the use of gas turbines or other power sources at the upstream facility.

Building a theory of energy efficiency for upstream OG industry in the most general form requires simplifying the practical approaches discussed in the literature for organizing and implementing energy efficient technologies. Table 2 represents the major findings and helps one derive important insights for these technologies' practical implementation. The quantitative literature review reveals general trends in the discussion about energy efficiency implementation. Generally, decision-makers and managers can approach energy efficiency implementation in three ways. First, optimal planning of the energy efficient system aims to improve environmental, operational, or/and economic performance. This type of planning is mostly strategic and involves long-term benefits. In the case of running projects for which the planning of a new energy system is very difficult, the existing energy system can be improved upon by incorporating energy efficient technology optimally (i.e., by retrofitting it, which means to integrate energy efficient technology in the existing energy system). This also involves strategic planning. Second, another of way of achieving energy efficiency is by optimizing the energy use of the existing systems/operations in order to reduce energy use and emissions. This type of planning can vary in its temporal horizon, but works on the tactical or operational planning horizons. This approach to achieve energy efficiency involves comparatively lower costs than does the first method. Third, optimizing the CO2 emissions of upstream OG operations constitutes another type of decision towards energy efficiency. Here, it can be argued that the best approach for the managers and decision-makers is to consider minimizing energy use and CO2 emissions by incorporating/planning energy efficient technologies—that is, to plan for energy efficiency for the whole life cycle of the specific OG operation. In other words, energy efficiency implementation and organization must be strategic, tactical, and operational in order to obtain the greatest fiscal, environmental, and efficiency benefits. Finally, net present value of the investment with set emission targets have been considered as the decisive factors for long-term energy efficient technology decision-making.

Upon looking at IES cases from the literature, and from the discussion in Section 2.3 on the basic concepts of energy efficient technologies, one can surmise that these systems adopt a life-cycle approach to the energy in question: that is, energy is used efficiently from source to the sink or for the duration of the life-cycle of the energy within the system. This can be seen in Figure 18, which displays the theory of a life-cycle approach of energy in efficient systems. The example used here is of a gas turbine which is used to meet certain energy requirements (energy consumption points). The gas turbine (the starting point of the energy life-cycle) provides the immediate energy demands while, at the same time, the byproducts of waste heat or flue gases are harnessed at the source and after the demand points. This utilization of waste energy from source to sink (Figure 18) presents the life-cycle theory of energy. Even after the reused energy is consumed at various demand points, the excess energy can either be stored or harnessed, keeping it within the system. The amount of excess energy, however, depends on the processes at the demand points. More energy-intensive processes will demand more energy, thereby producing waste energy at both sink and source. The theory just outlined may thus be considered as the life-cycle approach advocated in this study.

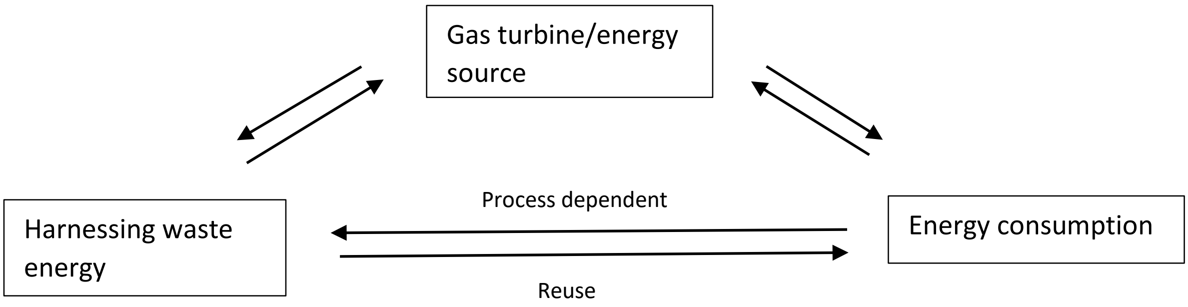

Figure 18: Visual illustration of the life-cycle of energy in an abstract upstream processing system

The contrasting theory suggesting that energy efficiency improvements will result in increased energy use seems largely to be outweighed by the benefits brought by the improvements. Nevertheless, one cannot deny the existence of these effects, even if quantifying them according to the concepts as discussed in Gillingham et al. (2015) (mentioned in Section 4.4) would require articulating and quantifying ideas that are rather abstract. It can be argued that contrasting concepts such as the Rebound effect, Jevons' paradox, and the energy efficiency gap exist and can be of value for policy-makers, but they are not as significant for the actual managers/decision-makers in the organization and implementation of energy efficient technologies. The reason that such considerations are of pertinence for policy-makers is because these effects can be controlled through the market, and the market can evidently be influenced by governmental regulations and policies. Similarly, barriers and drivers can be controlled through regulations and the market, and are pertinent for the implementation and organization of the energy efficient technologies. The literature review on the barriers and drivers to energy efficiency reveal that most barriers/drivers are internal to the firm/organization (refer to Table 3). Most importantly, governmental regulation can significantly influence the adoption of energy efficient technology. On the basis of the literature under review, it seems that imperfect information, capital market failure, split incentives, and a lack of government regulations constitute the most forceful barriers that impede the adoption of energy efficient technologies in the upstream petroleum sector. Well-planned governmental regulations can play a significant role in inducing firms to adopt energy efficiency in the upstream petroleum sector. Additionally, cost savings (for hedging risks against a volatile crude oil market), the influence of external stakeholders, and achieving a competitive advantage also appear as important drivers. Meanwhile, the adverse effects of governmental regulations, such as rebound effects, trade barriers, and investment deterrents, mostly prove to be short-lived. At any rate, such effects also motivate companies/producers/countries to increase their competitiveness in order to overcome these effects, since they cannot be left unchecked if the subject wishes to compete in the OG market. Further, the literature also supports the contention that regulations' adverse effects on competitiveness remain negligible (Jaffe et al. 1995). Nevertheless, literature on this subject specifically in connection to the upstream petroleum sector is insufficient. This would be a topic warranting future research, especially considering the importance of energy efficiency in this energy intensive sector.

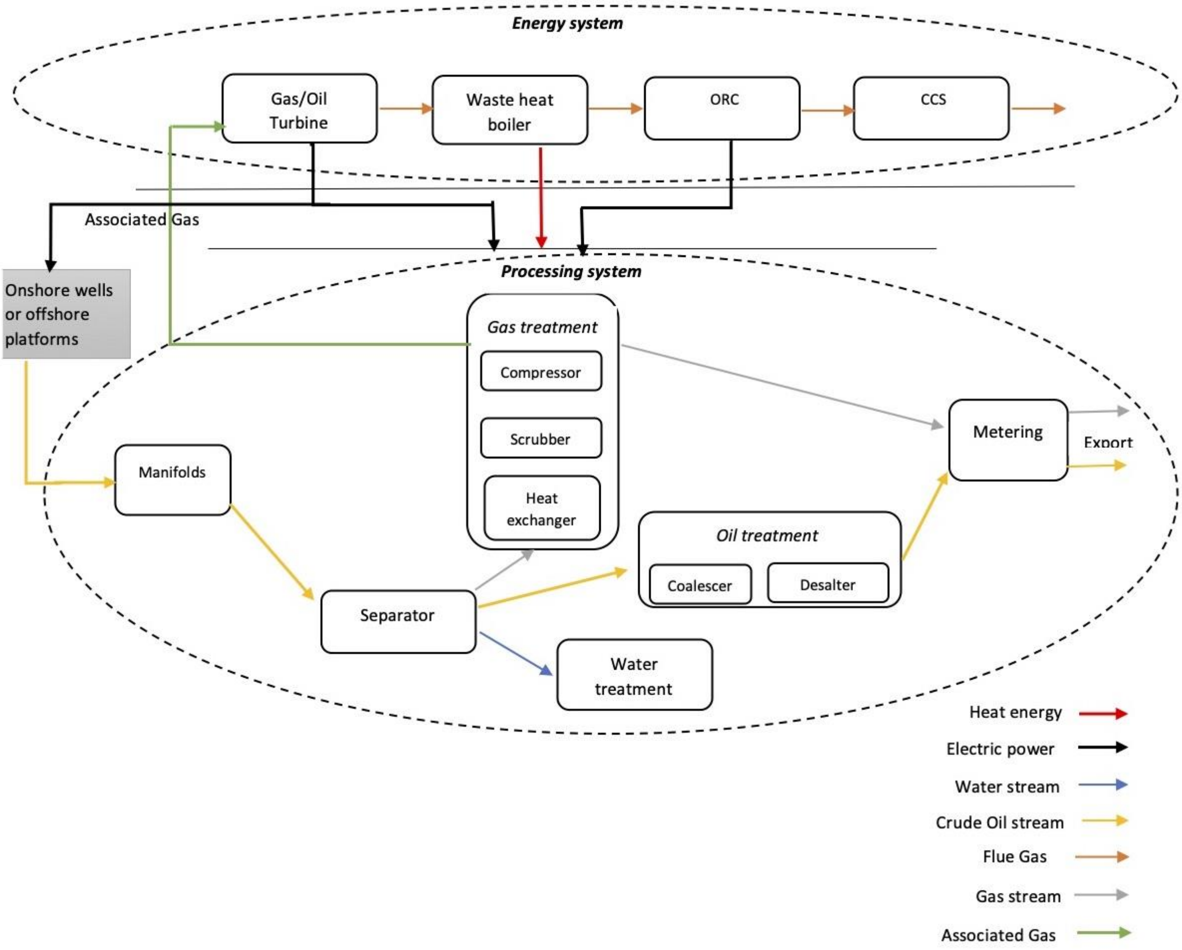

Figure 19: Abstract illustration of the proposed energy efficient technology incorporated energy system of an upstream petroleum facility

6.0 Conclusion

The main contribution of this thesis has been to systemize and organize the literature about energy efficient technologies. The aim has been to assist in the processes of organizing and implementing energy efficient technologies for the decision-makers/managers of the upstream OG industry and to guide future research in the field of energy efficiency.

The general trend in the research field of energy efficiency is for research looking at the use of energy efficiency practices in order to reduce CO2 emissions and to augment sustainability in general. Then there is research that has, in particular, been directed towards energy efficient technologies such as ORC, WHR, and CCS, examining how to integrate those technologies into OG platforms. Additionally, some research has been devoted to offshore OG platform electrification, but this is at a relatively young stage, especially when considering the use of renewable energy as the source of electricity source for offshore OG platforms. The theoretical implication of this general trend is that these different research strands complement each other, and support the idea that it is important to achieve energy efficiency within the upstream OG industry. Nonetheless, the research that explores platform electrification does not fully harmonize with the rest of the research on energy efficiency in this sector, and this is because platform electrification entails the use of energy that is external to the upstream facilities' energy systems. Indeed, the main goal behind platform electrification is to reduce the usage of hydrocarbons when generating power on OG platforms. Another theoretical implication of relevance for future research concerns the importance of considering operational, environmental, and economic benefits collectively in order to gain a more comprehensive understanding of how to implement energy efficient technologies. The major research trends and the literature that has been examined in this study also speak to the novelty of the presented research, because such a literature review has not been done before.

The proposed life-cycle view of the energy flow in upstream OG processing operations suggests that researchers organize their strategic decision-making processes by taking into account the entire lifespan of energy, that is, from source to sink. In strategic planning, the areas of energy input, energy use, energy waste, and energy destruction only as it pertains to a single form of energy (i.e., heat energy) has tended to fall under consideration. Life-cycle thinking, however, implies that tracking the flow of energy from source to sink, while also observing all types of energy wastage as they occur in an upstream system (i.e., in form of heat energy, flue gases, gaseous emissions, etc.) can allow for the identification of energy- and emission-saving opportunities on a holistic scale. Such an approach can then augment the selection of the most appropriate energy efficient technological solution, and the net present value indicator can be useful when evaluating all the benefits of the selected technology investment. Tactical and operational planning includes all actions that relate to the functioning of the energy efficient technologies (e.g., operating conditions, energy savings, amount of CO2 saved, etc.). The specific energy requirements of any given upstream facility constitute one of the main factors controlling energy demands, and have a significant effect on operative and strategic planning; a mathematical model that incorporates these case-specific conditions and works to optimize the operating conditions can resolve questions as to the case-specific applicability of the energy efficient technologies. Moreover, just such a mathematical model could also prove useful in strategic decision-making when it comes to selecting the appropriate technology for an upstream facility.

A practical conclusion offered by the present study for upstream OG companies, after reviewing the literature and analyzing the currently marketed solutions, is as follows. Ensuring the selection of appropriate technologies and the establishment of appropriate workflows while also taking into considering needs of their specific upstream facility remains entirely dependent upon the willingness of these companies' management teams to reap the benefits of the energy efficient technologies. This study has therefore attempted to assist managerial decision-making in this regard. In practice, it can serve as a starting-point to understand the main tradeoffs in energy efficient technology implementation and organization. For instance, in the case of the procurement of new energy efficient technology, the environmental, operational, and economical aspects should lie at the core of the decision-making process. Moreover, decision-making should be directed towards the best available options across all planning horizons. In other words, this study helps identify the main characteristics and variables underlying decision-making in the context of the organization and implementation of energy efficient practices and policies. The focus that has been suggested here on the generalized flow of energy in upstream OG processing facilities represents a starting-point for the investigation of energy integration and WHR opportunities in practice.

The analysis of the effect of governmental regulations on energy efficiency implementation in the upstream petroleum sector allows us to draw some practical conclusions for policy-makers. A top-down regulatory approach, seen in initiatives such as carbon tax, when supported by market-based mechanisms, such as subsidies, information programs, etc., can help overcome barriers and promote the drivers for companies to implement energy efficiency technology. A combination of bottom-up and top-down regulatory approaches can increase the competitiveness of domestic firms (Xie et al. 2017), and stimulate innovation (e.g., the corporate responses to carbon tax legislation in Norway). Another important conclusion is that environmental regulations can over time generate greater profits for domestic firms, and gradually increase the competitiveness of domestic firms in a global marketplace. This, conceivably, can boost the local economy and form a valuable asset for the country concerned, especially in the case of the OG industry. The literature surveyed here provides evidence that environmental regulations deter foreign firms from entering certain markets, and this therefore poses a hurdle when formulating top-down legislation, particularly in the developing world. Nonetheless, in the long run, these effects can be overcome at a governmental and organizational level by the benefits of improved energy efficiency. Putting this into a wider perspective, one can conclude that governmental regulations can create a win-win situation, especially if one keeps in view their ability to control and manage the contrasting concepts, barriers, and drivers towards energy efficiency adoption in the upstream industry. For example, policies can be directed to overcome barriers and can act as driving forces towards energy efficiency adoption. Regulations can help avoid capital market failure (a major barrier), overcome the barrier of imperfect information, reduce technical risk, promote interests of external stake holders, etc. These relationships can be proven in theory, but designing such a policy will require serious and long-term governmental efforts, which again will call for research in this matter. An interesting subject meriting further research would be the main conceptual tools needed by the governments to design an appropriate policy that would enhance the capabilities and competitiveness of local firms in terms of energy efficiency.

One of main limitations to this present literature review is that it remains general in scope and perspective. This thesis has not thoroughly examined the implications of thermodynamics analysis, the technological details of the IES, or various modeling methods. A comprehensive exploration of these details, and an energy efficiency comparison of certain technological alternatives and modeling approaches as well as the challenges associated with the deployment and operation of such technologies, would be an interesting area for future work. The present research merely forms the first step to assist OG managers in their consideration of energy efficient technologies as a viable method for them to achieve greater profitability, efficiency, and to reduce emissions produced by upstream OG operations. In some oil producing countries (e.g., Pakistan) with extensive experience in OG production and processing, companies often tend to adopt standard technologies for their upstream energy system. The costs, novelty, and need to adapt in order to operate new technology becomes the basis for those companies' hesitation towards adopting more energy efficient technologies in the first place. Uncertainty over the benefits of energy efficient technologies, along with the suspicion that the costs needed to invest in those technologies would not be recovered, encourages managers and/or decision-makers to adopt more conventional energy solutions. Yet the main disadvantage of standard solutions is that they are inefficient in their use of energy within the system, when in fact the energy that they lose could otherwise be used for the benefit of the overall operational system.

One of the main limitations to the present literature review has been the need to confine discussion to only the most relevant research material. Including a broader range of literature, both in temporal and in academic scope, may further strengthen efforts to build a theory through a literature review, such as has been the attempt in this study to build a theoretical model in the field of the organization and implementation of energy efficient technologies in the upstream OG industry. The nature of this research itself is the main reason explaining the exclusion of any data—either qualitative or quantitative—because the study builds on the extant literature. Nevertheless, the development of theory remains an important task in order to move a research field forward (Webster and Watson 2002).

The specific focus and topic of this research may constitute another limitation however, not least because technology can reasonably be expected to evolve. Over time, energy efficient technologies and the scientific paradigms underpinning them will likely change, and this evolution will bring in its wake new technologies and energy efficiency strategies. Further, the strong focus in this thesis on the upstream petroleum industry may also be one of its limitations, and the extent to which its conclusions can be generalized beyond the upstream petroleum industry must remain in question. The theoretical classifications employed within the concept matrices presented in this thesis can also be debated, and thus considered as a further limitation of this study. Finally, another potential limitation concerns evaluating the effects of governmental regulations and policies primarily in the developing countries. A good topic for prospective future research would be the analysis of the differences in how governmental regulations pertaining to upstream OG energy efficiency adoption and the response of the industry in response of these regulations differ between developing and developed countries, and what causes such differences.

7.0 Reference List

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