Engineering 29 (2023) 50–54

Contents lists available at ScienceDirect

Engineering

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

Views & Comments

Outlook of Energy Storage via Large-Scale Entrained-Flow Coal Gasification

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1. Introduction

The decarbonization of the energy sector, which greatly relies on fossil-fuel energy, requires urgent action on a global scale to reduce carbon emissions to a net-zero state and to mitigate the effects of climate change [1,2]. With a multi-level global energy transition already underway, there is an inevitable trend to use renewable energy to replace traditional fossil-fuel energy. By playing a key role in this energy transition, renewable energy will further promote the decarbonization of the energy sector and the improvement of national energy security. However, the technological development of renewable resources, such as solar, wind, biomass, and hydro, is greatly restricted by factors such as seasonality, a dependence on region, and intermittency [2]. Moreover, it is still difficult to achieve the short-term goals of directly and completely replacing fossil-fuel energy with renewable energy, due to issues related to key equipment, novel processes, replacement costs, and other economic and political factors. To obtain a sustainable and stable output of electricity and heat generated from renewable energy, energy storage technology can be used to combine renewable energy with either fossil-based energy or electricity grids, resulting in flexible and large-scale advantages [3].

Energy storage technology can be used to store renewable, unstable, or byproduct energy for auxiliary thermal/electric grid peak control, thereby reducing the consumption of fossil fuels and playing an essential part in achieving carbon neutrality in the energy transition [3]. As one of the world's largest energy consumers, China has decreased its proportion of coal consumption from 65.8% in 2014 to 56% in 2021, while increasing its clean energy use to 26% [4]. However, China's coal-based energy and chemicals industry still acts as a foundation and support for national economic development. With the implementation of China's carbon-neutrality policy, and as carbon-reduction work is carried out, the clean and efficient utilization of coal and its diversified integration with the new energy system must ensure the production scale of the coal-based energy and chemicals industry while effectively reducing carbon emissions [5].

Entrained-flow gasification technology is a key technology for the clean and efficient utilization of coal resources; it has already been widely used in the energy and chemicals industry in China and in other countries [6]. Other technologies, such as underground gasification, catalytic gasification, hydrogasification, supercritical water gasification, and plasma gasification, are in the stages of research, demonstration, and commercial application. Unlike other coal gasification processes, such as fixed-bed gasification and fluidized-bed gasification, entrained-flow coal gasification (EFCG) has the characteristics of wide adaptability to different types of coal feedstocks, large-scale gasification (currently a maximum of 4000 $t \cdot d^{-1}$ for coal), and high carbon conversion ($\sim$99%), so it aligns with the developing requirements of the modern large-scale coal-based chemicals industry [7]. Moreover, this technology has the potential for extended capacity and increased operating temperature and pressure. The main units in the EFCG process are coal feedstock preparation and transportation, EFCG, syngas purification and conversion, and wastewater treatment. The target product of EFCG—namely, syngas ($CO + H_2$)—is used to produce chemical products and fuels, such as methanol, olefin, oil, ethylene glycol, and natural gas [7]. Through EFCG and syngas production, new chemical industries can carry out the processes of coal to oil, coal to natural gas, coal to olefin (CTO), coal to ethylene glycol, coal to methanol (CTM), and so forth. The coupling synthesis of EFCG and residual fuel oil is a potential method for producing alcohols, acids, esters, and other products. Although EFCG technology effectively reduces the emission of pollutants, it still presents the issues of large carbon dioxide emissions and high energy consumption.

Within EFCG technology, processes with high energy consumption occur in the coal-pulverizing unit, air-separation unit (ASU), gasification, and pressure swing adsorption (PSA) of gas products, among others. Moreover, to produce chemicals such as methanol, ammonia, and olefin, the syngas from EFCG must be converted and the proportion of hydrogen must be increased, which inevitably results in the emission of CO_2. If these processes can directly utilize renewable energy or store it in the form of physical or

https://doi.org/10.1016/j.eng.2023.08.009

chemical energies, such as in the forms of pulverized coal (PC), liquid oxygen, liquid hydrogen, and liquid/solid carbon dioxide, a large-scale energy storage system will become possible.

In China, both Xinjiang Uygur Autonomous Region and Inner Mongolia Autonomous Region have rich coal and renewable resources, so the trend of coupling the synergistic development of large-scale EFCG technology with energy storage technology will be of great significance in improving the energy infrastructure, technology, and industry in these areas. With the utilization of renewable energy, such as biomass, water electrolysis (WE) using renewable energy, photolysis water, and so forth, a combined EFCG system can produce hydrogen-rich syngas, which can be used in high-efficiency fuel cells for transportation and power generation. In addition, when the costs of solar energy and wind energy can be offset by carbon tax, cheap methanol can be produced by combining wind energy, solar energy, and EFCG, and hydrogen can be produced via on-board methanol reforming and integrated with fuel-cell systems.

In this paper, we propose a pathway for energy storage within large-scale EFCG technology and analyze different energy storage patterns in feedstock preparation (PC and liquid oxygen), gas products (CO_2 and H_2), and the gasification process supported by green energy (Fig. 1). In the feedstock unit, air and coal are processed to form liquid oxygen and PC. Here, electricity generated from renewable energy sources can be used to make liquid oxygen, which can be used as energy storage. At the same time, renewable electricity can be used to grind PC, thereby storing renewable energy as physical or chemical energy in the form of the PC. In the gasification process, renewable energy can be used to supply energy for temperature maintenance, gas purification, the water vapor conversion reaction, and other processes. In this way, renewable energy can be stored in the final products, in the form of hydrogen energy or liquid carbon dioxide, which can then be stored in what is known as product storage. The subsequent production of methanol requires a portion of hydrogen; here, hydrogen generated via renewably powered WE can be used. The oxygen from this WE can be used as a gasifying agent or used to store energy in the form of liquid oxygen.

2. Energy storage via feedstock preparation

2.1. Energy storage via PC preparation

EFCG technology can be divided into PC gasification and coal–water-slurry (CWS) gasification, according to the feedstock type [7]. CWS is made of PC, water, and surfactant additives; it is transported to the burner of the gasifier through a CWS pump and pipeline. Commercial gasifiers that use CWS as a feedstock include the GE Energy (formerly Chevron Texaco, USA) gasifier, the opposed multi-burner (OMB) gasifier, the Tsinghua oxygen staged entrained-flow (OSEF) gasifier, and the Sinopec–ECUST (SE; ECUST stands for East China University of Science and Technology) gasifier [8]. PC gasification technology uses dried coal powder as the feedstock; commercial PC gasifiers include the Shell gasifier, Siemens gasifier, Prenflo gasifier, SE oriental gasifier, and HT-L gasifier [8]. Regardless of whether the feedstock is CWS or PC, the raw material must be ground to a particle size of less than 100 μm—a process that consumes a large amount of electric energy.

Here, we analyze the energy consumption of an EFCG unit for a CTM plant that produces 1×10^6 t of methanol per year as an example. This entrained-flow gasifier uses PC as the feedstock. The technical parameters of the CTM plant and the gasification unit are given in Table 1. We analyzed the energy consumption of the feedstock preparation for this EFCG unit. The coal used in the entrained-flow gasifier is Shenhua coal, which is a bituminous coal from China. For this gasification unit, the effective syngas production is 2.8×10^6 $Nm^3 \cdot h^{-1}$ (where Nm^3 is normal cubic meter), the coal consumption is 3400 $t \cdot d^{-1}$, and the carbon conversion is assumed to be 99.0%.

The gas resources for methanol production come from the PC entrained-flow gasification technology. According to our analysis, the energy consumption required for preparing 1 t of PC (not including the power of the drying system) is about 12.0 kW·h, and the total power consumption required for the preparation of 1 t of PC is about 1.7 MW. Using the PC preparation process, it is possible to store electric energy in the form of physical energy (i.e., in the form of PC)—a type of energy storage that can be maintained for a long period of time. During this storage period, power is effectively stored and the purpose of energy storage is realized. However, the preparation and transportation of PC require a drying

Table 1
Technical parameters of the EFCG unit for the annual production of 1×10^6 t of methanol.

Parameter	Value
Methanol production ($t \cdot a^{-1}$)	1.0×10^6
Unit operation ($h \cdot a^{-1}$)	8 000
Effective syngas ($Nm^3 \cdot h^{-1}$)	2.8×10^6
Carbon conversion (%)	99
Oxygen consumption ($Nm^3 \cdot h^{-1}$)	87 000
Coal consumption ($t \cdot d^{-1}$)	3 400
Coal consumption (kg, per 1000 Nm^3 of CO + H_2)	510
Oxygen consumption (Nm^3, per 1000 Nm^3 of CO + H_2)	310
CO_2 emission ($t \cdot h^{-1}$)	375

Nm^3: normal cubic meter.

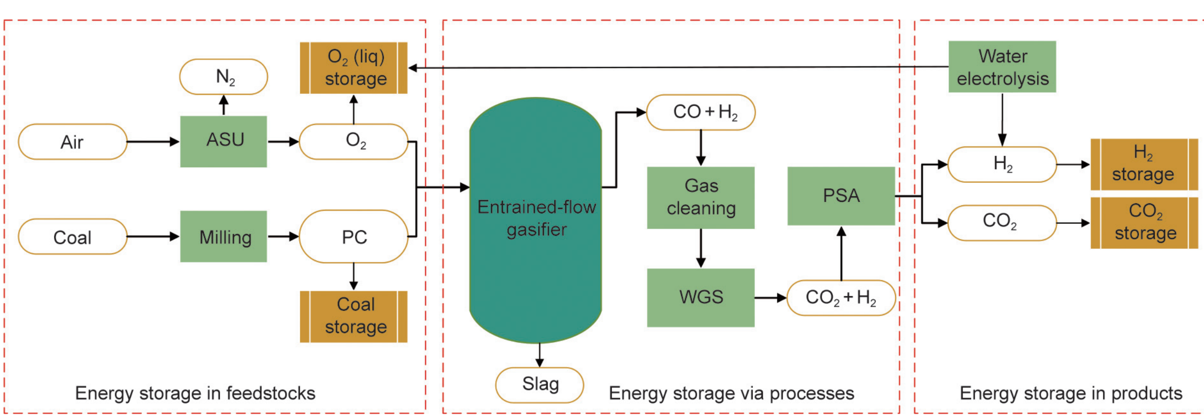

Fig. 1. Possible forms of energy storage within an EFCG system. WGS: water–gas shift; liq: liquid.

system to reduce moisture and prevent the agglomeration of PC. When the energy consumption of the drying system is included in the calculation, the total energy consumption for preparing 1 t of PC increases to 122.0 kW·h showing that the drying system consumes a great deal of energy. In summary, the scale of energy storage in the form of PC (including the drying system) during feedstock preparation in the gasification unit of a CTM plant with a production of 1×10^6 t of methanol per year will be about 17.3 MW. It should be noted that the scale of energy storage in this paper (i.e., megawatt) is determined to be the power that the system can store. Therefore, renewable electric energy can be stored in the form of physical energy in PC to obtain a long-term energy storage system, which by using renewable energy to replace the fossil-based electricity currently used to pulverize coal can effectively reduce the industry's reliance on fossil-based electricity and thereby reduce CO_2 emissions.

2.2. Energy storage via liquid oxygen preparation

The large-scale development of entrained-flow gasification technology will increase the consumption of both coal and the gasification agent, which is pure oxygen. In general, a cryogenic air-separation system is used to prepare liquid oxygen, which can be stored in the liquid state at high pressure for a long time. The oxygen purity after cryogenic air separation is 99.6%, and this process consumes about 0.4 $kW·h·Nm^{-3}$. For the EFCG unit with an annual output of 1×10^6 t of methanol, the amount of oxygen required for EFCG is calculated to be 87 000 $Nm^3·h^{-1}$, as shown in Table 1, and the power consumption is about 34.8 MW. When the cryogenic air-separation process is carried out using renewable energy, renewable power is stored as physical energy in the form of liquid oxygen, which is stable and long-lasting when stored in a tank. Therefore, by increasing the storage volume and number of tanks, renewable power can be stored in the form of liquid oxygen in the large-scale EFCG system. This form of energy storage is physical energy storage, similar to the energy stored in compressed air or a flywheel.

The application of energy storage in large-scale EFCG includes the feedstocks, such as PC and liquid oxygen. This type of energy storage transforms electric energy into physical or chemical energy in the form of PC and liquid oxygen; thus, in order to store significant quantities of energy, the PC and air-separation system require a large amount of power and a large scale. Energy storage in the form of PC and liquid oxygen requires a large enough site or additional sites, increasing the difficulty of site planning and local arrangement. Appropriate arrangement and optimization of the whole system and site planning are needed.

3. Energy storage in CO_2 products

The carbon conversion rate of a large-scale EFCG unit is about 99%, converting coal into gases (e.g., CO, H_2, and CO_2) and slag at a high temperature. Because the temperature of the gasifier is maintained via the combustion of part of the coal feedstock with oxygen, CO_2 will still be emitted, as shown in Table 2. The gas products of EFCG are mainly CO and H_2, which are considered to be midrate products in the CTM chemical synthesis industry. As shown in Table 2, the syngas produced by PC gasification has a greater proportion of CO and a smaller proportion of H_2. Therefore, the syngas must undergo the water–gas shift (WGS) process to increase its H_2 content and match the required stoichiometric ratio of H_2 to CO (2:1) for methanol synthesis. In the WGS, CO is reacted with H_2O to produce H_2 and CO_2. Separating the CO_2 from the H_2 consumes a considerable amount of energy, with about 3 t of CO_2 emissions being associated with 1 t of methanol production [9]. Thus, the quantity of CO_2 emissions associated with the industrial production of 1×10^6 t of methanol will be 375 $t·h^{-1}$. To reduce the power generated by the use of fossil-fuel energy, renewable energy can be used in the process of liquefying this CO_2, and the CO_2 can be compressively stored in a liquid or solid state. Calculations reveal that the energy stored as liquefied CO_2 based on the industrial production of 1×10^6 t of methanol is about 18.8 MW. Similar to liquid O_2 storage, increasing the storage volume and number of tanks of liquid CO_2 makes it possible to store more renewable energy.

4. Energy storage in H_2 via the combination of EFCG and WE

When the EFCG process is combined with the WE process, the hydrogen produced by WE can be used in EFCG to supply syngas with a higher stoichiometric ratio of H_2 to CO (2:1), which can then be used for methanol synthesis, removing the WGS from the traditional CTM process. Renewable energy can be used for the WE process, and the extra hydrogen from the WE can be considered as an energy storage medium. This combined system can realize the storage of renewable energy in a large-scale EFCG system while ensuring an unchanged level of methanol production.

By combining WE with EFCG, the coal consumption on the gasification side decreases, as shown in the calculated results in Table 3. The results indicate that the combined system of EFCG + WE can reduce both oxygen consumption and coal consumption to 43 000 $Nm^3·h^{-1}$ and 1680 $t·d^{-1}$, respectively, while the syngas production from the EFCG side is reduced to 1.4×10^6 $Nm^3·h^{-1}$. The hydrogen supplied by the WE is about 1.4×10^6 $Nm^3·h^{-1}$.

At present, the energy consumption for H_2 production by means of the alkaline electrolyzers produced by Nel Hydrogen (Nel ASA, Norway) can be as low as 3.8 $kW·h·Nm^{-3}$ [10]. Thus, the total power needed for this amount of hydrogen production via the Nel Hydrogen alkaline electrolyzers is about 537.3 MW. Moreover, the quantity of CO_2 emissions from the proposed combined process can be reduced to 184.7 $t·h^{-1}$—a reduction of about 50.7% compared with the emissions from Nel Hydrogen electrolyzers. The combination of EFCG with WE to produce hydrogen-rich syngas for methanol synthesis can further reduce the coal consumption, oxygen consumption, and carbon dioxide emissions.

We compared the scale of the energy storage via large-scale EFCG technology between two methods: ① an EFCG system and

Table 2
Syngas compositions of the EFCG unit for the annual production of 1×10^6 t of methanol.

Syngas composition	Volume fraction (%)
CO	63.76
H_2	28.90
CO_2	7.66
Other gases	0.68

Table 3
Technical parameters of the combined system of EFCG and WE, when used to produce 1.0×10^6 $t·a^{-1}$ of methanol or olefin.

Parameter	Methanol	Olefin
Production ($t·a^{-1}$)	1.0×10^6	1.0×10^6
Unit working hours per year (h)	8 000	8 000
Effective syngas from EFCG ($Nm^3·h^{-1}$)	1.4×10^6	5.4×10^6
Carbon conversion (%)	99	99
Oxygen consumption ($Nm^3·h^{-1}$)	43 000	1.7×10^6
Coal consumption ($t·d^{-1}$)	1 680	6 600
Hydrogen from WE ($Nm^3·h^{-1}$)	1.4×10^6	5.6×10^6
CO_2 emission ($t·h^{-1}$)	184.7	646.5

② a combined system of EFCG + WE. Detailed information is given in Fig. 2. We also compared the scale of the energy storage via the EFCG system for CTM versus CTO, for 1.0×10^6 t·a^{-1} of methanol or olefin production. For the CTM process, the scale of energy storage was as follows: 17.0 MW was stored as PC (including the energy consumption for drying, 24.1% of the total); 34.8 MW was stored as liquid O_2 (49.3% of the total); and 18.8 MW was stored as liquid CO_2 (26.6% of the total). For the CTO process, the scale of energy storage was as follows: 67.5 MW was stored as PC (25.0% of the total); 136.8 MW was stored as liquid O_2 (50.7% of the total); and 65.6 MW was stored as liquid CO_2 (24.3% of the total). Here, we do not consider the scale of energy storage in liquid H_2, because the H_2 is directly utilized in the methanol synthesis process. Thus, the total scale of energy storage of the EFCG unit is about 70.6 MW for CTM and 269.9 MW for CTO.

For the combined system of EFCG and WE, the scale of energy storage for CTM is as follows: 8.5 MW is stored as PC (including energy consumption for drying, 1.1% of the total); 17.2 MW is stored as liquid O_2 (2.2% of the total); 16.4 MW is stored as liquid CO_2 (2.1% of the total); and 190.7 MW is stored as liquefied H_2 (24.8% of the total). For CTO, the scale of energy storage increases, as follows: 33.7 MW is stored as PC (1.1% of total); 67.4 MW is stored as liquid O_2 (2.2% of the total); 57.5 MW is stored as liquid CO_2 (1.9% of the total); and 751.1 MW is stored as liquefied H_2 (24.8% of the total). Here, the greatest power consumption occurs in the WE process, which is 537.3 MW (69.8% of the total) for CTM and 2116.5 MW (69.9% of the total) for CTO. Thus, the total scale of energy storage via the combined system of EFCG + WE, including PC, liquid oxygen, liquid hydrogen, liquid CO_2, and WE, is about 770.2 MW. The big difference between the EFCG and EFCG + WE systems is due to the combination of WE and liquifying hydrogen. When all the H_2 is used for methanol or olefin synthesis rather than being used to store energy in the form of liquid H_2, the total scale of energy storage in the form of PC, liquid O_2, and liquid CO_2 is 70.6 MW for the EFCG unit and 579.5 MW for the combined system (EFCG + WE) for CTM. For CTO, the total scale of energy storage is 269.9 MW for EFCG and 2275.2 MW for EFCG + WE. Therefore, storing energy within the feedstock preparation and gas products of a large-scale EFCG system—either alone or in combination with electrolytic water energy—can result in energy storage as high as or even higher than the energy in a 100 MW to 1 GW energy storage plant.

The syngas from EFCG can be used to produce methanol, ethylene, ethylene glycol, natural gas, hydrogen, and so forth, and as these subsequent processes produce CO_2 gas, which ethylene products have the highest carbon emission index. Thus, this storage type of the green electricity is related to the carbon emission. Although the electric energy is stored as products (CO_2, H_2, etc.), the process carbon emissions increase the energy required for carbon separation and capture, which requires further estimation.

5. Energy storage via the EFCG process

The EFCG process is an endothermic reaction. At present, commercial EFCG technology can increase the conversion rate of coal to greater than 99%, with a cold gas efficiency of about 80%. During the operation, part of the injected coal is burned to provide heat for the gasification process and melt the coal ash to form slag that can be discharged. The EFCG process requires a great deal of heat from external connections to partially oxidize the coal, due to the high operating temperature (1300–1600 °C) and requirements for liquid slag discharge. Consequently, it is unavoidable for the traditional EFCG process to produce CO_2 emissions. As renewable energy, including solar, wind, biomass, and hydro, becomes widely used in industry, it will be possible to use renewably generated power and heat for EFCG. We propose the concept of using renewable energy to supply the EFCG process, which can be considered as a form of energy storage that results in chemical energy being stored as syngas. Under these conditions, 20% of the cold gas efficiency that is consumed in traditional EFCG will be effectively utilized, and all resources can be converted into syngas, with a final cold gas efficiency of close to or even greater than 100%. This process will greatly reduce CO_2 emissions, as it is an EFCG technology that is non-self-heating but rather depends on external heating. The thermal energy required for EFCG can be provided by renewable electricity or extra heat energy (e.g., solar energy, nuclear, and geothermal), and these supplying energies from renewable electricity or extra heat energy can be indirectly stored in the form of chemical energy as syngas, thereby realizing coupling between the EFCG system and the energy storage system. The disadvantages of storing energy via the EFCG process are the same as the disadvantages of using product storage to store energy. In addition to the increased production that would be required to achieve significant energy storage using EFCG, the issues of energy consumption and carbon emissions require further evaluation, and the issues of increased solid and liquid waste disposal also need to be considered.

6. Summary and outlook

Large-scale EFCG is a key technology for the clean and efficient utilization of coal or other carbonaceous fuels (e.g., residual oil,

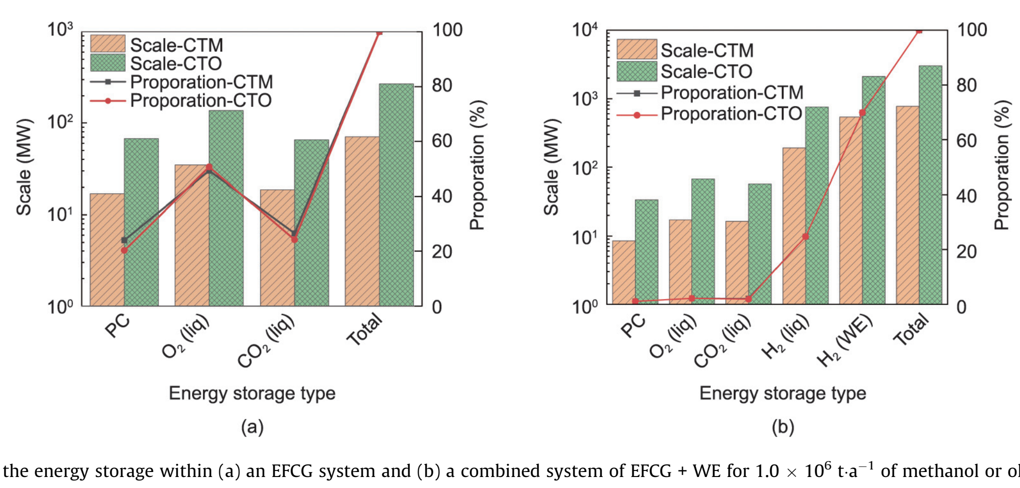

Fig. 2. Scale of the energy storage within (a) an EFCG system and (b) a combined system of EFCG + WE for 1.0×10^6 t·a^{-1} of methanol or olefin production.

petroleum coke, and natural gas) in the future. Improving the single-furnace processing capacity of the gasifier, reducing the energy consumption and investment, and comprehensively utilizing the discharged wastewater and ash waste are essential developments in enhancing the clean and efficient utilization of coal and renewable energy within a coupling system of traditional energy and new energy. Thus, these possibilities represent an opportunity to combine EFCG with large-scale energy storage. The development of this process can be flexibly coupled with the utilization of renewable heat and electricity as an energy storage mode in feedstock preparation, the gasification process, and product purification and storage. The results will effectively overcome issues related to the current utilization of renewable energy and reduce fossil-fuel consumption and CO_2 emissions.

In the future, renewable energy will occupy a major position in industrial applications. In addition to large-scale EFCG technology, power plants, the chemical industry, the iron and steel industry, the construction industry, and other industries that depend on coal, crude oil, and/or natural gas as fuel can potentially use this combined mode. Carbon emissions predominantly come from industries such as the electricity, steel, chemicals, cement, and transportation industries. By drawing on the ideas presented in this paper, large-scale energy storage can potentially be developed in these industries as well. Combining this energy storage mode with local advantages and resource characteristics offers the potential to enhance industrial production and reduce CO_2 emissions on a large scale, allowing countries to achieve their carbon-neutrality goals.

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