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System dynamics of oxyfuel power plants with liquid oxygen energy storage

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Abstract

Traditional energy storage systems have a common feature: the generating of secondary energy (e.g. electricity) and regenerating of stored energy (e.g. gravitational potential, and mechanical energy) are separate rather than deeply integrated. Such systems have to tolerate the energy loss caused by the second conversion from primary energy to secondary energy. This paper is concerned with the system dynamics of oxyfuel power plants with liquid oxygen energy storage, which integrates the generation of secondary energy (electricity) and regeneration of stored energy into one process and therefore avoids the energy loss caused by the independent process of regeneration of stored energy. The liquid oxygen storage and the power load of the air separation unit are self-adaptively controlled based on current-day power demand, day-ahead electricity price and real-time oxygen storage information. Such an oxyfuel power plant cannot only bid in the day-ahead market with base load power but also has potential to provide peak load power through reducing the load of the air separation unit in peak time. By introducing reasoning rules with fuzzy control, the oxygen storage system has potential to be further extended by integrating renewable energy resources into the system to create a cryogenic energy storage hub.

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Keywords: oxyfuel power plant; oxygen storage; system dynamics; load distribution; AnyLogic

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1. Introduction

Modern power grids are required to supply constant voltages at a certain frequency. Supply and demand therefore must be balanced across the entire grid (transmission and distribution). Due to anthropogenic activities, demand varyies periodically, which is usually compensated with variable reactive loads and even nonlinear loads, or with electricity provided by generators and distribution and transmission equipment. However, these strategies do not always work, especially in peak time. Increased peak demand to power grids has further stimulated interest in developing energy storage technologies to compensate the varying demand in a large extent. However, so far, most energy storage developments have been focused on stand-alone storage units that consume electricity and store energy in multiple forms for later use in power generation, such as gravitational potential of pumped water and mechanical energy of compressed air. For example, the Ffestiniog power station [1], a pumped-storage hydroelectricity plant near Ffestiniog, North-west Wales of UK, which can generate 360 MW of electricity within 60 seconds of the need arising with average efficiency 72–73%; the Huntorf power station [2], the world's first compressed air energy storage plant located at Huntorf, Germany. This power plant can provide 321 MW output power for 2 hrs daily in peak time. About 1.6 kWh of gas and 0.8 kWh of off-peak based-load electricity are required in order to generate 1 kWh of peak-load electricity. Such traditional energy storage systems have a common feature: the generation of secondary energy (e.g. electricity) and regeneration of stored energy (e.g. gravitational potential, mechanical energy) are separate rather than deeply integrated. Obviously, any form of energy conversion is subject to loss. These energy storage systems need the second conversion from primary energy to secondary energy.

Hu et al. [3] proposed a possible solution that integrates generation of secondary energy and regeneration of stored energy into one process and therefore avoids the energy loss caused by the second conversion (see Figure 1). They demonstrated this solution on an oxyfuel power plant with liquid oxygen energy storage using a techno-economic perspective. Due to the large air separation unit (ASU) in the oxyfuel power plant there is a significant penalty for net electrical efficiency. If the air separation load in peak time can be shifted to off-peak time to produce and store more oxygen, then more electricity will be generated at a higher price resulting in more benefits. Furthermore, oxyfuel combustion capture technology will be more competitive than it is today. However, their study only considered the particular scenario that the ASU operates full-load in off-peak time and it stops in peak time, but did not consider other more realistic scenarios, like derating operations of the ASU when facing a real power market. Building on the proposed solution [3], the scope of the current paper is concerned with integrating storage by using a control strategy to model the system dynamics of oxyfuel power plants with liquid oxygen storage when acting as a virtual power market.

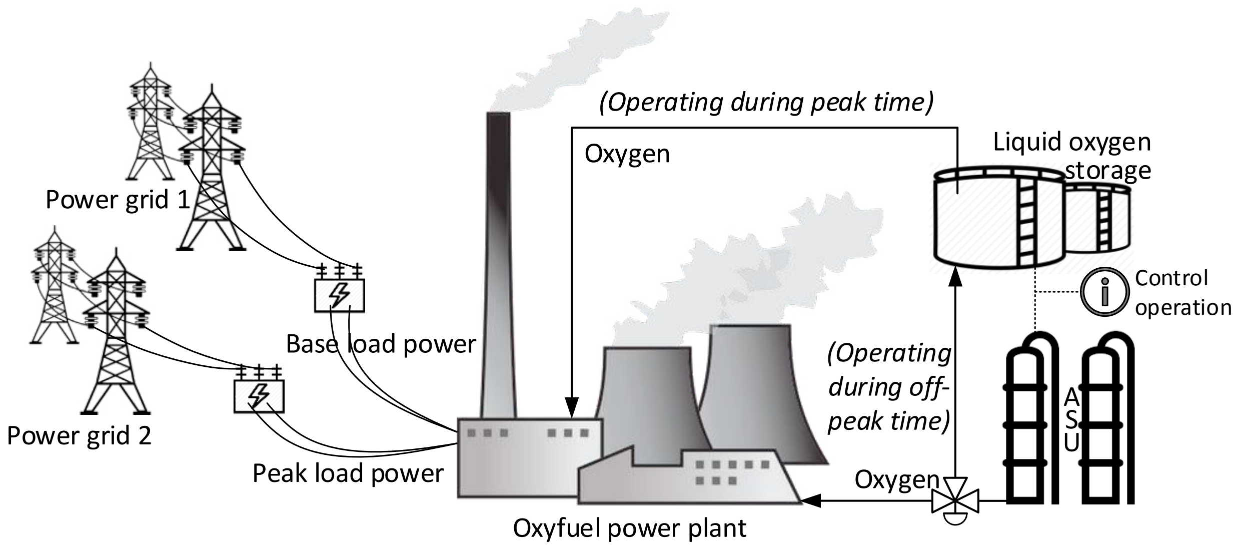


Fig. 1. Conceptual design of oxyfuel power plants with oxygen storage

2. Power market business model

Currently, the main arena for trading base load power is the day-ahead market. Daily trading is driven by planning. A buyer, typically a utility, needs to assess how much energy ('volume') it will need to meet demand the following day, and how much it is willing to pay for this volume, hour by hour. The seller, for example the owner of a power plant, needs to decide how much they can deliver and at what price, hour by hour. These needs are reflected through orders entered by buyers and sellers into the trading system. Simply put, taking the Nord Pool power market [4] as an example, 12:00 Central European Time (CET) is the deadline for submitting bids for power which will be delivered the following day. Hourly prices are typically announced to the market at 12:42 CET or later. Once the market prices have been calculated, trades are settled. From 00:00 CET the next day, power contracts are physically delivered (meaning that the power is provided to the buyer) hour by hour according to the contracts agreed.

In actuality, large coal-fired power plants act as the main sources of base load power to fulfill the base demand of end users round-the-clock. By introducing a liquid oxygen energy storage system, the oxyfuel power plant will be more flexible and extensible. Such oxyfuel power plant can not only bid in the day-ahead market with base load power but also has potential to provide peak load power through reducing the load of the ASU in peak time. As the capacity of oxygen energy storage is not so big, the buying and selling operations of the storage would have no observable consequence on the power spot market equilibrium, so this peak load power from oxygen energy storage can be only a price taker in the power market.

3. Development of the system dynamics model

A system dynamics model was built using AnyLogic® [5], which is a simulation software tool that supports three methods: system dynamics, discrete event simulation, and agent based modelling and allows users to create multi-method models. Figure 2 shows the flowsheet of an oxyfuel power plant with liquid oxygen energy storage. The power supply to the power grid (Power grid 1 in Fig 2) in current time follows the contract in the day-ahead market, expressed as a function of current-day power demand (CPD). The surplus power from the oxyfuel power plant has two uses: it is used to produce oxygen and used to provide peak load power to the power grid (Power grid 2). The load distribution of these two uses depends on the day-ahead electricity price (DEP) and the real-time oxygen storage (M_{ROS}). An idealised proportional controller is adopted to control the load distribution of the surplus power ($E_{surplus}$), as shown in Figure 3. The power consumption by the ASU (E_{ASU}) is determined by the smaller of the remaining storage space proportional factor (F_{RSS}) and the price proportional factor (F_{DEP}), as expressed in Equation 1.

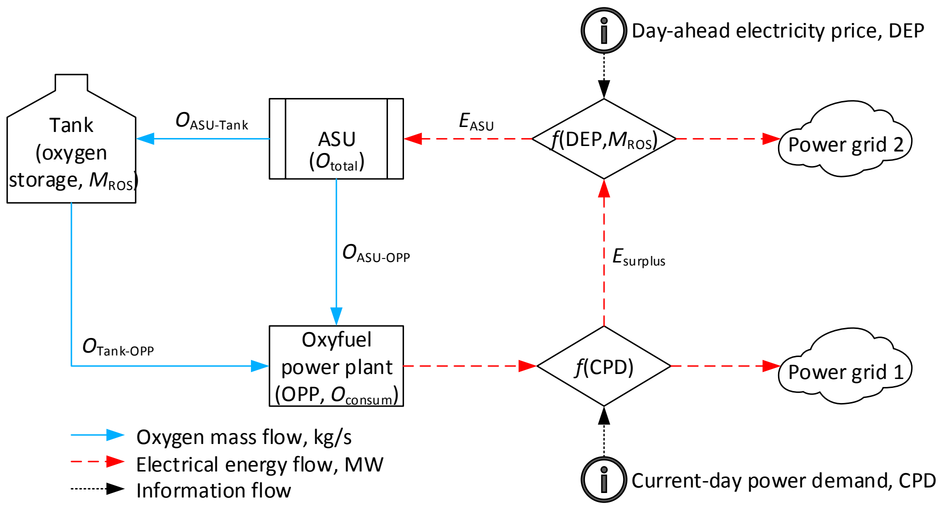


Fig. 2. Flowsheet of an oxyfuel power plant with oxygen storage

$E_{ASU} = E_{surplus} \times min\ (F_{RSS}, F_{DEP})$. *Eq.* (1)
where,
$F_{RSS} = 1 - F_{ROS}$ *Eq.* (2)
$F_{DEP} = E_{ASU} / E_{surplus}$ *Eq.* (3)
$F_{ROS} = M_{ROS} / M_{ROSmax}$ *Eq.* (4)

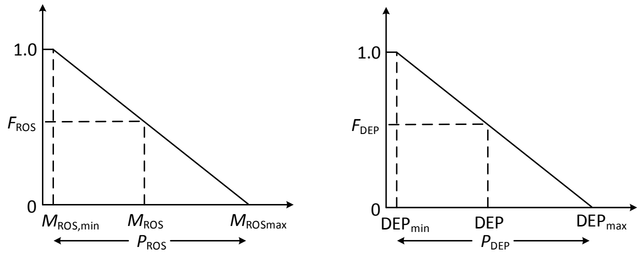


Fig. 3. Idealized proportional control of the load distribution of the surplus power

In other words, assuming enough storage space, in each moment, the lower the electricity price in the day-ahead, the more power that will be consumed by ASU to produce and store oxygen in the current-day. By contrast, the higher the electricity price, the less power that will be consumed by ASU, and therefore more surplus power can be sold to the power grid (2) as peak load power to maximise benefit. To ensure a continuous operation, there must be a certain amount of oxygen supplied to the oxyfuel power plant unremittingly. This amount of oxygen can either come from the ASU or come from oxygen tank, or from both at the same time, and is determined by how much of the surplus power can be used for oxygen production (E_{ASU}). The real-time oxygen flows in Figure 2 are governed by Equations 5 and 6.

$O_{AUS\text{-}OPP} = limitMax\ (O_{total}, O_{consum})^{\dagger}$ *Eq.* (5)

$O_{Tank\text{-}OPP} = limitMax\ ((O_{consum} - O_{AUS\text{-}OPP}), O_{consum})$ *Eq.* (6)

The data source of the systems dynamics model regarding the oxyfuel power plant with liquid oxygen energy storage referred to the previous work [3], as listed in Table 1. The uniform distribution function is used to randomly generate the current-day power demand (0 - 619 MW) and the day-ahead electricity price. Because of security concerns, once the real-time oxygen storage is less than 30% of the full storage capacity, the distribution of the surplus power will give priority to the oxygen production; in contrast, the priority will be given to the peak load power reselling if the oxygen storage is higher than 80% of the full storage capacity. In fact, these two boundary lines could vary with the fluctuation amplitude of power demand and electricity price. In this study, to cover most possible scenarios, only upper and lower limits were set for power demand and the electricity price. They can randomly change between the upper and lower limits. The smaller the fluctuation amplitude, the broader the band delineated by the upper and low limits. In fact, both power demand and electricity price have always been regular and predictable, such as peak and off-peak power demands and prices.

Table 1. Key technical parameters of the oxyfuel power plant with oxygen storage work [3]

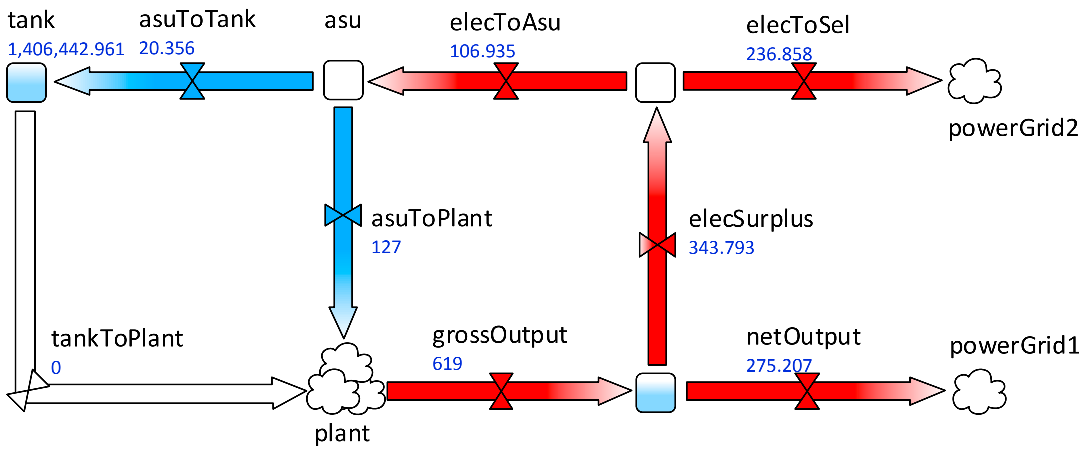
Gross power output [a], MW	619
Oxygen consumption (O_{consum}), kg/s	127
ASU specific consumption, kJ/kg O_2	725
Liquid oxygen density, kg/m^3	1141
Tank volume, m^3	2500
Min. electricity price, £/kWh	0.02
Max. electricity price, £/kWh	0.06

[a] Gross power output = Net power output + ASU consumption

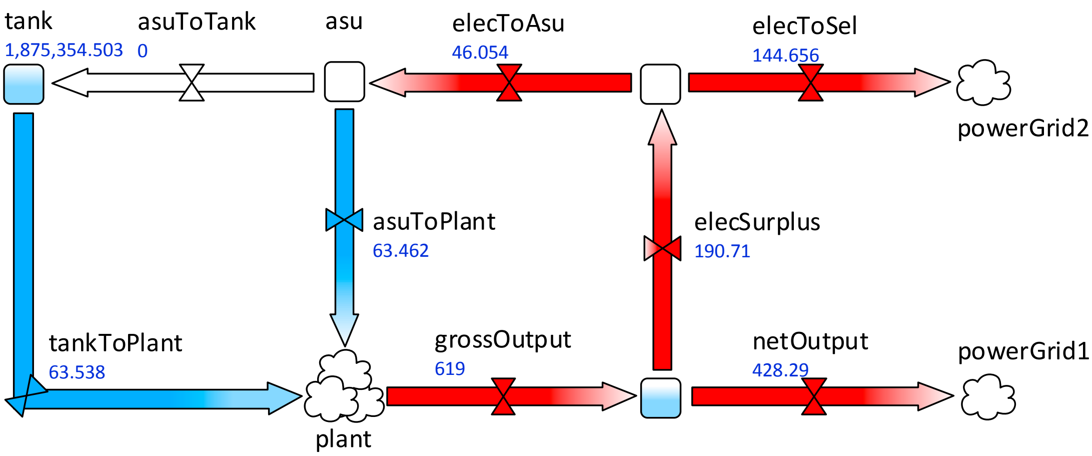
†Mathematical function *limitMax* (double x, double max), returns x if it is less or equal to max, otherwise returns max.

4. Results and discussion

Figure 4 shows the two main functions of the system operation of an oxyfuel power plant with liquid oxygen energy storage: charging (a) and discharging (b). The blue flows represent oxygen flows in kilogram per second (kg/s); and the red flows represent power flows in megawatt (MW). An accumulator (tank) is used to represent the stock of oxygen in kg. The oxyfuel power plant (plant) is the 'sink' of oxygen and also the 'source' of power, and the power grids 1 and 2 are the 'sink' of power in the system dynamics model. In the moment shown in Figure 4(a), 31% surplus power (106.935 MW) is used to produce oxygen, and the produced oxygen is not only enough for the continuous operation of the oxyfuel power plant but also there is a surplus for 'charging' the storage; the remaining surplus power (236.858 MW) is sold to the power grid 2 as peak load power. In contrast, in the moment shown in Figure 4(b), only 24% surplus power (46.054 MW) is used to produce oxygen, and the produced oxygen is not enough for the continuous operation of the oxyfuel power plant and hence a certain amount of oxygen (63.538 kg/s) must be from the 'discharging' of the storage to make up the balance.



(a) A moment of 'charging'



(b) A moment of 'discharging'

Fig. 4. Two main functions of the system operation, with representative moments

Figure 5 shows the real-time liquid oxygen storage over one week (simulated). Although changes in the level of energy storage are not regular, there is also no overshot of minima and maxima during the simulated time period. To some extent, this result justifies the robustness of the control strategy used in the system dynamics modelling. However, in reality, real-time control of the cryogenic air separation unit is very complex, which was not considered in this study. It is usually implemented by adjusting the set point values, such as air flow rate and high-pressure column reflux [6]. These adjustments on ASU are always accompanied by lag effects. Therefore, the idealized proportional control strategy for the load distribution in this study might be no longer applicable. However, fuzzy control [7] could be an effective strategy to solve the lag effect in ASU operation. By introducing reasoning rules, the oxygen storage system has potential to be further extended by integrating renewable energy resources, such as solar and wind, into the system to create a cryogenic storage hub.

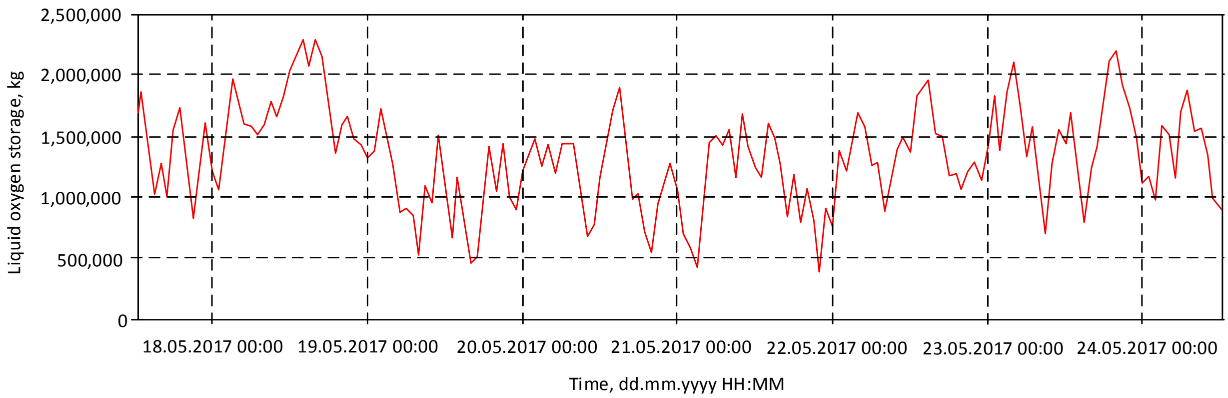


Fig. 5. Real-time liquid oxygen storage

5. Potential marketing model and benefits

As can be seen from this study, if an oxyfuel power plant (seller B in Figure 6), which normally sells base load power to a power grid under a long-term contract, integrates with liquid oxygen storage system, it can have a more flexible marketing model with power grids, such as bidding in the day-ahead market (seller A in Figure 6) and acting as a price taker in the peak load power market (seller C in Figure 6). These seller role changes in the power market can be achieved through the controlled operations of the liquid oxygen storage system and the air separation unit, but they have no extra operational costs to the power generation section and therefore have few negative consequences to the whole system.

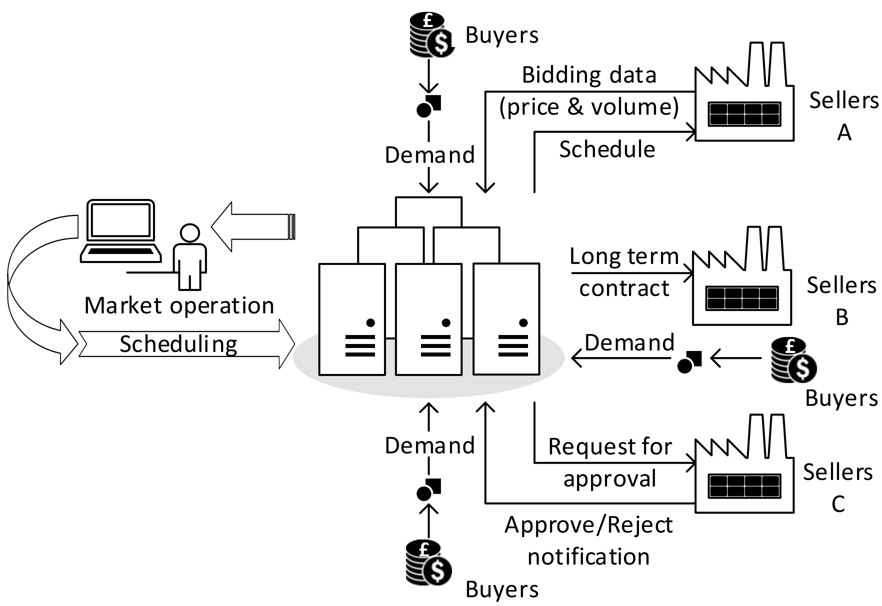


Fig. 6. Potential marketing model of oxyfuel power plants with liquid oxygen storage

In summary, as the regenerating of stored energy (energy consumed to produce oxygen) is integrated into power generation of oxyfuel power plants, there is no extra loss caused by the regenerating. To put it simply, for an oxyfuel power plant, oxygen consumption to support a continuous operation is constant, if there is no derating operation to the power generation section, no matter when the oxygen is produced. Oxygen production is like storing energy (e.g. gravitational potential, and mechanical energy); the oxygen consumption is like regenerating the stored energy. The only loss that might occur in the liquid oxygen (energy) storage is leakage, but it is negligible if compared with losses in traditional energy storages.

6. Conclusions

This paper presents a system dynamics model of the oxyfuel power plants with liquid oxygen energy storage. The oxygen storage and the power load of the air separation unit were controlled self-adaptively based on current-day power demand, day-ahead electricity price and real-time oxygen storage information. A case study showed that by introducing a liquid oxygen storage system the oxyfuel power plant was more flexible and extensible in the power market. Such an oxyfuel power plant can not only bid in the day-ahead market with base load power but also has potential to provide peak load power through reducing the load of the air separation unit in peak time.

Acknowledgements

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