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Retrospective and predictive optimal scheduling of nitrogen liquefier units and the effect of renewable generation

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HIGHLIGHTS

- Development of a binary program to optimally schedule flexible power loads.
- Retrospective optimisation to generate a scheduling key performance indicator.
- Discovery of renewable generation and spot market correlations for early 2017.
- Predictive optimisation of power loads using power pricing forecasts.

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ABSTRACT

The construction and application of a multiple nitrogen liquefier unit (NLU) optimal scheduling tool is discussed. Constrained by customer demands and subject to electricity spot market prices over a week-ahead horizon, a retrospective optimiser (RO) determines the minimum scheduling costs. Plant start-up penalties and inter-site optimisation capabilities are incorporated into the optimisation model to emulate realistic operational flexibilities and costs. Using operational data, actual process schedules are compared to the RO results leading to improved process scheduling insights; such as increasing afternoon NLU operation during the spring to utilise lower power pricing caused by high solar generation. The RO is used to output a trackable load management key performance indicator to quantify potential and achieved scheduling improvements. Subsequently, correlations between renewable energy generation and spot market power prices are developed. Forecast pricing is used within a predictive optimiser (PO) to automatically generate an optimal schedule for the week ahead to meet projected customer demands. The RO provides potential hindsight savings of around 11%, and the PO up to 8% (representing significant cost savings for such energy intensive processes).

1. Introduction

Cryogenic air separation and the subsequent liquefaction of gaseous products is highly energy intensive, with process optimisation and optimal scheduling of power loads critical to minimise costs, see Adamson et al. [1]. Where power loads are flexible, Merkert et al. [2] describe demand side management (DSM) strategies which reallocate power usage from a period of peak power price to another at a lower off-peak price to reduce overall costs. Load scheduling strategies can be adopted by companies to lower costs whilst maintaining the same production volumes rather than carrying out temporary energy reduction activities detrimental to production. Most DSM activities introduce process inefficiencies, such as additional process starts and stops, but can minimise overall costs by avoiding peak power pricing consumption.

Driven by financial motivations alone, many studies have been conducted to research optimal scheduling practises for air separation processes. Daryanian et al. [3] design an optimal operation scheduler for a week-ahead horizon with two key assumptions; (a) that hourly spot electricity prices are known, and (b) no additional energy costs are associated with start-up transitional modes. They compare the results to uniform plant scheduling with average spot pricing, revealing that varying production rate yields economic benefits. Similarly, Ierapetritou et al. [4] determine an optimal schedule for air separation processes in real-time pricing (RTP) environments, improving flexibility by considering pricing changes using a mixed integer linear programming (MILP) model implemented within a commercially available solver. By assuming electricity prices are known for the initial periods (days) of a time horizon, an autoregressive integrated moving average (ARIMA)

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Nomenclature

Abbreviations

ADRL	autoregressive distributed lag
ASU/s	air separation unit/s
DSM	demand side management
LMP	load management plan
MILP	mixed integer linear programming
NW	network wide
PO	predictive optimiser
RTP	real time pricing

Parameters

β	optimiser score (MW h)
Δ	variation from average (generation, price)
I_p	inter-site optimisation penalty (£)
J	cost function (£)
N	number of (time periods or NLUs)
R^2	coefficient of determination (%)
μ	average

Variables

δ	start-up binary coefficient
z	start-up coefficient

Subscript/Superscripts

A	actual NLU operation
int	inter-site optimisation
NW	network wide
ren	renewable generation source
t	discrete time point
$*$	optimal
ARIMA	autoregressive integrated moving average
KPI/s	key performance indicator/s
LN	liquid nitrogen
NLU/s	nitrogen liquefier unit/s
OS	optimiser score
RO	retrospective optimiser
TOU	time of use
C_{MW}	spot power cost (£/MW h)
G	renewable penetration (%)
NW_{sav}	network-wide savings (%)
P	power demand (MW h)
w	binary NLU running coefficient
ab	abortive start-up cost
j	NLU number
p	start-up power penalty
$solar$	solar generation
$wind$	wind generation
$\hat{}$	model

model can be developed to forecast prices for subsequent periods, assuming pricing can be explained by past values and the modelling error. Despite a maximum forecast accuracy of around 70%, simulation studies demonstrate that the forecasts were still effective at producing a near-optimal operating schedule due to following the pricing trends qualitatively rather than exactly quantitively. Karwan and Keblis [5] deploy a similar rolling time horizon model to Ierapetritou et al. [4] concurring that unless plant utilisation is very high, optimal scheduling in a RTP environment often provides economic benefits. By participating in additional demand side response and grid run energy market schemes, scheme incentives can be added as cost savings to further boost the distribution network profits of optimal scheduling, Zhang et al. [6].

Mitra et al. [7] generalise previous RTP optimal scheduling approaches by creating a deterministic discrete-time MILP model that allows optimal production planning whilst incorporating transitional plant models. Discrete-time formulations may not be fully representative of actual process dynamics the solution inevitably approximates the real optimal schedule), but MILP approaches are easy to solve with allocation of resource units to tasks and the costs calculated linearly, Floudas and Lin [8]. Applied to an air separation unit ASU) simulation using a commercial solver, the results estimated cost savings between 3.76% to 13.78% with the largest savings at lower plant utilisations. Model robustness is improved for suitability in situations where spot electricity prices are uncertain, see Mitra et al. [9], by deploying a historical pricing correlation to modify an uncertainty set, as proposed by Duzgun and Thiele [10]. Zhu et al. [11] argue that the multiple scenario approach adopted by Karwan and Keblis [5] and Ierapetritou et al. [4] generates results that are too conservative to be deemed optimal, as customer demands must be met over all scenarios. Instead, they develop a non-linear model using probabilistic constraints, where simulation case-studies trade-off profit maximisation whilst considering a tangible customer satisfaction index.

Most articles in literature consider optimisation of whole air separation processes leading to the use of thousands of variables and constraints, and the requirement for commercial solvers on dedicated processors. In previous work, see Adamson et al. [12] and Adamson et al. [1], we develop strategies to model and minimise power consumption of a network of ASUs and compressors in real-time primarily to meet customer demand requirements using minimal computational requirements. In this paper, we propose a higher-level optimal scheduling approach which enables ideal DSM of external nitrogen liquefier units (NLUs) supplied by gaseous pure nitrogen from ASUs. Firstly, we design a retrospective optimiser (RO) to combine industrial operational data with grid generation data and spot market power pricing to retrospectively analyse current DSM technique effectiveness. Then, we develop a novel predictive optimiser (PO) using power pricing forecasts generated from correlations between renewable generation data and spot market power pricing. The RO and PO tools are developed using free to use and accessible software, enabling operators to track and improve load management of large power loads for cost reductions. As opposed to previous work, we consider the required running hours, time of use (TOU), start-up transitional mode costs and inter-site transfers of liquid product to deliver a true estimate of the potential DSM savings.

Retrospective analysis has been undertaken extensively in fields such as medicine, aviation and professional sports, see Croos-Dabrera et al. [13], Dambier and Hinkelbein [14] and Lewis et al. [15]. This approach has been proved effective in preventing aviation disasters, where black box analysis and learning has created an exceptional safety record, see Syed [16]. However, retrospective learning techniques are not typically utilised by the operational aspects of the process industries. By applying retrospective analysis techniques to the results obtained from the RO, it is demonstrated that a better understanding of optimal scheduling can be developed to enable less conservative scheduling. The RO results are compared to the actual NLU schedule in hindsight to produce a DSM key performance indicator (KPI) for process scheduling. Retrospective analysis is carried out to compare the RO results to factors known to effect power pricing such as the time of day or increasing influence of renewable generation.

The increasing penetration of unpredictable and intermittent renewables, such as wind and solar PV, has led to renewable generation

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