Energy 250 (2022) 123794

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

Flexible operation of a mixed fluid cascade LNG plant for electrical power management

Ivan Ying Xuan [a], Charlotte Skourup [b], Jørgen B. Jensen [b], Trond Haugen [b], Nina F. Thornhill [a, *]

[a] Department of Chemical Engineering, Centre for Process Engineering, Imperial College London, London, SW7 2AZ, UK
[b] ABB Energy Industries, Ole Deviks Vei 10, 0666, Oslo, Norway

ARTICLE INFO

Article history:
Received 12 February 2021
Received in revised form
16 February 2022
Accepted 17 March 2022
Available online 24 March 2022

Keywords:
Electrical power management
Flexible operation
Liquefied natural gas
Load shedding

ABSTRACT

The paper discusses operation and control of a process for the liquefaction of natural gas in which the refrigeration compressors are driven by electric motors. The aim is to enable the plant to accommodate contingencies in the availability of electrical power and to continue running when there is a shortage of electrical power, avoiding the significant economic impact of a shutdown. The article provides a detailed first principles analysis of the relationships between the electrical power consumption of the process, the production rate of the liquefied natural gas, its exit temperature, and its purity. By doing this, it is possible to ascertain settings for operating the process at various levels of power consumption. The results show that the process can operate with reductions of electrical power of 30% or more. Hence, power shortages could be managed by operating the process flexibly to make best use of the available remaining power, rather than by shutting down. The paper also discusses how such a system could be implemented industrially and identifies aspects that require further study.

1. Introduction

Demand for Liquefied Natural Gas (LNG) is growing significantly, and new plants are increasingly being driven by electricity under the control of a power management system. The concept to be examined in this paper is electrical power management of an electrically-driven LNG plant by means of flexible process operation. The *flexibility* of an electricity-intensive process refers to a response that enables the plant to withstand a disturbance and remain operational.

A typical disturbance in an electricity-intensive process is a change in the availability of electrical power, for instance due to an electrical contingency. This article proposes a power management and process control system for the mixed fluid cascade LNG process that enables the process to remain operational in the face of changes in available electrical power. The results will be of interest to energy companies building and operating electrically-driven LNG, and to equipment manufacturers who supply control systems, drives and motors for such plants.

1.1. Liquefied natural gas

Liquefaction enables natural gas to be transported from remote production sites to centres of population where the gas is used. Various commentators highlight the role of LNG in terms of security of supply and in enabling the transition to net-zero energy production. Clemente [1] cites an increase in demand for LNG over the next ten years of 40–50% driven by increased use of gas to replace oil and coal and by providing back-up for the intermittency of renewables. Energy companies are expanding their LNG production capacity, for instance BP has announced a doubling of LNG capacity between 2020 and 2030.

Emissions standards, plant efficiency and expected availability are driving new investments in electrically-driven LNG production in which electric motors rather than gas turbines are the prime movers of refrigeration compressors. For example, Total has announced the intention to produce LNG in Oman powered by 80 MW of solar generation and battery storage. Freeport LNG [2] who operate the largest electrical LNG plant in North America and Skiebe [3] spell out the significant advantages of electrically-driven LNG including efficiency improvements from motors with variable speed drives, greatly reduced emissions of CO_2, and flexibility of operation.

* Corresponding author.
E-mail address: n.thornhill@imperial.ac.uk (N.F. Thornhill).

https://doi.org/10.1016/j.energy.2022.123794
0360-5442/

1.2. Power management in industrial sites

Electricity-intensive processes are often located in industrial sites where electricity is generated and distributed locally under the control of a site power management system. During an abnormal situation such as an electrical contingency, a typical site power management system disconnects electrical loads until the consumption is equal to or lower than the remaining available power. This operation is named load shedding. Industrial examples in oil and gas and refining have been presented by Pacheco et al. [4] and Ravikumar et al. [5].

Load shedding is an effective strategy when the required reduction can be achieved by combining a number of small loads. Shoreh et al. [6] highlight that electrically-driven industrial processes can most easily adapt to the available power if the operations are batch-wise. A reduction of power consumption is achieved by scheduling fewer batches. However, gas handling facilities such as gas export plants and LNG typically have low granularity, i.e. a small number of very large loads. For instance, Freeport LNG has three 75 MW motors driving the refrigeration train.

With low granularity, adjusting the power consumption to the desired level is not always possible by load shedding. In that situation, load shedding can over-compensate with the result that some of the available power is unused. Moreover, if the disconnected equipment is crucial for operation, the whole process shuts down, causing significant economic impact due to loss of production and the costs of restarting the plant, as quantified by Kim and Cho [7] and in an outage in a European LNG plant, [8]. Therefore, there is a strong incentive to exploit flexibility in the process to keep the plant running.

Gas export and LNG plants are continuous operations. Mohd Noor et al. [9] examined a gas export plant and showed that reducing the allocated power has propagated effects throughout the process. This means that the overall production rate must change and the available power has to be distributed in a way that is consistent with the mass and heat balances of the whole process train. This requires a very good understanding of the window of flexible operation. Moreover, implementation requires a deep understanding of the characteristics of the electrical equipment and machinery of the plant.

1.3. Contribution of the paper

The key novel idea in this paper is to reduce electrical power consumption by decreasing the power allocated to the process, rather than switching the equipment off. In normal operation, an electrical distribution system adapts to the demands of the electrical equipment that runs the process. With the proposed system, by contrast, when the electrical supply becomes constrained the electricity consumption will immediately change to fit the constraints. This new way of operating has become possible in recent times because of developments in electrical drives.

Reducing power consumption affects the production rate. Therefore it is necessary to establish a new operating point that is consistent with the available power. The new operating point also has to be consistent with process constraints, for instance, maintaining a minimum flow rate through compressors.

The analysis in this paper maps the relationships between the available power, the production rate, and the characteristics of the produced LNG, namely its exit temperature and composition. The map also considers the limitations of the process and the equipment, to obtain an envelope of feasible operation. Compared to conventional load shedding, the results show that flexible operation of the mixed fluid cascade LNG process can allow the whole plant to ride through an additional 30% loss of available electrical power without shutting down.

1.4. Considerations for implementation

The proposed system must reduce the electrical power consumption of the process on a time scale similar to that of a circuit breaker in load shedding. The paper describes how this can be achieved in a modern electrical motor drive. At the same time, the system must send new set points to the process controllers so that the process moves towards an operating point consistent with the available power. The paper discusses a modification to a typical plant-wide control structure for the LNG process that would facilitate this task. The paper also briefly discusses the dynamic response of the transient behaviour as the LNG plant moves towards its new set point.

1.5. Layout of the article

The next section provides background and context for the work and places it in the context of related work. Section 3 introduces the LNG process, the modelling principles used in this paper, and the solution approaches for solving the model. Section 4 shows the results from the LNG model and defines the envelope of flexible operation. Section 5 discusses the results and suggests potential industrial uses of the findings. Practical implementation issues are discussed in Section 6, and the paper concludes with a discussion of the implications, limitations and next steps.

2. Background and context

This section reviews the state of the art in industrial power management systems in the production sites of large-scale process industries. Electricity-intensive processes may also be involved in demand response, either by adjusting their power consumption in response to signals from the external power grid, or by load shifting to take advantage of time-sensitive prices.

2.1. Electrical power management within an industrial site

Singh et al. [12] gave the viewpoint of Bechtel, an engineering procurement contractor in the oil, gas and chemicals industry, of the requirements of industrial power management systems in the production sites of large-scale process industries. The paper describes an integrated power management system for an industrial site that has its own power generation. A central function is to ensure balance between generation and consumption. Normally, this is done by control of the generators, but in the event of an electrical contingency load shedding will be used. The power management system system should be integrated with the distributed process control system. Integration makes it possible to propose schemes such as the one outlined in this paper, whereby set points for the process flow controllers can be sent from the power management system.

Pacheco et al. [4] described an implementation of a power management system in a large-scale methanol plant in Egypt. The system provides electrical monitoring, control and power management, and also asset monitoring for high currents in pump motors. Besides a discussion of the relevant communications and industrial IT systems, the authors explained the philosophy behind their load shedding scheme and gave an explanation of its implementation. The power management system continuously checks the state of the distribution system and if there is an outage, load shedding is initiated. The load shedding strategy classifies loads according to their criticality, with the least critical being shed first. The most critical load group was not included in the load shedding scheme. Critical equipment is typically safety related and in the event of an emergency it was powered by backup generation until the plant could be shut down safely. The methanol plant did not have the turn-down capability that we are proposing in this article, but some plant flexibility was considered. For example, a load such as a cooling water pump was considered less critical if the resulting temperature deviation would have only a minor impact on the process. The paper shows an example where 80% of the load was shed with the remaining 20% of critical loads powered by an emergency diesel generator to ensure a safe shutdown. Hence the load shedding scheme provided an orderly shutdown of production rather than riding through a shortage of available power.

Ravikumar et al. [5] described a power management system in a very large Saudi Arabian oil refinery with 2 GW of generation and no connection to the public utility grid. The role of the power management system is critical because the site is a microgrid requiring its own frequency control and balancing. The authors discussed the requirements for rapid shedding of loads in the event of a contingency, and how this is done at their site within a time-scale of about one to two seconds. Their system includes 50 sheddable loads comprising induction and synchronous motors, and 33 critical loads. Shedding enables a minimum number of generators to remain on line to supply critical loads during a safe shutdown. The paper also enumerates the types of contingencies that need to be accommodated, such as a circuit breaker opening under load, or overload of a transformer.

Khatib et al. [13] described a load shedding system in an Australian LNG facility. They identified over 100 loads that could be shed, and others that would never be shed. An example in their power system simulator showed a loss of 9 MW of generation would be managed by 20 MW of shedding of non-critical load and subsequent backing-off of another generator by 11 MW to achieve a balance. The total electrical power of the site was 162 MW.

Olsen et al. [14] described real-life challenges of operating an all-electric LNG plant in a remote location with a weak grid connection. The LNG site has its own power station for electricity generation. A connection to the public power grid is also present for synchronization and import of electricity when needed, and so that the power station can provide support to the grid. At times the protection systems of the weak grid triggered disconnection and islanding of the LNG site. The authors devised and implemented a scheme to shed load within the LNG site as an alternative to disconnection. The scheme has given an overall improvement of the stability of the public grid in the north of Norway because the generators within the LNG site stay connected, while the minimum load is shed to minimize the impact on the LNG process.

2.2. Load shedding within an industrial site

From the point of view of research activity, the main interest has been in load-shedding to achieve balance between available power and power being consumed, with a view to avoiding shut-downs and where possible prioritizing production by utilizing remaining available power.

Sapari et al. [15] recently conducted a comprehensive review on load shedding schemes for distribution networks in island mode, i.e. without connection to the public electric power grid. The topics reviewed are relevant to this article because industrial sites tend to have balanced generation and consumption with limited inflow from the public grid. The power generation in such a site must ensure voltages and frequencies are within the acceptable range. Control of frequency requires balancing of real power between generation and consumption.

The authors of the review examined more than 60 articles putting forward concepts and ideas for adaptive and intelligent load shedding schemes. In general, adaptive load shedding includes an estimation of power imbalance derived from a measurement of frequency to give greater precision in balancing, compared with conventional load shedding that sheds load in a pre-programmed way according to the measured frequency. The review concluded that optimal load shedding is still an open issue, where *optimal* means that the minimum load is shed to maintain balance with the available power, and also that the technical and economic impacts on the plant are minimized. The review did not identify any prior work on flexible operation in load shedding, whereby the power supplied to a load would be reduced rather than shed.

Van der Wal et al. [16] described the load shedding methods used in an industrial power management system in the event of an electrical contingency. The fast load shedding system is an adaptive system according to the classification of Sapari et al. [15]. It uses electrical power balance estimates of the available power. A very rapid calculation is achieved by means of prior enumeration of every possible network contingency, so that the estimates are based on a look-up table. A conventional load shedding system provides backup.

Bevrani and co-workers [17] discuss load shedding from the perspective of maintaining frequency stability in a wide-area electricity transmission grid. The system frequency of a grid can be maintained at a constant value only if overall generation matches power consumption by the loads. The authors review the challenges arising from integration of renewable generation and the increasing electrification of industrial loads. Specifically, they discuss demand response from controllable and flexible loads and highlight that switching of loads can enable a fast response for frequency support. In this context, a *load* refers to a whole industrial site or an aggregation of distributed loads. The articles discussed in the review cover fast frequency control by switching of aggregated thermostatic loads such as domestic refrigeration, and from aggregations of electric vehicles. Their recommendations call for more research in the area of frequency control from flexible loads.

The above discussion shows:

- Power balancing by shedding of loads is needed by the power management systems used in industrial sites:
  - Load shedding schemes prioritize non-critical loads and identify critical loads that must not be shed;
  - Adaptive load shedding schemes make use of estimates of power imbalance and try to select loads for shedding in an optimal way;
  - Load shedding works best when large numbers of small non-critical loads are available for shedding.
- Wide area transmission grids use load-shedding to maintain the system frequency:
  - Conventional schemes apply blackouts to selected areas;
  - Advanced and future schemes will make use of demand response schemes from controllable and flexible loads.

If loads can be operated flexibly by turning down their power consumption, then the scope of an industrial power management system would be extended compared to a scheme restricted to load shedding of non-critical loads. It would be possible to avoid shut-downs by riding through periods of reduced availability of power.

2.3. Flexible operation of electricity-intensive processes

This section considers the state of the art in flexible operation of electricity-intensive processes for the purposes of managing the electrical power consumption.

Flexible operation can offer economic benefits such as scheduling higher levels of production for times when electricity process are low [6,18–20], and integration of renewable energy sources into future power systems [21–24]. As discussed in the Introduction, flexible operation for the purposes of power management is facilitated when a process comprises multiple batch units that can operate independently, whereas integrated plants and continuous plants have to take into account the propagated effects of a reduction of power.

The paper of Hoffmann et al. [25] begins with a concise account of the factors to be considered in operating electricity-intensive industrial processes. The authors highlighted the following points and observe that flexible operation and operation at an optimal steady state need trade-offs that require a weighted optimization:

- Plants are designed to run at a specific, optimized production rate;
- Deviations from the optimum affect production rate and reduce return on investment;
- Flexible operation provides opportunities for demand response by:
  - Exploitation of time-sensitive electricity prices by shifting production, known as load shifting;
  - Provision of paid-for grid balancing services such as load shedding or load reduction.

A comprehensive review on demand response from Samad and Kiliccote [26] suggested that automated demand response would be an important direction for research. The concept is that an electricity-intensive industrial site would change its production in response to signals from the operator of the electric power grid. They gave examples from a range of industries including aluminium and cement production as well as from commercial refrigeration and freezing.

The case studies presented by Hoffmann et al. [25] are from electrochemical industries such as chlorine production. The authors make the point very strongly that understanding the opportunities from flexible operation in the electrochemical industries requires a deep understanding of the process to know if a process can be made flexible and to what extent.

Bruns et al. [27] comment on the importance of chemical industries in demand response giving two criteria for participation as high use of electrical power as primary feedstock, and flexibility. Flexibility requires the production rate to be increased or decreased within a give timespan, while still remaining within the window of feasible operation. The authors identified air separation and chloralkali production as primary candidates.

2.4. Studies in flexible operation for demand response

Electricity-intensive industries in use or under study for flexible operation are listed below. The relevance to the present article is that the results from demand-response studies for shifting production or for paid-for balancing services are also applicable to flexible operation for power management within an industrial site.

2.4.1. Aluminium smelting

An aluminium production line comprises multiple electrolysis pots that can be started and stopped independently, providing high granularity. The duration of curtailment of a pot is limited by the cooling rate and the need to keep the contents molten. Samad and Kiliccote [26] and Todd et al. [28] discuss an implementation at ALCOA showing curtailments of around 30 min and a reduction in power consumption of 70 MW out of a total of 470 MW. Kirkerud et al. [29] have estimated the potential for flexible operation of aluminium smelting in Norway is 25% of the total power consumption of these plants.

2.4.2. Steel production

The arc furnace of the melt shop is an electricity-intensive operation within steel-making that can participate in load shedding and also in load shifting [6]. Paulus and Borggrefe [30] reported in 2011 that roughly half the arc furnaces in Germany were registered with the electricity grid operators for load shedding services, whereby they would reduce electricity consumption by stopping batches with advance warning of an hour or more. However, there are knock-on effects in other parts of the steel making process. For example, Hadera et al. [31] considered the scheduling problem of shifting production to take advantage of time-sensitive electricity pricing, while also considering integration with the hot rolling mill. A strong constraint in the schedule was to minimize the reheating of material from the melt shop, which would have a penalty in terms of the use of natural gas for reheating.

2.4.3. Chlorine manufacture

Paulus and Borggrefe [30] identified electrochecmical process as having potential for flexible operation. Chlorine is made in multiple electrolysis cells and the process has high granularity. Hoffmann et al., however, have warned that chlorine production alone has limited potential for flexible operation because of the dangers of storing chlorine [25]. Storage would be needed to supply continuous downstream processes that use the chlorine. Therefore it is better to consider chlorine production and the downstream processes together. The study identified the potential for a 25% reduction or a 5% increase in electrical power consumption over a period of two to three hours.

2.4.4. Bitumen heaters

Cheng et al. [32,33] described practical and simulation studies for the UK's National Grid on dynamic frequency support by switching banks of industrial bitumen heaters. Like aluminium and chlorine, such a system has high granularity. The results showed the heaters could be switched off in 0.7s for a duration of up to 300 min. The study showed power consumption of 80 MW being reduced to 10 MW.

2.4.5. Refining and petrochemicals

There have not been many studies in refining and petrochemicals, however Gholian et al. [34] examined the potential for load control and reduction of peak demand in oil refineries. There was no overall reduction of power consumption, rather electricity consumption was shifted to take advantage of cheaper prices. The interdependency between processing units had to be considered. In a continuous refinery process, material moving through one unit has to be received by downstream units, or in batch operation, a downstream unit has to start at a scheduled time relative to another. Therefore, flexible operation in refineries requires the running of an optimization program to understand the implications of decisions.

2.4.6. Air separation processes

Air separation processes are utilities that supply demand. Since demand can fluctuate, these processes are inherently designed for flexible operation. The flexibility can also be exploited for electrical power management. Caspari et al. [20] presented a design for reduction of energy costs with electrical power consumption adjustable between 3.5 MW and 28 MW depending on the electricity price. If flexibility is exploited to follow energy prices rather than meeting customer demand, then the plant needs storage that enables customer to be supplied when the plant is turned down.

2.5. Power management of LNG by flexible operation

The literature reviewed has placed the work of the current paper in context. The main findings are as follows.

There is a limited number of studies in flexible operation in oil and gas production for the purposes of electrical power management. In general, these studies report shedding of loads in order of priority to achieve a safe shutdown, rather than for balancing of consumption and available power. The reason for this is that these plants typically have a small number of large loads, and moreover the loads are within an integrated process. Shedding any one of the loads is likely to cause the whole process train to shut down. If load shedding in an LNG site is restricted to non-essential loads such as lighting and air conditioning then the response may not be so large, as can be seen in the Australian study by Khatib et al. [13] in which non-essential loads comprised only 20 MW out of 162 MW.

The challenge for our work is to reduce the power consumption of the large loads within an integrated LNG process by operating at a lower throughput than normal so that the whole plant can ride through a period of reduced power availability. To do this requires a deep understanding of the propagated effects of the power reduction. For instance, in the mixed fluid cascade LNG process, the power reduction has to be spread in a way that is consistent with the mass and energy balances of the process, while also respecting operating constraints such as avoidance of compressor surge.

It is of great interest for LNG to respond to and recover from a contingency with minor loss of production, and to avoid a shutdown. A shutdown leads to total loss of production for many days. The present paper gives insights into the operation of the LNG process, its control system and its electric equipment. The study will determine the window of feasible operation and how the process can be operated within this window without violating constraints. The proposed system for flexible operation has the potential to enable an LNG plant to tolerate a significantly larger reduction in available power than is achievable at present.

3. LNG model and solution approaches

This section introduces the liquefied natural gas process, shown in Fig. 1. This text analyses the process with a steady-state model that comprises thermodynamic equations, and mass and heat balances. The model was developed and solved in Matlab and Simulink r17.

3.1. Previous work

Various authors have examined optimization of the refrigeration cycles for LNG. Brodal et al. [35] have compared the optimal designs of several mixed fluid cascade LNG designs. They highlighted the role of the pressures in the refrigerant cycles, among other findings. Xuan et al. [36] identified that operating pressures for mixed refrigeration fluids that are close to the vapour-liquid equilibrium minimize energy consumption. Ding et al. [37] developed a model in Aspen HYSYS to explore a range of performance enhancements to reduce energy consumption, while Xu et al. [38] proposed a control system that would vary the composition of the refrigerant under closed loop control to adjust to changes in working conditions. The assumption in these cited works is that the plant operates at a steady optimal state. Flexible operation of LNG that takes the process away from its normal operating point has not been a previous topic of study.

3.2. Description of the process

The LNG process is an electricity-intensive process, and depending on the size of the installation, the consumption ranges between 30 and 200 MW [11]. The process acts as an electrically-driven heat pump that conveys the heat from the natural gas to the sea. Fig. 1 shows a mixed-refrigerant cascade cycle based on Stockmann et al. [10]. In this process, natural gas (the blue stream in Fig. 1) enters the process at a pressure of 30 bar, and it is liquefied using three stages of refrigeration, precooling (brown), liquefying (red), and subcooling (green).

Each refrigerant absorbs heat from the natural gas in the heat exchangers (HEX_{Prec}, HEX_{Liq}, and HEX_{Sub}) and releases it to the sea through the sea coolers (SC_{Prec}, SC_{Liq}, and SC_{Sub}). At the end of the process, a valve (V_{NG}) decompresses the natural gas, thus, it is crucial to subcool the natural gas so that it does not present a vapour phase when it decompresses.

Each refrigerant undergoes a Joule-Thomson cycle to absorb the heat from the natural gas. The Joule-Thomson cycle in this process uses electrically-driven compressors, and therefore, the electrical power consumption of the plant has consequences on the performance of the process. There is a relationship between the power consumption of the plant and the amount of heat absorbed from the natural gas. The amount of heat absorbed affects the LNG production rate, its temperature at the exit of the process, and its composition.

The formulation in this paper follows from the detailed first-principles model of Xuan et al. [36]. The pressures at the refrigeration compressors are held at constant values reflecting the operating values specified in the patent of Stockmann et al. [10].

3.3. Mass and heat balances

3.3.1. Balances in the heat exchangers

The natural gas leaves each heat exchanger at a specific temperature, and to ensure that it reaches those temperatures, the model performs heat balances on each heat exchanger.

$$F_{Prec} = \frac{F_{NG1}(h_{NG2} - h_{NG1})}{h_{P4} - h_{P1}} + \frac{F_{Liq}(h_{L2} - h_{L1}) + F_{Sub}(h_{S2} - h_{S1})}{h_{P4} - h_{P1}} \tag{1}$$

$$F_{Liq} = \frac{F_{NG3}(h_{NG5} - h_{NG3}) + F_{Sub}(h_{S3} - h_{S2})}{h_{L5} - h_{L2}} \tag{2}$$

$$F_{Sub} = \frac{F_{NG5}(h_{NG6} - h_{NG5})}{h_{S6} - h_{S3}} \tag{3}$$

where F is the flow rate in mol s^{-1}, and h is the specific enthalpy in J mol^{-1}. The subscripts Prec, Liq, and Sub, respectively refer to the streams of the precooling, liquefying, subcooling refrigeration cycle, and NG refers to the natural gas streams.

Eqs. (1)–(3) rely on the enthalpy of the streams. The model uses thermodynamic equations to calculate these enthalpies and extracts the equations from Poling [39] and Nieto et al. [40]. The equations given in Ref. [36] adapt the Redlich-Kwong Soave equation of state [41,42] for a mixture of hydrocarbons presenting vapour and liquid equilibria.

3.3.2. Balances in the flash drum

This paragraph explains the balances in the natural gas flash drum (FD_{NG}). This flash drum separates the heavy compounds that condense during the precooling stage. The model assumes that the temperature of the streams entering and leaving the flash drum are the same, so the temperatures of NG_2, NG_3, and NG_4 are the same.

The mass balance in the flash drum is:

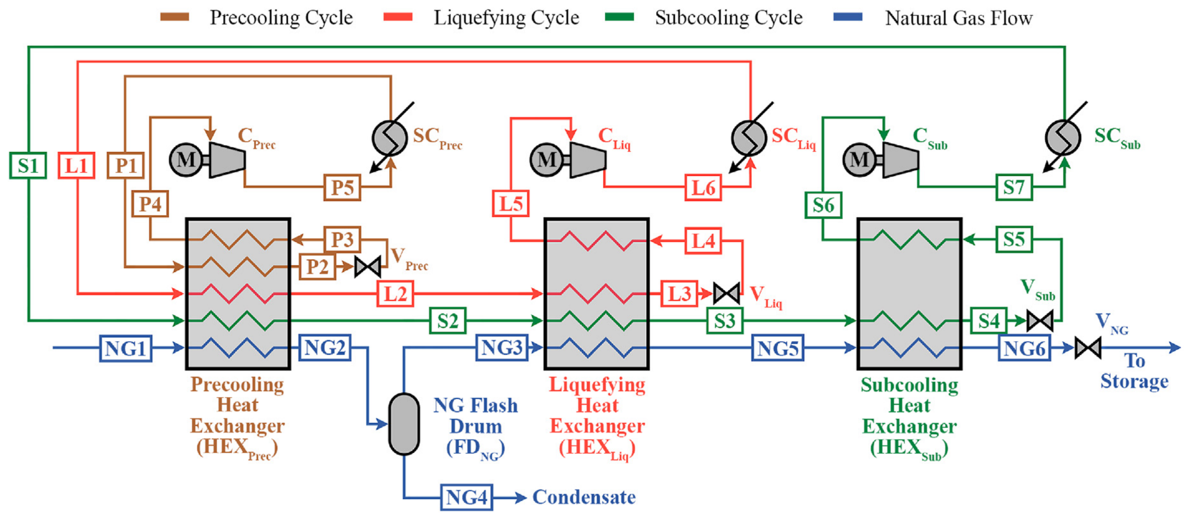

Fig. 1. Liquefied Natural Gas process. The picture is a representation of the process introduced in the patent by Stockmann et al. [10]; and is based on the mixed fluid cascade process by Linde [11].

$$F_{NG2} = F_{NG3} + F_{NG4} \tag{4}$$

The flow rate and composition in NG_3 and NG_4 depend on the temperature in the flash drum; a higher temperature generates more vapour, but with a lower percentage of lighter components. The model uses the Redlich-Kwong Soave equations along with the Rachford-Rice algorithm [43] to calculate the vapour fraction in the flash drum, and the composition of each stream.

3.4. Power consumption in the LNG plant

The power consumed by the LNG plant is the sum of the electrical power consumed by the compressor motors of each refrigeration cycle. The difference of enthalpies between the suction and discharge streams determines the power consumption.

$$\begin{aligned} W_{Prec} &= \frac{F_{Prec}(h_{P5} - h_{P4})}{\eta_{Prec}} \\ W_{Liq} &= \frac{F_{Liq}(h_{L6} - h_{L5})}{\eta_{Liq}} \\ W_{Sub} &= \frac{F_{Sub}(h_{S7} - h_{S6})}{\eta_{Sub}} \\ W_{Total} &= W_{Prec} + W_{Liq} + W_{Sub} \end{aligned} \tag{5}$$

where W_{Prec}, W_{Liq}, and W_{Sub} are the power consumed by each compressor in W, W_{Total} is the overall consumption of the plant in W, and η is the isentropic efficiency of the compressor.

3.5. Compressor map

The isentropic efficiency is an attribute of each compressor, and it depends on the flow rate and the pressure ratio. Usually, the compressor map gives the relationships of these variables. Fig. 2 represents an example of a compressor map, which shows that the isentropic efficiency varies when the flow rate varies.

The compressors can vary the pressure and the flow rate of the refrigerants. The model considers that the discharge pressure of the compressors is constant during the analysis, and a variation of the power consumption affects only the refrigerant flow rate.

The discharge pressures used in this work are 15 bars for the precooling compressor (C_{Prec}), 15 bars for the liquefying compressor (C_{Liq}), and 35 bars for the subcooling compressor (C_{Sub}). These values are identified in Stockmann et al. [10] and reflect industrial practice.

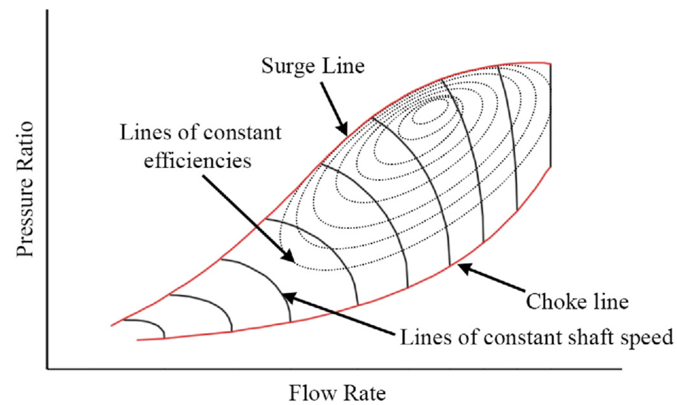

Fig. 2. Notional compressor map. The graph represents lines of constant speed (solid black), and lines of constant efficiencies (dotted black) for given flow rate and pressure ratio in a compressor. The operation must be between the surge and choke lines (red). This figure is adapted from Miller [44].

The model uses a look-up table presented in Miller [44] to determine the isentropic efficiency of the compressor. In the text by Miller [44] the look-up table considered the flow rate and the discharge pressure of the compressor. The model in the present article, however, does not consider a change in the pressure, and keeps the discharge pressures of the compressors constant. Therefore, the isentropic efficiency in the model depends only on the flow rate.

3.6. Solution approaches

The model fixes the temperature of all streams, except for streams NG2, and NG6. The model assumes that the piping system does not cause any drop in pressure. The temperature in stream NG2 is the temperature of the flash drum (FD_{NG}) that separates the heavy compounds in the natural gas stream after the precooling stage. Thus, varying the temperature in NG2 has impacts on the flow rate and composition of the natural gas streams after the flash drum, and therefore, on the LNG production rate and composition. Additionally, changing the temperature in NG6 has effects on the heat to be removed from the natural gas, and therefore, the temperature in NG6 impacts the natural gas flow rate.

The model has three degrees of freedom, and the independent variables are:

- LNG production rate (stream NG6)
- LNG composition
- Natural gas temperature at the exit of the process

The independent variables are related to the LNG properties. The calculations give various values to these properties to obtain the power consumption of the plant. As a result, the model finds an envelope of feasible operation showing the relationships between the LNG properties and the power consumption.

During the calculations, the isentropic efficiency is set at its maximum (0.75) when the plant operates at its nominal values:

- The LNG production rate is 15.5 kmol s^{-1} (7.5 MTPA)
- The CH_4 content in the LNG is 92.2% mol. This corresponds to a temperature at the flash drum of 238.15 K
- The natural gas temperature at the exit is 107.15 K

With these values, the power consumption of the plant is 200 MW. The model assumes that the operating point crosses the surge line when the isentropic efficiency falls below 0.65. As mentioned, in a power reduction event, the flow rate of the refrigerants decreases, and therefore, the surge line is crossed when the flow rate of the refrigerants reaches a certain point. This is further discussed in the next section.

The methodology for calculating the thermodynamic properties of each stream is found in Xuan et al. [36]. The open source dataset for these calculations is available on-line [45].

4. Results

Section 4 introduces the results of the LNG model calculations. It divides into four subsections, three for showing and discussing the impacts of the LNG properties (production rate, temperature, and composition) on the power consumption, and one for the impacts of combining the three effects. Section 5 will discuss, explain and give insights into the results.

The LNG properties have effects on the enthalpy of the natural gas streams. Eqs. (1)–(3) show that the enthalpies of the natural gas streams have an impact on the flow rate of the refrigerants. Thus, varying the LNG properties affects the isentropic efficiency of the compressors and the power consumption of the plant.

4.1. Effect of the production rate

The model sets the minimum isentropic efficiency at 0.65. Fig. 2 shows that, for a constant pressure, when the flow rate decreases, the isentropic efficiency decreases and the operating point gets closer to the surge line. Observing Eqs. (1)–(3), the flow rate of the refrigerants varies when the natural gas flow rate changes. Therefore, a reduction in the natural gas flow rate decreases the isentropic efficiency of the compressors.

Fig. 3 shows that the sub-cooling compressor will be the first to approach the surge condition if the natural gas flow rate decreases. This is because the ratio between the flow rate of sub-cooling refrigerant and natural gas is higher than for the other two refrigerants.

From Fig. 3, the subcooling compressor reaches the minimum isentropic efficiency (red circle) when the LNG production rate decreases to 57.3%.

Fig. 4 shows the effects of varying the LNG production rate on the summed power consumption of all three compressors for fixed LNG temperature and composition. From Eqs. (1)–(3), the flow rate of the refrigerants is linearly proportional to the natural gas flow rate. However, the graph in Fig. 4 presents a curvature. This curvature is due to the reduction in isentropic efficiency when the LNG production rate decreases.

Fig. 4 shows that the power consumption of the plant decreases when the LNG production rate reduces. If the LNG production rate reduces, the refrigerants absorb less heat to liquefy it, and therefore, the flow rate of the refrigerants can decrease, causing the compressors to need less power.

The shaded area in Fig. 4 represents the minimum achievable LNG production rate. The flow rate and the power consumption have to be on the right-hand side of this area. Thus, if the surge constraint is adequately represented by an efficiency of 0.65, reading from the vertical axis in Fig. 4, the power consumption can be reduced to 64.5%.

4.2. Effect of the LNG composition

The LNG composition varies when the temperature in the flash drum (FD_{NG} in Fig. 1) changes. The model assumes the purity of the LNG to be proportional to its content of methane. Increasing the temperature reduces the overall percentage of methane in the vapour stream NG4 because methane is diluted with heavier components. Raising the temperature also results in a lower flow rate in the condensate stream.

The vapour flow rate is the same as the LNG flow rate, therefore the solution in this section proceeds by setting the value of the LNG flow rate to 15.5 kmol s^{-1} . The temperature is the independent variable and the model calculates the feed and condensate flow rates. Fig. 5 shows the effects on the flow rates of NG2, NG3, and NG4 of varying the flash drum temperature. When the temperature in the flash drum increases, the flow rate in the condensate stream decreases, and therefore, the feed flow decreases to keep the production rate constant.

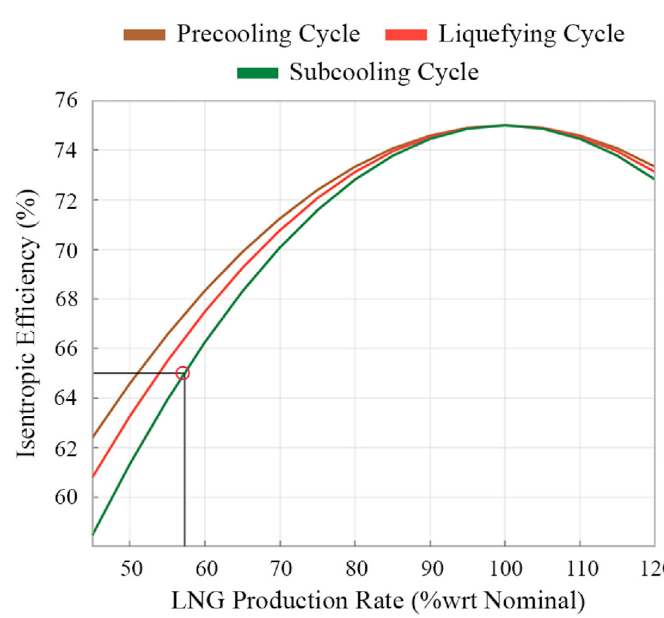

Fig. 3. Effects on the compressor isentropic efficiency of varying the LNG production rate (% wrt nominal production rate). The figure represents the isentropic efficiency of the precooling (brown), the liquefying (red), the subcooling (green) compressors.

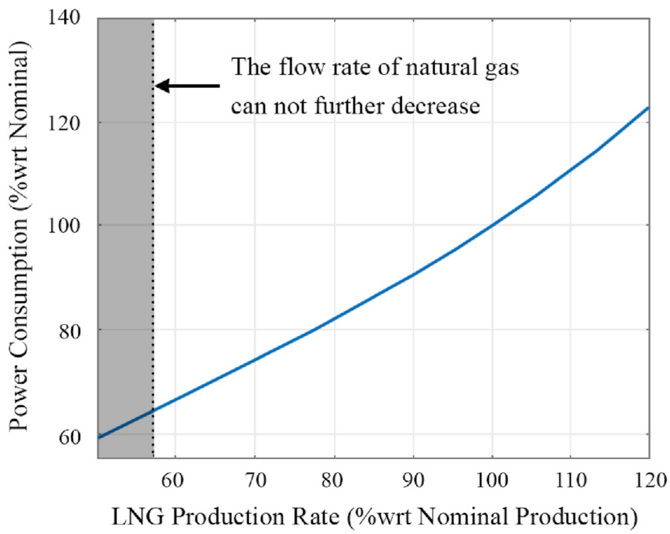

Fig. 4. Effect on the overall power consumption (% wrt nominal consumption) of varying the LNG production rate (%wrt nominal production rate).

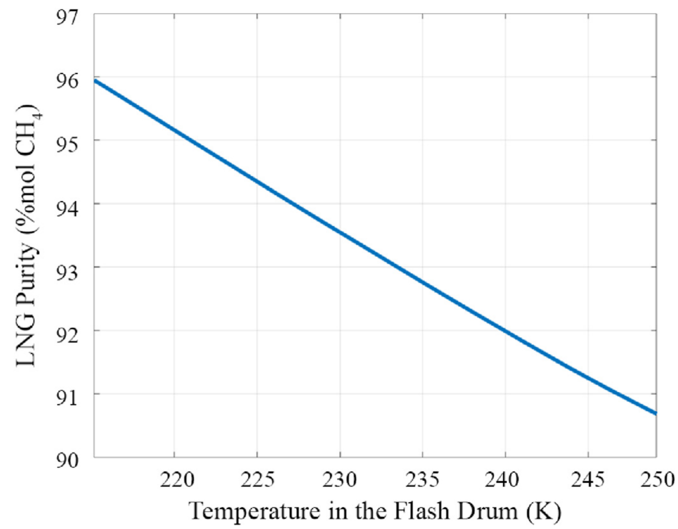

Fig. 6. Effects on the LNG purity (% mol CH_4) of varying the temperature in the flash drum (K) with a constant production rate of 15.5 kmol s^{-1}

4.2.1. *Relationship with the flash drum temperature*

When the temperature in the flash drum decreases, the composition of the vapour is richer in methane, and the condensate is richer in heavier compounds. Fig. 6 presents results from the model showing the impact on the LNG purity of varying the temperature in the flash drum.

Thus, from Figs. 5 and 6, for a constant production rate, when the flash temperature increases, the plant needs to process less feed flow rate, but as a trade-off, the LNG is less pure.

4.2.2. *Relationship with the electrical consumption*

Fig. 7 shows the impact on the power consumption of the plant when the temperature in the flash drum changes for fixed LNG production rate at exit of the process. The vapour fraction is determined using the Redlich-Kwong Soave and the Rachford-Rice equations. For a fixed production rate, the consumption of the plant reaches a minimum at 227 K.

The curvature in Fig. 7 is due to the effects on the specific enthalpy of varying the temperature in the flash drum. The following paragraphs give an insight into these relationships.

4.2.3. *Relationship with the natural gas enthalpies*

Fig. 8(a) shows the specific enthalpy of each natural gas stream in the process when the temperature in the flash drum changes. As shown in the figure, changing the temperature in the flash drum affects the composition of streams NG3, NG5, and NG6. The specific enthalpy of a stream decreases when the presence of lighter components increases.

From Fig. 8(a) even though the temperature in the flash drum increases, the specific enthalpy in NG3 (yellow) remains virtually constant. This is due to the decrease of the percentage of CH_4 in NG3, which would cause the specific enthalpy of stream NG3 to decrease. However, in practice the specific enthalpy of NG3 remains

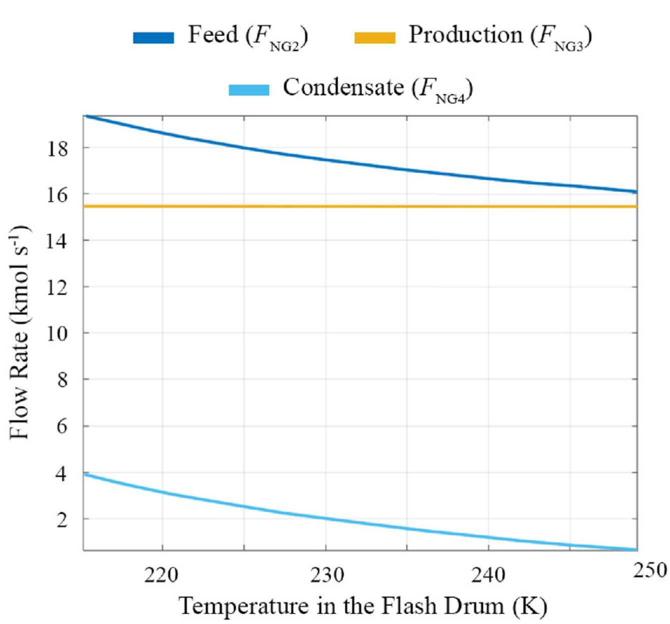

Fig. 5. Effects on the flow rate of the feed (dark blue), and condensate (clear blue) streams (kmol s^{-1}) of varying the temperature in the flash drum (K) with a constant production rate of 15.5 kmol s^{-1}

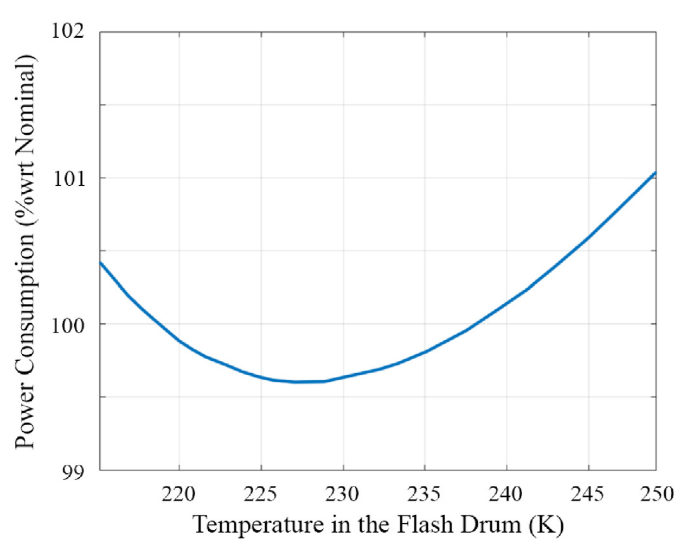

Fig. 7. Effects on the power consumption of the plant (%wrt nominal consumption) of varying the temperature in the flash drum (K) with a constant production rate of 15.5 kmol s^{-1}.

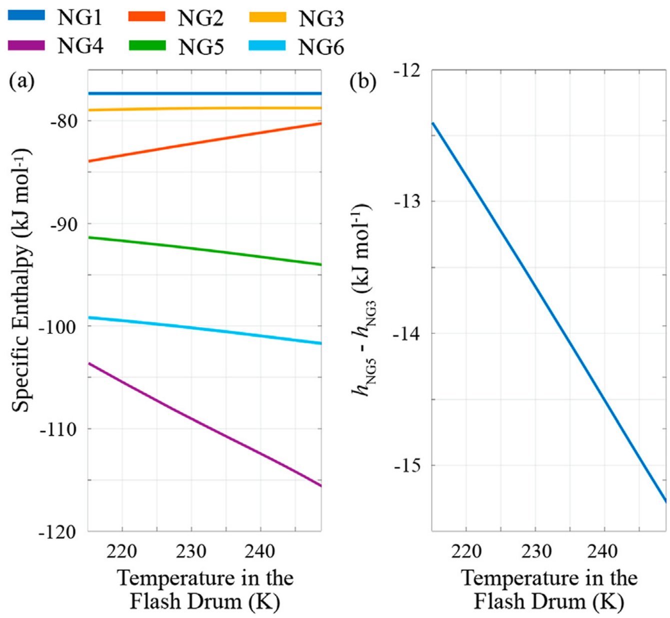

Fig. 8. Effects on (a) the specific enthalpies of the natural gas streams (kJ mol^{-1}) and (b) the difference between specific enthalpies in NG5 and NG3 (kJ mol^{-1}) of varying the temperature in the flash drum (K).

roughly constant due to an increased temperature in the flash drum. The temperature in NG5 (green) does not vary, but the composition changes, so when the temperature in the flash drum increases, the specific enthalpy in NG5 decreases because the its CH_4 content decreases.

From Eq. (2), the liquefying refrigerant flow rate is inversely proportional to the difference of enthalpies between NG5 and NG3. Fig. 8(b) shows that the higher the temperature in the flash drum, the higher the difference between NG5 and NG3, and consequently, the higher the flow rate of liquefying cycle (L streams in Fig. 1). Fig. 9(b) shows that the liquefying refrigerant flow rate increases when the temperature in the flash drum increases. The same argument can be applied to the flow rates of refrigerants in the precooling and subcooling cycles (P and S streams in Fig. 1). For the precooling flow rate, the relevant streams are NG1 and NG2, and for the subcooling flow rate, the relevant streams are NG5 and NG6.

Fig. 9 shows the flow rates of the refrigerants when the temperature in the flash drum changes. The flow rate that is more affected by the change of temperature in the flash drum is the liquefying refrigerant, whose flow rate is linearly increasing. On the other hand, the precooling and the subcooling flow rates decrease when the temperature in the flash drum increases. The combination of these three flow rates causes the electrical consumption to find a minimum at the 99.5% of its nominal value when the temperature in the flash drum is 227 K.

4.3. Effect of the LNG exit temperature

Fig. 10 shows the effects of changing the LNG temperature at the exit of the process (NG6 in Fig. 1) on the power consumption when the production rate and the composition are fixed. The power consumption decreases when the LNG temperature at the exit increases. The shaded area represents the range of temperatures in which the natural gas presents a vapour phase, which must be avoided. Therefore, for a fixed production rate and composition, raising the LNG temperature at the exit of the process can reduce the power consumption to 97.5% of the nominal value, corresponding to a power reduction of 5 MW.

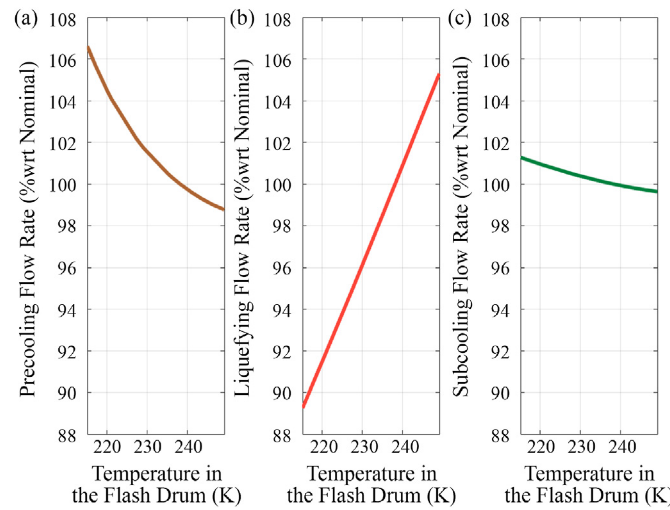

Fig. 9. Effects of varying the temperature in the flash drum (K) on refrigerant flow rates as % wrt nominal value: (a) precooling, (b) liquefying, and (c) subcooling.

For a higher LNG temperature, the subcooling refrigerant needs to remove less heat from the natural gas, and therefore, the subcooling flow rate can be decreased.

Fig. 11 shows the refrigerant flow rates when the LNG temperature changes. As discussed, the subcooling flow rate decreases when the LNG temperature at the exit increases. The precooling and the liquefying refrigerants absorb heat from the subcooling refrigerant. Thus, the precooling and liquefying flow rates decrease when the subcooling flow rate decreases. It is the reduction of the three refrigerant flow rates that causes the power consumption of the process to decrease.

4.4. Combined effects

This section discusses the effects on the power consumption of varying two or more LNG properties simultaneously. As discussed, the power consumption can be reduced to 64.5% of the nominal value by varying the production rate, to 97.5% by varying the LNG

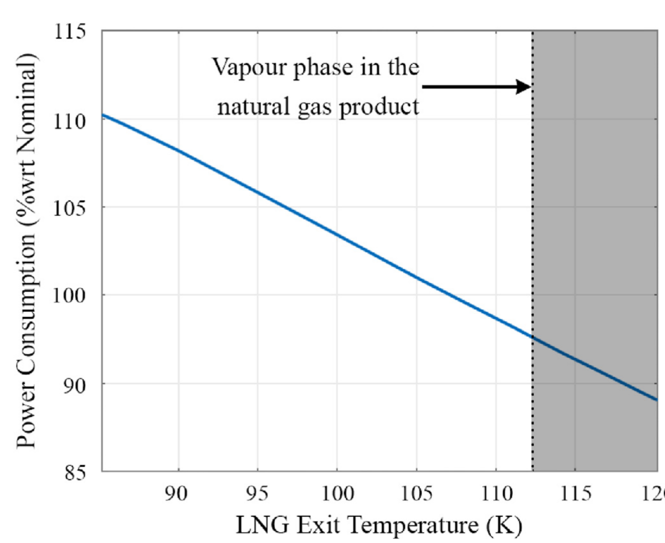

Fig. 10. Effect on the power consumption (%wrt nominal value) of changing the LNG exit temperature (K). The natural gas product presents a vapour phase in the shaded area.

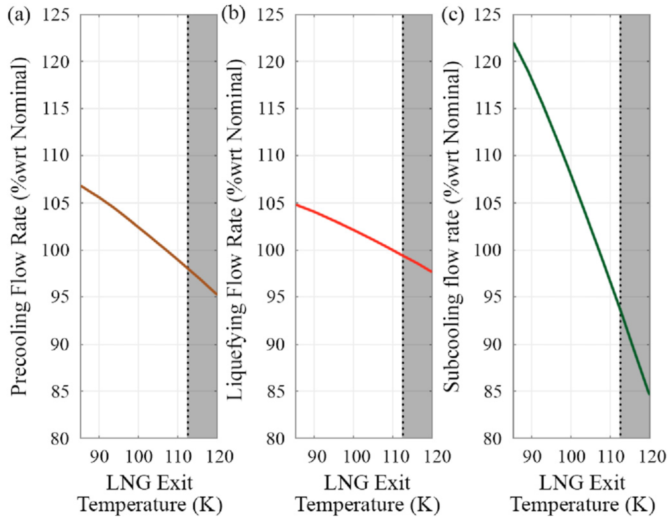

Fig. 11. Effects of varying the natural gas exit temperature (K) on the refrigerant flow rates as % wrt nominal value: (a) precooling, (b) liquefying, and (c) subcooling. The natural gas product presents a vapour phase in the shaded area.

exit temperature, and to 99.5% of the nominal value by varying the flash drum temperature. Thus, the most effective way of reducing the power consumption is by decreasing the production rate. This section now observes if adjusting the LNG exit temperature or the flash drum temperature can ameliorate the reduction in production rate while achieving the same power reduction.

4.4.1. Effect of the production rate and LNG exit temperature

Fig. 12 shows the effect on the power consumption of varying the LNG production rate and LNG exit temperature. The power consumption increases when the LNG production rate increases, or when the LNG exit temperature decreases.

In Fig. 12, the red dot labelled as 'A' represents the nominal operating point. If the power consumption is to be reduced, there are three alternatives, represented with tagged red dots. To exemplify this, the power is reduced to 80% of the nominal consumption:

- Point B: Varying the exit temperature without changing the production rate: With this alternative, the operating point falls in the shaded area, obtaining as a result a vapour natural gas.
- Point C: Varying the production rate while maintaining a constant exit temperature: The process achieves the desired power reduction and the production rate decreases to 77.5%.
- Point D: Varying both the production rate and the LNG exit temperature: The process achieves the desired power reduction and the production rate decreases to 79.4%.

Therefore, if the process reduces its power consumption to 80%, increasing the LNG exit temperature increases the production rate by 1.9% compared to changing only the production rate. This corresponds to an increase of 0.294 kmol s^{-1}, or 1060 kmol h^{-1}. On the other hand, changing the temperature implies an operating point closer to the saturation point. Therefore, it is important to have a tight control system if the LNG temperature at the exit temperature is to be changed.

4.4.2. Effect of the production rate, LNG exit temperature, and LNG composition

This paragraph discusses the effects on the power consumption of varying all three of the LNG production rate, the LNG exit temperature, and the LNG temperature in the flash drum.

Fig. 13 represents the relationships that the process has to satisfy for various levels of power consumption and various values of LNG exit temperatures. The colours of the curves correspond to various levels of power consumption, and the intensity of each curve represents different LNG exit temperatures. As discussed in the results of the individual effects, the effect of varying the production rate on the power consumption is more pronounced than the effect of varying the temperature in the flash drum.

For instance, if the power consumption is to be reduced to 80%, any orange curve gives the relationship between the temperature in the flash drum, the LNG exit temperature, and the LNG production rate. The highest represented temperature is 112.15 K because that is the LNG saturation point, and the shaded area represents the surge constraint presented in Fig. 3. Thus, the graph considers the LNG exit temperature and the production rate limits. Thus, Fig. 13 gives the envelope of feasible operation.

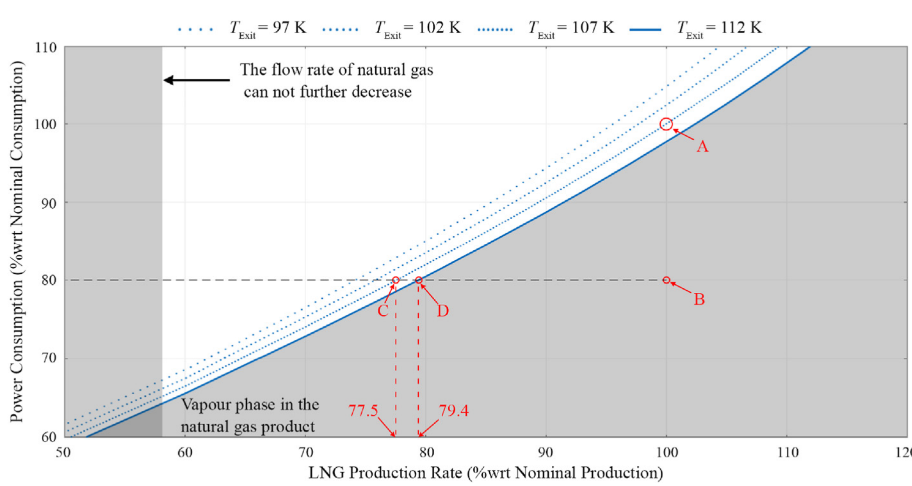

Fig. 12. Effects on the electrical power consumption (% wrt nominal value) of varying the LNG production rate (% wrt nominal value) and the LNG exit temperature (K). Each curve represents a different LNG exit temperature. The left-hand side shaded area represents the surge constraint presented in Fig. 3, and the curved shaded area represents the maximum temperature allowable in the natural gas exit stream.

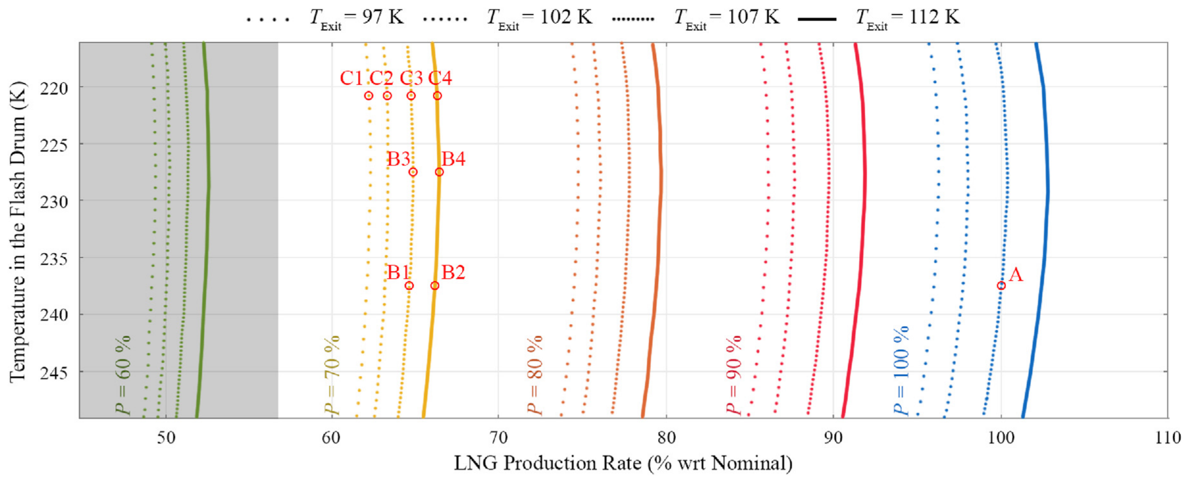

Fig. 13. Envelope of feasible operation for the LNG process. The graph represents the relationships between the temperature in the flash drum (K) and the LNG production rate (% wrt nominal value) for various levels of power consumption (% wrt nominal value) and LNG exit temperatures (K). The colours represent various levels of power consumption, and the intensity of the curves represent the exit temperature.

4.5. Verification and validation of results

Table 1 shows a comparison of values from the model against published values from Stockmann et al. [10] as the original designers of the process. The values in the model lie within the ranges specified by the designers. The LNG temperature after subcooling (stream NG6) has been adjusted to be a few degrees below the published design value, however, because industrial practice is to operate below the temperature at which the LNG will vaporize, as shown in Fig. 12.

5. Discussion of the results

Each tag in Fig. 13 represents a different operating point. Tag ‘A’ is the nominal operating point, with an LNG production rate of 15.5 kmol s^{-1}, an LNG exit temperature of 107.15 K, and a temperature in the flash drum of 238.15 K.

Fig. 13 shows contour lines for power consumption between 100% and 70% of the nominal value. If the power is to be reduced to 70% there are various alternatives:

- Changing the production rate solely (tag ‘B1’): The LNG exit temperature remains at 107.15 K, and the temperature in the flash drum at 238.15 K. The production rate has to decrease to 64.4%.
- Changing the production rate and the exit temperature (tag ‘B2’): The LNG exit temperature increases to 112.15 K and the temperature in the flash drum remains constant at 238.15 K. The production rate has to decrease to 66.2%.
- Changing the production rate and the temperature in the flash drum (tag ‘B3’): The temperature in the flash drum decreases to the minimum found in Fig. 7 (227 K) and the LNG exit temperature remains constant at 107.15 K. The production rate has to decrease to 64.6%.
- Changing the production rate, the temperature in the flash drum, and the exit temperature (tag ‘B4’): The temperature in the flash drum decreases to 227 K and the LNG exit temperature increases to 112.15 K. The production rate has to decrease to 66.5%.
- If the natural gas product must contain 95% methane, the temperature in the flash drum has to be 221 K. Tags ‘C1’ to ‘C4’ represent various levels of production rate depending on the LNG exit temperature:
  - ‘C1’ represents an exit temperature of 97 K. The production rate has to decrease to 62.2%.
  - ‘C2’ represents an exit temperature of 102 K. The production rate has to decrease to 63.2%.
  - ‘C3’ represents an exit temperature of 107 K. The production rate has to decrease to 64.7%.
  - ‘C4’ represents an exit temperature of 112 K. The production rate has to decrease to 66.3%.

Table 2 enumerates the results for various levels of power consumption. From Table 2, reducing the power consumption forces the LNG production rate to decrease. Increasing the exit temperature to 112.15 K ameliorates the production rate by an average of 2%. Decreasing the temperature in the flash drum to 227 K ameliorates the drop in production rate by an average of 0.3%. However, changing both exit temperature and temperature in the

Table 1
Comparison of model with the design values in Stockmann et al. [10].

Parameter	Industrial practice	Model
Precooling compressor discharge pressure	10–20 bar	15 bar
Liquefying compressor discharge pressure	10–20 bar	15 bar
Subcooling compressor discharge pressure	30–60 bar	35 bar
LNG temperature in flash drum (NG2)	−35C to −55C	238.15 K (−35C)
LNG temperature after liquefying (NG5)	−80C to −100C	173.15 K (−100C)
LNG temperature after subcooling (NG6)	−150C to −160C	107.15 K (−166C)
Nominal production rate	n/a	15.5 kmol s^{-1} (7.5 MTPA)
Nominal power consumption	n/a	200 MW

Table 2
Maximum achievable production rate for various levels of power consumption, when varying the operational variables of the process.

Power	Production rate	LNG Exit temperature and production rate	Temperature in the flash drum and production rate	LNG exit temperature, temperature in the flash drum and production rate
100%	100	102.4	100.4	103.1
90%	89.4	91.5	89.7	91.9
80%	77.5	79.3	77.8	79.7
70%	64.4	66.2	64.6	66.5

flash drum ameliorates the drop in production rate by an average of 2.5%. Thus, the combined effect of the two temperatures is greater than the sum of individual effects.

The reasons for this behaviour is the specific heat capacity (kJ kmol^{-1} K^{-1}) of the natural gas. Decreasing the temperature in the flash drum to 227 K changes the composition of the natural gas, which decreases the specific heat capacity in NG6. Thus, increasing the temperature in NG6 stream along with having a lower heat capacity in NG6 reduces the amount of cooling required from the subcooling refrigerant. Therefore, both effects further reduce the subcooling flow rate, and consequently, the electrical power consumption of the plant.

6. Industrial implementation

The previous section showed there is scope for operating an LNG plant flexibly to take account of a reduction in available power. The results show that the plant could feasibly operate at 70% of its nominal power consumption and thus accommodate a 30% reduction in the available power. This section discusses how such a system might be implemented.

6.1. The industrial need for flexible operation

In the authors' opinion, flexible operation can provide an attractive alternative to shutting down the plant. The time taken to restore broken circuits or to restart a tripped generator is relatively short (typically an hour or two), but it can take many days to carry out safety checks and restart a large LNG plant. Press reports from 2012 describe how a 20 min power failure caused a shutdown of several days in an LNG plant [8]. The industrial need is for a system that enables the plant to ride through the period of power reduction without shutting down. Such a system must immediately reduce the electrical power consumed by the LNG process. At the same time, the system must send new set points to the process controllers, so that the process moves towards a new steady-state operating point that is consistent with the available power. The paper has determined these operating points.

6.2. Implementation of an immediate power reduction

The motor drives must reduce the electrical power consumption of the process by the necessary amount on a time scale similar to that of a circuit breaker, typically within 200 ms. This can be achieved in a motor drive with direct torque control.

Direct torque control allows the torque delivered to the motor to change within the required time scale [46]. Since the mechanical power delivered by the electric motor is the product of torque and speed, a rapid change of torque also implies a rapid change in the electrical power consumption at the input to the drive.

Once the electrical power consumption has been reduced utilizing the fast effect of the direct torque controls, the process control system should take the process to a desired steady state compatible with the available power. It is also necessary to consider the optimum recovery back up to full speed after the electrical condition has cleared. The recovery should be smooth so that the extra transient power consumption does not overload the electrical power grid.

6.3. A plant-wide control structure for flexible operation

6.3.1. Flow rate control

Following the plant-wide control guidelines of Luyben et al. [47] the flexible LNG plant requires an independent flow controller to regulate the flow of natural gas through the process. In LNG plants, the independent flow controller is often located on the product stream and is shown in Fig. 14(b) at the lower right as FC10. When the electrical power is reduced, then this controller must receive a new set point from Table 2 for a flow rate that is consistent with the available power.

6.3.2. Ensuring an overall mass balance

The natural gas stream typically has several stages of processing before it reaches the liquefaction section. Pressure controllers on all vessels ensure a mass balance. If the pressure is kept steady, then the steady-state gas flow rates into and out of the vessel are the same. The pressure control valves must adjust the flow of gas entering each vessel, as shown in Fig. 14.

It takes a long time for the effects of a change of set point of the product flow rate to propagate upstream to PC3 and FC3. If a large set point step change in flow rate gives too large a disturbance to the upstream pressure controllers, more advanced schemes can be applied, for example by means of a feed-forward signal from the set point of controller FC10 to the FC3 flow controller. FC3 controls the flow of gas from the gas pipeline into the first stage of processing. The idea is to adjust the set point of FC3 and the position of valve PCV3 at the same time as the adjustment of FCV10. That way, the flow of natural gas into the site is adjusted at the same time as the flow out of the site. Feedforward enables an approximate mass balance to be established immediately, and any residual imbalance is taken care of by the pressure control loops such as PC2 and PC3.

6.3.3. Refrigerant flow rates

If the LNG flow rate changes, it is also necessary to adjust the flow rates of refrigerants. This would be done by means of ratio controllers. For example, the set point for the flow controller FC13 of the precooling refrigerant is adjusted proportionally to the flow rate of LNG as measured by FT10. The constant of proportionality is ratio r_{13}. By this and similar mechanisms, all refrigerant flow rates are adjusted automatically when the flow rate of the LNG changes.

6.3.4. Temperature and composition control

Adjustments to the LNG exit temperature and the flash drum temperature are achieved by adjusting the ratios between the refrigerant flow rates and the flow rate of natural gas. The output of temperature controller TC11 that controls the LNG exit temperature modifies r_{11} and r_{12}. The output of TC13, which controls the flash drum temperature, modifies the ratio r_{13}.

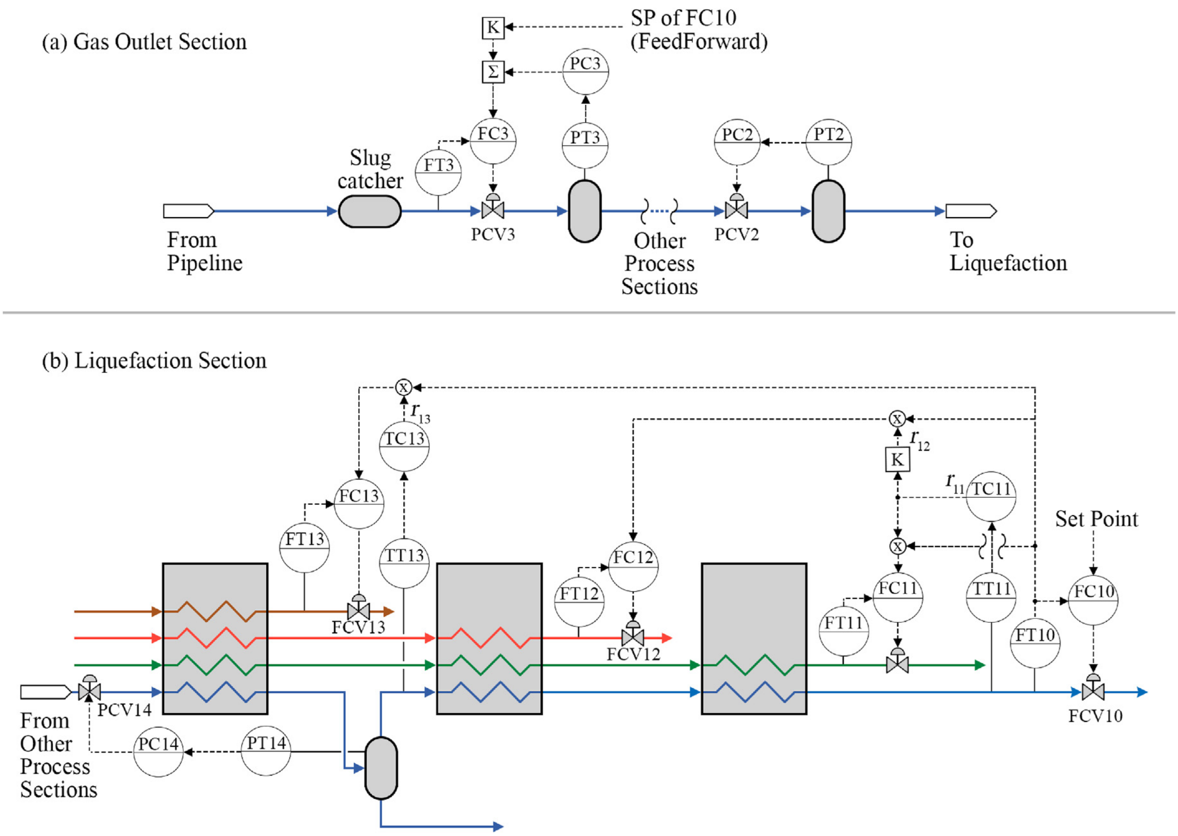

Fig. 14. Proposed plant-wide control scheme for flexible operation. (a) represents the gas outlet section containing the feedforward controller for the production rate, and (b) represents the liquefaction section studied in this paper.

6.4. Transient dynamics

6.4.1. Assumption of well-behaved transients

As discussed, a direct torque drive allows the electrical power supplied to the process to be reduced almost instantaneously. However, it takes time for the process to move to its new operating point consistent with the available electrical power because there is stored rotational energy in the compressors and stored thermal energy in the process. There is a transient period during which the excess stored energy is dissipated.

The LNG model in this paper is a static model. Therefore, there has been an assumption in the work that any dynamic transients will be well-behaved. This assumption must now be examined. Two potential problematic effects are likely to be a transient rise of temperature of the LNG stream, and the other is that the operating points of the refrigeration compressors move towards the surge line.

6.4.2. Rise in temperature of the LNG stream

If the flow rate of the natural gas stream were to reduce less rapidly than the flow rate of a refrigerant during the transient period then there would be a transient reduction of cooling of the natural gas stream. This might cause the final LNG temperature to approach the saturation point and hence not be fully liquefied.

Good control of the LNG flow rate is the key to addressing this problem. The transient effect can potentially be mitigated by the use of a feedforward controller that makes an anticipatory adjustment to the flow rate of gas entering the plant discussed in Section 6.3.2.

Fazlollahi et al. [48] and He and Ju [49] have studied the transient behaviour of an LNG plant when the plant undergoes a disturbance that affects the refrigerants or the natural gas streams. They found that the LNG did not reach the saturation temperature and attributed this to the thermal inertia of the refrigerants that was sufficient to ride through the transients. Hence, it seems a safe assumption that the anticipated transient in the LNG temperature can be managed.

6.4.3. Surge in the refrigeration compressors

A rapid reduction in the torque delivered to a compressor leads to a reduction of the rotational speed and mass flow rate through the compressor. During such a transient, the pressure ratio usually changes less quickly than the speed and mass flow rates. Therefore, the operating point of the compressor first moves to the left on the compressor map of Fig. 2 and can approach the surge line before reversing and settling at the new operating point [50]. Management of this transient will be important for industrial implementation of the proposed scheme for flexible operation.

A potential solution is to make use of an electrical drive with ride-through capability. Wymann and Jörg [46] discussed model-predictive torque control that continues to provide partial torque and speed control even during a power outage making use of rotational energy stored in the machines. These new drives have been proved to avoid compressor surge in industrial gas compressor stations when the available electrical power reduces abruptly [51]. Such technology would also be suitable for the purposes of flexible operation.

7. Implications, limitations and future work

7.1. Flexible operation of LNG

As discussed earlier, flexible operation of integrated continuous processes is a challenge requiring very careful consideration of the propagated effects of a change in available power. Our results show that the mixed fluid cascade LNG process has the operational flexibility to allow a reduction in power consumption of around 30%, (60 MW in a total of 200 MW). If one also takes into account 20–25 MW of shedding of non-essential load as identified by Khatib et al. [13] then there is scope for riding through a power reduction of more than 40% without shutting down.

The main effect of a reduction in power consumption is that the production rate of LNG is lowered. During normal operation, an LNG plant works close to maximum capacity, hence there will not be opportunities for over-producing to make up loss of product. However, the primary motivation for making use of the operational flexibility of the LNG process is to avoid a shut-down of the whole plant, which would lead to total loss of production. In terms of the duration of operating at reduced power, the main consideration will be the time taken to restore normal levels of power availability, which typically takes a few hours after an electrical contingency. Fulfilling orders would be a factor if operation at reduced power were to extend for a longer period.

7.2. Comparison with other results

Table 3 places the results in the context of quantitative results that have been reported by other researchers and industrial practitioners. The majority of the applications fall into the category of demand management, either by load shedding in response to signals from the operator of the electricity grid [25,28,29,32,33], or load shifting to take advantages of time-sensitive electricity pricing [20]. The applications of Pacheco et al. [4] and Khatib et al. [13] were for load shedding by a site power management system within an industrial site.

As discussed earlier, rapid demand response for grid balancing and frequency support is facilitated by large numbers of batch units that can operate independently of one another. Quantitative results have been reported from ALCOA [28] for an implementation in aluminium smelting showing 70 MW of reduction being provided for frequency support for the power grid. The studies by Cheng et al. in collaboration with the UK's National Grid predicted a very significant reduction of more than 85% could be available by cutting power to banks of bitumen heaters. However, when the process uses electricity for heating there is a finite duration for the power reduction because the contents of the heated pots cannot be allowed to solidify. In the case of ALCOA, the duration was about 30 min, while the bitumen pots were estimated to survive for 5 h.

Load shifting has been used successfully in air separation plants. Caspari et al. [20] demonstrated an operating range from 3.5 MW to 28 MW. Air separation is a continuous process that is flexible by design because industrial gases are utilities and the air separation plant has to meet varying demands from customers. Such a plant requires storage in order to use its flexibility to exploit time sensitive pricing. The duration of a reduction in power consumption depends on the amount of storage available.

Relevant comparisons for power management within a site are those for large-scale continuous processes. Pacheco et al. [4] described load shedding for a safe shutdown in a methanol plant, while Khatib et al. [13] discussed load shedding in an LNG production site. The main interest in both cases was an orderly shut down, and in the case of LNG, also for a partial load shedding for a small electrical contingency. The partial load shedding made use of 20 MW of non-essential load out of a total of 162 MW. Neither application considered operating the LNG process at reduced throughput.

The results of this paper compare favourably in terms of the amount and duration of power reduction. Combined with conventional load shedding in LNG, the results show that flexible operation of the LNG process has potential to ride through a reduction in available power of 30% or more. In terms of demand response, the same reduction could in principle be provided in response to signals from the operator of the power grid. This capability would be useful in the scenario described by Olsen et al. [14] where an LNG plant is located in a remote location with a weak power grid. However, LNG is not a likely candidate for demand response services in general, because these services are most easily provided by sites that have high granularity with batch rather than continuous processes.

7.3. Limitations and future work

Flexible operation of an LNG plant for power management is not straightforward because of the complexity of the process. It is a continuous process, and any reduction in power has to be spread very carefully across the whole process. It requires modern electrical drives that can reduce the power supplied to the plant on a timescale similar to that of a circuit breaker, and a process control system that will manage a transient reduction of all flow rates while maintaining mass and energy balances and respecting other constraints. Its applicability is limited compared with load shedding in highly granular plants using banks of independent batch

Table 3
Comparison with related research work, where quantitative data are available.

Authors	Industry	Application	Timescale	Power reduction
Todd et al. [28],	Aluminium smelting	Load shedding in response to signals from operator of power grid.	30 min	70 MW in 470 MW.
Kirkerud et al. [29],	Aluminium smelting	As above	not stated	25%
Hoffmann et al. [25],	Chlorine manufacture	As above	2–3 h	25% reduction or 5% increase.
Cheng et al. [32,33],	Bitumen heating	Load shedding for frequency support of UK's National Grid.	up to 5 h	Reduction from 80 MW to 10 MW.
Caspari et al. [20],	Air separation	Load shifting to exploit time-sensitive electricity prices.	not stated	Envelope of flexible operation was between 3.5 MW and 28 MW.
Pacheco et al. [4],	Methanol production	Load shedding in the site for orderly shutdown.	n/a	80% of load shed, 20% powered by emergency generator for safe shutdown.
Khatib et al. [13],	LNG production	Shedding of non-essential loads in the site.	not stated	20 MW out of 162 MW.
Current work	LNG production	Flexible operation of essential load.	hours to days	60 MW out of 200 MW.

units. On the other hand, a successful implementation would avoid shutdowns and lost production.

The main limitation of the investigation presented in this article is that the model is approximate. It is validated and shows a good match to open source industrial data, but it is generic and does not describe any specific LNG installation. Nevertheless, the model is based on sound principles of physics and chemistry. The use of a first principles model allows extrapolation to operating conditions outside the narrow envelope of normal operation. Such a model provides a quantitative examination of trends and trade-offs, and insights into the trends and trade-offs.

The model calculates steady states of the process that are compatible with various levels of available power. It is not a dynamic simulation and therefore leaves open questions for future work about the transient response as the process moves between steady operating points. The article has nevertheless given a qualitative discussion of the transient trajectories, and also discussed how possible compressor surge events can be avoided.

Industrial implementation in a specific process will require the real characteristics of the process fluids and equipment such as valves, compressors, motors and drives. The authors suggest that the next step would be to examine the feasibility of the proposed flexible operation scheme using a proprietary industrial simulator and plant experiments. The steps would be to generate and verify the process set points consistent with various levels of available power. It is also necessary to examine the dynamic behaviour and to evaluate the need for more complex control structures.

8. Conclusions

Flexible operation of an electricity-intensive process gives robustness against disturbances in the availability of electrical power. It provides an alternative to load shedding by reducing the electrical power provided to the process equipment rather than shutting down. Flexible operation has the potential to allow a process to ride through a temporary reduction of electrical power while making use of the remaining available power.

This paper presented a detailed model of a natural gas liquefaction process (LNG) based on the mixed fluid cascade refrigeration process. The research has identified operating points that are consistent with various reductions in the available power supplied to the refrigeration compressors. Key process variables are the LNG production rate, LNG temperature at the exit of the process, and the LNG composition. Results from the model show that the LNG process can readily accommodate a 30% reduction in available power while staying within its operating limits.

The results give process set points for each reduction in power. A flexible operation system must send these new set points to the process controllers so that the plant moves to a new steady state that is consistent with the available power. The main effect of a reduction of available power is that the LNG production rate decreases. However, for a given power level, it is possible to mitigate the reduction in production rate by means of adjustments to the LNG purity and the exit temperature of the LNG product.

The reduction in the electrical power provided to the process must happen fast, on a time scale similar to that of a circuit breaker. The paper has identified electrical drive technology that can achieve this requirement. At the same time, the process controllers receive the new set points and the plant starts to move towards the new steady state that is compatible with the power being provided to the plant. The paper has proposed a plant-wide control structure for this purpose.

The overall conclusion is that flexible operation of an LNG process is feasible and would enable such a process to remain operational during a partial loss of electricity supply.

Author credits

Ivan Ying Xuan: Conceptualization, Formal analysis, Methodology, Writing – original draft, Artwork. **Charlotte Skourup:** Supervision, Reviewing and editing, Resources, Funding acquisition. **Jørgen B Jensen:** Formal analysis, Methodology, Reviewing and editing. **Trond Haugen:** Conceptualization, Methodology, Reviewing and editing. **Nina F Thornhill:** Conceptualization, Writing, Reviewing and editing, Supervision, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors are grateful to Jan Wiik and Stein Trostheim of ABB AS for discussions and insights concerning industrial implementation. This work was supported by ABB under the ABB Imperial College Strategic Alliance framework. The first author gratefully acknowledges full financial support for his PhD from ABB.

References

[1] Clemente J. The world's liquefied natural gas market is roaring back. 2021. https://www.forbes.com/sites/judeclemente/2021/06/04/the-worlds-liquefied-natural-gas-market-is-roaring-back/. [Accessed 12 February 2022].
[2] Freeport LNG. eLNG means electric and eco-friendly. 2022. https://freeportlng.com/our-business/elng. [Accessed 12 February 2022].
[3] Skiebe R. All-electric LNG maximizes process control in the arctic. 2020. https://assets.siemens-energy.com/siemens/assets/api/uuid:88cb7d7c-548a-4d8d-b46e-93540d20ddd2/gp-mar-apr2020-electric-lng-article.pdf. [Accessed 12 February 2022].
[4] Pacheco F, Refaat H, Pescosolido D. Power management system in an industrial plant. In: Petroleum and Chemical Industry Conference (PCIC); 2012. p. 1–7. https://doi.org/10.1109/PCICON.2012.6549640.
[5] Ravikumar KG, Alghamdi T, Bugshan J, Manson S, Raghupathula SK. Complete power management system for an industrial refinery. In: IEEE Petroleum and Chemical Industry Conference (PCIC); 2015. p. 1–9. https://doi.org/10.1109/PCICON.2015.7435114.
[6] Shoreh MH, Siano P, Shafie-khah M, Loia V, Catalão JP. A survey of industrial applications of demand response. Elec Power Syst Res 2016;141:31–49. https://doi.org/10.1016/j.epsr.2016.07.008.
[7] Kim K, Cho Y. Estimation of power outage costs in the industrial sector of South Korea. Energy Pol 2017;101:236–45. https://doi.org/10.1016/j.enpol.2016.11.048.
[8] Anon. Hammerfest LNG shut after power failure. 2012. http://www.equinor.com/en/news/archive/2012/11/19/Nov19HammerfestLNG.html [Accessed 27 March 2022].
[9] Mohd Noor I, Thornhill NF, Fretheim H, Thorud E. Quantifying the demand-side response capability of industrial plants to participate in power system frequency control schemes. In: 2015 IEEE Eindhoven PowerTech; 2015. p. 1–6. https://doi.org/10.1109/PTC.2015.7232363.
[10] Stockmann, R., Forg, W., Bolt, M., Steinbauer, M., Pfeiffer, C., Paurola, P., Fredheim, A.O., and Sorensen, O., Method for liquefying a stream rich in hydrocarbons 2001. US Patent 6,253,574 B1.
[11] Linde AG. LNG technology. Optimised solutions for small- to world-scale plants. Pullach, Germany: Linde AG: Engineering Division; 2018. https://www.linde-engineering.com/en/images/LNG-technology_tcm19-4577.pdf.
[12] Singh S, Ristanovic D, Bhatia N, Murray M. Engineering and execution challenges in power management system implementation for industrial power systems. In: IEEE Petroleum and Chemical Industry Conference (PCIC); 2016. p. 1–9. https://doi.org/10.1109/PCICON.2016.7589214.
[13] Khatib A, Mallya D, Dai B, Costa R. Turbine load-sharing and load-shedding system for an Australian LNG facility. In: IEEE Petroleum and Chemical Industry Conference (PCIC); 2019. p. 1–9. https://doi.org/10.1109/PCIC30934.2019.9074511.
[14] Olsen R, Gabrielsen GB, Breidablik y, Geerts WH. Smart grid solution applied in an E-LNG plant, Dynamic System Protection Scheme (DSPS) in weak national grids. In: Petroleum and Chemical Industry Conference Europe (PCIC Europe); 2013. p. 1–8. https://ieeexplore.ieee.org/xpl/conhome/6573519/proceeding.
[15] Sapari N, Mokhlis H, Laghari J, Bakar A, Dahalan M. Application of load shedding schemes for distribution network connected with distributed generation: A review. Renew Sustain Energy Rev 2018;82:858–67. https://doi.

org/10.1016/j.rser.2017.09.090.
[16] Van der Wal O, Haugen T, Holsten PE, Lems F. Not on my watch. How ABB's power management system prevents multi million dollar shutdowns. ABB Rev Issue 3 2005:31–5. https://library.e.abb.com/public/718f71033e668575c125707b004a7fc3/31-35%203M546_ENG72dpi.pdf.
[17] Bevrani H, Golpîra H, Messina A, Hatziargyriou N, Federico Milano F, Ise T. Power system frequency control: An updated review of current solutions and new challenges. Elec Power Syst Res 2021;194:107114. https://doi.org/10.1016/j.epsr.2021.107114.
[18] Mitra S, Grossmann IE, Pinto JM, Arora N. Optimal production planning under time-sensitive electricity prices for continuous power-intensive processes. Comput Chem Eng 2012;38:171–84. https://doi.org/10.1016/j.compchemeng.2011.09.019.
[19] Merkert L, Harjunkoski I, Isaksson A, Säynevirta S, Saarela A, Sand G. Scheduling and energy – industrial challenges and opportunities. Comput Chem Eng 2015;72:183–98. https://doi.org/10.1016/j.compchemeng.2014.05.024.
[20] Caspari A, Offermanns C, Schäfer P, Mhamdi A, Mitsos A. A flexible air separation process: 1. Design and steady-state optimizations. AIChE J 2019. https://doi.org/10.1002/aic.16705.
[21] Lund H. Renewable energy strategies for sustainable development. Energy 2007;32:912–9. https://doi.org/10.1016/j.energy.2006.10.017.
[22] Lannoye E, Flynn D, O'Malley M. Evaluation of power system flexibility. IEEE Trans Power Syst 2012;27(2):922–31. https://doi.org/10.1109/TPWRS.2011.2177280.
[23] Holttinen H, Tuohy A, Milligan M, Lannoye E, Silva V, Müller S, et al. The flexibility workout: Managing variable resources and assessing the need for power system modification. IEEE Power Energy Mag 2013;11(6):53–62. https://doi.org/10.1109/MPE.2013.2278000.
[24] Dranka G, Ferreira P. Review and assessment of the different categories of demand response potentials. Energy 2019;179:280–94. https://doi.org/10.1016/j.energy.2019.05.009.
[25] Hoffmann C, Hübner J, Klaucke F, Milojević N, Müller R, Neumann M, Weigert J, Esche E, Hofmann M, Repke JU, Schomäcker R, Strasser P, Tsatsaronis G. Assessing the realizable flexibility potential of electrochemical processes. Ind Eng Chem Res 2021;60(37):13637–60. https://doi.org/10.1021/acs.iecr.1c01360.
[26] Samad T, Kiliccote S. Smart grid technologies and applications for the industrial sector. Comput Chem Eng 2012;47:76–84. https://doi.org/10.1016/j.compchemeng.2012.07.006.
[27] Bruns B, Di Pretoro A, Grünewald M, Riese J. Indirect demand response potential of large-scale chemical processes. Ind Eng Chem Res 2022;61(1):605–20. https://doi.org/10.1021/acs.iecr.1c03925.
[28] Todd D, Caufield M, Helms B, Starke M, Kirby B, Kueck J. Providing reliability services through demand response: A preliminary evaluation of the demand response capabilities of Alcoa Inc. 2009. Technical report ORNL/TM-2008/233. Oak Ridge National Laboratory, http://info.ornl.gov/sites/publications/files/Pub13833.pdf. [Accessed 12 February 2022].
[29] Kirkerud J, Nagel NO, N, Bolkesjø T. The role of demand response in the future renewable northern European energy system. Energy 2021;235:121336. https://doi.org/10.1016/j.energy.2021.121336.
[30] Paulus M, Borggrefe F. The potential of demand-side management in energy-intensive industries for electricity markets in Germany. Appl Energy 2011;88(2):432–41. https://doi.org/10.1016/j.apenergy.2010.03.017.
[31] Hadera H, Harjunkoski I, Sand G, Grossmann I, Engell S. Optimization of steel production scheduling with complex time-sensitive electricity cost. Comput Chem Eng 2015;76:117–36. https://doi.org/10.1016/j.compchemeng.2015.02.004.
[32] Cheng M, Wu J, Galsworthy S, Ugalde-Loo C, Gargov N, Hung W, Jenkins N. Power system frequency response from the control of bitumen tanks. IEEE Trans Power Syst 2016;31:1769–78. https://doi.org/10.1109/TPWRS.2015.2440336.
[33] Cheng M, Wu J, Galsworthy S, Gargov N, Hung W, Zhou Y. Performance of industrial melting pots in the provision of dynamic frequency response in the Great Britain power system. Appl Energy 2017;201:245–56. https://doi.org/10.1016/j.apenergy.2016.12.014.
[34] Gholian A, Mohsenian-Rad H, Hua Y, Qin SJ. Optimal industrial load control in smart grid: A case study for oil refineries. In: 2013 IEEE Power and Energy Society General Meeting; 2013. p. 1–5. https://doi.org/10.1109/PESMG.2013.6672710.
[35] Brodal E, Jackson SR, Eiksund OR. Performance and design study of optimized LNG mixed fluid cascade processes. Energy 2019;189:116207. https://doi.org/10.1016/j.energy.2019.116207.
[36] Xuan IY, Pretlove J, Haugen T, Thornhill NF. Determining the minimum energy requirement of an LNG process: New insights into the impact of the vapour liquid equilibrium. Energy 2020b;203:117785. https://doi.org/10.1016/j.energy.2020.117785.
[37] Ding H, Sun H, Sun S, Chen C. Analysis and optimisation of a mixed fluid cascade (MFC) process. Cryogenics 2017;83:35–49. https://doi.org/10.1016/j.cryogenics.2017.02.002.
[38] Xu X, Liu J, Cao L, Pang W. Automatically varying the composition of a mixed refrigerant solution for single mixed refrigerant LNG (liquefied natural gas) process at changing working conditions. Energy 2014;64:931–41. https://doi.org/10.1016/j.energy.2013.10.040.
[39] Poling BE, Prausnitz JM, O'Connell JP. The properties of gases and liquids. Fifth ed. Boston: McGraw-Hill; 2000.
[40] Nieto R, González M, López I, Rodríguez J. Termodinámica. Second ed. Universidad Politécnica de Madrid; 2013.
[41] Soave G. Equilibrium constants from a modified Redlich-Kwong equation of state. Chem Eng Sci 1972;27(6):1197–203. https://doi.org/10.1016/0009-2509(72)80096-4.
[42] Soave G, Gamba S, Pellegrini LA. SRK equation of state: predicting binary interaction parameters of hydrocarbons and related compounds. Fluid Phase Equil 2010;299(2):285–93. https://doi.org/10.1016/j.fluid.2010.09.012.
[43] Rachford H, Rice D. Procedure for use of electronic digital computers in calculating flash vaporization hydrocarbon equilibrium. J Petrol Technol 1952;195(2):327–8. https://doi.org/10.2118/952327-G.
[44] Miller AS. Compressor conceptual design optimization.. Master's thesis. Georgia Institute of Technology; 2015. http://hdl.handle.net/1853/53598.
[45] Xuan IY, Pretlove J, Haugen T, Thornhill NF. Data set: determining the minimum energy requirement of an LNG process: New insights into the impact of the vapour liquid equilibrium. 2020. https://doi.org/10.5281/zenodo.3831441.
[46] Wymann T, Jörg P. Power loss ride-through in a variable speed drive system. In: Petroleum and Chemical Industry Conference Europe (PCIC Europe); 2014. p. 1–9. https://doi.org/10.1109/PCICEurope.2014.6900057.
[47] Luyben ML, Tyreus BD, Luyben WL. Plantwide control design procedure. AIChE J 1997;43(12):3161–74. https://doi.org/10.1002/aic.690431205.
[48] Fazlollahi F, Bown A, Ebrahimzadeh E, Baxter LL. Design and analysis of the natural gas liquefaction optimization process - CCC-ES (Energy Storage of Cryogenic Carbon Capture). Energy 2015;90:244–57. https://doi.org/10.1016/j.energy.2015.05.139.
[49] He T, Ju Y. Dynamic simulation of mixed refrigerant process for small-scale LNG plant in skid mount packages. Energy 2016;97:350–8. https://doi.org/10.1016/j.energy.2016.01.001.
[50] Tveit GB, Bakken LE, Bjørge T. Compressor transient behaviour. In: ASME Turbo Expo; 2004. p. 813–21. https://doi.org/10.1115/GT2004-53700.
[51] Fretheim H, Van De Moortel S. Battling severe winters. World Pipelines 2017;17(12):76–80. https://www.worldpipelines.com/magazine/world-pipelines/december-2017/.