Optimal scheduling of an integrated biogas-cogeneration system with flexible fuel management

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Abstract

The share of renewable energy resources for electricity generation is growing with the deepening of the penetration of intermittent, weather-dependent sources, which is leading to a transformation of demand and supply patterns. In order to compensate this variability in the power balance, a promising alternative is bioenergy. Traditionally, biogas digesters have been designed to provide a continuous supply of biogas. This implies that electricity generation from biogas is no more dispatchable than other non-dispatchable renewable sources like wind and solar power. Nonetheless, there are ways to make bioenergy capable to modulate its power output to provide grid support services (e.g., load following) and possibly capitalise on peak electricity market prices. This can be achieved through the flexibilization of power generation by making use of substrate management, biogas storage, capacity increases to cogeneration systems or upgradation of biogas to biomethane. In order to do so, there is a need to develop a comprehensive framework to link the downstream process of meeting power generation targets to the upstream process of biogas production. This unifying model needs to consider the mechanisms of the various biochemical pathways along with the performance characteristics of typical cogeneration units. In response to this need, in this thesis, we propose an integrated mixed-integer linear programming (MILP) model formulation for operational planning of a typical biogas-fired power plant.

The framework modelled in this thesis considers flexibility in terms of variable gas production through infeed management, storage of biogas (to defer the biogas supply to times of high demand), ramping and heat-to-power ratio of multi-energy systems. Given that the process of anaerobic digestion is characterised by a high level of complexity and sensitivity to substrate characteristics and operating conditions, there needs to be a trade-off between the accuracy and the extensive parameters required for modelling purposes. To this end, we develop the model on three modifications of the sigmoid function which not only reduce the dependence of the model on numerous parameters, but also the approach of developing the model makes it linear as a whole. This upstream model is linked to a biogas storage and a cogeneration system through a linear balance equation. We adopt a data-driven approach to model the cogeneration aspect of our framework and also propose the use of extraction maps to indirectly model the variability of heat-to-power ratios. The proposed modelling technique can be utilised in two ways. Firstly, it can be used to determine the

optimal time-of-feed, quantity-of-feed and biogas storage level to meet the optimal generating schedule of a cogeneration system located at the gas production site. Secondly, it can be used to assess the economic benefit of the various flexibilization techniques to determine the best strategy for a particular plant. Several scenarios are thus investigated, and the results are demonstrated for not only the individual components of the framework but also the integrated structure as a whole.

Abrégé

La croissance de la proportion des énergies renouvelables dans la production d'électricité s'accompagne d′une augmentation de la pénétration de sources d'énergie intermittentes, tributaires des conditions météorologiques, ce qui entraîne une transformation des modèles de l'offre et de la demande. Une alternative prometteuse permettant de compenser cette variabilité dans l'équilibre production-consommation est la bioénergie. Traditionnellement, les digesteurs de biogaz ont été conçus pour fournir un approvisionnement continu en biogaz. Cela implique que la production d′électricité à partir de biogaz n′est pas plus contrôlable que d′autres sources renouvelables non répartissables telles que l′énergie éolienne et solaire. Néanmoins, il existe des moyens de rendre la bioénergie capable de moduler sa production d′électricité afin de fournir des services d′assistance au réseau (par exemple, le suivi de charge) et éventuellement de tirer profit des prix de pointe du marché de l′électricité. Cet objectif peut être atteint grâce à la flexibilisation de la production d'électricité grâce à la gestion du substrat, au stockage de biogaz, à l'augmentation de la capacité des systèmes de cogénération ou à la valorisation du biogaz en biométhane. Pour ce faire, il est nécessaire "élaborer un cadre global permettant de relier le processus en aval visant à atteindre les objectifs de production d'ènergie au processus en amont de la production de biogaz. Ce modèle unificateur doit prendre en compte les mécanismes des différentes voies biochimiques ainsi que les caractéristiques de performance des unités de cogénération typiques. En réponse à ce besoin, nous proposons dans cette thèse une formulation d′optimisation linéaire à nombres entiers mixtes (MILP) pour la planification opérationnelle d′une centrale typique alimentée au biogaz.

Le cadre modélisé dans cette thèse prend en compte la flexibilité en termes de production variable de gaz via le contrôle de l′entrée de la centrale, le stockage du biogaz (pour différer l′approvisionnement en biogaz en périodes de forte demande), la montée en puissance et le rapport chaleur / puissance des systèmes multi-énergie. Étant donné que le processus de digestion anaérobie se caractérise par un niveau élevé de complexité et de sensibilité aux caractéristiques du substrat et aux conditions de fonctionnement, il convient de trouver un compromis entre la précision et les nombreux paramètres requis pour la modélisation. À cette fin, nous développons le modèle sur trois modifications de la fonction sigmoïde qui non seulement réduisent la dépendance du modèle à de nombreux paramètres, mais également

rendent linéaire l'approche de développement du modèle dans son ensemble. Ce modèle en amont est lié à un système de stockage de biogaz et à un système de cogénération au moyen d'une équation d'équilibre linéaire. Nous adoptons une approche orienté données pour modéliser l'aspect cogénération de notre étude et proposons également l'utilisation de cartes d'extraction pour modéliser indirectement la variabilité des rapports chaleur / puissance. La technique de modélisation proposée peut être utilisée de deux manières. Tout d′abord, elle peut être utilisée pour déterminer le moment optimal d′alimentation, la quantité d′alimentation et le niveau de stockage du biogaz afin de respecter le calendrier de production optimal d′un système de cogénération situé sur le site de production de gaz. Ensuite, elle peut être utilisée pour évaluer les avantages économiques des différentes techniques de flexibilisation afin de déterminer la meilleure stratégie pour une centrale donnée. Plusieurs scénarios sont ainsi étudiés et les résultats sont démontrés non seulement pour les composants individuels de l'étude mais également pour la structure mixte dans son ensemble.

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List of Acronyms

AD	Anaerobic digestion
ADM1	Anaerobic digester model 1
CHP	Combined heat and power
CS	Cattle slurry
DyBim	Dynamic biogas model
GS	Grass silage
GT	Gas turbine
HRSG	Heat recovery steam generator
HRT	Hydraulic retention time
LP	Linear programming
MILP	Mixed integer linear programming
MINLP	Mixed integer non-linear programming
OLR	Organic loading rate
RES	Renewable energy sources
SBS	Sugar beet silage
ST	Steam turbine
UC	Unit commitment

List of Symbols

Indices

s	Type of substrates
t	Time step of the operating horizon
$\tilde{t}$	Time step for feed insertion
k	Index of breakpoints for lambda method
n	Index of cogeneration units

Parameters

k_s^a, k_s^f, k_s^{sl}, k^c	Kinetic rate constants for the biochemical reactions of substrate s
V_s^{max}	Maximum biomethane potentialof substrate s
X	Fraction of readily degradable part to the total quantity of feed
ρ_s	Density of substrate s
S_s	Volume of substrate s
H^{min}	Minimum hydraulic retention time
OLR^{max}	Maximum organic loading rate
TS_s	Total solids in substrate s
VS_s	Volatile solids in substrate s

ν	Maximum volumetric capacity of digester
M_l^{mc}	Maximum digester capacity for solid intake
$M^{constant}$	Constant quantity of feed
$Store^{max}$	Maximum volumetric biogas storage capacity
γ^l	Biogas leakage rate
ϵ	Energy density of methane
η	Efficiency of cogeneration system
θ^r	Heat-to-power ratio of cogeneration system
$\hat{c}_s^{sub}$	Cost of substrate s
$\hat{p}_t^s$	Spot market price at t
m_1, m_2	Slopes depicting the operating region in extraction maps
r_1, r_2	Boundary intercepts for extraction maps
F_n^{max}	Maximum fuel capacity for cogeneration unit n
r^h	Ratio of heat generated to the total process steam extracted
$\overline{E}_n$	Maximum electrical generation capacity of unit n
$\overline{Q}_n$	Maximum heat generation capacity of unit n
$\underline{E}_n$	Minimum electrical generation capacity of unit n
$\underline{Q}_n$	Minimum heat generation capacity of unit n
RU_n	Maximum allowable upward ramp for steam turbine of unit n
RU_n^{st}	Maximum allowable upward ramp at start for steam turbine unit n
RD_n	Maximum allowable downward ramp for steam turbine unit n
RD_n^{sd}	Maximum allowable downward ramp at shutdown for steam turbine unit n

UT_n	Minimum up-time for unit n
DT_n	Minimum down-times for unit n
$\hat{c}_n^{st}$	Start-up cost for unit n
$\hat{c}_n^{sd}$	Shut-down cost for unit n
$\hat{c}_n^{m}$	Maintenance cost for unit n
$\hat{c}_n^{f}$	Cost of generation in cogeneration system n

Variables

$\alpha_{n,k,t}$	Continuous variable associated with breakpoint k of unit n at time t
v_t^{in}	Incoming volume of a biogas storage at t
v_t^{out}	Outgoing volume of a biogas storage at t
$v_{s,t}$	Volume of methane produced by substrate s at t
$e_{n,t}$	Electrical power generation of unit n at t
$f_{n,t}$	Fuel consumption of unit n at t
$q_{n,t}$	Heat generation of unit n at t
$M_{s,\tilde{t}}$	Quantity of infeed of substrate s at time $\tilde{t}$
C_s^{sub}	Cost of utilisation of substrate s
P_t	Income from spot market sales at t
C_t^{st}	Total start-up costs at time t
C_t^{sd}	Total shut-down costs at time t
C^{gt}	Cost of generation of power at time t
$Store_t$	Storage level utilised at time t
u_t	Binary variable, which is 1 if a unit is running at time t

u_t^{st} Binary variable, which is 1 if a unit is committed at time t

u_t^{sd} Binary variable, which is 1 if a unit is decommitted at time t

Functions

$\vartheta_1(.)$ Non-linear electrical generation characteristic of a gas turbine

$\vartheta_2(.)$ Non-linear heat generation characteristic of a gas turbine

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Chapter 1

Introduction

1.1 Background

Worldwide, the energy ecosystem is in the midst of a major paradigm shift, with the share of renewable energy sources (RES) expected to increase to 12.4 % by 2023 [1]. This transition from a well-established fossil fuel-based power sector is driven by a strong narrative of global climate change and reducing the carbon footprint. Ambitious goals as those elaborated in the Paris Agreement [2] have brought together more than 195 countries to integrate renewable energy sources in their energy landscapes. The International Energy Agency forecasts that 70% of the global electricity generation growth would be met by renewables by 2030, with hydropower meeting 16 % of the total electricity demand, trailed by wind (6%), solar photo-voltaic (4%) and bioenergy (3%). Such a high share of weather-dependent, intermittent RES should give rise to a highly fluctuating supply profile which calls for increase in accuracy of meteorological forecasts, modifications in power products and market conditions, expansion of the power grid and reshaping the existing one, refinements in the energy policies and a holistic improvement of the energy technologies, both renewable and non-renewable [3].

An increase in bioenergy adoption in the power market holds substantial promise as an alternative. Not only is bioenergy production unaffected by hourly meteorological changes it is also easily storable and an effective waste management tool. The conventional usage of biogas plants entails a continuous production which is either processed and then sold in gas form or burnt to generate heat and/or electricity. In the wake of temporal fluctuations in market conditions and prices, it is reasonable to assume that this approach is economically suboptimal. In fact, studies have found a positive correlation between financial policies and adoption of biogas as a major source of energy. As of 2016, the leading producer of biogas power in the world, Germany, had 9004 biogas installations with a total installed capacity of 4116 MW power, contributing to almost 9% of gross energy supplied [4] mainly because of flexibility premium [1] and fixed feed-in tariffs. Fiscal incentives to use biogas as vehicular fuel in countries like Sweden and feed-in tariffs in the UK have indeed prompted more usage of bioenergy [5]. It is reasonable to assert that disrupting the status quo by opting for a demand-oriented *flexible* biogas production is not only an economically prudent perspective [6] but also fundamental in compensating the increasing volatility due to other renewable resources.

Defining flexibility in electricity generation

Before discussing the various aspects of flexible biogas production, it is important to define *flexibility* in the context of energy systems. A broad definition of the term would be "the extent to which a power system can modify its electricity production and consumption, in response to variability, expected or otherwise" [7]. Several definitions of *operational flexibility* insist on the availability of "the ramping capacity of a system to meet the changes in load" [8], within the purview of system stability and "pre-determined cost thresholds" [9]. Thus, flexibility conceptualises the idea of *matching* the load with supply over all temporal and spatial units and can be categorised as demand-side management and supply side flexibility (by installing additional storage devices or modifying the operation of the generation units).

To modulate the flexibility of a biogas power plant, there are several levers at the designers' and operators' disposal. They include: substrate type and feeding management, the choice of biochemical methods implemented, facility for upgradation of biogas to biomethane on-site, biogas storage systems, type and capacity of fuel conversion engines [10]. *Substrate management* refers to "influencing and managing the amount and type of substrate en-

[1] *Flexibility premium* is a fiscal incentive given to biogas plants in Germany for stipulated excess production. This policy, introduced in 2012, is meant to encourage investments in expansion of biogas plant capacities.

tering the biogas plant, as different substrate types can be added at different time points and in different amounts to generate the expected gas output" [3]. Such modifications in *time-of-feed* and *quantity-of-feed* are made, at present, on a seasonal basis. Reference [11] introduces the concept of *multifactorial* substrate management, wherby the the insertion of substrates are done to enable continuous utilisation of gas for predefined blocks of time, when the average demand for gas is higher[2]. In [11–13], it is shown that infrequent feeding of substrates (as opposed to continuous feeding) at the stipulated intervals reduces storage requirements by about 45 %, albeit at the cost of additional power generation capacity. This reduction in storage is enabled by production of biogas mostly during times of high electricity prices and its subsequent utilisation as soon as it is produced. The authors in [14] present another interesting approach for making the operation of a biogas digester flexible, which involves upgrading[3] the biogas to biomethane followed by injection into the biomethane grid, which branches out into several utilisation channels like production of electricity and heat at both onsite and offsite cogeneration plants, utilisation as vehicular fuel and also being used as a major input material in certain chemical industries. This topology, thereby, reduces the onsite storage requirements of biogas by allowing dissociation of production and utilisation of biogas. Another approach to dynamic demand-oriented feeding is proposed in [16] where discontinuous feeding in fixed-bed reactors is studied by influencing the biochemical process of anaerobic digestion in three different ways. Even though the results are promising, mass adoption of fixed-bed technology as opposed to continuously stirred-tank reactors will require substantial financial incentives and further studies to analyse the scalability of the obtained results because of the high-ended technological and economic investments required. Depending upon the duration of flexibility requirements, [17] identifies three main flexibility categories (short-, medium- and long-term) and maps them to specific markets and technical implementation requirements, as seen in Table 1.1.

[2]The selection of time slots are done mostly by roughly dividing the day into periods of high electrical load (or high market prices) and low electrical load (or low market prices) on the basis of historical data.

[3]Here, upgradation of biogas to biomethane is defined as a method of cleansing and transforming raw biogas (having 15% to 60 % carbon dioxide) to biomethane which has reduced carbon dioxide levels (1% to 3 %) [15]. Following the process of upgradation, biomethane is injected into the grid to be mainly used as vehicular fuel.

Table 1.1 Approaches of flexible power generation, based on duration of response

Reaction time	Category	Markets	Technical requirements
Up to 5 mins	Short-term	Primary control reserve (to balance the net frequency)	Fast start stop operation of combined heat and power (CHP) plant
5 to 15 mins	Short-term	Secondary control reserve (to balance the net frequency)	Fast start stop operation of CHP
15 mins to 6 hours	Mid-term	Intra-day market	Increased CHP capacity, gas storage
6 hours to 1 day	Mid-term	Day-ahead market, balancing residual loads	Feedstock management, gas utilisation management systems, heat storage, increased CHP capacity and/or gas storage
1 to 7 days	Mid-term	Balancing residual loads	Feedstock management, gas utilisation management systems, heat storage, increased CHP capacity and/or gas storage, substrate-storage capacity
1 week to 3 months	Long-term	Derivative markets, balancing residual and seasonal demand	Feedstock management, gas utilisation management systems, heat storage, increased CHP capacity and/or gas storage, long-term substrate storage capacity

1.2 Research motivation

Anaerobic digestion is a "multi-stage, dynamic, highly non-linear process dependent on the interaction between various micro-organisms, operating conditions like temperature, pressure, pH, concentration of organic matter and the chemical constituency of the substrates" [18]. This prompts the requirement of empirical data and specialised expertise in this field to model the process. Models described in [19], [20] are beneficial in simulating the process, but are limited in their applicability in the context of the optimisation of operations due to them being highly non-linear and dependent on a large number of paramters. The works investigating the flexible operation of biogas digesters in power markets like [11], [12] are based on Anaerobic digester model 1 (ADM1), which is very difficult to implement without specialised knowledge of the microbial pathways and extensive knowledge of the chemical constituents and various kinetic rates associated with each substrate. [4]

Reference [21] investigates the economic profits of flexible operation of biogas plants in a German spot market, where additional storage capacity is studied to provide tertiary reserve. Other works like [22] provide economic models to determine the profitability of utilising biogas plants in a market driven primarily by the price of electricity. These works

[4] The standard ADM1 has 29 biochemical and physico-chemical processes described by numerous non-linear ordinary differential equations and 37 kinetic coefficients and a large number of parameters for each type of infeed.

do not model the biogas digester explicitly, but are concerned only with the utilisation of storage to increase profits in a power market.

Thus, even though bioenergy holds the promise to be an economically viable technique for ensuring power system security in times of fluctuating demand, there is a glaring void in the literature in providing a model which appends the flexible operation of a biogas digester to the operation of a multi-energy system in a demand-driven scenario, without discounting their individual complexities. Reference [17] reports that research on full-scale industrial implementation of flexible biogas production is lacking, especially in the knowledge of the interaction of both biological and mechanical components of a biogas-fuelled CHP plant and the impact of electrical and thermal load changes on the biological processes.

This thesis aims to equip integrated biogas-CHP plant operators with a comprehensive framework which capitalizes on the flexible substrate management, usage of biogas storage and intrinsic flexibility of a cogeneration unit. The objective of the framework is to provide decision support in two areas: reducing operating costs while meeting the electrical and heat loads and maximising the profits obtained by selling electricity to the spot market. The aim of the proposed methodology is to present a simple, linear model formulation of the anaerobic digestion process which can be easily integrated into an optimisation model, without loss of accuracy. References [14] and [23] have both modelled theoretical biogas plants by various kinetic models, but the non-linear structure of their formulations pose a challenge to their integration within a power generation-driven operational planning problem. In this thesis, a linear kinetic model linking the quantity of substrates to the biogas yield is implemented, with the kinetic parameters obtained from the literature.

For the power generation facility, we model a cogeneration system, whereby the non-linear performance curves of gas turbines are linearised by exploiting the convexity of the characteristic function. This thesis also investigates the contribution of variable heat-to-power ratios in the flexible operation of the plant.

Research in [24] shows that combustion engines for biogas operate at 50% nominal capacity which leads to almost a 3% loss of electrical efficiency. The lower calorific value of biogas as compared to natural gas and other fuels also contributes to reduced efficiencies of operation of integrated power systems. This necessitates an investigation into increasing the inherent efficiency of biogas-fuelled CHP, which is one of the main motivations behind studying the variable heat-to-power capability of steam turbines in Chapter 3. Furthermore, a flexible operation of CHP is better suited to address a mismatch in electrical and heat demands [25].

An exhaustive review of the literature has brought forth a gap in the presence of a general model which can be applied to investigate the applicability of biogas plants to match the load profile (or the trend of electricity market prices) and generate an optimal schedule of insertion of substrates and utilisation of storage capacity. It is to be noted that the idea of flexibility employed in this thesis is derived from the *tracking theory* in [26], which translates to generation of bioenergy "capable of producing a trajectory equal to the net load realization (of both heat and electricity) over the operational horizon". In a spot market scenario, this concept is modified to encompass the trend of electricity market prices to maximise the revenues obtained from electricity sales.

The high penetration of RES in power system has given rise to an urgent need to answer the following questions:

- What should be an optimal feeding strategy of a biogas plant when it is operated directly to supply the net load and how efficient is that strategy in following the load?
- What is the optimal operating schedule for a cogeneration system which is concurrent to the operation of the biogas digester?
- What is the economic gain made by exploiting the flexibility of a semi-decoupled [5] cogeneration system?
- What is the revenue that can be obtained by following such a strategy in a spot market and what is the marginal profit of inclusion of storage in such a case?

[5] A *decoupled* cogeneration system is one in which production of heat and electricity are completely independent of each other, like a system comprising of auxiliary boilers for heat production and gas turbines producing only electricity. An example of a *coupled* system is a back-pressure steam turbine whereby heat and electricity are produced at a constant ratio. In this thesis, a *semi-decoupled* unit denotes with partial dependence between electricity and heat generation, like a system having extraction steam turbine with variable heat-to-power ratios.

This thesis aims to build the foundation to answer these questions, from a short-term operational planning perspective.

Thesis contributions

To summarise, the major contributions of this thesis are :

- Implements an approach on existing non-linear kinetic models describing biogas production, which enables linear representation of the complex processes of anaerobic digestion.
- Presents a data-driven modelling approach to analyse the intrinsic flexibility that can be provided by variable heat-to-power ratio in cogeneration plants.
- Provides an integrated mixed-integer linear programming (MILP) problem formulation to optimize the operations of a biogas plant interconnected with a CHP unit. This simultaneously provides for optimal feeding management of the digester and optimal heat and power generation setpoint decisions as driven by either by fluctuating heat and power demands or by electricity spot prices.

1.3 Thesis organization

The remainder of the thesis is structured as follows.

Chapter 2, titled *Optimal operation of a biogas digester with operational flexibility*, describes the conventional approach of operating biogas plants and provides a comprehensive review of the emerging multi-factorial flexibilisation technologies in this domain. Various biochemical processes are explained and a framework for generating the optimal operating strategy of the biogas plant is presented. This data-driven framework bestows linearity and reduces the computational complexity of an intrinsically non-linear process. Historical datasets are utilised to analyse the economic implications of using demand-driven biogas plants using the framework. It also serves to appraise the profitability of such an approach, as opposed to the conventional one, in a spot market.

Chapter 3 is titled *Optimal scheduling of a cogeneration plant with supply-side flexibility* and inspects the effect of having a variable heat-to-power ratio in a multi-energy system like a combined heat and power plant. It uses linearisation techniques and introduces the use of extraction maps to characterise the performance of gas turbines and steam turbines respectively, to obtain a mixed integer linear formulation for the scheduling problem. This formulation serves as a simple tool for investigating the impact of having a semi-decoupled heat and electrical generation in the wake of differing load trajectories.

Chapter 4, titled *Integration of substrate management with optimal scheduling of a co-generation plant* integrates the flexible approaches of the previous chapters to provide an in-depth analysis on their impacts on the integrated operation of the plant.

Chapter 5 discusses the scope of furthering the research conducted in this thesis. It attempts to summarise the findings of our work and the insights this thesis strives to deliver.

Chapter 2

Optimal operation of a biogas digester with operational flexibility

2.1 Overview

Traditionally, energy production from biogas entailed a fixed temporal feeding strategy for continuous production of biogas, which was either used for localised utilisation or sold to the grid, whereas, the present focus on renewable power generation has brought forth an emphasis on demand-driven operability of a biogas digester. Integration of a load-following capability will require increased influence over time-of-feed and choice and quantity of substrates, as opposed to the conventional approach. To this end, we propose a computationally affordable mathematical model of a biogas digester, which meets the heat and power demands at minimum operating costs (or maximises the revenue obtained from selling electricity to the spot market). An analysis on the impact of flexible feeding management on the operations of the digester is also conducted.

In this chapter, the theory behind the anaerobic digestion process is first elucidated followed by a general description of the prevailing biogas technology in the power market and a brief review of existing research on the aspect of operational flexibility of biogas generation. *Operational flexibility*, in this context, is defined as the ability of a biogas digester to change its feeding and storage strategies to meet the fluctuations in net demand[1]. To

[1]The net demand for electricity is the difference between the total demand and the supply by other renewable resources.

incorporate this, the biogas digester is described by modelling the biogas yield by first order kinetic models based on the widely used Gompertz function [27], which is a time-dependent sigmoid function first introduced by Benjamin Gompertz for the study of demographics. An example of the Gompertz function is given in (2.1)

$$f(t) = ae^{-be^{-ct}} \tag{2.1}$$

where a is the upper aymptote when time approaches $+\infty$, b is the displacement along the horizontal axis and c is the growth rate [2]. Fig. 2.1 depicts a standard Gompertz function with $a = 1$ and $b = 1$, for different growth rates.

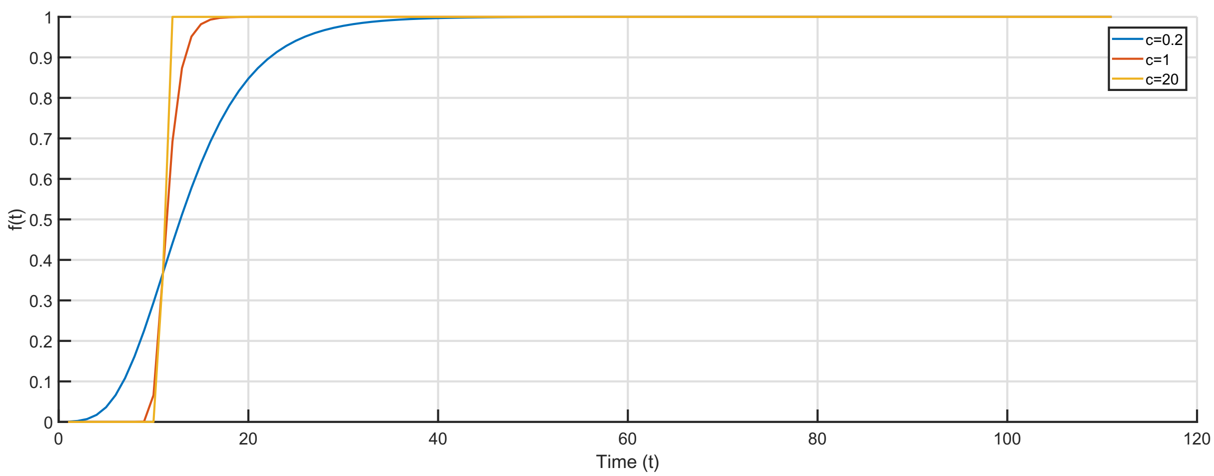

Fig. 2.1 A standard Gompertz function with varying growth rates

Even though the models are inherently non-linear (Fig. 2.1), the modelling approach proposed in this chapter simplifies it, which enables it to be used in a MILP format without loss of accuracy or without addition of any linearisation methods. The addition of a biogas storage provides additional flexibility, albeit at additional storage costs, by enabling the plant to store biogas at times of low demand (or low market prices) and utilise the biogas at times of high demand (or high market prices). In order to capitalise not only on the temporal shift in generation (with the help of substrate management) but also the decoupling of generation and utilisation (using biogas storage), we examine the behaviour of the model in the presence of an electricity spot market.

[2]In this thesis, $f(t)$ will be used to denote the cumulative biogas yield.

2.2 Theory of anaerobic digestion

Anaerobic degradation is a biological process where “organic carbon is converted by subsequent oxidations and reductions to its most oxidized state (CO_2), and its most reduced state (CH_4) by a wide range of microorganisms in the absence of oxygen” [28]. The other by-products are hydrogen sulphide and moisture, both of which are removed before methane is fed to the cogeneration plant. The production of a specific volume of methane is dependent on a variety of biological, chemical and operational factors like substrate concentration, pH, temperature, organic loading rate (OLR), hydraulic retention time (HRT), C:N ratio of the constituents.

From the perspective of operation, the parameters of major consequence are temperature, hydraulic retention time and organic loading rate. Although temperature rise has a positve correlation with increase in microbial activity (which translates to increase in biogas yield from a specific quantity of substrate) [29], most state-of-art biogas plants are usually operated at mesophilic temperatures (20-40°C) as opposed to thermophilic range (above 40°C) as the high incremental cost of producing biogas per degree rise in temperature does not justify such increase in operating temperatures.

The *hydraulic retention time* is the average residence time of a given quantity of organic matter in the digester in steady-state conditions and is given by

$$HRT = \frac{Volume\ of\ reactor}{Volumetric\ inflow\ rate} \tag{2.2}$$

Even though a lower HRT is associated with lower capital costs (small digester size) and physical footprint, a lower HRT often does not allow the organic matter to reach its full biogas potential before being thrown out and can also lead to instability if HRT is less than 8-10 days [30]. Also, the choice of an optimal HRT is subject to the type of substrate chosen. In this chapter, we are concerned only with the lower bound on the HRT as that has major reflection on the stability of our system. Since this thesis deals with more than one substrate type, we take the minimum HRT for the most slowly degradable substrate as minimum HRT for the whole unit [3].

Another important feature is the *organic loading rate* which is given by

$$OLR = \frac{Volatile\ solids\ added\ per\ day}{Volume\ of\ reactor} \tag{2.3}$$

Microbial analysis reveals that an appropriate increase in OLR favours biogas production, while excess OLR is one of the major causes of system failure [31]. Reference [32] gives an optimal OLR for stable operating conditions, which has been adopted in this thesis, to prevent a system breakdown.

Equipped with this knowledge, we formulate a framework for generating an optimal feeding schedule in the remaining sections.

2.3 Relevant literature

In order to appropriately model flexibility techniques in a biogas digester coupled to a power plant, one must have a thorough knowledge of the technical and biological aspects of the process of anaerobic digestion. To this respect, literature abounds in both experimetal [33], [34], [10, 13, 35–37] as well as modeling studies [38], on the anaerobic digestion process.

The authors in [33] provide a detailed model of power production from anaerobic digestion of a single substrate with the aim of optimising the energy produced. The model is highly non-linear and based on stoichiometric equations with two different combined cycle configurations to choose from, but it provides an interesting insight into the effect of the temperature, pressure and chemical composition of biomass in the energy production. The aim of the research is to determine the operating variables of two thermodynamic cycles for the gas engine to optimise the energy obtained from a single type of substrate. It claims that the total energy production remains invariant to the change in substrate composition. However, the following studies present conflicting views. Reference [34] provides

[3] This assumption is justified as the impact of co-digestion on the choice of minimum HRT is beyond the scope of this thesis.

experimental methods to optimise the biogas production through varying the inoculum[4] to substrate ratio. The authors provide empirical evidence to prove that the efficiency of biochemical reactions in the anaerobic digestion process is substantially dependent on the substrate concentration. Infact, the bacterial metabolism might be negatively affected at very low substrate concentrations. On the other hand, with excessive substrate concentrations, the process might be inhibited due to overloading by intermediates. In order to combat the adverse impacts of overloading and inhibition of microbial activity, several constraints (2.11-2.12) are added in our model in the following section. Another modeling technique is presented in [35] which describes a Monod[5] type model to predict the methane potential of a particular substrate. Even though the results are fairly inconclusive regarding the upper bound for substrate concentration, a minimum level of substrate concentration has been obtained. This rate-limiting substrate level (in terms of volatile solids) is found crucial in predicting the methane yield.

R. O'Shea et al. in [14] kinetically models the biogas production and compares the experimental results of gas production with the theoretical models. Interestingly, the kinetic models achieved an average R^2 value greater than 0.9, which makes them fairly accurate for modeling purposes[6]. It is to be noted that even though kinetic modeling has given fairly reasonable predictions, the impact of a number of biochemical factors is often neglected in such models, which can lead to an over-estimation or under-estimation of the yield. Furthermore, [39] argues that the kinetics of the degradation are highly sensitive to the experimental conditions like microbial activity and sample accessibility.

On the operational flexibility of a biogas plant

In order to make the production of biogas flexible, the impact of the feeding regime on the anaerobic digestion process has to be studied. In [36], after studying two feeding regimes of maize silage, Lv et al. concluded that changes in feeding regime brings increased variability in biogas production, even though the overall biogas yield remains unchanged. The

[4] An inoculum is a methanogen-rich partially digested waste medium.

[5] A Monod equation, generally, depicts the growth rate of a micro-organism as a function of the limiting amount of substrate.

[6] R^2 value is a statistical metric to predict how well the model fits the empirical data. A high R^2 value is generally indicative of data points closer to the fitted regression line.

authors agree that more feeding regimes at different intervals need to be investigated before upscaling this method of flexibilisation. For substrates with slow degradation, the experiments in [37] show that the anaerobic digestion process is highly adaptable to increased feeding frequency with the degradation rate of the maize silage substrate becoming twice in case of tripled feeding frequency. As regards the process stability, Vrieze et. al. shows in [40] that intermittent feeding of the same substrate or varying the composition of substrate bestows higher functional stability to anaerobic digestion. Muaky et. al. provides conclusive results in [10] on the impact of dynamic feeding regime on the process stability. Experiments carried out with cattle slurry, maize silage and sugar beet silage show that the biogas production process can be made highly flexible through various diurnal feeding regimes with different combination of substrates at high OLRs. An analysis clearly reflects how flexibilisation impacts financial savings of the plant. An attempt to replicate the findings of laboratory-scale trials was endeavoured in [13] to inspect its feasibility on an industrial scale. The study showed positive results on the scalability of flexible feeding to a commercial scale.

The authors in [41] adapt a linear programming model (MODEST) to optimise biogas production to meet heat and electrical demand as well as for upgrading to biomethane. The model formulation involves energy flows with consideration for long-term planning objectives. Based on energy flows alone, without directly considering the bio-kinetics of the process of anaerobic digestion, it throws light on the relationship between integration of a CHP to a biogas plant and increase in profits. In [12], flexible scenarios of demand-driven power production from biogas are assessed, and an economic analysis is presented with regards to the Swedish electricity market. In this paper, a dynamic biogas plant model (DyBiM) is developed and connected separately to the ADM1 to study the technical requirements and economic implications of increasing gas storage capacity, changing the feeding times and increasing CHP capacity. In this, the ADM1 was first run for feeding periods of 1, 3, 6 and 12 hours and biogas produced was fed into the storage. Hereafter, the CHP was run for two scenarios, 9.6 hours and 19.2 hours and the electricity generated was sold to the market. Even though the model showed a decoupled operation of the biogas digester and the CHP with investigation done for a few feeding strategies and a predefined operation of a CHP plant with two units, the results show a positive correlation between flexibilisation and profit maximisation. However, more investigations need to made regarding the optimality of the chosen feeding periods and the adaptability of the model to various market prices.

Willeghems et. al. uses a sigmoid function to kinetically model the biogas digester [23] and attempts to address gap between the technical and economic anaerobic digestion (AD) models for long-term generation planning strategies. The problem is formulated as a non-linear programming (NLP) model which is solved to choose the substrates that would optimise the HRT and OLR to maximise the profits obtained by selling the heat and electricity (at fixed prices) to the market. Even though the modelling technique used in this paper has inspired the mathematical formulation of the digester in this chapter, the impact of flexibility techniques of biogas production on the daily operating costs of cogeneration units, the efficacy of changing the feeding regime in response to a fluctuating electric demand (or fluctuating market prices) and the effect of varying the substrate quantity on the operation of the unit remain unexplored. This chapter aims to approach these research gaps.

2.4 System Model Formulation

2.4.1 Plant model

The plant model, which will be used henceforth in this thesis, contains a biogas digester, a biogas storage and a cogeneration system, whose cascading interconnections are inspired from the plant described in [42]. The model described in this chapter is, inherently, single input multiple output (SIMO) as can be seen in Fig. 2.2. The various components of the plant model are described in detail in the following sections.

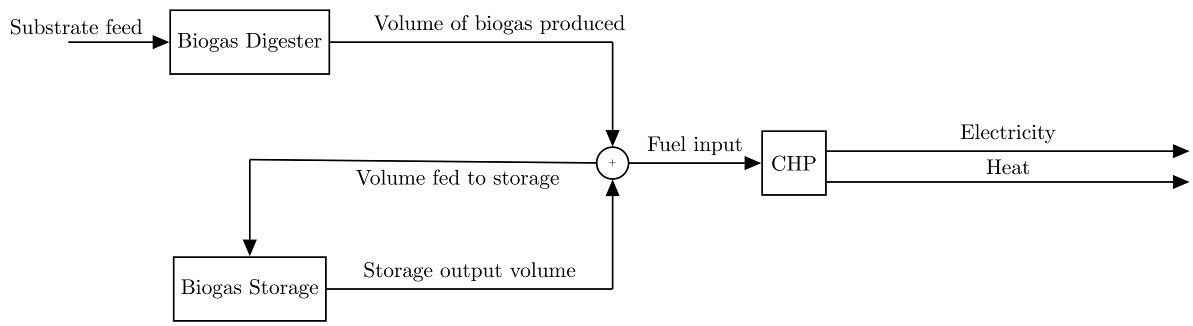

Fig. 2.2 Schematic representation of the plant model

2.4.2 Biogas digester

Cumulative production characteristic

In this thesis, the three kinetic models which describe the anaerobic digestion process are based on the sigmoid function, and each of them characterises the methane or biogas yield[7] of three broad categories of substrates : easily degradable, slowly degradable and one which has a mixture of both. Equations (2.4)-(2.5) are modified Gompertz equations while (2.6) is a standard sigmoid function. For fast degradable substrates like beet silage, (2.4) most accurately describes the methane production. This modified Gompertz equation had the highest accuracy in describing the degradation kinetics of substrates in [43]. The experimental trials cited in [14] also proved the accuracy of this model for substrates having readily degradable parts.

$$v^c_{s,t} = V^{max}_s(1 - \exp(-k^a_s t)) \tag{2.4}$$

The second kinetic model (2.5) had recorded the second highest accuracy, in experiments conducted by the authors in [44], in predicting the biomethane potential of anaerobic sludge, which has a combination of readily and slowly degradable organic matter. V^{max}_s is the maximum methane that can be produced on complete degradation of one kilogram of volatile solids[8] of a given substrate. X is the amount of readily degradable part relative

[7]The model outputs yield in terms of biogas or methane on the basis of the values of parameters chosen.

[8]Total solids (TS) describes the dry matter of a substrate which is obtained by heating the substrate at 105°C till it is completely devoid of moisture. Volatile solid (VS) concentration is the organic fraction of the TS of a substrate. The biogas potential of a substrate is usually measured in terms of its VS content,

to total quantity of substrate, the constant k^f denotes the rate of decay for X and k^{sl} is the rate constant for the less readily degradable part. This kinetic equation is especially accurate for solid organic substrates [45].

$$v^c_{s,t} = V^{max}_s(1 - X\exp(-k^f_s t) - (1 - X)\exp(-k^{sl}_s t)) \tag{2.5}$$

The third formulation, (2.6), is a Monod type model, like the classic ADM1, which allows for a slower decline in gas production in the later parts of the degradation process, which is beneficial for samples with high contents of slow degradable complex materials [44]. During operation, the plant operator needs to make an appropriate selection of model, depending on the biological make-up of the substrate.

$$v^c_{s,t} = V^{max}_s(\frac{k^c_s t}{1 + k^c_s t}) \tag{2.6}$$

Similarly, k^a and k^c are the kinetic rate constants (in days^{-1} which is denoted as d^{-1}) for the respective models.

To use these kinetic models in the framework, the following should be kept in mind.

- The output obtained by the kinetic models gives the methane volume in terms of VS of a substrate. In order to obtain the output in terms of dry substrate feed quantity, it is imperative to know the TS of each substrate[9].
- The output of the digester is obtained in terms of energy (MWh) by multiplying the volume of methane obtained (in m^3) with the energy density of methane, ϵ (2.17a), followed by conversion to average power (MW) by dividing by 24 hours, as the time step considered in this case is one day.

The total methane yield per quantity of a substrate at any time t is calculated using the above equations, provided that the substrate has been added at $t = 0$ days or immediately, at the beginning of the time horizon. Intuitively, this means that t days after feeding one kilogram of *volatile solids* of a particular substrate to a digester, the total biogas produced

which is expressed as a percentage of TS.

[9]The reader is requested to refer to Table A.1 for the TS and VS values used in this thesis.

is $v(t)$, provided there has been no insertion or deletion of feed or biogas to or from the digester, respectively. Fig. 2.3 illustrates the cumulative methane yields of three different types of substrates; sugar beet silage being the fastest degradable to cattle slurry being the least degradable. As expected, sugar beet silage produced the maximum methane with a steeper rise in production as compared to the other substrates. The cumulative production of all three substrates plateaus after about the first 10 days of insertion, due to steady decrease in the rate of production till the maximum methane potential is reached.

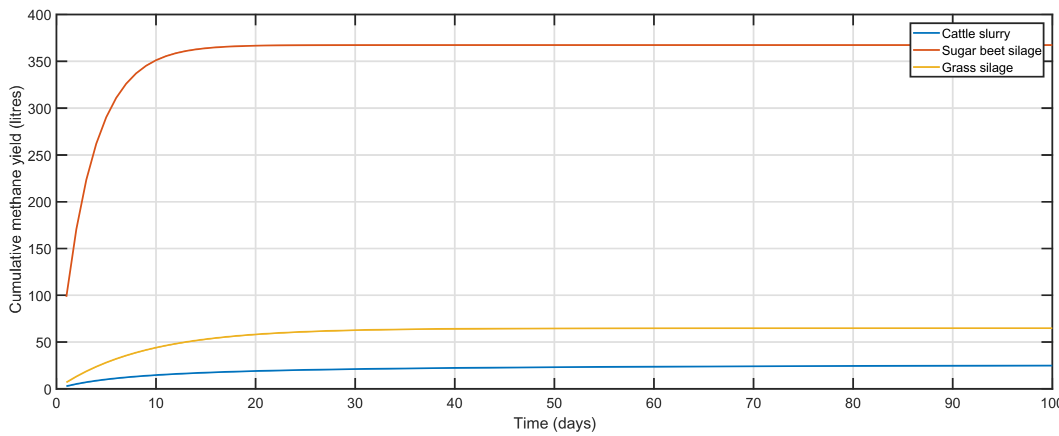

Fig. 2.3 The cumulative methane yields of various substrates shown by kinetic models

Daily production characteristic

To meet a biogas demand at each interval t, it is imperative to calculate the biogas yield during a particular day so that the movement of biogas from the digester to the plant at each time interval is accounted for. For this purpose, the discrete biogas yield $v_{s,t}$ at time t is the difference of the cumulative yield at t and $t-1$. A similar approach has been adopted in [23]. Fig. 2.4 shows that sugar beet silage produces almost ten times more methane within the first day as compared to cattle slurry and grass silage. Grass silage has twice the rate of production than cattle slurry. Beet silage, hence, is a better candidate for substrate during peak electricity and/or heat demands (or high market prices).

$$v_{s,t} = V_s^{max}\left[\left(\frac{k_s^c t}{1+k_s^c t}\right) - \left(\frac{k_s^c (t-1)}{1+k_s^c (t-1)}\right)\right] \tag{2.7}$$

It can be seen that biogas production of substrate s at time t is dependent on two param-

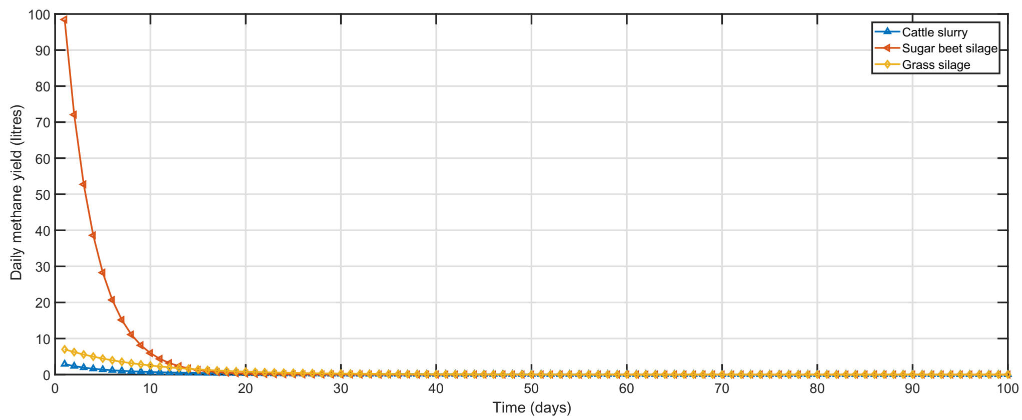

Fig. 2.4 The daily methane yield obtained

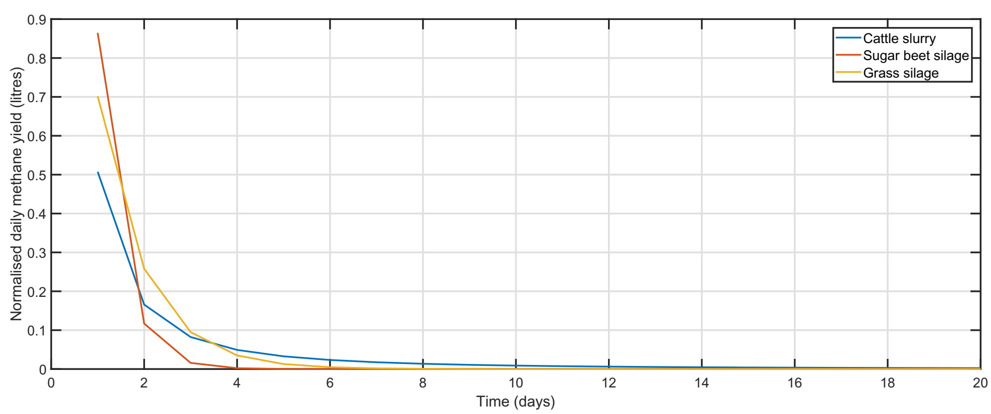

Fig. 2.5 The normalised daily methane yield obtained

eters, V_s^{max} and kinetic rate constants associated. Given that V_s^{max} for the substrates have much higher range of values as compared to kinetic rate constants, it will intrinsically influence the biogas yield more due to its larger value. But this does not necessarily mean that this parameter is more important as a predictor of yield, especially during comparison of yields by different substrates. Hence, for purposes of comparative analysis, Fig. 2.5 shows the normalised daily yield, wherein the parameters V_s^{max} and the kinetic rate constants have been normalised to lie in in the range of [1,2] by the method of feature scaling[10]. When both features have been scaled, the following insights can be drawn. It shows that even though beet silage is better at producing higher biogas yields to match the peaks in demand, it also produces less biogas at subsequent time periods (as it reaches its maximum methane potential the fastest), as compared to grass silage and cattle slurry. Since cattle slurry degrades at a slower rate as compared to grass silage, it produces more biogas than the other two substrates at later time periods. Thus, cattle slurry is a better candidate if the demand for biogas (or market prices) is fairly constant over long periods of time during which the substrate can be inserted at constant intervals to maintain the biogas production level. The methane potential of grass silage is less than beet silage, but it degrades at a similar rate from $t = 2$ to $t = 3$ days while it degrades at a slower rate at subsequent time periods. This makes it a better candidate for moderately constant demand profiles having reduced demand peaks. This is further evident in Fig. 2.6 which provides the yield of substrates relative to beet silage. It can been that during $t = 10, ..., 45$, the yield of cattle slurry increases as time progresses and even though, the yield of grass silage increases as compared to beet silage, its yield is less compared to that of cattle slurry. Thus, in cases where demand remains fairly constant or predictable, cattle slurry is the best candidate for biogas production not only because of its production profile but also because it is the cheapest substrate per unit mass. Some European countries often give subsidy to use cattle silage as a substrate.

The quantity and time delay for fluctutating methane demand

To find out the approximate quantity of substrate which satisfies a particular biogas demand, a formulation linking the substrate quantity in kilogram to the biogas output is required, which is an original contribution of this thesis. As is evidenced from the previous equation, there is a time delay between the addition of feed and production of biogas. Let this delay be t_d. For the biogas production required at t, the delay t_d can be obtained as $t_d = t - \tilde{t}$ where $\tilde{t}$ is the time of insertion of substrate. Let the quantity of substrate s added

[10] To rescale an attribute or parameter x between an arbitrary set of values $[a, b]$, we use

$$x^{scaled} = a + \frac{(x - x_{min})(b - a)}{x_{max} - x_{min}}$$

where x_{min} and x_{max} are the minimum and maximum values of x.

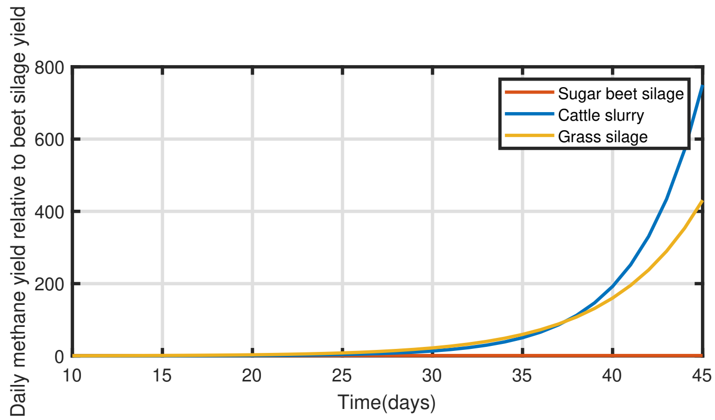

Fig. 2.6 The daily methane yield obtained relative to beet silage yield

at time $\tilde{t}$ be $M_{s,\tilde{t}}$. Thus, the methane produced by that substrate at any time t where $t > \tilde{t}$ is given by [11]

$$v_{s,t,\tilde{t}} = M_{s,\tilde{t}} V_s^{max} \left[\left(\frac{k_s^c (t - \tilde{t})}{1 + k_s^c (t - \tilde{t})} \right) - \left(\frac{k_s^c (t - \tilde{t} - 1)}{1 + k_s^c (t - \tilde{t} - 1)} \right) \right] \tag{2.8}$$

Fig. 2.7 shows the dependency of methane yield on the mass of the substrate inserted at $t = 0$. With increasing mass, the maximum specific methane yield increases and the decrease in volume after the first day becomes steeper. This characteristic of methane production is exploited by inserting appropriate quantities of substrates to provide increasing upward as well as downward ramps in gas production.

Equation (2.8) shows that the volume of biogas at time t is dependent on the product of $\tilde{t}$ and $M_{s,\tilde{t}}$ which makes it non-linear. Another aspect of the anaerobic digestion process is that for a specific quantity of substrate added at $\tilde{t}$, its biogas production is not limited to the corresponding $(\tilde{t}+1)$ time, but needs to be accounted for in all the subsequent time periods[12]. This aspect is reflected in

[11] We are using only one of the kinetic equations for illustration purposes.
[12] If substrate is not chosen at a $\tilde{t}$, $M_{s,\tilde{t}} = 0$ for that particular $\tilde{t}$.

$$v_{s,t} = \sum_{\tilde{t}=0}^{t-1} M_{s,\tilde{t}} V_s^{max} \left[\left(\frac{k_s^c(t-\tilde{t})}{1+k_s^c(t-\tilde{t})} \right) - \left(\frac{k_s^c(t-\tilde{t}-1)}{1+k_s^c(t-\tilde{t}-1)} \right) \right] \tag{2.9}$$

Interestingly, the technique of adding a summation over $\tilde{t}$ in (2.8) to obtain (2.9) has a purpose which is two-fold. The summation ensures that the biogas produced at time t takes into consideration the impact of all the substrates inserted from $\tilde{t} = 0$ to $(t-1)$. Secondly, due to this particular approach, the calculation of biogas production at each t becomes a linear function of mass of substrate s inserted at every time step till $(t-1)$. This approach is instrumental in linearising the biogas kinetic model so that it can be incorporated into a LP structure. This linearisation also does not degrade the accuracy of the existing formulation as it is sampling the biogas yield at discrete intervals and is valuable in analysing the operation of an integrated biogas-CHP system using a MILP framework.

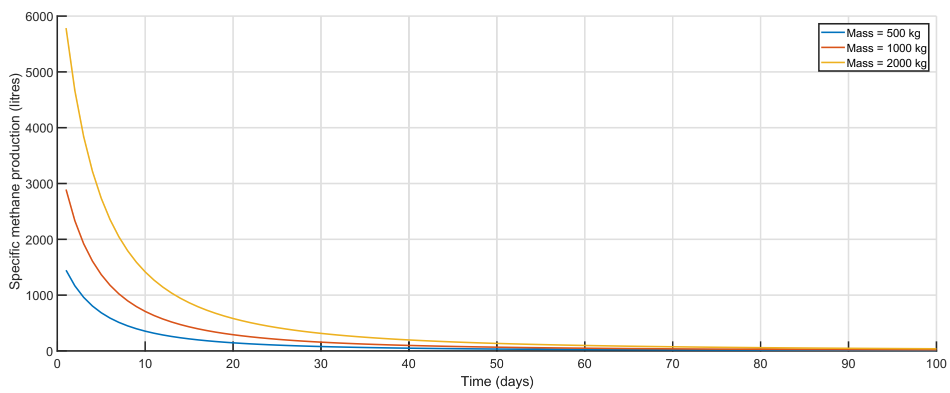

Fig. 2.7 The difference in discrete yields due to difference in mass input for sugar beet silage

Interestingly, Fig. 2.7 shows that even with increasing the mass, the time taken for the methane yield to fall to 90% from its peak is almost the same, with a divergence of maximum 10 days for an increase of mass by four times. This makes it easier to parametrise a minimum HRT, without much loss of yield. For instance, if the maximum allowable substrate amount is 2000 kg, the minimum HRT for the whole system can be assumed to be 30 days without significant loss of biogas.

Process stability

Instability in a biogas digester mainly leads to the death of microorganisms or their premature removal from the digester. This affects the biochemical stability of the digester and has an adverse impact on the production of biogas. Beyond the immediate impact of degradation kinetics on the digestion process, maintaining feasibility warrants preserving the biochemical stability for the entire duration of the process. The effective residence time of substrates and the loading rate of substrates are of utmost concern for ensuring the biochemical 'process stability' [46]. Disruption of process stability can result in inhibition of process which will ultimately have an adverse impact on methane production. Instability in the operation may also result in the death of microorganisms due to accumulation of toxic matter.

In order to circumvent the major causes which can lead to digester instability, the following constraints pertaining to HRT and OLR have been included in the model. Equation (2.11) guarantees that the feed remains in the digester for a minimum residence time (H^{min}), to ensure that the microbial culture is not *washed out* with the substrates before it can reproduce. Even though HRT varies with the type of substrates, for the purposes of simulation, we have considered the time taken by the least biodegradable substrate to reach 95% of its potential as the minimum HRT, to ensure minimum loss of bioenergy in case of a premature removal. Equation (2.10) is used to obtain the substrate volume S_s by dividing the mass of substrate M_s by the substrate density ρ_s. By the definition given by (2.2), the active digester volume ν is divided by the total substrate volumetric flow at each $\tilde{t}$ to obtain the HRT of the system.

$$S_{s,\tilde{t}} = \frac{M_{s,\tilde{t}}}{\rho_s}, \forall \tilde{t} = [1, ..., T-1] \tag{2.10}$$

$$\frac{\nu}{\sum_s S_{s,\tilde{t}}} \geq H^{min}, \forall \tilde{t} = [1, ..., T-1] \tag{2.11}$$

Lastly, (2.12) checks the accumulation of volatile acids in the digester by imposing an upper limit on OLR (OLR^{max}) [23], further ensuring that the process is not inhibited. This equation is obtained according to the definition of OLR given by (2.3).

$$\sum_s \frac{(M_{s,\tilde{t}} \; TS_s \; VS_s)}{\nu} \leq OLR^{max}, \; \forall \tilde{t} = [1, ..., T-1] \tag{2.12}$$

Technical constraints

Every insertion of substrate at $\tilde{t}$ into the digester leads to an increase in biogas yield in the digester. To restrict the biogas production to the maximum working capacity (ν), the following constraint is added.

$$\sum_s v_{s,t} \leq \nu, \; \forall t \in T \tag{2.13}$$

The digester model also needs to have a physical constraint to prevent excess insertion of the digestible substrate, at each $\tilde{t}$. This is ensured by (2.14) where $M_{\tilde{t}}^{mc}$ denotes the maximum digester capacity for solid intake.

$$\sum_s \sum_{j=0}^{\tilde{t}+1} M_{s,j} \leq M_{\tilde{t}}^{mc}, \; \forall \tilde{t} = [1, ..., T-1] \tag{2.14}$$

2.4.3 Biogas storage

Most biogas plants already have an internal storage space realised by impermeable gas membranes on the roof, capable of housing 2 to 6 hours of biogas production [21]. An external storage system provides much larger capacity and is not plagued by the issues of measurement discrepencies as an internal storage [47]. The modelling of biogas storage involves a selection of one of the three decisions : to inject the gas, to withdraw the gas or not use the storage. This can be modelled by (2.15) [48] where the losses due to increase in pressure due to factors like solar irradiation [21] are denoted by γ^l. (2.16) limits the maximum stored biogas at any time to the maximum storage working capacity $Store_{max}$.

$$Store_t = (1 - \gamma^l) Store_{t-1} + v_t^{in} - v_t^{out}, \; \forall t \in T \tag{2.15}$$

$$Store_t \leq Store^{max},\ \forall t \in T \tag{2.16}$$

2.4.4 Cogeneration system

Given that this chapter focuses on the management of substrate and storage devices, the cogeneration system is formulated as a constant efficiency CHP plant with a linear dependency between the electrical and heat outputs. The gas input to the plant is f_t which is obtained by (2.17a) where v_t^{in} and v_t^{out} describe the movement (in litres) of biogas to and from the biogas storage.

$$(\sum_s v_{s,t} + v_t^{out} - v_t^{in})\epsilon = f_t,\ \forall t \in T \tag{2.17a}$$

$$f_t \eta = e_t,\ \forall t \in T \tag{2.17b}$$

$$e_t \theta^r = q_t,\ \forall t \in T \tag{2.17c}$$

Here, η is the constant efficiency of the plant, and θ^r denotes the heat-to-power ratio. The parameter ϵ denotes the energy density of methane. The generated electrical (e_t) and thermal (q_t) powers satisfy daily load profiles [13].

2.5 Objective function

The main operating costs of a biogas plant are the fuel costs which include the costs of transportation and handling and pre-treatment of substrates. The maintenance costs of the digester include handling and removal of digestate, upgrading costs of methane and thermal costs. The pre-treatment costs of substrates are already included in the substrate costs denoted by $\hat{c}_s^{sub}$ (Table A.1). The other costs associated with digester maintenance are not included but their implications on the economics of a commercial biogas plant have been discussed in the subsequent sections. The spot market electricity prices at each time t is given by $\hat{p}_t^s$ (€/MWh) which is multiplied to the electricity sold to the spot market e_t^s.

[13] The daily heat load is the sum of the district heating load and the digester's thermal requirements.

Δt ensures correct dimensioning of the objective function[14].

$$\sum_{\tilde{t}=0}^{T-1} \sum_{t=1}^{T} (C_{\tilde{t}}^{sub} - P_t) \tag{2.18}$$

where

$$C_{\tilde{t}}^{sub} = \sum_{s} \hat{c}_s^{sub} M_{s,\tilde{t}}, \ \forall \tilde{t} = [1, ..., T-1] \tag{2.19}$$

$$P_t = \hat{p}_t^s e_t^s \Delta t, \forall t \in T \tag{2.20}$$

2.5.1 The optimisation problem

The LP optimisation problem can be stated as minimising the objective function (2.18) such that the constraints (2.9), (2.11)-(2.17c) are satisfied.

2.6 Scenarios

The purpose of this chapter is to analyse the impact of three facets of operational flexibility, namely feeding intervals, substrate management and biogas storage, in a biogas digester, with the aim of meeting the fluctuating demands or maximising profits through spot market sales. For this purpose, several scenarios are simulated and the results are compared against a base case.

Base case parameters and data preparation

The reference case consists of a hypothetical mesophilic biogas plant of maximum capacity ν = 50000 m^3, which is being fed a constant-ratio (by dry weight) mixture of dairy cow slurry (CS), sugar beet silage (SBS) and grass silage (GS) (CS:SBS:GS = 4:1:3) at the start of every day. For purposes of stability, OLR^{max} was considered to be 2.5 kgVSm^{-3} per day [49] with a minimum hydraulic retention time of 100 days. The kinetic parameters and the costs of each substrate are given in Table A.1. Relatively speaking, beet silage has the highest cost (0.022 € /kg) followed by grass silage (0.003 € /kg) and operators are given a

[14] The objective function 2.18 is utilised only in presence of an electrical spot market, as described in Section 2.7. However, for scenarios where the driving factors are the electrical and heat demands only, the objective function is modified to $\sum_{\tilde{t}=0}^{T-1} \sum_{t=1}^{T} C_{\tilde{t}}^{sub}$.

financial incentive or subsidy if they use cattle slurry in their plants which makes its cost negative (-0.00044 € /kg). It is a demand-driven biogas plant, satisfying 1% of the electrical load [50][15] and the heat load of 10 commercial buildings. The thermal requirements of the plant are assumed to be a constant of 0.5 MW and added to the heat load profile. The electrical load profile is modified (Fig.2.8) by doubling the demand over $t = 27, ..., 32$ and reducing it by the same amount over $t = 68, ..., 79$ such that the average load remains unchanged. This is done to illustrate the degree of flexibility offered by the approach. The cogeneration plant has a constant efficiency of 40% and a heat-to-power ratio of 1.2. The nominal CHP electrical power rating for this chapter has been assumed to be 200 MW.

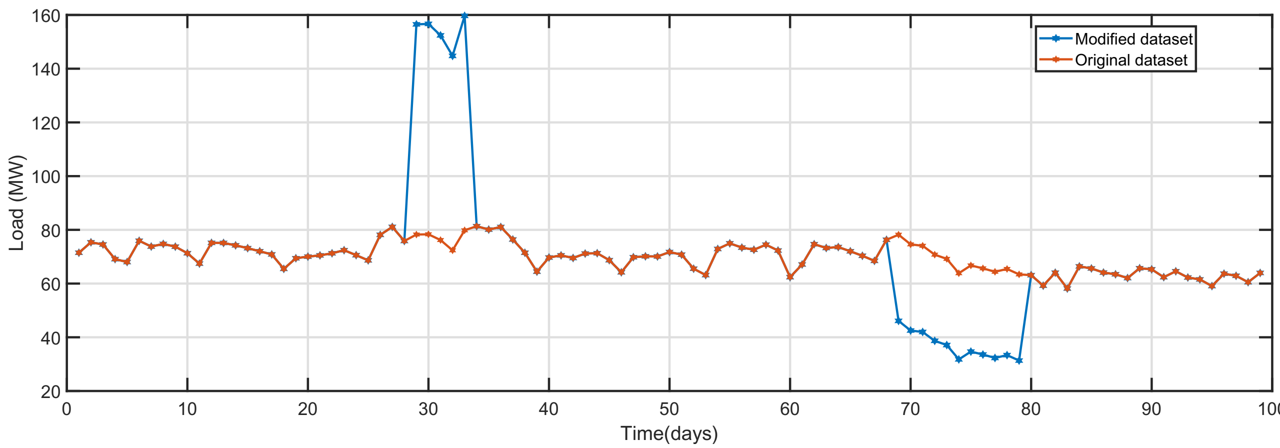

Fig. 2.8 The daily electrical load data and the modified data used for simulations

Substrate management cases

- The first scenario offers flexibility in selecting both the time of insertion and mass of each type of substrate selected.
- The second scenario involves the inclusion of biogas storage to the first scenario.

2.6.1 Results

Before analysing the results, we need to define the metric on which the efficacy of flexibilisation is measured in this chapter. Besides the economics of operation being a chief

[15]The load profile is the daily peak load value of Germany, provided for year 2014 by ENTSO-e.

metric, we also assess the velocity ramps of bioenergy production where the velocity ramps in this chapter are solely concerned with those of the substrate management, variable gas production and storage. The velocity ramp of bioenergy generation is adopted from [51]

$$r \uparrow = \frac{(e_{t^a} - e_{t^b})}{(t^a - t^b)} \tag{2.21}$$

$$r \downarrow = \frac{(e_{t^a} - e_{t^b})}{(t^b - t^a)} \tag{2.22}$$

While considering an integrated biogas-CHP system, the velocity ramps of biogas production are limited by the non-linear characteristics of the cogeneration system as it is the place where the final conversion from biogas to power happens. However, in this chapter, our cogeneration system performance is assumed to be linear, with a constant efficiency and a constant heat-to-power ratio. Hence, the velocity ramps of fermentation are reflected by the electrical power generation profile of the integrated system. Therefore, in (2.21), a positive ramp ($r \uparrow$) is calculated from the difference of electrical generations at t^a and t^b where e_{t^a} is greater than e_{t^b} when t^a is greater than t^b. For (2.22), a downward ramp ($r \downarrow$) is obtained when e_{t^a} is greater than e_{t^b} for t^a less than t^b.

Depending upon the generation profile, we also study the bandwidth of power generated over the operating horizon and how closely it approaches the *power amplitude* of the load profile [51].

$$\Delta e = \frac{(e^{max} - e^{min})}{e^{max}} \tag{2.23}$$

Here, the bandwidth of electrical generation is obtained relative to the maximum electrical power generated (e^{max}).

The reference case scenario is able to meet the demand at all times only if the gas capacity and maximum mass constraints of the digester were violated by a considerable margin. This scenario was not only run with the given data set, but with other datasets as well, and it showed infeasibility 75% of the times. That is the case because cattle slurry, which is highly incentivised and makes up for 50 % of the total infeed, has the least contribution to the total electrical generation (and hence, the total power generation) as seen in Fig. 2.9.

It can be argued that this infeasibility can be circumvented by increasing the proportion of beet silage in the infeed. However, increasing the beet silage for the base case led to a violation of the maximum volume constraint of the digester. Even though $\Delta e = 557$ MW, the positive ramp is 18.56 MW d^{-1} for the first 30 days after which the ramp becomes 0. This shows that even though, theoretically, there is a high bandwidth of generation, the flexibility offered is minimal due to the generation stagnating with reduced incremental increase of biogas production. This is expected as the substrates are fed in equal quantities at the same time each day.

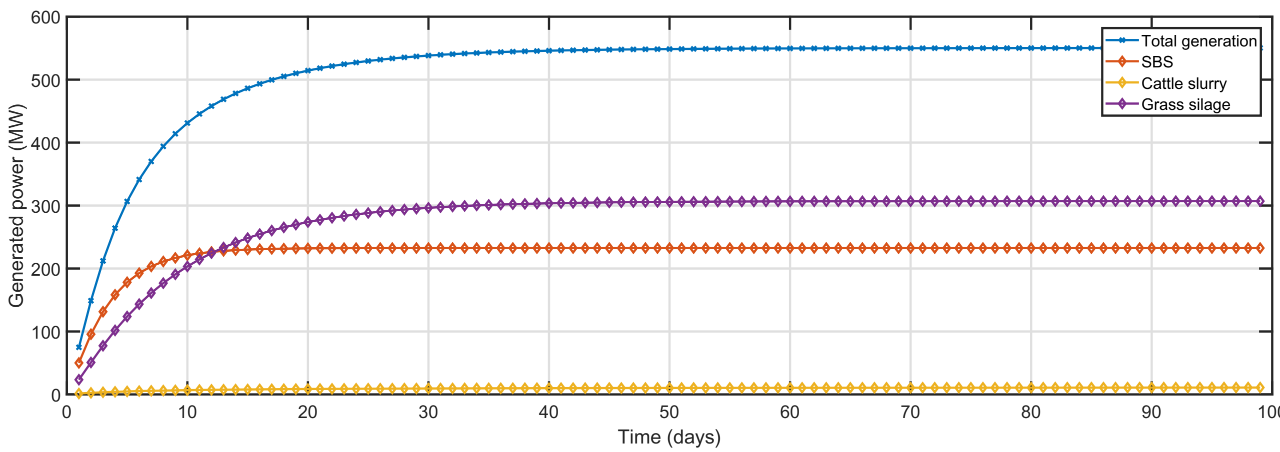

Fig. 2.9 Reference case

When the feeding management is opportune (Fig. 2.10 - 2.11), the generation is able to meet the demand without violating capacity constraints. The system in Fig. 2.10 provides a total maximum positive ramp of $r \uparrow = 82$ MW d^{-1} and downward ramp of $r \downarrow = 15$ MW d^{-1}. It matches the Δe of the electrical load schedule perfectly. Similar performance is obtained in Fig. 2.11 although the gas storage smoothens out the velocity ramps of gaseous production and hence, the generation schedule does not truly reflect the biogas volumetric production schedule which is shown in Fig. 2.12. This clearly shows that an optimally-timed feeding strategy provides a 3.4% increase in upward ramping capabilities and 15% increase in downward ramping capabilities which translates to a substantial reduction in operating costs. The optimal feeding strategy chosen for this scenario has an insertion of sugar beet silage to meet the peak demands as it is the fastest degradable, while grass silage is inserted almost regularly, to maintain the generation level. Interestingly, even though cattle slurry is highly incentivised as compared to other substrates, it is not considered as a viable input in a 'load following' scenario due to its high *energy cost*[16], which is defined as the cost of producing one unit of energy. This is so because the quantity of cattle slurry needed to produce one MWh of energy is too high as compared to other feedstocks. This means that the energy content of one kilogram of cattle slurry is lower than other substrates considered in this thesis. Hence, in order to use cattle slurry to produce the same unit of energy as beet silage, one needs to increase the digester size by a large amount [17], and it also increases the post-digestion handling costs. So, cattle slurry is never chosen in this scenario where meeting the electrical load is the driving factor, even after being incentivised because of costs like those associated with larger digester size, post-digestion handling costs far outweigh the subsidy obtained from using cattle slurry as a substrate. It is to be noted that even though post-digestion costs have not been included in the optimisation problem, the huge quantity of cattle slurry required to produce one MWh of energy makes it infeasible to maintain all the technical constraints to meet the demand, or if one were to increase the digester size to make it feasible, the costs incurred would be higher than using other feedstocks.

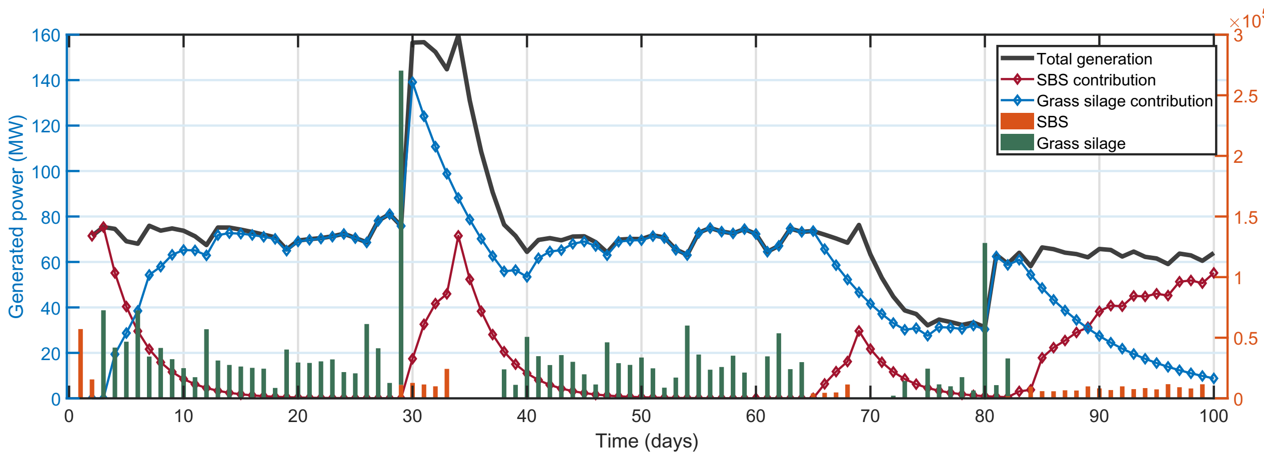

Fig. 2.10 Substrate management without storage

[16] Here, the term "energy cost" implies a sum total of substrate costs, post-digestion handling costs and costs associated with digester size required to produce one unit of energy.

[17] The mechanical constraints like digester size would otherwise be violated.

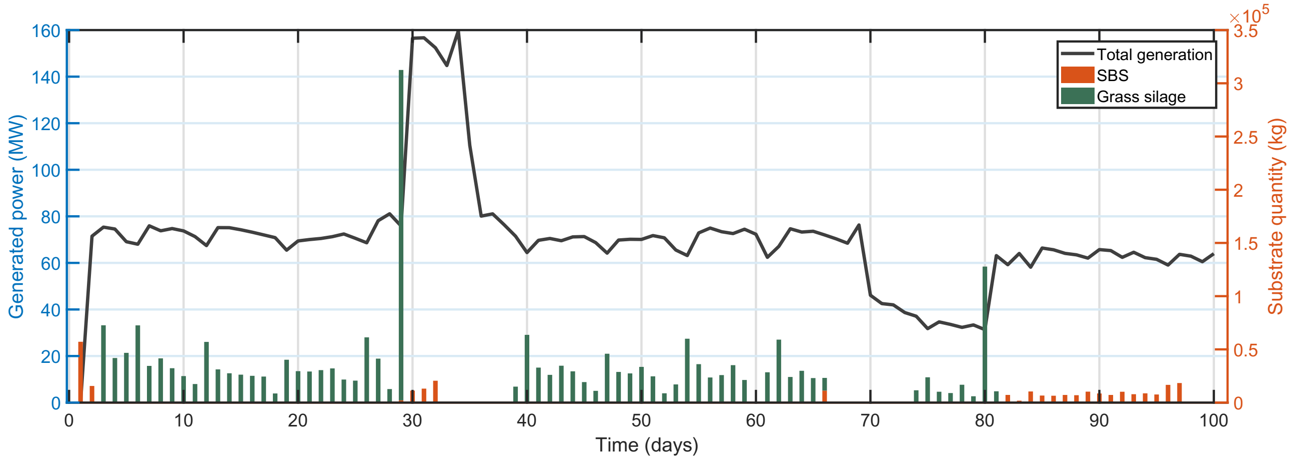

Fig. 2.11 Substrate management with storage

On the metric of operating costs, the substrate management saves the plant 88 % of its daily operating costs as compared to the conventional approach. Inclusion of storage in addition to a well-timed feeding strategy is not considered economically optimal for a long-term planning (only a 0.5 % increase in savings) as storage comes with high installation and maintenance costs [18]. Table 4.2 summarizes the costs and relative performance improvements achieved with the different feeding strategies.

However, reduction in operating costs in the range of 90% can be argued to be highly improbable, given that the plant is operating at a constant efficiency of 40% and at a capacity lower than its maximum capacity. This is can be justified due to the existence of a bias which might have been introduced in the reference case. It is to be noted that the percentage reduction in operating costs are obtained relative to the reference case. This reference case has been assumed to consist of a daily feeding of cattle slurry, beet silage and grass silage in the ratio of 4:1:3. This ensures that on every day of the operating horizon, substrate costs are net positive. In comparison, the optimal feeding strategies have days when the substrate costs are zero or substantially low. Due to this, the optimal operating costs of substrate management scenarios are very low as compared to the reference case. This means that with different feeding ratios in the reference case, the reduction in operating costs for the other cases will change. It is reasonable to assume that if the ratio of constant feeding was chosen such that it was closer to the average optimal mix, the

[18]The costs of storage were not considered in this scenario.

percentage reduction in costs for substrate management cases will be substantially lower than 90%. However, this analysis stresses on the economic implications of having a substrate management to meet a fluctuating load profile, and shows that there will always be a net reduction in operating costs when it is compared to the conventional approach. This analysis also sheds light on the increase in savings when one uses two attributes of flexibility, substrate management and biogas storage. The aim of this study is to provide a qualitative analysis of the advantage of the methods of flexibilsation as compared to the conventional approach and the implications they have on the operation of a plant. The quantitative values, which hold true for this particular hypothetical reference case only, are used to support the quantitative analysis and provide a general understanding of the relative operating costs.

Table 2.1 Economic implications of the scenarios in presence of fluctuating load profiles

	Operating cost (€)	Percentage reduction in costs
Reference case	110,566.70	-
Substrate management without storage	13,266.33	88%
Substrate management with storage	12,691.77	89.5%

Fig. 2.12 shows that storage was mostly utilised at times of increased downward ramping, but the maximum storage capacity of 1000 m^3 was never utilised. This is because, during low electrical and heat demands, substrates were not inserted into the digester thereby reducing the biogas supply when required. This makes it reasonable to assume that an external storage is an economically viable option to provide a buffer against heavily fluctuating load profiles. However, since the feeding strategy provides increased ramping in gas production, a storage level will be beneficial when the lack of technical expertise or initial investment does not allow the plant to have a flexible feeding strategy.

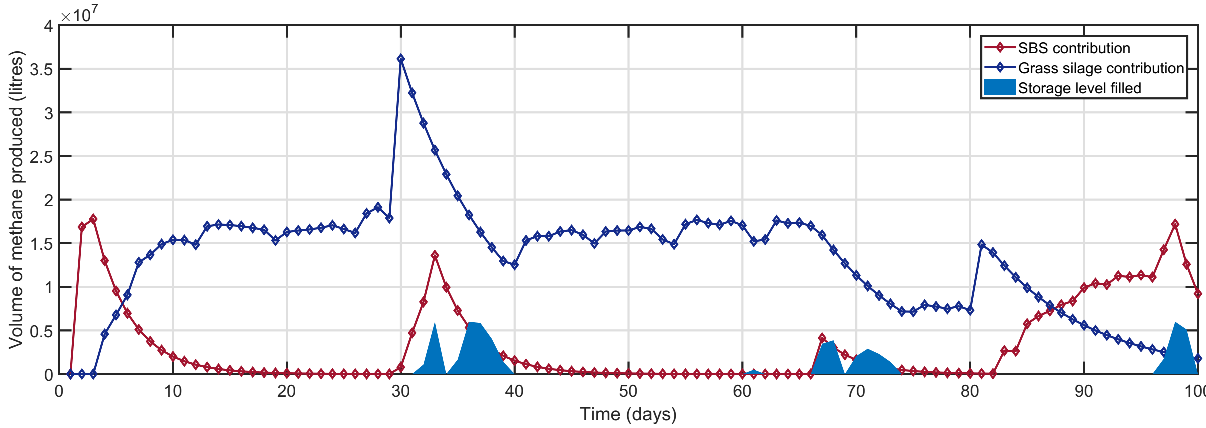

Fig. 2.12 The volume of methane produced in scenario 2

2.7 Behaviour in the spot market

To study the behaviour of the various operational objectives, we use the hourly spot prices obtained from EPEX - day ahead market (one of European electricity markets) [52]. The heat demand of the system was assumed to be a constant 0.5 MW to meet its own thermal needs. To match the level of granularity of the simulations, we consider the maximum spot price level of every day to obtain the input electricity prices for this section (Fig. 2.13). The digester capacity considered was 5000 m^3 and the biogas storage was considered to be 20 % of the total digester capacity, i.e. $Store_{max} = 1000$ m^3. The technical parameters of the cogeneration unit are not changed from the ones assumed in the previous section.

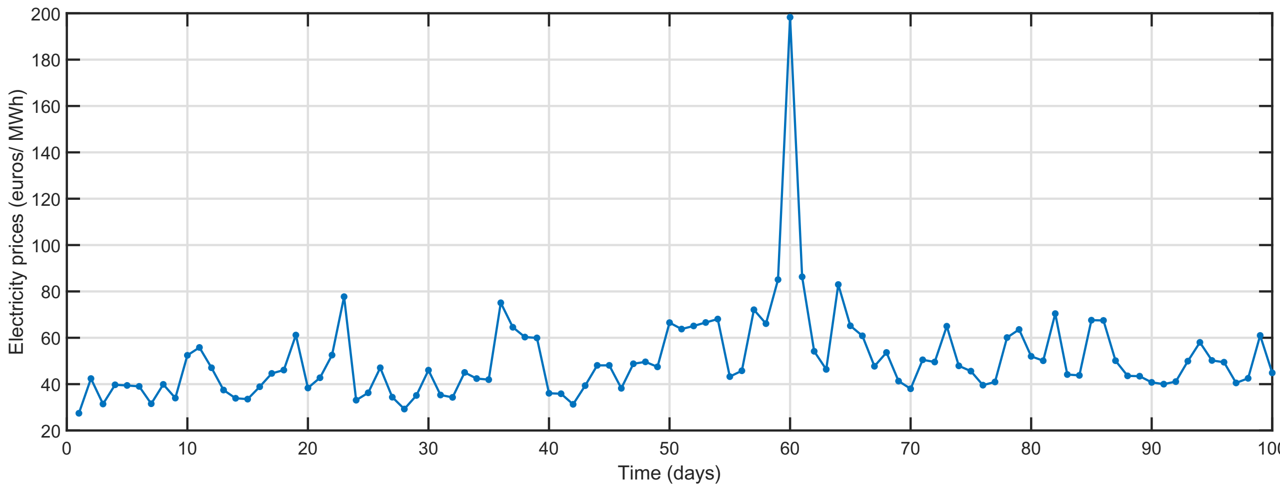

Fig. 2.13 The modified spot prices for the first 100 days

It was found (Table 2.2) that on applying the substrate feeding strategy without storage led to increased sales as compared to constant feeding with storage. Thus, as a strategy of flexiblisation, substrate feeding management performs better economically as compared to inclusion of a biogas storage. However, upon investigating the MW of electrical power sold to the market (Fig. 2.14), it is found that a substrate management chooses to reduce the gas production whenever the spot prices fall below the 40 €/MWh mark. This is attributed to the fact that it is optimal to reduce gas utilisation when the revenues are less than cost of producing biogas. Inspite of being inadequate in tracking the trend of spot market prices to sell more at times of high prices (mainly because sugar beet silage which is instrumental in providing the velocity ramps is quite expensive), the profitability of this method can be attributed to an optimal selection of substrate mix. It opts for a continuous insertion of grass silage to maintain a substantially high production of gas at all times and an infrequent insertion of cattle slurry to tap into the incentives provided by its usage, constrained only by the physical restrictions of the digester (Fig. 2.15). It is to be noted that our optimisation problem is myopic in nature, which is why the electricity sold reduces from $t = 88$. This is an inherent bias of the scheduling problem wherein it does not consider the fact there is existence of operating times beyond the stipulated planning horizon chosen, and behaves as if the electricity prices drop to zero beyond the operating horizon chosen. Hence, it does not favor any input of substrates during the last hours of the operating horizon as can be seen from Fig. 2.15.

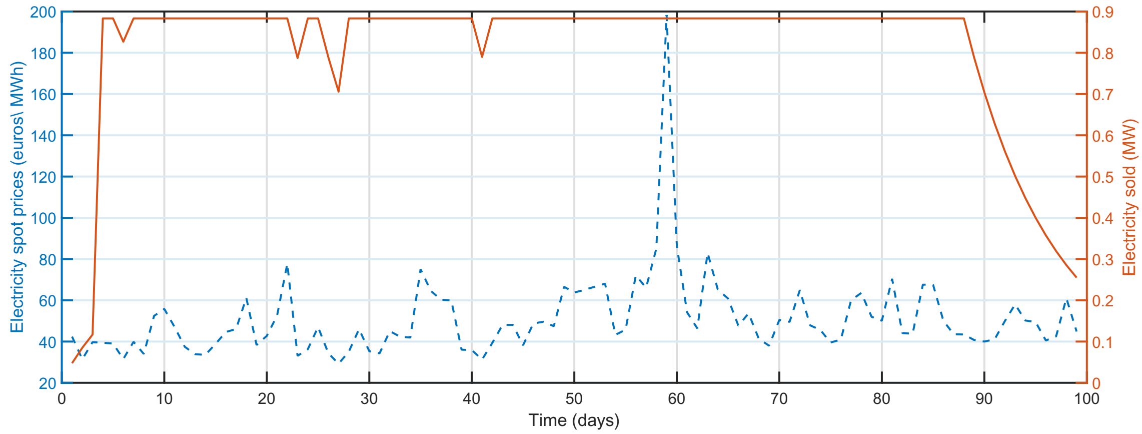

Fig. 2.14 Impact of substrate management in spot market-without storage

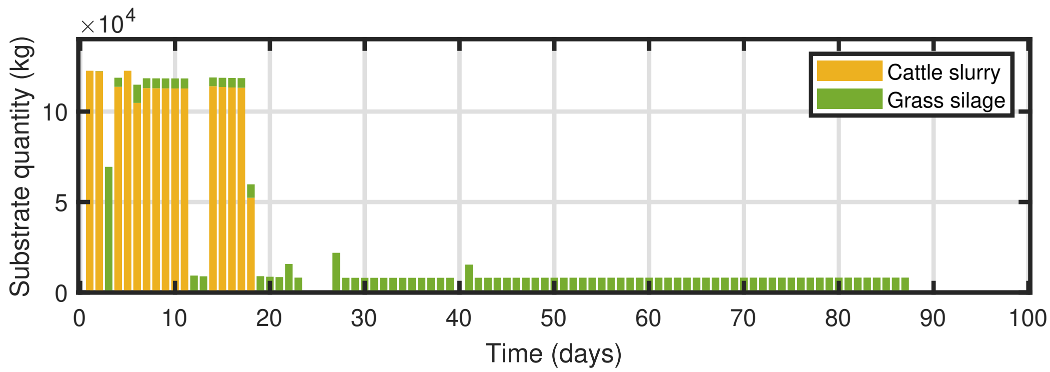

Fig. 2.15 Substrate management profile in a spot market without storage

Substrate management, as described in this thesis, involves the choice of substrates and time of insertion of substrates. The former form is possible only when there are more than one substrate to choose from. As it has previously been mentioned, due to the high cost of beet silage, it was not found to be a suitable candidate during average electricity prices. Hence, beet silage was inserted only during price spikes and not at other times. Nonetheless, as compared to the conventional approach, the approach of optimising the choice of substrates proved to be profitable due to the presence of grass silage and cattle slurry, both of which do not suffer from high substrate costs. As regards to the flexibility in time of insertion of substrates, optimal scheduling of substrates will still be profitable as compared to conventional approach of continuous generation of biogas. In the context of expensive substrates like beet silage, it was found that optimising the quantity of beet silage (in the case of it being the only substrate) inserted and through scheduling the usage of biogas storage, the economics of operation showed a net profit, if there were price spikes like the one at $t = 60$. It can be deduced that even in the presence of substrate management, beet silage will be cost prohibitive at average electricity prices. The optimal scheduling of biogas, as described in this chapter, is aimed at increasing plant profitability in comparison to a conventional approach by proper selection of choice and quantity of substrates and their feeding times. Thus, during average electricity prices, it increases plant profitability by choosing grass silage and cattle slurry over expensive substrates like beet silage. Hence, during low electricity prices, this approach will be successful in all the cases where there is a mixture of substrates to choose from or where the substrate does not suffer from high substrate costs in scenarios having only one type of infeed. Given that substrate management usually involves more than one of type of substrate, this method will be more profitable as compared to a conventional approach, even if one of the feedstocks is cost-prohibtive at average electricity prices. In fact, substrate management aims to acheive profitability through optimal choice of substrates, even during average electricity prices.

A very important bias which might have been introduced in the simulations is regarding the constant mass selected for the reference case. There are several approaches to select the constant mass. One method is selecting the masses inverse to the proportion of biogas produced. This often caused the model to become infeasible as the digestate holding capacity of the digester was sometimes not sufficient. Selection of substrate quantity in equal proportions leads to huge financial losses due to the difference in the power costs involved. Hence, to keep bias to the minimum, the substrates were chosen with grass silage having the maximum proportion and cattle slurry in a 1:2 ratio to grass silage. The sugar beet silage was kept to minimum because of its high costs. Such a selection is inspired from the flexible substrate management strategy to have minimum operating costs without violating the constraints. Since this bias has implications only on the quantitative values pertaining to the chosen hypothetical reference case and does not impact the operation of the plant or the qualitative discussion of the same, it does not pose a concern to the comparative study of the various approaches of operational flexibility.

Fig. 2.16 shows the added benefit of two points of flexibilisation, namely dynamic infeed selection and gas storage. It shows that inclusion of storage enables the cogeneration system to reduce its spot market sales when the price is low and increase its sales when the price is high. This deferring of gas utilisation is more pronounced in the presence of storage. During the first 10 days, a constant feeding strategy takes time to reach its methane potential, leading to reduced sales. This is corrected by greater insertion of grass silage in the first 10 days as compared to the rest of the time horizon. Such a feeding strategy is able to maintain a higher level of gas production without the insertion of beet silage, which leads to substantial savings. The velocity ramps of gas utilisation increased two-fold with substrate management. Even during low prices, like at $t = 27$, $r \downarrow$=0.2 MW without storage while $r \downarrow$=0.5 MW with storage. In contrast, the constant feeding strategy was not able to substantially ramp down its power generation as it was constrained by the maximum storage volume. Even though the storage volume levels for both cases, namely dynamic feeding and constant feeding, were same, a well-timed feeding strategy was able to maximise the plant's profits more. Thus, one can see that a harmonized feeding management with storage provides increased ramping which translates to increased profitability by following the general price trends. Table 2.2 shows that in presence of a biogas storage, a dynamic feeding strategy increased the profits of the plant by almost 50 %.

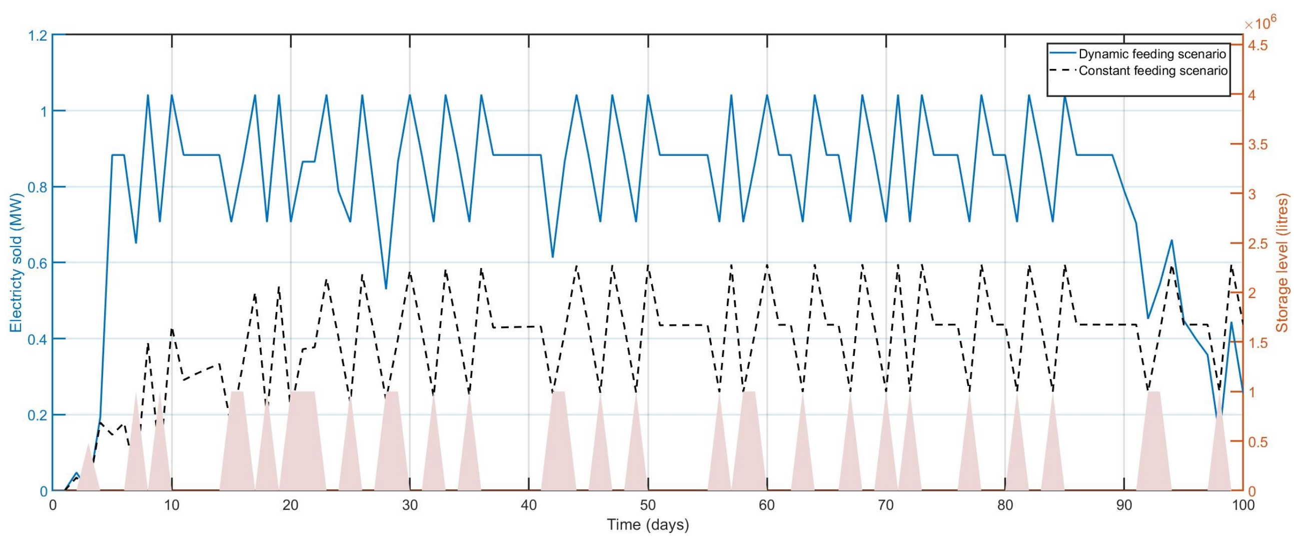

Fig. 2.16 Impact of substrate management in spot market- with storage

Table 2.2 Economic implications of the different flexibility approaches in the presence of spot market

	Net profits (€)	Percentage increase in profits
Constant feeding with storage	1886.00	-
Substrate management without storage	2742.84	45.38%
Substrate management with storage	2805.79	48.77%

Economic analysis of storage inclusion

The results of the optimisation problem show a positive correlation between external storage and profits of the plant. However, sizing of the storage is also a deciding factor in determining whether the increase in profits can be justified in the wake of installation costs of the storage. To do this we perform a sensitivity analysis to compare the rates of change in costs with increasing size of storage. The cost function for an external biogas storage (three quarter of a sphere [19]) is obtained from [42]. In (2.24), $c^{storage}$ is the specific cost in €/m^3 and x is the active storage volume in m^3.

$$c^{storage} = 3397.9x^{-0.585} \tag{2.24}$$

This analysis is based on the premise that a feeding management is already in place. Thus, it aims to provide an insight into the marginal profits obtained upon the inclusion of storage. In Fig. 2.17, the increase in profits is obtained by subtracting 2742.84€ from the optimal objective function values with different biogas storage sizes, followed by dividing the difference by the storage size for specific increase in profits.[20]

[19] This construction was selected as it is one of the most prevelant types of external storages used.

[20] 2742.84€ is the optimal objective function value of the substrate management case without storage, in the presence of a spot market.

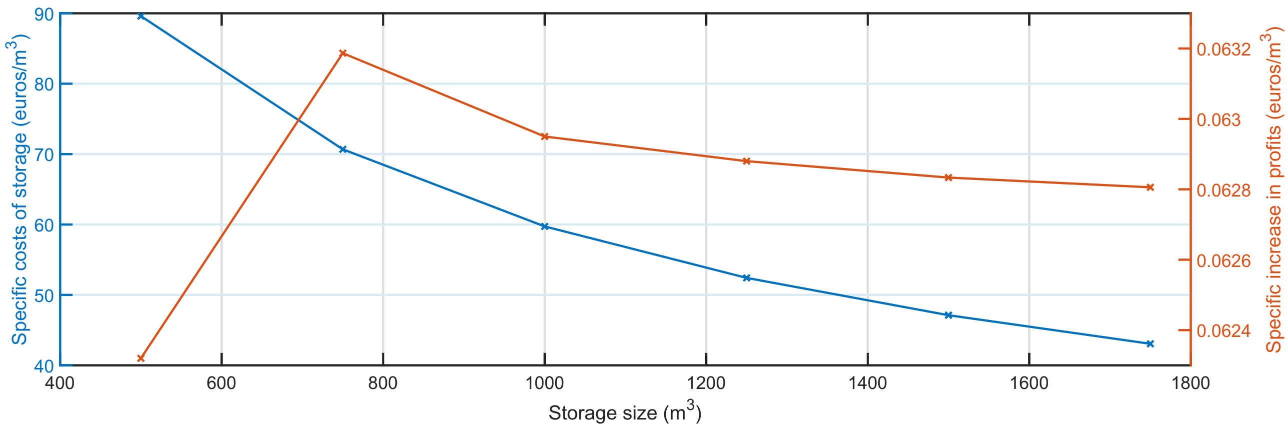

Fig. 2.17 Comparision of specific costs of storage with profits incurred per m^3 of storage space

This study reveals that with increasing size, the profits per m^3 decreases at a rate less than the decrease in specific costs. This can be used to predict whether an installation of biogas storage or increasing storage capacity is indeed profitable. Another interesting insight is that profits increase at 750 m^3 against a decrease in specific cost in this case. Hence, we can conclude that for the biogas plant considered in this section, the optimal size corresponding to the given spot market prices is 750 m^3. This study can be used to design the optimal size of a biogas storage for a given plant size, given average spot market prices and a given substrate supply. However, this study does not take into consideration the pipework required which connects the storage to the plant, costs of labour and other balance of system costs.

2.8 Discussion

This section provides an insight into the choice of models for describing the operation of a biogas digester.

One of the most detailed and accurate state-of-art models of anaerobic digestion is ADM1 which is a non-linear, dynamic model consisting of 39 states, 22 stoichiometric, 19 composition and 37 kinetic parameters. These parameters are dependent on the substrate infeed and the authors in [53] assert that the estimation of most uncorrelated parameters were found difficult due to the interconnectivity between the states. Also, input to the model is in terms of chemical oxygen demand, which requires further experimental verfication for each substrate. Works in the literature have adopted ADM1-based models for optimisation of biogas production like [54] where advanced pattern recognition methods based on machine learning algorithms were utilised. The authors in [55] utilise the Monod-based kinetic equation of ADM1 to obtain the optimal substrate blend for maximising biogas production. Highly granular models based on stochastic algorithms [56] are also utilised to optimise the biogas production. Even though these highly complex models are more accurate at predicting the biogas yield, their applicability is constrained by the availability of data.

For the purposes of formulating a digester model appropriate for operational planning purposes, more parsimonious models are utilised. Indeed, there are few works in literature where ADM1 is utilised for operational planning purposes. For instance, the authors in [12] use ADM1 in conjunction with a cogeneration unit model to obtain a demand-oriented biogas production model. Such an implementation, however, does not shed light on the integrated operation of the system as the biogas digester model (ADM1) was simulated separately and the results were then utilised for studying the demand-oriented operation of a cogeneration system.

For the purposes of meeting the research objectives of this thesis, the anaerobic digester model had to be simplistic whose usage does not require extensive knowledge of parameters and which can be easily integrated into a deterministic, linear programming formulation. A suitable candidate meeting all the prerequisites of the required digester model was found to be based on a sigmoid model which required knowledge of only 2 parameters for each substrate for its application. The three sigmoid equations on which our model is based have been widely used in literature to describe the anerobic digestion process. As regards to accuracy of the models in predicting the biogas yield, several works [14], [43], [44] have experimentally validated the kinetic formulations used in this thesis. Hence, the choice of these kinetic models was made on the ground of them fulfilling the basic requirement of our research objective, i.e., to be able to model the anaerobic digestion process appropriately, within a moderately accurate range, without requiring complex computations and extensive knowledge of biochemical parameters and pathways.

It is to be noted that the contribution of this chapter is not the kinetic formulation of the anaerobic digestion process but the modelling approach to integrate an already established, non-linear, kinetic model into a LP structure and utilise it to investigate the efficacy of various approaches of flexibility. As has been discussed previously, the modelling approach does not change the accuracy of the well-established parent models. This is the first work, to the best of our knowledge, that makes an attempt to provide a detailed unified framework for the optimal integrated operation of a biogas digester and a cogeneration plant, which impedes our ability to demonstrate a performance comparison. Nevertheless, the deployment of this model, as demonstrated in this thesis, is beneficial in obtaining an understanding of the dynamics of operation of a combined biogas-CHP system with the performance of each strategy of flexibilisation compared and analysed in detail.

2.9 Summary

In this chapter, a multi-factorial substrate management was implemented along with dynamic production of bioenergy through storage capabilities. A modelling approach based on kinetic equations was introduced. This modelling approach serves two advantages. It makes it possible to predict the bioenergy obtained from different substrates with the help of fewer parameters (we need to know only three substrate-specific parameters as compared to 78 or more in other modelling techniques present in literature), thereby obliterating the need to have extensive knowledge of the microbiological characteristics of the substrates to predict the methane yield. Secondly, it formulates a linear optimization problem whose goal is to obtain the optimal feeding strategy in terms of time and quantity of feed to minimise the operating costs.

This problem formulation is then applied to provide the feeding strategy to meet a fluctuating demands of heat and electricity or maximise spot market revenue sales. It is found that this flexible production of biogas leads to considerable savings, much more than that provided by storage of biogas. It is to be noted that the costs taken in this model are of substrates only, and we do not take into consideration the biogas purification investment. The biochemical constraints assumed in the model provides the necessary robustness to prevent system instability.

We also provide a study to assess whether an increase in biogas storage (which can enable an increase in profits) is justified in the wake of its high installation costs. The study helps to parametrise the optimal storage size to obtain the maximum profits per m^3. However, this study is lacking in its accountability of long-term investment and maintenance costs of a storage.

In this chapter, we have assumed several important aspects of power generation from biogas. We have not considered the non-linear characteristics of the cogeneration system . Even though a fluctuating heat profile and the thermal requirements of the digester have been considered, an analysis on the efficacy of substrate management in meeting two disparate load profiles have not been made. We also assumed a constant efficiency system, which is not a realistic representation. The timescale for a change in feed-rate to affect the change in electricity and heat generation is in the order of days. This is because the rate constant was taken in terms of days^{-1}. Hence, this approach will not be suitable for a scheduling problem having time instances of 1 hour or when the plant needs to participate in an hour-ahead electricity market. Therefore, in-case a real time demand and supply response was required, this approach needs to be modified so that a substrate management can impact the power generation within an hour[21]. These limitations have been addressed in the succeeding chapters.

[21] The general practice of running unit commitment in the industry is to take a time-step of one hour and not one day.

Chapter 3

Optimal scheduling of a cogeneration plant with supply-side flexibility

3.1 Overview

A short-term operational schedule of a combined heat and power plant is proposed in this chapter. Given a number of different types of co-generation units, it allows for day-ahead selection of the start-up/shut-down schedules, the generation set-points to meet the electrical and heat demands while minimising the production and maintenance costs, at each time instance over a chosen time horizon. The short-term scheduling problem of a co-generation plant is a derivative of the classical unit commitment problem in power systems. Cogeneration plants are multiple output systems as compared to single output thermal or hydroelectric power system, which necessitate elaborate modeling of the interdependencies between the output channels.

Depending on the number of operating variables, a cogeneration system usually has two categories of components as follows [57]:

- *One degree of freedom* cogeneration units where the operating variable is only fuel, like gas turbines without supplementary firing and internal combustion engines, or non-condensing steam turbines.
- *Two degrees of freedom* cogeneration units where the operating variables are fuel and extraction valve control for extraction/condensing steam turbines, or fuel and firing

temperature for gas turbines with supplementary firing.

In this chapter, the congeneration system is modelled to capture intrinsic flexibility offered by the presence of multiple operating variables[1]. In particular, due to its inherent ability to control the extraction of steam from the system, extraction/condensing steam turbines provide additional flexibility in the form of varying the heat to power ratio over a given range. The system model, hence, has a mixture of both gas turbines and extraction/condensing steam turbines which simultaneously produce heat and electricity.

At part-load operating states, there is a non-linear decrease in the global efficiency of the system which translates into non-linearity in the performance of the system. This non-linearity is captured in the performance curves of the system which can be easily obtained from manufacturers' data or published literature. For the sake of reducing the computational complexity of the scheduling problem and to utilise the array of advanced linear optimisation softwares available today, the performance curves of the system components are linearised by a piecewise linear approximation method, commonly known as the λ-method [58]. Using extraction maps which provide linear, discrete representation of the extraction valve control, the steam turbine performance is modelled. The ease of using readily available data coupled to the linearity offered by the extraction maps makes it the preferable approach for modelling the performance of the units. This chapter, thus, illustrates an approach of supply-side flexibility in power systems by integrating two types of units, one with fast response times (gas turbines) and the other offering a dynamic heat to power ratio (steam turbine). An analysis on the suitability of the units in tracking the load profiles is then made, both in the presence and absence of electricity sales to the day-ahead market.

This chapter, thus, proposes a MILP formulation of a multi-energy system whose operational flexibility allows for superior tracking of heat and electrical loads of dissimilar trajectories.

[1]Non-condensing steam turbines like backpressure turbines allow the heat exhausted from the steam turbine to be utilised for heating requirements. However, they do not allow any control over the process heat that might be produced. Hence, they lack the flexibility of having a variable heat-to-power ratio as can be obtained in condensing steam turbines like extraction turbines.

3.2 Relevant literature

In the past few years, as power system landscape has been shifting with increasing interest in RES and climate change mitigation, academia has seen several works on the scheduling of co-generation plants. These works primarily focus on the different strategies of modeling of the CHP usually for feeding a district heating network.

In [59], Mitra et al. give a detailed mathematical model of a cogeneration plant with the components modeled on the basis of the various operating modes. This generalised model captures the transitional behaviour of the cogeneration plant with a focus on the start-up and shut-down characteristics. Koller et al. in [60] approached the scheduling problem of a cogeneration plant with a generic unit commitment model whereby assuming the performance of CHP units to be linear in terms of efficiency. Even though this assumption leads to significant deviation from a more realistic depiction, the method serves as a foundation for further work on unit commitment problems of cogeneration units.

The non-linearity in the performance curves of cogeneration plants is captured in [57] where the authors use piecewise linearisation to obtain a MILP formulation of the unit commitment problem of a CHP plant. The authors propose a model which considers the simultaneous use of different prime movers, compression heat pumps, auxiliary boilers and absorption chillers to provide for not only electrical and heat demands but also cooling demands. The model formulation, however, does not address the difference in ramping capabilities of the different systems as the focus of the research is mainly to analyse the accuracy of the linearisation method adopted. The method of linearisation adopted leads to $O(nm)$ binary and continuous variables and $O(nm)$ constraints, thereby making the MILP formulation computationally challenging and difficult to solve. Risto Lahdelma et al. propose a novel sliding time window method of MILP formulation for optimising the operating schedule of a co-generation plant in [61]. This method assumes a 5 day time-window for calculating the optimal costs, with the window "sliding" or moving forward by a day during each simulation. It accounts for the change in weather conditions which in turn affects the heat demand. The performance of the CHP is obtained by convex combination of extreme points of the characteristic operating region. The power to heat ratio is considered constant as only a backpressure unit is modelled in the formulation.

These works contain locally-situated CHP plants and hence, does not focus on the inclusion of a transmission network. To address this challenge of interconnecting multi-site energy systems, transmission constraints were first introduced in [62]. Using a two-stage power simplex method, this work incorporates the network flow model into the scheduling problem of a co-generation plant. An interesting perspective to approach this model is the inclusion of uncertainty of system contingencies, as has been illustrated in [63] which adopts a stochastic approach to the unit commitment problem. Another approach to modelling the characteristic of CHP exploits the thermodynamic process parameters [64], with a separate representation of the different phases of start-up and operation. This approach, however, does not bestow consequence to the computational expenditure involved and hence, is formulated as a highly complex mixed integer non-linear programming (MINLP) optimisation problem.

Even though literature abounds in different scheduling approaches for multi-energy plants, there is a substantial gap on flexibility of generation and its analysis, which can be primarily attributed to multitudinous linkages between the varied energy forms. Most existing works resort to inclusion of thermal storage [57] or installation of new units to bridge the gap. This chapter attempts to focus on the inherent flexibility of the existing system, and analyses its impact on the scheduling formulation. This is done by exploiting the fast ramping capabilities of gas turbines and semi-decoupled operation of extraction steam turbines which provides us with an array of heat-to-power ratios. In [65], the authors propose discretizing the efficiency and heat-to-power ratios over various loading levels to formulate a dynamic programming model. This and [66] are the only existing works in literature, to our knowledge, which have explicitly modelled the heat-to-power ratios of co-generation plants in the context of optimal scheduling. The approach which is adopted here exploits the state-of-art MILP solvers, unlike [65] where dynamic programming is used and [66] where the system is highly non-linear and formulated as MINLP.

3.3 System Model Formulation

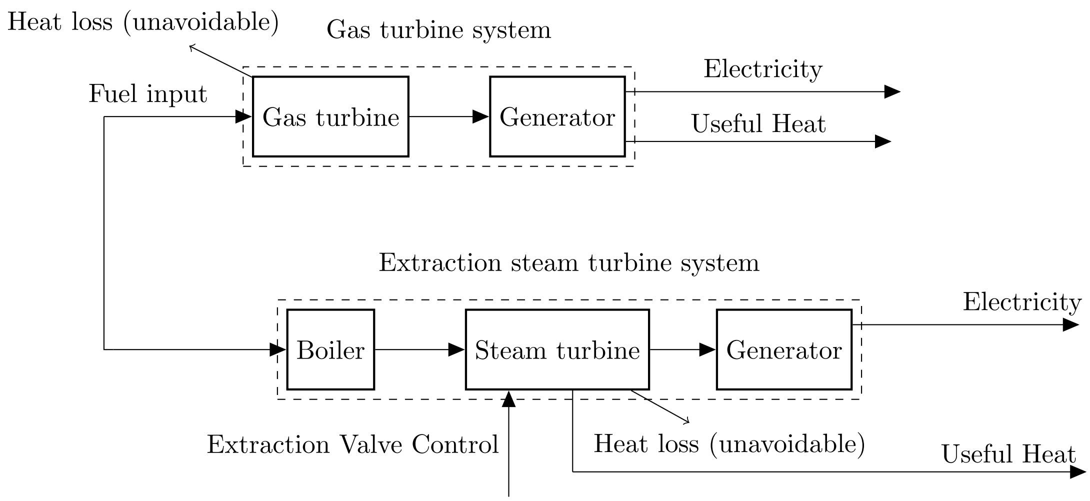

Fig. 3.1 Schematic representation of the cogeneration system

The MIMO system model considered in this chapter consists of two types of units, gas turbines without supplementary post firing (one operating variable) and extraction steam turbines (two operating variables). As seen in Fig. 3.1, the first system consists of a gas turbine-generator set with fuel intake as the operating variable. The second system is a boiler-steam turbine-generator set whereby there are two points of control: fuel intake and extraction valve opening of the steam turbine.

3.3.1 Gas turbine performance

A gas turbine converts fuel into electrical energy and the heat leaving the turbine (as exhaust gases) is sent to heat recovery steam generator (HRSG) to be either stored in thermal storage or used directly for district heating or industrial purposes. Here, the heat recovered is utilised to meet the heat demand[2]. In this thesis, the gas turbine considered is not ideal, i.e, there is always some heat which is wasted (q_n^{waste}) (as mentioned as "Heat

[2]It is useful to define the term *process heat* in this context. *Process heat* is the useful heat generated by a cogeneration system and is utilised for "economically justifiable processes of heating or cooling" like district heating or industrial use [67].

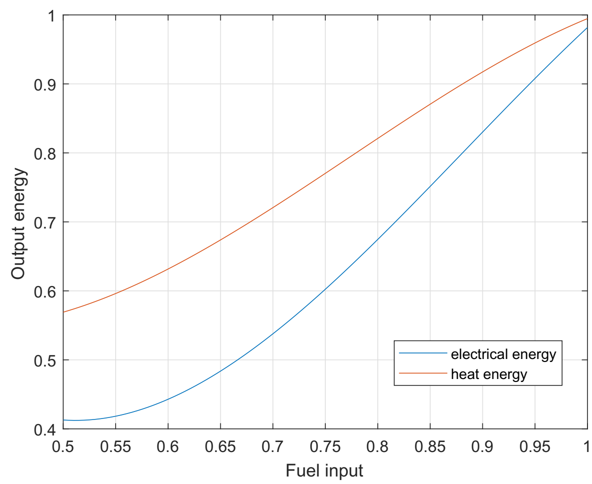

Fig. 3.2 Normalised performance curve for gas turbine

loss (unavoidable)" in Fig. 3.1) and cannot be utilised for meeting the demand. Hence, the total efficiency or thermal efficiency[3] of the gas turbine in this thesis is never 100%. The performance of a gas turbine thereby solely depends upon the fuel consumption, albeit non-linearly, i.e.,

$$e_n = \vartheta_1(f_n), \forall n \in \{GT\} \tag{3.1}$$

$$q_n = \vartheta_2(f_n), \forall n \in \{GT\} \tag{3.2}$$

where ϑ_1 and ϑ_2 are non-linear functions, which can be obtained from manufacturers and e_n and q_n are the electrical and useful heat outputs of the gas turbine[4].

[3]The thermal efficiency, as considered in this thesis, is obtained as [68]

$$Thermal\ efficiency\ (\eta_{th}) = \frac{Net\ useful\ generation}{Total\ fuel\ input}$$

where "net useful generation" is sum total of useful heat and electricity generation.

[4]In terms of conservation of energy, the following holds true

$$f_n = e_n + q_n + q_n^{waste}$$
$$\eta_{th} = \frac{e_n + q_n}{f_n}$$

Fig 3.2 [57] provides the non-linear performance curves for the gas turbine units used in this thesis. The set $\{GT\}$ encompasses all gas turbines in the cogeneration system.

Linearisation of the performance curve

For the sake of preserving the convexity of the feasible region of operation, the performance function is approximated by the λ- method [58].

The theory of the λ -method

Consider a univariate non-linear function, $y = g(x)$, which is discretised at $x = 1, 2, 3..., z$ with z being the point on the right extreme of the domain. For a distinctive value of λ lying between 0 and 1, any point lying between two successive discrete values of x is obtained by the *convex combination* of the two discrete points. To elucidate, for a x' between x_3 and x_4,

$$x' = \lambda x_3 + (1 - \lambda)x_4 \tag{3.3}$$

Subsequently, the linearised function $y_{x'}$ is given by

$$y_{x'} = \lambda y_{x_3} + (1 - \lambda)y_{x_4} \tag{3.4}$$

Intuitively, λ can be obtained if one interpolates the function at x' from the two breakpoints.

$$\lambda = (x_4 - x')/(x_4 - x_3) \tag{3.5}$$

The MILP formulation of λ-method

Initially, the performance curves ($\vartheta_1(f_n)$ and $\vartheta_2(f_n)$) are sampled at z breakpoints on the axis denoting fuel input, i.e., at $f_{1,n}, ..., f_{z,n}$ coordinate points [5]. To ensure that f of a particular unit is associated with a proper breakpoint, a variable α is defined for each breakpoint where α_k [6] is continuous between 0 and 1. In order to ensure an accurate choice

[5] z should not be confused with n. In this thesis, all the gas turbine units are considered identical. For this subsection, we are dealing with describing the linearisation of a performance curve of any one of the units and hence, n is not of any consequence in this subsection. z denotes the total number of breakpoints.

[6] The index k is associated with each breakpoint. To elucidate, the breakpoints on the fuel axis are at f_k where $(k = 1, ..., z)$. This is for only one gas turbine. For n systems, we would use the notation $\alpha_{k,n}$.

of breakpoints for the linear approximation, it is crucial to impose that the only non-zero values of α, in the set of *increasing order* of α, are associated with k and $k+1$. For this purpose, we introduce a binary variable $d_{k,n}$ for the specific interval spanned by $f_{k,n}$ and $f_{k+1,n}$ for a particular n where $k = 1, ..., z-1$. It should be noted that $d_{z,n} = 0$.

$$\sum_{k=1}^{z-1} d_{k,n} = 1, \ \forall n \in \{GT\} \tag{3.6}$$

$$\alpha_{k,n} \leq d_{k-1,n} + d_{k,n}, \ \forall n \in \{GT\} \tag{3.7}$$

Equation (3.6) dictates that only the d associated with the selected breakpoint k takes a non-zero value. For example, for a gas turbine n, if the selected breakpoint is $k = 3$, then, by (3.6), only $d_{3,n} = 1$. By that example, (3.7) ensures that only $\alpha_{3,n}$ and $\alpha_{4,n}$ are non-zeroes.

To incorporate (3.3), we need to make sure that $\alpha_3 = \lambda$ and $\alpha_4 = 1 - \lambda$. In a more general sense, this is ensured by

$$\sum_{k=1}^{z-1} \alpha_{k,n} = 1, \ \forall n \in \{GT\} \tag{3.8}$$

$$f_n = \sum_{k=1}^{z-1} \alpha_{k,n} f_{k,n}, \ \forall n \in \{GT\} \tag{3.9}$$

Subsequently, for a particular system, for any value of f where $f_k \leq f \leq f_{k+1}$, the function, ϑ_1 is then approximated to ϑ_1^a by a convex combination of $\vartheta_1(f_{k,n})$ and $\vartheta_1(f_{k+1,n})$, where $(k = 1, ..., z-1)$. The process is repeated for $\vartheta_2(f_n)$.

$$\vartheta_1^a = \sum_{k=1}^{z-1} \alpha_{k,n} \vartheta_1(f_{k,n}), \ \forall n \in \{GT\} \tag{3.10}$$

This method of piecewise linearisation uses *special ordered sets* (SOS) of type 2, which restricts the maximum number of consecutive variables (α_k) having non-zero value to two.

The state-of-art MILP solvers have in-built packages for handling SOS 2 sets which is advantageous as special branching rules are employed for 'enhancing the enumerative phase' [58]. Consequently, one can neglect (3.6) -(3.7) from the formulation.

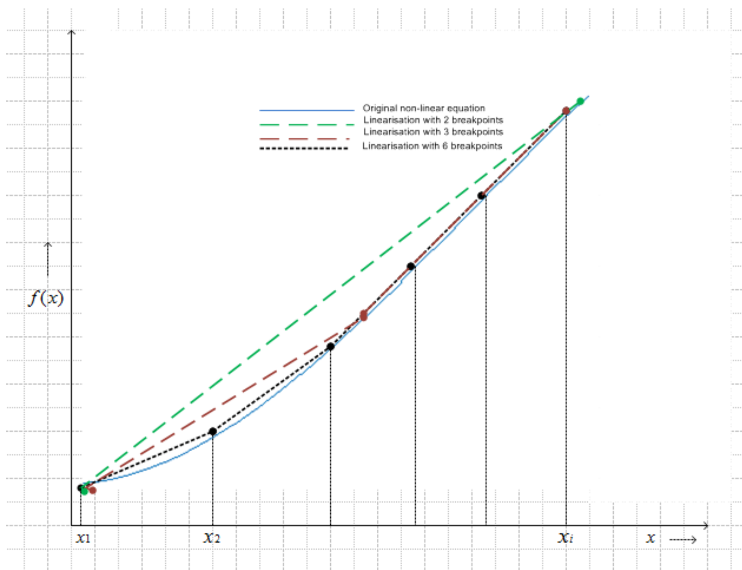

Fig. 3.3 Linearisation of the performance curve using different breakpoints

These equations will hold only if the cogeneration plant is always committed or running. To incorporate the ON/OFF states of the units, a particular α_k is chosen only when binary variable u_t associated with that unit is 1 or ON at time t.

$$\sum_{k=1}^{z-1} \alpha_{k,n,t} = u_{n,t}, \ \forall n \in \{GT\}, \ \forall t \in T \tag{3.11}$$

It should be noted that with increasing the number of breakpoints, the accuracy of linearisation increases (Fig. 3.3), which comes at a cost of computational time, as is evidenced in Section (3.5).

3.3.2 Extraction steam turbine performance

An extraction steam turbine is equipped with an extraction valve which is controlled to extract process steam according to the heat demand profile. The steam turbine, hence, has two operating variables, namely extraction steam flow and the input steam flow. The presence of controlled extraction confers the system the ability to have variable heat-to-power ratio, which provides for a semi-decoupled generation of heat and electricity.

Working of an extraction steam turbine

The extraction steam turbine is fitted with a controllable valve which allows drawing out of steam at some predetermined intermediate pressure [68]. This heat, denoted as $q_n^{extracted}$,[7] is utilised as process heat to meet the heat demands. The amount of steam extracted or drawn out can be controlled by the extraction valve, i.e, one can determine $q_n^{extracted}$ by controlling the valve. The remaining steam is converted to electricity e_n and is later rejected from the condenser as waste heat q_n^{waste} [68]. This waste heat, q_n^{waste}, is condensed in the condenser and fed back to the boiler as feedwater. Hence, q_n^{waste} cannot be utilised to meet the thermal demands of the cogeneration system. According to [67], a steam extraction turbine is classified as a *flexible unit* as it can adjust the heat-to-power ratio according to the heat demand. This steam turbine can be operated in *full cogeneration mode* where "the heat extraction is maximum and *full condensation mode* where $q_n^{extracted}$ is zero and electrical generation is maximum[8]. The heat-to-power ratio can be varied along these extremes" [67].

Modelling the extraction steam turbine using extraction maps

To the best of our knowledge, this is the first instance in literature where extraction maps of steam turbine are utilised to model traditionally neglected extraction valve control. This approach of modelling a steam turbine is termed as a *data-driven* approach as the extraction maps are directly obtained from the manufacturer, making the model based on readily available data. In [69], the authors use non-linear thermodynamic dependencies to model the extraction steam turbine, but do not consider the extraction valve control, to maintain computational affordability. In [59], Mitra et al. use a simplified extraction diagram to obtain the feasible region of operation. The extreme points of the map are joined in the convex hull approach, and a two-stage steam turbine is modelled based on the two extreme

[7]It should be noted that this $q_n^{extracted}$ is same as q^n which is the useful heat generation of an extraction steam turbine.

[8]The maximum heat extraction and the maximum electrical generation have to conform to the technical requirements as elucidated later.

lines of the feasible region.

The following assumptions are made to implement the extraction maps in the modelling formulation.

- The steam flow input to the turbine is produced by a boiler which takes in fuel and produces steam with a constant efficiency.
- The mass flow rate of steam is converted to energy by multiplying it with the specific enthalpies of the obtained steam [70].
- The extraction flow lines are a measure of the extraction steam flow.
- The operating set point is bound by backpressure line and extraction line, obtained from the output profile of a generic extraction unit [71].

In Fig. 3.4 [72], the lines A-B and lines C-F are the generation limits of electricity produced by the turbine (3.12). Here, $\underline{E}$ is the lower bound on electricity generation and $\overline{E}_n$ is the upper bound on the generation[9]. The set $\{ST\}$ comprises of all the extraction steam turbines in the system.

$$\underline{E}_n \leq e_n \leq \overline{E}_n, \forall n \in \{ST\} \tag{3.12}$$

Line E-F gives an upper bound on the input steam flow to the turbine which translates to an upper fuel limit F_n^{max} as given in (3.13).

$$f_n \leq F_n^{max}, \forall n \in \{ST\} \tag{3.13}$$

The line A-D represents a zero steam extraction line whereby the useful heat generated will be nil. This means that the fuel is used to produce only electricity[10]. In (3.14), the

[9] Electricity generation is obtained in MW.

[10] It is to be noted that this, however, does not mean that heat wasted (q_n^{waste}) is zero. Even when useful heat generation is zero ($q_n^{extracted} = q_n = 0$), the fuel is essentially used to produce electricity and non-usable, waste heat. This waste heat is not utilised or controlled in any way by the optimisation problem but due to its presence, the efficiency of the steam turbine at line A-D is never 100%.

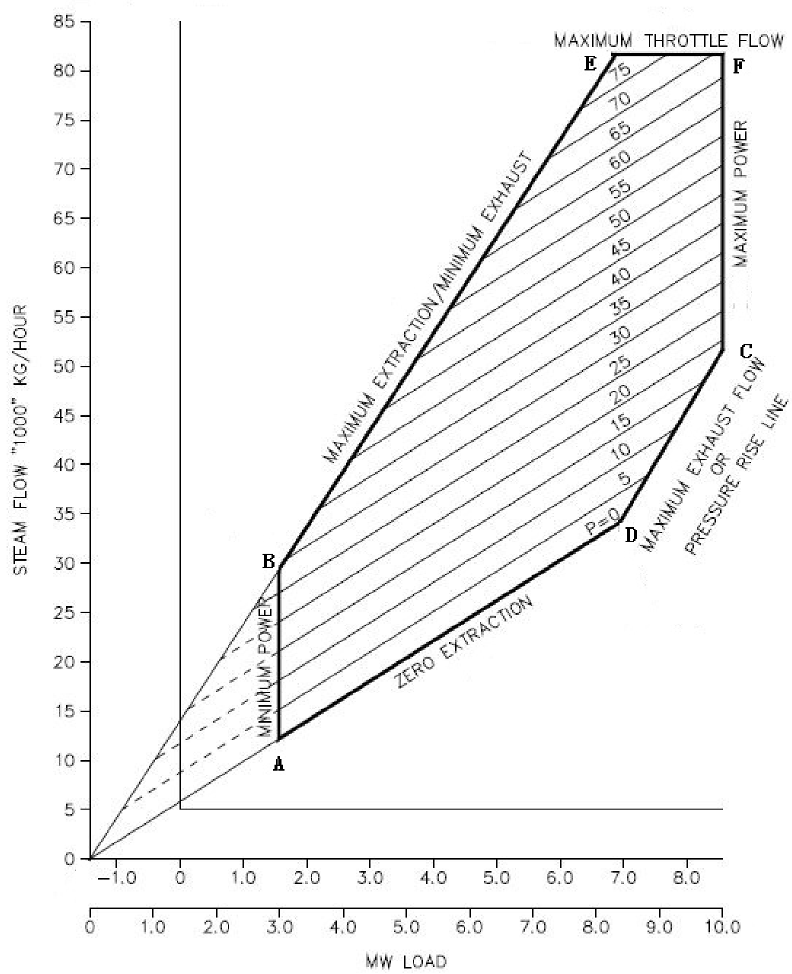

Fig. 3.4 Extraction map of a generic steam turbine (modified from [72])

electrical power output is modelled as a linear function of fuel intake with intercept c, which is a function of the percentage of valve opening v, with v discretised between its minimum and maximum values. The intercept c takes up constant values at the discrete intervals of valve openings and denotes the extracted or process steam (q_n) in MW corresponding to a specific valve opening percentage. It is evident that the higher the degree of discretisation, the more flexibility one can achieve in terms of range of heat-to-power ratios or the number of admissible operating set-points. The constant m_1 is the inverse of the slope of line A-D.

$$e_n = m_1(f_n - c(v)), \forall n \in \{ST\} \tag{3.14}$$

To prevent overheating and for thermodynamic stability, there is always a minimum steam flow to the exhaust section which is defined by line B-E [72]. This *exhaust steam* is important to maintain mechanical stability of the machine and even at maximum extraction, there is some heat which is wasted as exhaust heat[11]. The control of the extraction valve is possible only in the feasible region bounded by lines A-D, C-D and B-E, as shown by (3.15).[12]

$$m_2 f_n + r_1 \leq e_n \leq m_2 f_n + r_2, \forall n \in \{ST\} \tag{3.15}$$

The constant m_2 is the inverse of the slope of lines C-D and B-E. The heat output of an extraction steam turbine is directly proportional to the extraction steam output as shown by (3.16). The constant r^h takes into account any heat loss that might occur during the extraction process. From (3.14) - (3.16), one can obtain the maximum and minimum heat-to-power ratios.

$$q_n^{extracted} = r^h c(v), \forall n \in \{ST\} \tag{3.16}$$

It is to be noted that the there is always a substantial amount of heat, about 50% to 60% of total fuel input which is wasted as unavoidable heat loss and this waste heat (q_n^{waste}) is not controlled by the two operating variables. To elucidate, let us define q_n^{waste} as the total heat wasted and $q_n^{extracted}$ as the *useful heat output/heat extracted*. Then, at all times, the

[11] *Exhaust steam*, which is sent out through the exhaust section of the turbine, is considered to be a part of unavoidable and uncontrollable heat waste q_n^{waste}.

[12] In terms of conservation of energy, the following holds true

$$f_n = e_n + q_n^{extracted} + q_n^{waste}$$

operation of the extraction steam turbine maintains

$$f_n = e_n + q_n^{extracted} + q_n^{waste}, \forall n \in \{ST\} \tag{3.17}$$

$$q_n^{waste} > 0 \tag{3.18}$$

$q_n^{extracted}$ is referred to as q_n throughout this thesis. Therefore, the variation of heat-to-power entails the variation of $q_n^{extracted}$ to e_n. For example, if q_n^{waste}= 50% of fuel intake, this extraction steam turbine can allow the $q_n^{extracted}$ and e_n to be varied such that

$$q_n^{extracted} + e_n = 0.5 f_n, \forall n \in \{ST\} \tag{3.19}$$

$$q_n^{extracted} \geq 0, e_n \geq 0 \tag{3.20}$$

Understanding flexibility of the extraction steam turbine

Flexibility is defined as the ability to follow the load profile without compromising on the system stability at each time step. In the context of supply-side flexibility, an extraction steam turbine has a dynamic range of operating points, each with different heat to power ratios. It is to be noted that this flexibility is only applicable for a cogeneration system which has to meet both heat and electrical demands.

For a gas turbine, the electrical output has only one degree of freedom, i.e., it changes solely with the fuel intake. Correspondingly, the heat generated is also a constant multiple of the electrical output. Hence, during times of low heat demand (i.e, when the MW of heat required is much less as compared to MW of electricity demand) and high electrical demand, the gas turbine will consume fuel to generate heat according to the constant heat-to-power ratio (which is usually in the range of 0.9-1.2). This lack of control over the heat generation will eventually lead to reduced efficiency and higher operating costs during disparate demand profiles, as can be seen in the following sections. On the other hand, it is evident from the performance map in Fig. 3.5 that for one fuel input f_1, there can be a range of values of electrical output, from e_1 to e_6, as illustrated. To elucidate, the extraction valve allows the operation to move from zero heat-to-power ratio (line A-D)[13] to ratios more than 1 (provided $(e_n + q_n) < f_n$, according to the laws of thermodynamics).

[13]As mentioned earlier, there is a substantial amount of heat wasted as q_n^{wasted} even when heat-to-power ratio is zero.

Hence, the operating point of an extraction turbine is chosen such that it can best satisfy both the heat and electrical demands, in a decoupled manner. This flexibility of operation is missing in a gas turbine. In order to confer same degree of flexibility in a system with gas turbines, we can use a combined cycle system involving a gas power cycle (gas turbine) topping a vapor power cycle (steam turbine) [68].

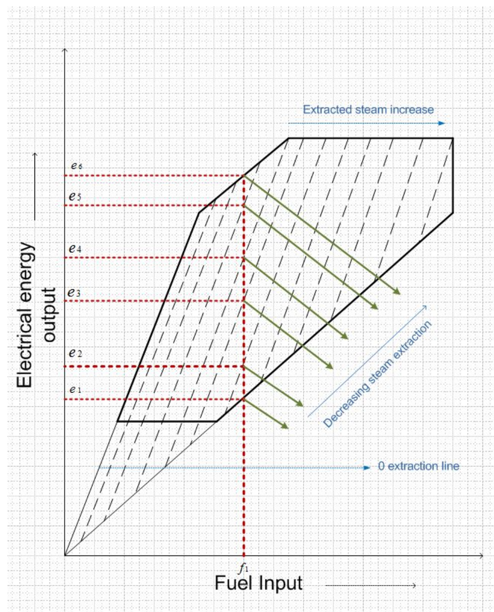

Fig. 3.5 Operation of an extraction steam turbine

It is to be noted that the *heat-to-power ratio*, as used throughout this thesis, has been defined according to [67,73,74], as the ratio of useful heat generation to electrical generation. To use the notations used in the previous sections, heat-to-power (htp) is obtained as[14]

$$htp = q_n/e_n \tag{3.21}$$

An extraction steam turbine is a condensing type of steam turbine, which means that the heat exhausted as waste heat from the turbine cannot be utilised to as process heat. As

[14]For the sake of brevity, q_n is used throughout this thesis to mean useful heat generation. Hence, q_n is same as $q_n^{extracted}$ for an extraction steam turbine system. To further clarify, for an extraction steam turbine, 3.21 can be written as

$$htp = q_n^{extracted}/e_n$$

elucidated in [68], it is not possible to include q_n^{waste} in the definition of heat-to-power ratio. This is because if the useful heat generation is considered to be the sum of q_n^{waste} and $q_n^{extracted}$, the total efficiency of the cogeneration system will always be 100% which is thermodynamically impossible and hence, not realisable in practice.

3.3.3 Technical constraints

Generation limits

There is a constraint on the maximum and minimum generation that can be produced by the units each hour, which is described as an operational range for the units. The binary variable $u_{n,t}$ denotes the state of the unit n at time t, i.e., $u_{n,t} = 0$ if the unit is decommitted or shut down at t and 1 otherwise. $\underline{E}_n$ and $\overline{E}_n$ denote the minimum and maximum allowable electrical generation in MW for unit n. Similarly, $\underline{Q}_n$ and $\overline{Q}_n$ denote the minimum and maximum allowable useful heat generation in MW for unit n.

$$u_{n,t}\underline{E}_n \leq e_{n,t} \leq u_{n,t}\overline{E}_n, \forall n \in \{GT\}, \forall t \in T \tag{3.22}$$

$$u_{n,t}\underline{Q}_n \leq q_{n,t} \leq u_{n,t}\overline{Q}_n, \forall n \in \{GT\}, \forall t \in T \tag{3.23}$$

For a steam turbine, the electrical generation limits are obtained by slightly modifying (3.12) as obtained in (3.24). The generation limits for heat generation are obtained from the feasible operating states, (3.13) - (3.24).

$$u_{n,t}\underline{E}_n \leq e_{n,t} \leq u_{n,t}\overline{E}_n, \forall n \in \{ST\}, \forall t \in T \tag{3.24}$$

Start-up and shut down characteristics

Depending upon the various phases of operation of the gas turbines and steam turbines, the start-up methods (cold, warm and hot) and shut down methods can vary whereby the power output in each method follow a particular trajectory [75]. In this thesis, the start-up procedure is modelled to combine the soak and dispatch phase of gas and steam turbines. Here, N denotes a summation of sets $\{GT\}$ and $\{ST\}$. The units are committed or de-committed according to (3.25)-(3.26) within the range allowed by the minimum up and down times [76], denoted by UT_n and and DT_n respectively.[15]

$$\sum_{j=t-UT_n+1}^{t} u_{n,j}^{st} \leq u_{n,t}, \forall n \in N, \forall t \geq UT_n \tag{3.25}$$

$$\sum_{j=t-DT_n+1}^{t} u_{n,j}^{sd} \leq 1 - u_{n,t}, \forall n \in N, \forall t \geq DT_n \tag{3.26}$$

Ramping constraints

Another point of difference between the working of gas and steam turbines lies in their ramping capabilities. Gas turbines without post firing have ramping capabilities faster than the duration of two successive time steps (i.e., ≤ 60 minutes) and hence, are not subjected to this constraint, during the dispatch phase. This fast ramping functionality offered by gas turbines also offer some degree of flexibility during times of large changes in load (both heat and electrical) which is investigated in the later sections. The steam turbines, on the other hand, have moderately slower ramping capabilities and for consecutive time-steps when there are no start-up or shut-down procedures, the ramping flexibility is constrained by RU (maximum ramp-up limit) and RD (maximum ramp-down limit). These also take into consideration the ramping of the boilers feeding the turbines. The allowable power ramps during start-up and shut down are less than at other operating times and hence, denoted separately as RU_n^{st} (for start-up) and RD_n^{sd} (for shut-down) [75].

$$(e_{n,t} - e_{n,t-1}) \leq RU_n u_{n,t-1} + RU_n^{st} u_{n,t}^{st} + \overline{E}_n(1 - u_{n,t}), \forall n \in \{ST\}, \forall t > 1 \tag{3.27}$$

$$(e_{n,t-1} - e_{n,t}) \leq RD_n u_{n,t} + RD_n^{sd} u_{n,t}^{sd} + \overline{E}_n(1 - u_{n,t-1}), \forall n \in \{ST\}, \forall t > 1 \tag{3.28}$$

For $t = 1$, the equations for ramping up change to

$$e_{n,t} \leq RU_n^{st} u_{n,t}^{st}, \forall n \in \{ST\}, t = 1 \tag{3.29}$$

[15] $u_{n,t}^{st}$ is a binary variable, which is 1 if a unit is committed at t and 0 otherwise, and $u_{n,t}^{sd}$ is a binary variable, which is 1 if a unit is decommitted at t and 0 otherwise.

Energy Balance

In this multi-energy system, both heat and electricity (in MW) is supplied to meet the respective demands at each time t.

$$\sum_n e_{n,t} = \sum_n e^s_{n,t} + e^{nl}_t, \forall t \in T \tag{3.30}$$

$$\sum_n q_{n,t} = q^{nl}_t, \forall t \in T \tag{3.31}$$

In (3.30), e^{nl}_t is the net load obtained as a difference of total load and load supplied by other RES. Similarly, q^{nl}_t in (3.31) is the net heat demand obtained by adding the thermal requirements of the anaerobic digester to the district heating demand. In this chapter, q^{nl}_t is same as the district heating demand as the anaerobic digester has not been considered. To denote the electricity sold to the spot market, we have included $\sum_n e^s_{n,t}$.

3.4 Objective function

Given that the proposed scheduling problem aims at maximising the profit for the utility or the price-taker,the objective function is the daily operation cost of the system. The cost of operation comprises of generation costs, operation and maintenance costs and start-up costs and the revenues from selling electricity to spot markets.

$$\min \sum_{t=1}^{T} C^g_t + C^m_t + C^{st}_t + C^{sd}_t - P_t \tag{3.32}$$

$$\tag{3.33}$$

where

$$C^g_t = \sum_n \hat{c}^f_n f_{n,t}, \forall t \in T \tag{3.34}$$

$$C^m_t = \sum_n \hat{c}^m_n u_{n,t}, \forall t \in T \tag{3.35}$$

$$C_t^{st} = \sum_n \hat{c}_n^{st} u_{n,t}^{st}, \forall t \in T \tag{3.36}$$

$$C_t^{sd} = \sum_n \hat{c}_n^{sd} u_{n,t}^{sd}, \forall t \in T \tag{3.37}$$

$$P_t = \sum_n \hat{p}_t^{s} e_{n,t}^{s} \Delta t, \forall t \in T \tag{3.38}$$

The generation cost C_t^g is proportional to the fuel intake, the maintenance cost C_t^m is proportional to the total number of hours the unit stays committed. Even though the start-up and shut-down costs are non-linear functions of the time the unit has been on/off respectively, they are considered to be constant here for the sake of simplicity. P_t is the revenue obtained by selling electricity to the day ahead spot market[16].

The heat produced by biogas is mainly used for district heating or industrial heating purposes and at present, there is not much market for trading heat energy (unlike electrical energy) [17]. Therefore, the system formulated in this thesis is concerned with maximising its profit by electricity sales only.

The mixed integer linear programming is formulated as (3.32) subject to constraints (3.9)-(3.11), (3.13)-(3.31).

3.5 Scenarios

This section deals with the implementation of the model in different scenarios. The optimisations are performed by the CPLEX solver [77] in GAMS, on a Intel core i7 processor having 6 GB RAM. The scenarios are described as follows. It is to be noted that for all the scenarios, the heat demand profile is obtained from twenty commercial buildings in the city of Atlanta, Georgia in the year 2012, and the electric load is obtained from [78] (Fig. 3.6). For the purpose of this illustration, the time horizon is 7 days, with granularity of one hour, i.e. 168 hours.

[16]The Δt in (3.38) denotes the time step of operating horizon.

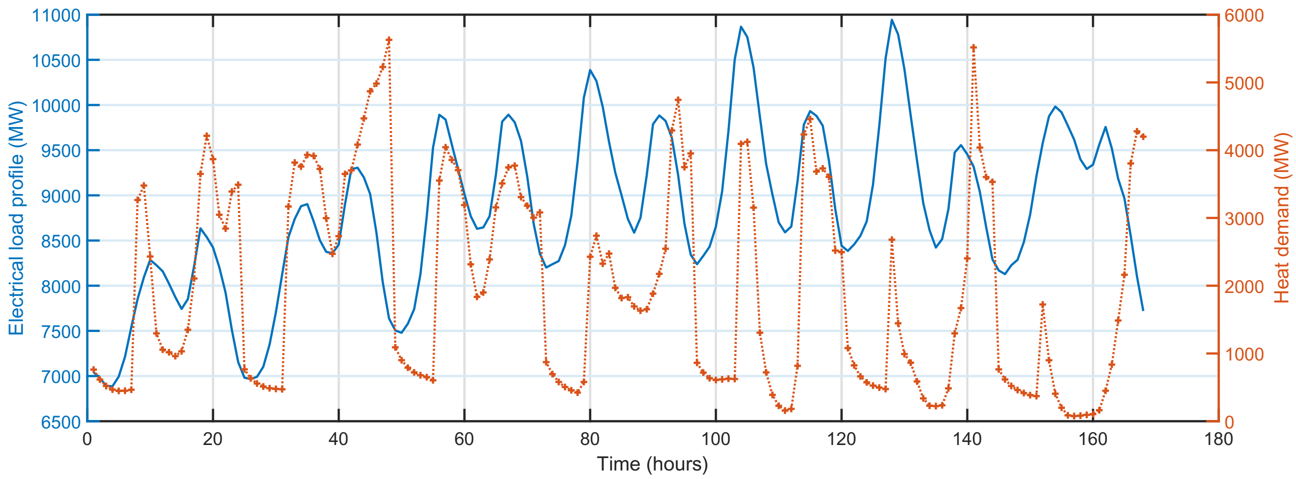

Fig. 3.6 Load profiles used for scenarios

Scenario 1

This involves four identical gas turbine systems with parameters as described in Tables A.2-A.3, found in Appendix A. This case, besides being the reference case against which the flexibility of having variable heat-to-power ratio is measured, is also used to analyse and bring forth the efficacy of the linearisation technique adopted. The constant heat-to-power ratio was assumed to be 1.7 [79] for this simulation.

Table 3.1 Impact of piecewise linearisation

	5 breakpoints	10 breakpoints	20 breakpoints
Optimal value obtained (million €)	343.79	324.25	318.43
Number of variables	6040	9400	16120
Time taken (s)	13.1	166.9	193
Optimality gap (%)	0.07	0.02	0.07

The reference case was compared in terms of the number of breakpoints chosen for piecewise linearisation of the performance curves. As can be seen in Table 3.1, increasing the number of breakpoints leads to a better approximation of the characteristic curve which comes at the cost of an increasing computational time. The computational complexity is dependent on $N_k \cdot N_t$ where N_k is the total number of breakpoints and N_t is the total time of operation considered. It is found that the reduction in objective function value (20 breakpoints compared to 5 points) due to better approximation is 7.38 % which becomes insignificant as the number of breakpoints and time steps increase. This is of utmost concern as in the power industry, scheduling problem is run at a granularity of maximum one hour for a period of one year. For our short-term scenario, it was found that the computational time increased by almost fifteen times when the number of breakpoints increased by 15 coordinates. Given that this formulation may become a victim to the curse of dimensionality, selecting the number of breakpoints is a matter of a trade-off between accuracy and the computational time requirements.

Scenario 2

This case consists of four identical extraction steam turbine systems with similar technical parameters as the gas turbines. Steam turbines are more expensive as compared to gas turbines, which is reflected in their maintenance costs. Tables A.4 - A.5, in Appendix A, describe the parameters of the steam turbines used. The values assumed for m_1, m_2 and r^h are 0.45, 0.12 and 0.8 respectively.

Scenario 3

This involves a mixture of two identical gas and two identical steam turbines, to analyse the flexibility provided intrinsically by both the units, when all other parameters are maintained constant.

3.6 Results and discussion

The metric on which we have assessed efficacy of the type of flexibility is the electrical efficiency of the system. Fig. 3.7 shows that the average efficiency[17] of all the steam turbines (η= 32 %) in Scenario 2 [18] was five points higher than the average efficiency of the gas turbines (η= 27 %) in Scenario 1. The reason is attributed to the greater degree of control available in steam turbines, which makes them more flexible to adapt to two disparate load profiles with minimum fuel expenditure. To illustrate, the time range $t = 140, ..., 160$

[17] The efficiency was calculated by dividing the total electrical generation of the whole system (and not individual units) by the total fuel intake.

[18] The reader is requested to consult Fig. B.3 on page 91 for a detailed description of the electrical and total efficiencies of individual systems of Scenario 2.

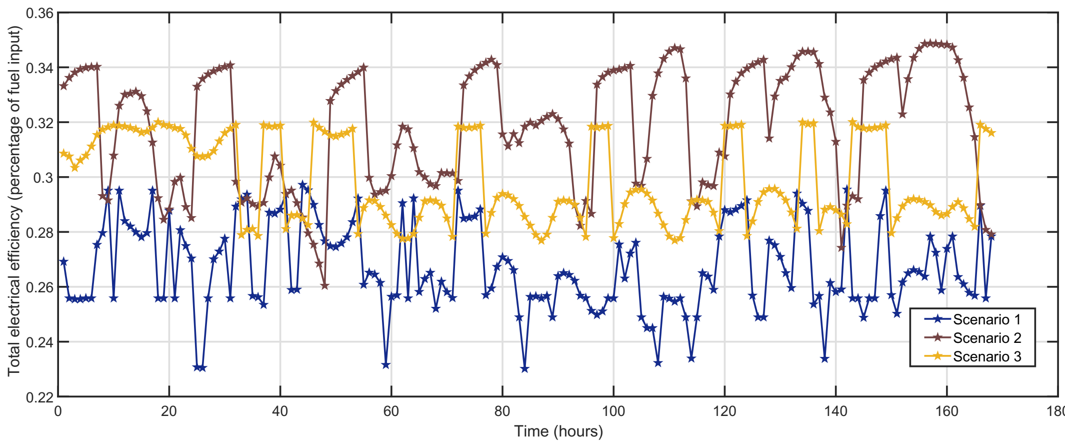

Fig. 3.7 Average electrical efficiency of the unit over the time horizon

is a region of two disparate trends in the load profiles with the electrical load showing an uptrend and heat demand showing a steady decrease. During this time range, the efficiency of gas turbine units drop considerably because even though heat demanded is low, the high constant heat-to-power ratio makes it imperative for higher heat generation even during low demands. This in turn, leads to additional amount of fuel being drawn to generate useful heat at the constant ratio and this generated heat being wasted (as there is not enough demand) and hence, a drop in electrical efficiency as compared to steam turbine system. The steam turbines control the extraction valve output to reduce the useful heat generation (which translates to lower heat-to-power ratios as seen in Fig. 3.8) by extracting less heat and the steam turbine operates close to line A-D of the extraction map, as can be seen from Fig. B.1 in Appendix B, on page 89. The functionality of extraction steam turbines to match two disparate load profiles can be seen from their electrical and heat generation profiles (Fig. B.1). Moreover, a more detailed explanation of the the electrical and total efficiencies of steam turbines of Scenario 2 can be found in Appendix B. To corroborate the fact that during the operation of the plant q_n^{waste} is always non-zero, we can see that at $t = 157, ..., 160$, electrical efficiency is at 35% (Fig. 3.7) even when heat-to-power ratio is very close to zero[19].

[19] The reader is requested to consult B.1, for further explanation on heat generation and heat loss in case of Scenario 2.

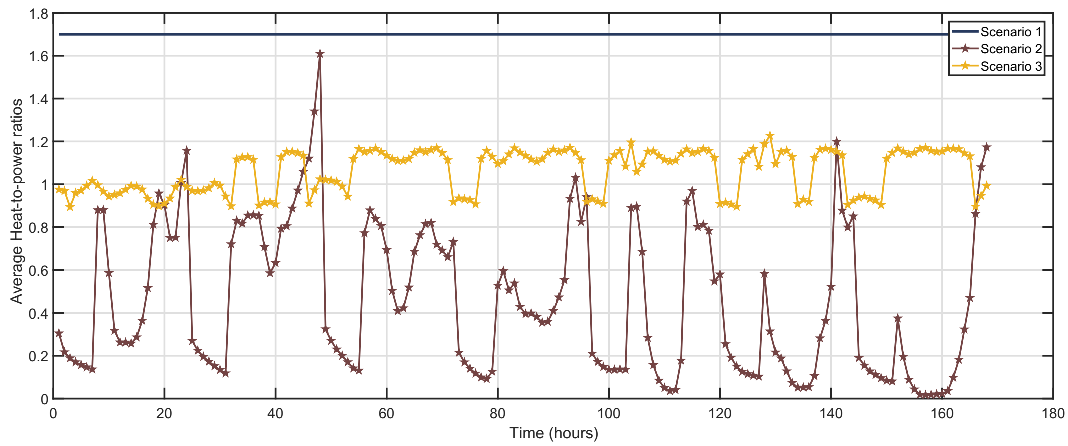

Fig. 3.8 Variation in heat-to-power ratios

Fig. 3.8 shows that a constant heat-to-power ratio leads to loss of process heat as waste thereby decreasing the total efficiency drastically. On average, the loss of heat[20] in Scenario 1 is 13330 MW per hour for this particular heat profile and heat-to-power ratio. Thus, it can be deduced that the system depicted in Scenario 1 will perform better than the other systems when the general trend of the electrical and heat load profiles reflect the specific heat-to-power ratio of the system. However, realistically, when the electric demand is usually higher than or disparate to heat demand, Scenario 1 will lead to considerable energy losses (as there will be not be enough demand for the useful heat generated) which translates to economic losses as shown in Table 3.2 (this happens because more fuel is drawn to produce heat according to the constant heat-to-power ratio but most of this useful heat is wasted due to low demand)[21]. Due to this loss of efficiency, Scenario 2 shows a 11.8% reduction in operating costs as compared to Scenario 1 in Table 3.2. An important insight obtained after running the simulations with different values of m_2 is that the average efficiencies were linearly proportional to the value m_2, as a greater m_2 depicts a greater feasible operating region for the plant.

To analyse the performance of Scenario 3 in Fig. 3.7 and Fig. 3.8, it is imperative that

[20] The loss of heat is calculated as the difference between useful heat generation and heat demand. A positive loss of heat entails generation of useful heat in excess of heat demanded, which eventually leads to process heat being released as waste in the absence of thermal storage.

[21] It is to be noted that, on an average, unavoidable heat losses as waste heat (q_n^{waste}) per hour is 26%

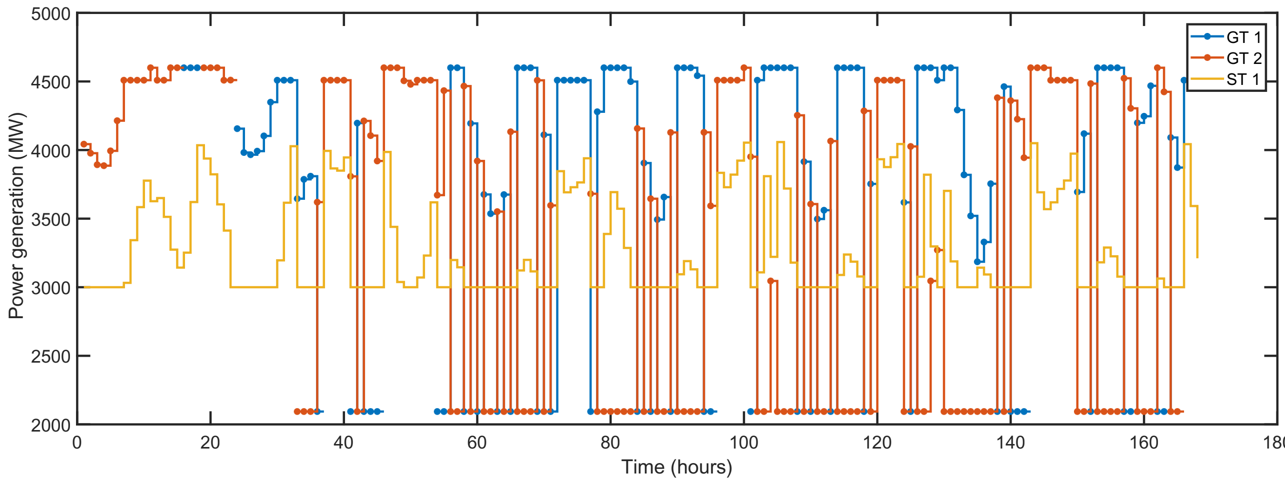

Fig. 3.9 The generation schedule in scenario 3

we study its generation schedule (Fig. 3.9). By the optimal generation schedule obtained, it is seen that the gas turbines mostly operate at the minimum and maximum allowable capacities and are decommitted at times of reduced electrical power demand. This scenario shows that due to fast ramping capabilities and short minimum uptimes and downtimes as compared to steam turbines, gas turbines are preferred to provide an additional generation when the steam turbine is not being able to meet the load completely due to the slow ramp-up capability. The steam turbine is constantly running and the gas turbines are dispatched only when the electricity demand is high. This contribution of majority generation [22] by the gas turbines brings down the average efficiency of Scenario 3 to 30%. Also, the steam turbine operates mostly on the line A-D (Fig. 3.4), which means that, given a high generation of heat by gas turbines (which satisfies the heat demand at most times), preferred mode of operation of the steam turbine is the zero extraction mode (at most times). This functionality allows Scenario 3 to track the demand profiles better and hence, enjoy a higher efficiency as compared to Scenario 1. Scenario 3 exhibits two types of flexible operation: fast ramping capabilities of gas turbines and variable heat-to-power ratio of steam turbines.

According to Table 3.2, Scenario 3 has a higher operating cost than Scenario 2. This is attributed to the lower flexibility of gas turbines, which contribute the most to the max-

for Scenario 1.

[22]This explains the high heat-to-power ratio of Scenario 3.

imum generation. This scenario sheds valuable insight on the applicability of a variable heat-to-power generation ability. We can, hence, deduce that a steam turbine will be highly beneficial in scenarios where there are both heat and electrical demands and where load matching capabilities are of paramount importance.

Table 3.2 Economic implications of the scenarios

	Total cost (million €)
Scenario 1	318.43
Scenario 2	280.42
Scenario 3	298.94

The motivation behind the simulations conducted in this chapter and throughout the thesis is to find out the flexibility offered by gas turbines and steam turbines. For this reason, it is imperative to have two disparate demand profiles for comparison basis. However, it is to be noted that in cases where only electrical demands need to be met, gas turbines are more efficient than steam turbines and are more cost-effective due to reduced maintenance costs. They also have better ramping capabilities than steam turbines. This chapter analyses the heat-to-power ratio of a cogeneration system and in terms of flexibility, it was found that extraction steam turbines were more flexible than gas turbines due to more controllability over useful heat generation. This flexibility offers the steam turbine more efficiency in times of diverging trends in the two demand profiles. One can also have more flexibility in a combined cycle system with gas cycle topping a vapor cycle (steam turbine). This chapter tries to ascertain the advantages conferred to a system due to the presence of a variable heat-to-power ratio. Hence, it should be kept in mind that the extraction steam turbines are more efficient than gas turbines only during the cases illustrated above. Also, this behaviour is beneficial in cases where tracking of load and matching the separate demands simultaneously is found necessary.

3.7 Summary

This chapter provides an analysis of the intrinsic flexibility (in terms of variable heat-to-power ratios) conferred to a cogeneration unit, as opposed to a gas turbine (without post-firing). The non-linear performance curves of the gas turbine were linearised using a piecewise linearisation technique and a data-driven approach for modelling an extraction steam turbine was proposed. The use of extraction maps to model a two-degrees of freedom extraction steam turbine is the first in literature, to the best of our knowledge. A derivative of the classical unit commitment formulation was adopted to integrate the complexities of a semi-decoupled operation of a cogeneration unit. Three scenarios were then described and simulations carried out to analyse the impact of flexibility on the operation of a co-generation unit.

It is found that even though extraction steam turbines are more promising in following the disparate heat and electrical load profiles, they can fall short of meeting sudden fluctuations in load due to their slow ramping capabilities. To circumvent this drawback, a system having both the units is proposed and its impact on the flexibility of the system is analysed. This integration of two types of units has lower operating costs as compared to a system with only gas turbines, due to higher efficiencies of conversion. Given that this system has a higher cost of operation as compared to a system consisting solely of steam turbines, the matter of prudent selection of the system depends on the trajectories of electrical and heat loads the unit as a whole has to supply to. This can be done by inspecting historical data and employing various forecasting techniques during the planning period .

In this chapter, the focus has been on analysing how effective the variable heat-to-power capability is in meeting the both electrical and heating loads and obtain a nuanced perspective on the optimising the operation in such a case only. It can be reasonably asserted that studying the performances of the three system types in the presence of an electrical spot market will not shed any additional insight as there is no trading market for heat sales to provide a basis for comparison. Hence, (3.38) is considered in the next chapter where other strategies of operational flexibility are also considered.

The results show that the inherent flexibility offered by control of extraction valves in steam turbines holds promise for load matching in future net zero communities, a concept which is slowly being adopted on a larger scale in European countries [80]. At present, solar cells are implemented to realise this idea. In order to utilise bioenergy as a an alternative or complement to PV cells in such communities, one requires a system with higher efficiencies (due to the low calorific value of biogas) which makes the system investigated in this chapter a better candidate as compared to conventional gas turbines. Further analysis on the integration of biogas fuel to a system offering variable heat-to-power generation is presented next in Chapter 4.

Chapter 4

Integration of substrate management with optimal scheduling of a cogeneration plant

4.1 Overview

This chapter combines the dynamic feeding strategy proposed in Chapter 2 with the optimal scheduling of a cogeneration plant, described in Chapter 3. Given a fluctuating demand for both heat and electricity (or fluctuating spot market prices for electricity), an integrated multi-energy plant model is optimised which provides the operating strategy for both the biogas digester and the cogeneration plant. The optimal schedule of the cogeneration plant provides the plant operator with the amount of biogas yield required to meet the hourly heat and electricity demand. The kinetic model of biogas digester equips the plant operator to predict the optimal temporal and quantitative feeding strategy of the digester to meet the specific biogas yield. The integrated model, simultaneously selects the type cogeneration units, the start-up/shut-down scheme of the selected units and the dynamic feeding strategy of the digester, with the aim of minimising the daily operating costs. Furthermore, we provide a brief analysis on the performance of the model in a spot market scenario. The last section of the chapter discusses the technical shortcomings of the model when it is applied in a realistic setting and presents hypothetical modifications to address the limitations.

4.2 Model and simulation parameters

The model is formulated as a MILP in GAMS and the optimisations are solved using the branch and cut algorithm of CPLEX [77]. This integration of model formulations from Chapter 2 and Chapter 3 calls for several modifications. First, the model in Chapter 2 assumed a constant efficiency cogeneration system, with a constant heat-to-power ratio. This model of CHP is replaced by the system model of Chapter 3 which allows a much larger selection of operating points, by virtue of its intrinsic flexibility. It also incorporates the non-linearity of performance curves which translates to load-dependency of the efficiency of the system.

The granularity of time horizon considered in this chapter is one hour as opposed to one day, and hence, the kinetic rate constants, which are of paramount importance in determining the methane yield, must also be modified[1]. The minimum HRT has also been changed to 192 hours and the maximum OLR has been assumed as 0.00015 kg/l per hour.

The constant electrical efficiency considered in Chapter 2 was 40 %, which is higher than the average electrical efficiencies obtained in Chapter 3. To accommodate for this reduction in efficiencies in the integrated system, the digester capacity has been increased from 50000 m^3 to 500000 m^3. Interestingly, this increase in digester capacity will increase its own heat demand, which is added to the hourly heat demand profile as a constant over the entire optimisation horizon. The implications of efficiency on the operating costs will be discussed later in this chapter. The hourly heat demand profile is obtained from the same data-set as Chapter 2 and has been scaled down to include the thermal requirements of one commercial building in the city of Atlanta, Georgia.

To ensure feasibility in operation, the electric load profile for the integrated model is 1% of that in Chapter 3 [78]. This ensures that the biogas digester has sufficient capacity to meet the total power demand continuously, during the time horizon. The technical parameters associated with the CHP units, like the sizing of the gas turbines and steam turbines are also scaled down to 1 % of the values considered in Chapter 3 (Table A.2-A.5). The heat

[1]The modified values are obtained either from published literature [14] or by dividing the original values by twenty-four, where such legitimate sources are not available.

demand profile takes into account the cost of heating the digester at 30°C , which is linearly dependent on the capacity of the digester. In order to keep the digester heated constantly at the mesophilic temperature, the heat requirement assumed is a constant 30 MW. Fig. 4.1 shows a scaled heat demand and a scaled (10% of the original) electric load curve [78]. This particular dataset of demands is interesting as it will shed light on the behaviour of systems in presence of huge disparities in the electric and heat requirements.

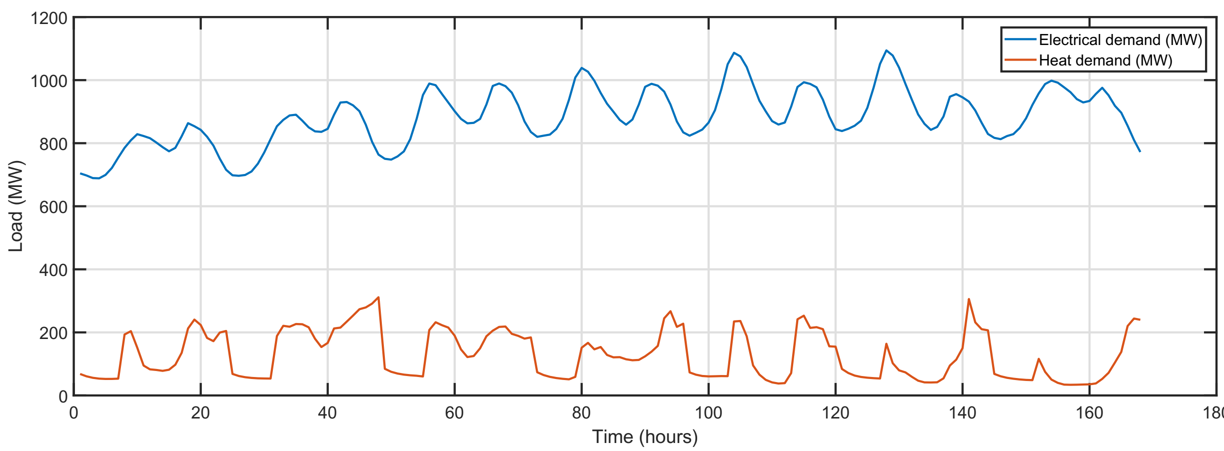

Fig. 4.1 The load profiles used for simulation

Scenarios

To investigate the various strategies of flexibilisation and obtain an understanding as regards to their efficacy, several scenarios studied. *Scenario 1* allows dynamic substrate management combined to only gas turbines units in a CHP. *Scenario 2* is similar to the previous case with the cogeneration unit comprising solely of extraction steam turbines. *Scenario 3* allows for flexible substrate management and both varying heat to power ratio and fast ramping capabilities, with the cogeneration unit comprising of equal proportions of gas turbines and steam turbines. Scenarios 1 to 3 are driven by motive of meeting the heat and electrical demands with minimum operating costs. *Scenario 4*, which comprises of systems having an added flexibility in terms of storage of biogas, leads to further analysis on how profitable it is to have an external storage in the presence of a spot market for electricity.

4.3 Results

Technical evaluation

In this thesis, the metric on which the flexibility of the proposed methodology is based is how closely the generation of the plant *tracks* or follows two separate load profiles simultaneously. This also dictates the presence of flexibility on the digester side, or ‘fuel flexibility’, one could say.

Table 4.1 Economic implications of the scenarios

	Substrate costs (€)	Maintenance costs (€)	Start-up and shut-down costs (€)
Scenario 1	42,940	46	150
Scenario 2	42,807	250	30
Scenario 3	39,256	169	70

Table 4.1 gives a comparison of the three main costs incurred : Substrate costs, maintenance costs and start-up and shut-down costs. It is found that Scenario 3 has reduced overall costs are due to its reduced substrate costs. Scenario 2 has the highest maintenance costs and lowest start-up and shut-down costs, which is expected given the higher minimum up and down times of steam turbines and higher costs associated with maintenance. Scenario 3 shows a 8.7% reduction in total operating costs as compared to Scenario 1 and a 8.5% reduction as compared to Scenario 2. Hence, given the electricity and heat demands, from a short-term operational planning perspective, the proposed model performs economically superior.

Fig. 4.2 shows that the optimal feeding strategy for a gas turbine type cogeneration system is frequent feeding of smaller quantities of sugar beet silage, with feedings of grass silage at the beginning to match the demands. On the contrary, Fig. 4.3 shows that the optimal strategy of steam turbines is very infrequent feedings of high quantities of sugar beet silage. This is mainly because gas turbines are not able to accommodate the higher velocity ramps of gas production, whereas steam turbines are able to smoothen out the higher ramps by controlling the extraction valve opening. In both the cases, beet silage is preferred over other substrates , even though the operator is paid to utilise cattle slurry [2] as a feedstock. The rationale driving such a choice is both biological (sugar beet silage is fast degradable and has maximum potential) and technical (the amount of feedstock that can be present in the digester at each t has an upper bound).

Interestingly, the gas turbines suffer from increased operating costs, as the constant heat-to-power ratio requires a high thermal generation to match its high electrical generation, even though the heat demand is considerably lower. On the other hand, a varying heat-to-power ratio of the steam turbine allows it to handle the velocity ramps of production by ramping up its electricity generation , while having considerably lower heat generation. It is to be noted that the maximum electrical efficiencies in both the scenarios were considered identical, to reduce parameter bias in the results.

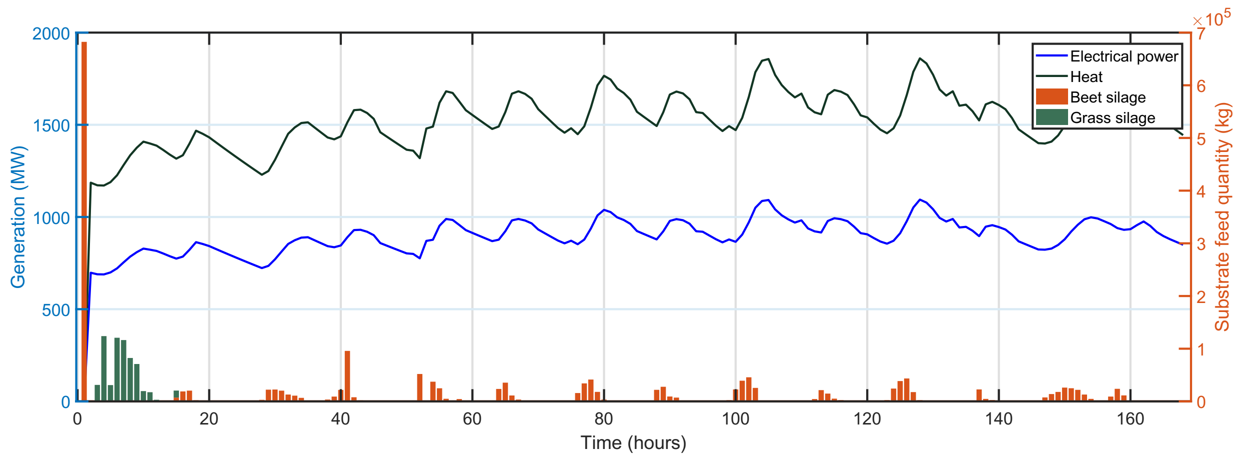

Fig. 4.2 Behaviour of gas turbines when substrate management is applied-Scenario 1

[2]The reader is requested to refer to Table A.1, in the Appendix A, for the costs associated with various substrates.

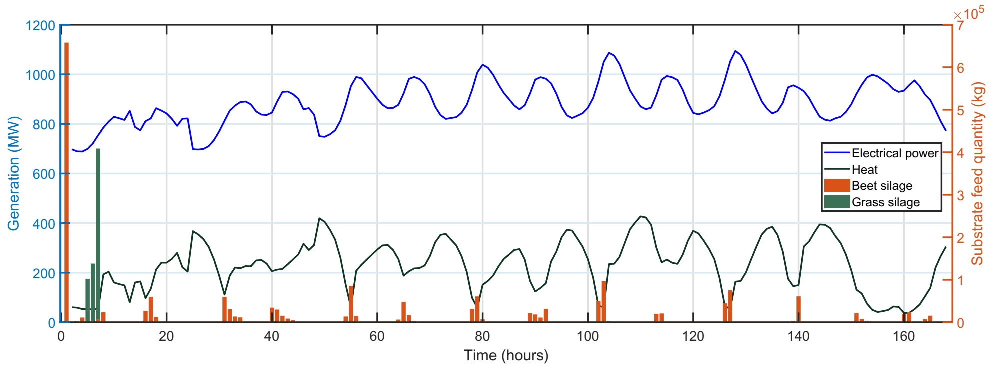

Fig. 4.3 Behaviour of steam turbines when substrate management is applied- Scenario 2

Fig. 4.4 gives the optimal feeding strategy for an integrated unit containing both gas and steam turbines. It has the lowest substrate costs as it the beet silage is fed in lower quantities and grass silage contributes more to the total infeed as compared to other scenarios. Gas turbines provide the intial starting power followed by one steam turbine and two gas turbines supplying the demands for the rest of the time horizon. The gas turbines contribute to the heat generation as per the constant heat-to-power ratio and the difference between the their generations and heat demanded is fed by the steam turbines which is able to operate at zero extraction mode when there is no steam demanded. This enables Scenario 3 to have a heat generation less than the electricity generation, unlike in Scenario 1. This also leads to a reduction in operating costs.

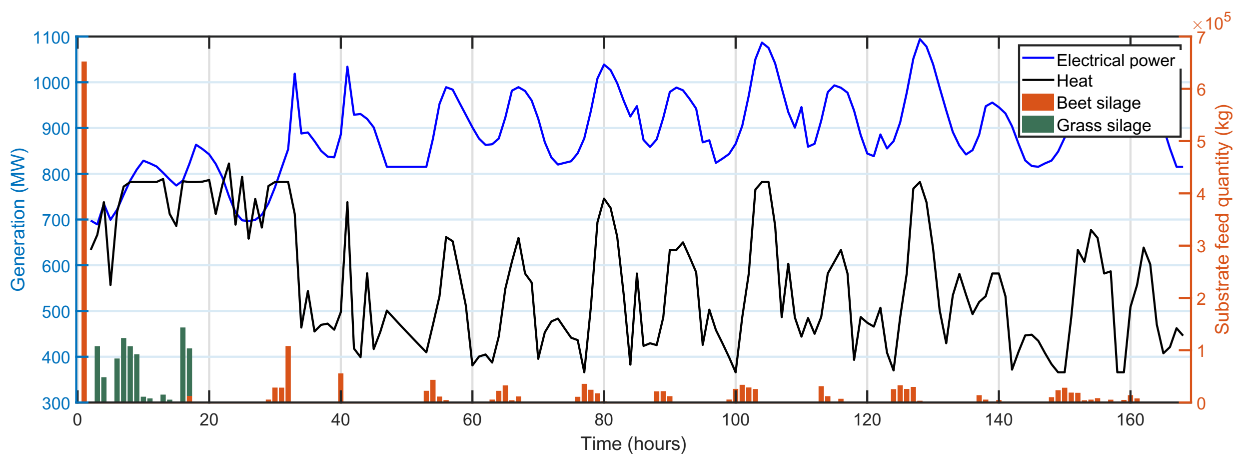

Fig. 4.4 Behaviour of combined system when substrate management is applied- Scenario 3

Sensitivity of generation set-points to substrate management

In order to understand the reason behind the higher costs incurred in Scenario 1 as compared to Scenario 2, it is important to understand how each type of cogeneration unit behaves in the presence of a fluctuating gas production. Fig. 4.5 provides an insight to the same. It can be seen that both the systems receive almost equal levels of methane volume. In fact, during the time range $t = 30, ..., 40$, the steam turbines take in more fuel and are also subjected to higher ramps of gaseous production (an average of 0.02a m^3 per hour for Scenario 2 as compared to 0.013a m^3 per hour [3]). The maximum velocity ramp of gaseous production fed to the gas turbine system is almost 0.4a m^3 per hour (at $t = 40$) whereas that of steam turbine is around 0.47a m^3 per hour (at $t = 101$). To obtain a nuanced perspective about the performance of the two scenarios, the study of the time regions of high velocity ramps are imperative.

- During the time range $t = 98, ..., 103$, the heat demanded is fairly constant at 31 MW wheras the electricity load profile shows an uptrend from 800 MW to around 1000 MW. The steam turbines follow the electric demand perfectly while reducing their heat extraction to match the low heat demand. The velocity ramps of gaseous production had no impact on the ability of the steam turbine to follow to disparate trends. This adds value to the deduction that steam turbine system is able to smoothen out the fuel input ramps. This is attributed to its ability to allocate more fuel for producing electricity (as it has a higher load) and more choice in selecting set-points of generation enables it to have a generation schedule fairly unaffected by the sudden increases in gaseous input.

- During the time range $t = 39, ..., 42$, both the heat and electricity loads are increasing in value, with the heat loads at around 22 % of the electricity loads. The gas turbines follow the electric demand perfectly but generates useful steam much higher than demanded. The constant heat-to-power ratio of the gas turbine system does not allow it to absorb the ramps of fuel input and the impact can be visible on its 'tracking' abilities. This behaviour is better observed in time range $t = 50, ..., 55$.

[3] Here, a denotes 10^5.

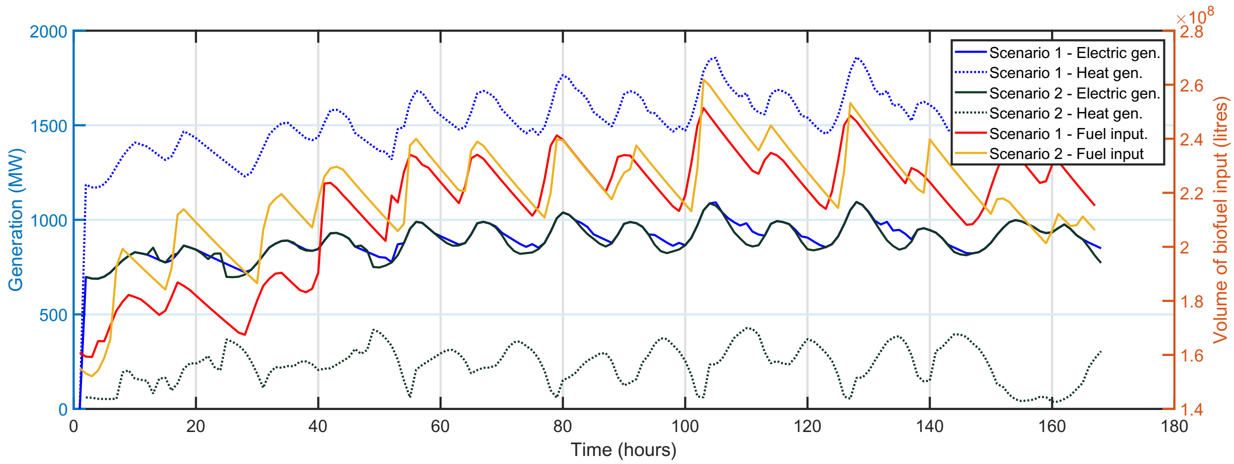

Fig. 4.5 Reaction of cogeneration units to flexible methane generation

Behaviour in the presence of a spot market

This section analyses the dynamics of system performance in presence of a spot market (Scenario 4). Fig 4.6 shows the spot market prices (obtained from an European electricity market EPEX) for the first 168 hours of the year 2014 [52]. We analyse the added benefit of having a biogas storage in this case. The system has to meet a constant heat demand of 30 MW at all times to satisfy its own heating needs. In this case, we consider 1000 m^3 of biogas storage , which at a nominal capacity of 1 MW gives storage facility for 10.6 hours. The allowable digester capacities remain unchanged.

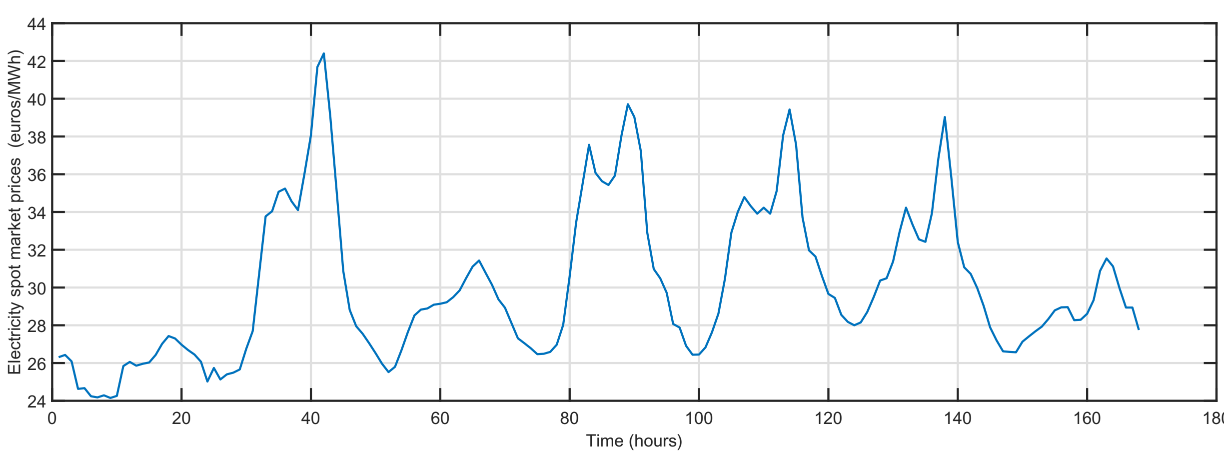

Fig. 4.6 Spot market prices for the first 168 hours

In conventional biogas plants, due to continuous feeding, it becomes economically beneficial to have a biogas storage to defer the fuel supply to times of higher demand [81]. For plants selling electricity to the spot market, such a storage can act as a means of storing biogas in times of low prices and utilising it in times of high prices. However, in the presence of a varying substrate management, the performance of the system with an added layer of flexibility is important to gauge whether undertaking the added expenditure of installing the storage is economically optimal.

Table 4.2 Economic implications in presence of spot market

	Profits from spot market sales (million €)	Increase in profits
GT with continuous feeding	6.86	-
GT with substrate management	7.43	8.3%
ST with substrate management	7.86	14.5%
Combined with substrate management	7.64	11.4%
GT with storage and substrate management	7.88	14.7%
ST with storage and substrate management	7.87	14.7%

For these particular spot prices , the economic analysis in Table 4.2 shows that inclusion of storage storage leads to no or insignificant increase in the profits from spot market for the steam turbines. On the other hand, inclusion of storage led to about a 6.5% increase (as compared to the base case) in profits for a system with GT. This can be attributed to the fact that gas turbines are not good at handling the velocity ramps of gaseous production and a gas storage is, in such a case, beneficial in storing the excess gas production at times of low prices. After studying the optimal operating schedule obtained, it was seen that the gas turbine system without storage had a more frequent feeding strategy and an almost constant quantity of substrates (mainly cattle slurry and grass silage) fed as inputs. On addition of storage, the intervals between the feeding times increased as the ramps in gaseous production were absorbed by the storage and the electricity generation of the system was better at capturing the trend of the spot market. Interestingly, addition of storage provided similar profits for both gas and steam turbines. This leads to a conclusion that with storage, both the systems perform equally well and hence, if the driver for the operator is profit maximisation, either of the systems can be chosen for optimal operation. In the system with steam turbines, the biogas storage was utilised only at $t = 167$ to store the excess gaseous production which is further proof to the conclusion that the intrinsic flexibility offered by the extraction valve control equips the steam turbines with better functionality at handling the infrequent feeding strategy. This also corroborates the hypothesis that having a constant heat-to-power ratio constraints the flexibility of a cogeneration system.

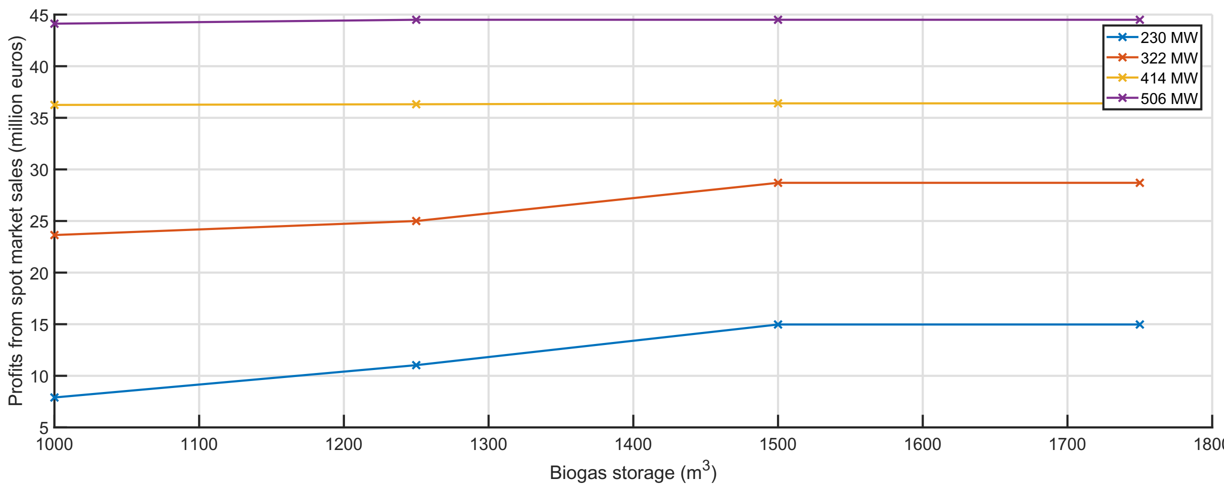

Fig. 4.7 Impact of nominal capacity of GT and biogas storage capacity on the gross income

In order to see how the nominal capacity of a cogeneration unit system with only gas turbines and substrate management has an impact on the gross income of the plant, several simulations were run for Scenario 4. Initially, we took the lowest nominal electrical capacity of the gas turbine system required to meet the heat demand of the digester while meeting the technical constraints (230 MW) and then progressively increased the capacity. Fig. 4.7 shows that the income increases progressively by increasing the nominal capacity of the system. However, the impact of storage sizes decreases with increase in nominal capacity. At 230 MW, there is perceptible change in the gross income with increase of biogas storage capacity. However, with increasing nominal capacities, the gas turbines can increase their fuel intakes, which is why increasing storage capacity at high nominal capacities did not have any perceptible difference to the income of the plant. Also, even at 230 MW, the profits increase till a storage capacity of 1500 m^3, which in this case can be taken as the optimal storage size as there is no increase in profits at higher storages. Thus, we can infer that, in order to increase profits in this scenario, it is only economically feasible to include storage if the nominal capacity of the plant is lower than the gas production capacities. Both installation of storage and increasing plant capacity incur huge investment costs and therefore, any decision regarding the choice of investment need to be made after conducting long-term planning studies.

4.4 Discussion

The work done in this thesis tries to assess the applicability of biogas flexibilisation methods in meeting the electric and heat demands (or maximising the profits obtained through spot market sales). It attempts to provide an insight into the integrated operation of a substrate management system with a cogeneration plant by formulating the anaerobic digestion process linearly and incorporating it into a MILP form. However, this work is based on a number of assumptions which need to be kept in mind, to prevent any bias in analysis.

The biogas process has been modelled by its kinetic parameters, which, even though might be a fairly accurate way of theoretically modelling a biogas plant [14], needs to backed by further experimental analysis. We have considered only the limiting values of OLR and HRT, in order to maintain the stability of the process. However, the kinetic parameters might vary according to the OLR value considered and there needs to be more experiments conducted to get conclusive results. This research is based on the premise that the values of OLR, HRT and corresponding kinetic parameters have been ascertained from conclusive empirical results. We would like to clarify that the assumption of dividing the kinetic parameters (in terms of per day) by twenty-four to obtain the kinetic parameters for the hourly regime is a highly approximate linear extrapolation. However, after studying the published literature, it was found that for substrates where both the diurnal and hourly values were available, the relationship between the values were too random to deduce an appropriate scaling factor or function. However, we assert that this research should be utilised to find out the feasibility of using one strategy against another and the formulation should be made use of to find out the possible revenues of changing the mode of operation of a biogas plant.

In order to understand how the hourly changes in the demand profile might impact the substrate management and biogas storage, this chapter considers kinetic rate constants in the order of hours. In order to accomodate this modification, the parameters like sizing of the digester have been increased. One implication of this change in timescale is that the quantity of infeed inserted is much higher. There might be also an apprehension regarding the feasibility of an hourly feeding regime to meet the demand. References [82] and [14] have both shown experimentally that such a feeding regime has no adverse impact on the stability of the biological process or the methane output. We also assume that the biogas production is already in the steady-state when this simulations are run. This might lead to a major discrepancy as there is a lag in production of biogas in case its in start-up or transient phase. It is meant to encourage the usage of bioenergy by making it more economical, and hence, such a discrepancy in generation depending upon the start-up or steady state can be easily corrected by introducing a lag factor [83] in the model.

Another important biological aspect that this thesis neglects is the effects of co-digestion on the methane yiield. There has been several studies [84] which show that methane production improves due to co-digestion, and it also leads to a change in the kinetic parameters. This thesis focused on the operational aspects of co-digestion and assumed a perfect knowledge of the kinetic parameters. After a comprehensive review of literature, it was assumed that co-digestion of the chosen substrates will not have any negative impacts on stability.

In our modelling approach, we assume that the biogas produced goes through the purification processes such that there is no potential variation in the methane content produced. The pre-treatment costs of each substrate are already considered in the substrate costs. The post-digestion costs incurred are assumed to be same for each substrate. Hence, our cogeneration units are modelled with the assumption that they have sufficient robustness to handle the methane produced by various substrates,, without any degradation in efficiency.

For the boiler feeding the steam turbine, we have assumed a constant efficiency of conversion of energies. We assert that this assumption did not bias the simulation as the parameters of both the turbines were considered accordingly.

4.5 Summary

In this chapter, we integrated the system models introduced in Chapters 2 and 3, to find out how the biological process of anaerobic digestion impact the generation profiles of co-generation units. After simulating several scenarios, it was found out that gas turbines, due to their constant heat-to-power ratios, are challenged in their ability to match disparate heat and electrical load profiles. They suffer from increased operational costs due to their high fuel intake to match the high heat demand even though the electrical load demanded is comparatively lower. Steam turbines, on the other hand, are able to allocate their generation to match the higher heat demands without increasing their electrical generation. Furthermore, this disparity in operating costs between the two systems were made more pronounced by the fact that gas turbines were ill-equipped to handle the frequent ramps in gas production whereas, steam turbines were better at smoothening out the fluctuations in gaseous production, so that the generation schedule was not adversely impacted.

Another important insight obtained was regarding the inclusion of biogas storage. It was found out that a biogas storage led to a substantial improvement in gas turbine system, by enabling it defer production to times of high demand or high spot prices. Further analysis revealed that the profits from spot market sales increases with increase in nominal capacity of gas turbines and also the biogas storage capacity. The study is helpful in gauging an optimal size of the biogas storage to glean most profits.

Chapter 5

Conclusion

This thesis presented an integrated framework which is formulated as an optimisation problem, which can be solved by the state-of-art MILP solvers to obtain the optimal substrate feeding strategy and the start-up, shut-down schedule for a cogeneration unit, to match the fluctuating demand. The research also provided an investigation into the dynamics of a flexible system in the context of a biogas plant in a power market. The key findings of the research are summarised below.

Chapter 2 introduced the concept of flexibilisation of biogas digesters at two points of operation: substrate rationing and 'time of feed', and storage of biogas for deferring production of energy. The results obtained show how the adoption of the multi-factorial substrate management techniques and storage strategies reduced the daily operating costs. When the driving factor was minimising the operating costs while meeting the electric and heat loads, the dynamic feeding strategy provided 88 % reduction in costs as compared to the conventional feeding strategy. In the presence of an electrical spot market, it was found that substrate management provided 45% more profits as compared to inclusion of storage, thereby showing that for the specific plant in the chapter, the optimal flexibilisation strategy is concerned with changing the feeding regime. An investigation into the optimal sizing of biogas storages was made which enabled us to calculate the optimal storage size for maximising the profits from a daily operational planning perspective.

Due to its low calorific values as compared to other fuels like natural gas, biogas requires combustion engines of higher efficiencies. Chapter 3 focused on the power generation by cogeneration systems, with a study into flexibility options offered by gas turbines and steam turbines. Gas turbines have fast ramping capabilities but often, have low efficiencies due to constant heat-to-power ratios. Hence, in a scenario where both heat and electrical loads have to be met simultaneously, extraction steam turbines proved to be better alternatives as they can provide variable heat-to-power ratios depending upon the hourly heat and power demands. However, steam turbines have very slow ramping capacities and the results obtained in this chapter demonstrate a combination of both systems to be the most effective in terms of load balancing capabilities and reducing operating costs.

Finally, Chapter 4 integrated the models from the previous chapters to optimise the performance of both the biogas digester and the cogeneration system. Various scenarios were explored to study the usefulness of each system in 'tracking' both heat and electrical loads. It was found that selection of operating set-points for a cogeneration system was highly sensitive to fluctuations in fuel intake, in case of systems having constant heat-to-power ratios. Investigation of the performance of the systems in a spot market for electricity revealed that a system with steam turbines outperformed the gas turbine system and the combined gas and steam turbine system by a considerable margin. However, introduction of storage enabled the system with gas turbines to perform as well as a steam turbine system. This was possible as the biogas storage provided the gas turbine system with added functionality of deferring the production to times of high spot prices. A parametric study made on the relationship of biogas storage sizes and obtained profits also showed a positive correlation between both.

5.1 Future work

This work leaves scope for several directions of subsequent research, which is summarised as follows.

At present, biogas plants are not profitable unless incentives are provided for bioenergy. To demonstrate whether the optimal feeding strategy provided, which is highly profitable from the perspective of operating costs, makes the biogas plants profitable enough for mass adoption, life cycle assessment needs to be done, while considering all the costs associated with changing the plant design to accommodate such a strategy, the installation costs of a gas storage, costs of labour, cost of physical footprint etc. One can also modify the formulation for determining the optimal sizing of the digester, CHP or gas storage.

This work does not consider the synergistic impacts of co-digestion which can be another promising area of research. Given that anaerobic digestion is a biochemical process, optimisation of biogas production with a focus on biochemical parameters, instead of operational ones needs to be looked into. There are several works addressing the optimisation of biogas production by optimal selection of biochemical parameters, but there is a research gap in integrating such models to a cogeneration system.

In Chapter 3, we demonstrated a relationship between efficiency of a cogeneration system and the heat-to-power ratio. This can be extended to study the impact of thermal storage in such a system and how the heat-to-power ratio is effected by presence of an external system which can defer the heat demand.

Appendix A

Economic and Technical Parameters

A.1 Substrate management parameters

Table A.1 Substrate parameters used in the simulations

Substrate	TS (%)	VS (%)	ρ (kg/l)	k (d^{-1})	V^{max} (l_{CH_4}/kg)	$\hat{c}^{sub}$ (€ /kg)
SBS	98	85	0.2	0.312	367.4	0.022
GS	20	80	0.869	0.1128	65	-0.00044
CS	85	12	0.99	0.134	18.462	0.003

A.2 Cogeneration system parameters

Gas turbine Parameters

Table A.2 Economic parameters of gas turbine

Parameter	Basis	Value
$\hat{c}^{st}$	Number of start-ups [€ /h]	10
$\hat{c}^{sd}$	Number of shut-downs [€ /h]	10
$\hat{c}^{m}$	Operating hours [€ /h]	0.1
$\hat{c}^{f}$	Fuel costs [€ /MW]	60

Table A.3 Technical parameters of gas turbine

$\overline{E}$ (MW)	$\underline{E}$ (MW)	$\overline{Q}$ (MW)	$\underline{Q}$ (MW)	UT (h)	DT (h)
4600	2070	7820	3519	3	3

Steam turbine parameters

Table A.4 Economic parameters of steam turbine

Parameter	Basis	Value
$\hat{c}^{st}$	Number of start-ups [€ /h]	10
$\hat{c}^{sd}$	Number of shut-downs [€ /h]	10
$\hat{c}^{m}$	Operating hours [€ /h]	0.5
$\hat{c}^{f}$	Fuel costs [€ /MW]	60

Table A.5 Technical parameters of steam turbine

$\overline{E}$ (MW)	$\underline{E}$ (MW)	$\overline{F}$ (MW)	UT (h)	DT (h)
4600	2070	80000	7	5

RU^{st} (MW/h)	RD^{sd} (MW/h)	RU (MW/h)	RD (MW/h)	
3045	3600	2500	2500	

Appendix B

Extraction steam turbine

B.1 Operation of an extraction steam turbine

This section provides information regarding the operation of extraction steam turbine.

To understand the optimal operation of steam turbine, we can refer to the generation profile of Scenario 2 of Chapter 3 (system consisting of 4 identical steam turbines) as described in Fig. B.1. Steam turbine 1 (ST 1) is not committed at all. At all times, only ST 2, ST 3 and ST 4 are operating. [1]

ST 4 is operating at minimum electrical generation and the $q_{4,t}^{extracted}$ is 0. This is obtained from Fig. B.1 and Fig. B.2.[2] This, however, does not imply 100 % efficiency of electrical conversion as is shown in Fig. B.3. ST 4 operates at a constant electrical efficiency[3] of 35 % as 65 % of heat is wasted as $q_{n,t}^{waste}$, while no heat is extracted (i.e, $q_{4,t}^{extracted} = 0$ MW).

ST 3 operates according to the generation profile in Fig. B.1 with 0 useful heat out-

[1] Let us define $f_{n,t}$ as the steam input to the steam turbine, $q_{n,t}^{waste}$ as the total heat wasted at time t and $q_{n,t}^{extracted}$ as the useful heat output/heat extracted, and $e_{n,t}$ as the electrical generation. All the values are in MW. The indices n and t are meant to describe the steam turbine and time, respectively.

[2] Fig. B.2 shows the heat to power ratio of ST 2 only because it is zero for all other steam turbines.

[3] For conservation of energy, we have

$$f_{n,t} = e_{n,t} + q_{n,t}^{extracted} + q_{n,t}^{waste} \tag{B.1}$$

put. One interesting insight can be drawn from its operation. For ST 3, the electrical efficiency is maintained at 35 % throughout. This means that, given $q_{3,t}^{extracted} = 0$ MW, we have

$$f_{3,t} = e_{3,t} + q_{3,t}^{waste} \tag{B.2}$$

This means that, at times like $t = 128$ when electrical generation is high, more fuel is drawn by the system to maintain the constant efficiency of 35% (Fig. B.3). To compare, the electrical generation is increased from 2070 MW at $t = 126$ to 4273 MW at $t = 128$. This increase in electrical generation is enabled by increasing the fuel intake from 5914 MW of biogas at $t = 126$ to 12209 MW at $t = 128$. Thus, this further corroborates the fact that there is always a non-zero $q_{3,t}^{waste}$ and from the fact that electrical efficiency is remaining constant, it is evident that more fuel is wasted as $q_{3,t}^{waste}$ at $t = 128$ than $t = 126$. Hence, there is infact, an increase in waste heat with increase in electrical generation, but their percentages with respect to the fuel intake remain same.

ST 2 is the only steam turbine which produces both heat and electricity. The region of importance is $t = 150, ..., 160$ in Fig. B.2 where the heat-to-power ratio almost becomes zero, but is not zero as $q_{3,t}^{extracted}$ is at its minimum but not at 0 MW. At this time, the electrical efficiency of the plant increases to almost 35 % (Fig. B.3) but can not reach 100% because of the heat wasted. Fig. B.3 shows the total efficiency which is the efficiency of conversion of biogas to useful heat and electricity. As can be seen, the total efficiency of the system reaches a maximum of 52% at $t = 48$. At that time, electrical generation reduces to 3498 MW to enable the heat extracted to rise to 5628 MW. Also, at times when the electricity generation is high, less heat is extracted from the valve and also more fuel is drawn which reduces efficiency (as seen in $t = 32$). This further proves that electricity output is increased by drawing in more fuel and reducing the quantity of heat extracted and not by reducing waste heat.

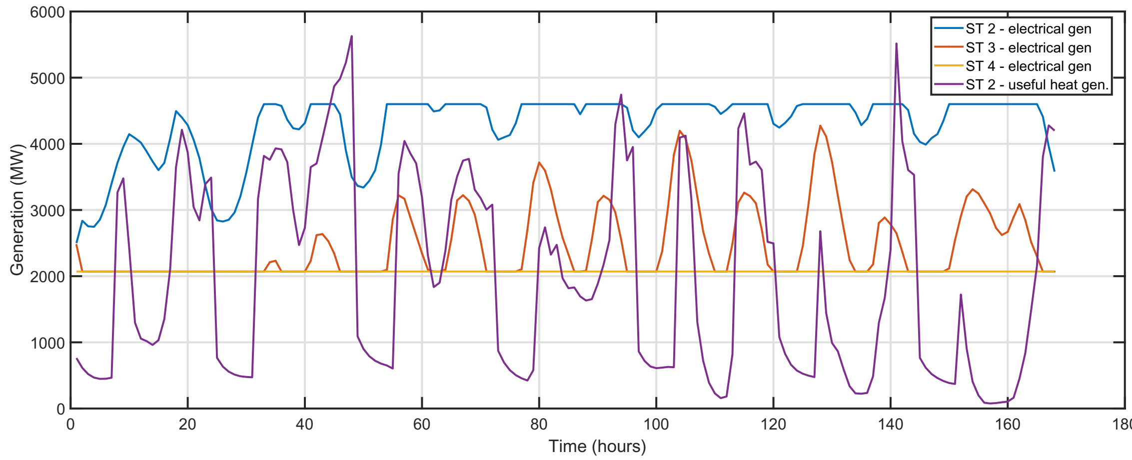

Fig. B.1 Generation profile of Scenario 2

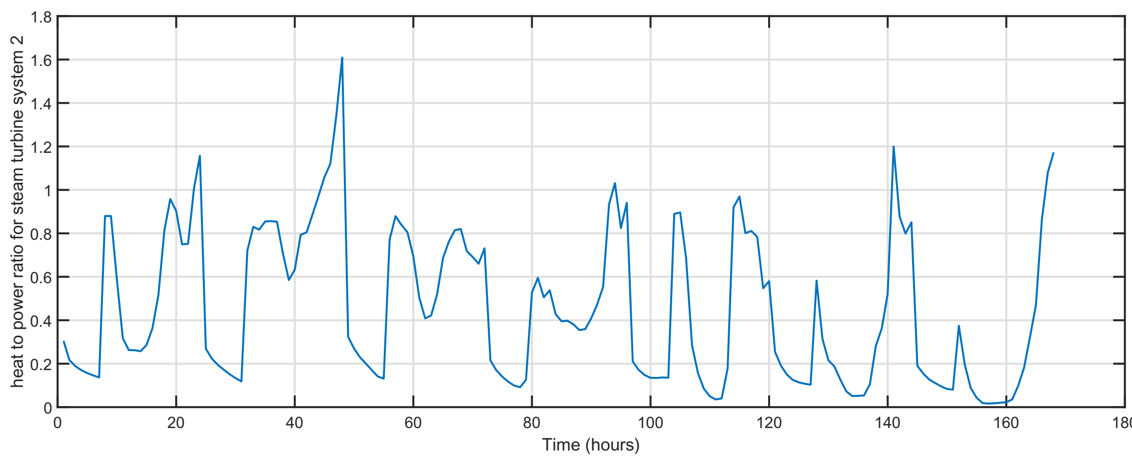

Fig. B.2 Heat-to-power ratios for steam turbine 2

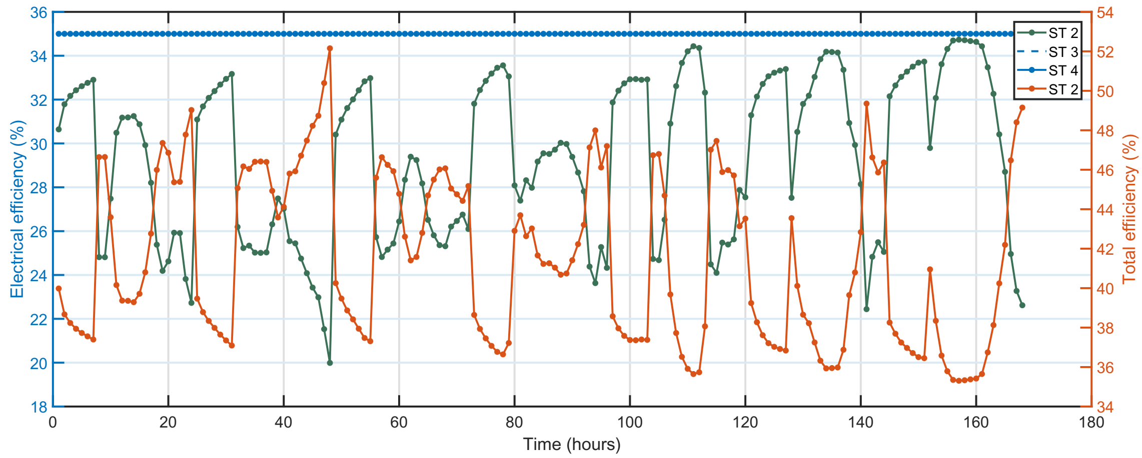

Fig. B.3 The efficiencies of the systems in Scenario 2

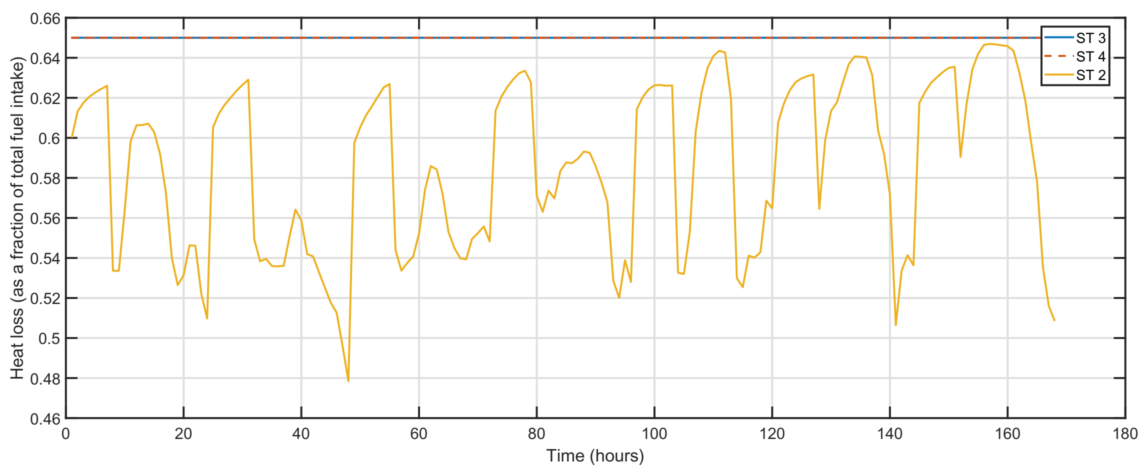

Fig. B.4 The heat lost as waste heat

Fig. B.4 shows the heat lost as a function of the total fuel intake. The average heat loss of ST 2 is 58% of the total fuel intake whereas it is 65% for ST 3 and ST 4.
To summarise, the steam turbine has variable heat to power ratio which allows it to vary the ratio of electrical and useful heat generation. There is always a large percentage of fuel which gets converted to waste heat, which cannot be controlled and hence, we can not increase electrical generation by reducing the waste heat. We are only concerned with controlling both useful heat and electricity generations. It is to be noted that this waste heat is not constant but varies within the range of 50% to 65% of the biogas energy intake.

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