Energy 152 (2018) 960–973

Contents lists available at ScienceDirect

Energy

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

Electricity storage needs for the energy transition: An EROI based analysis illustrated by the case of Belgium

Gauthier Limpens[*], Hervé Jeanmart

Institute of Mechanics, Materials and Civil Engineering, Université catholique de Louvain, 1348 Louvain-la-Neuve, Belgium

ARTICLE INFO

Article history:
Received 22 December 2017
Received in revised form
26 March 2018
Accepted 31 March 2018
Available online 4 April 2018

Keywords:
Energy storage
EROI
Power to gas
Seasonal storage
Energy transition
Energy management

ABSTRACT

To face climate changes and energy dependency, governments encourage their industries and communities to increase the share of renewable energy (RE). However, the RE production is mostly inflexible. The risk of unmatching electricity market grows. Tools such as power plant flexibility, import/export, demand side management, storage and RE curtailment are developed to handle this problem. This study focuses on the energy storage mix required for the energy of the electricity system to high RE shares. An hour based model is developed in order to optimise the renewable energy and storage assets by maximising the energy return on investment (EROI) while respecting power fluxes constraints. The model is used to quantify the storage needs for the energy transition of Belgium. An in-depth analysis is performed for four scenarios. Depending on the RE deployment and nuclear share, EROI between 5 and 10.5 are obtained. Large scale storage is required as soon as the energy mix has more than 30% of RE. With more than 75% of RE, power to gas becomes unavoidable. This study highlights that curtailment can be limited to less than 5% of RE production. These values are the result of the optimum between increasing storage, RE capacity and curtailment.

1. Introduction

In 1917, an engineer wrote: ”It has long been recognized that mankind must, in the near future, be faced by a shortage of power unless some means were devised for storing power from the intermittent sources of nature … [The] problem of storing them in a practical way … has for many years engaged the attention of the most eminent engineers, among whom may be mentioned Edison, Lord Kelvin, Ayrton, Perry …” [1].

This problem is resurfacing nowadays because of the energy transition which aims at decarbonising energy sources. To face climate changes and energy dependency, the European Union, among others, drives its members towards an energy transition from fossil fuels to renewable and low carbon energy.

Renewable energies (REs) are intermittent and irregular. They do not fit the electricity demand. A risk of unmatching market grows and tools such as power plant flexibility, import/export, demand side management, storage and RE curtailment are developed to face this issue.

Recent works focusing on the energy transition evaluated storage needs for a fully renewable electricity in Europe [2–4]. They highlighted a needed storage capacity of around 100–300 TWh with an optimal RE mix. Nowadays the only large scale technology for electricity storage is Pumped Hydro Energy Storage (PHES). Gross PHES European potential is estimated at around 11.4 TWh and is reduced to 4 TWh if land use constraints are respected [5]. Approximately half of it is in the Alps and another half in the Scandinavian countries [5–7]. Therefore, the well-known gravity storage potential is one order of magnitude lower than the required amount of storage for Europe. Hence, other technologies will be required to answer the energy transition storage needs.

Storage of electricity can be done with different technologies, at different scales and for different applications. The most promising technologies are summarised in Fig. 1 (adapted from other works [8–11]).

These technologies are split in two families: ”chemical” and ”mechanical”. In the ”chemical” family, batteries and flow batteries use ions to store electrons, and Power to Gas (PtG) uses electrolysers to transform electricity into hydrogen. Hydrogen can be transformed, to improve storage properties, into ammonia or, by assuming an available source of carbon dioxide (CO_2), into methane or synthetic liquid fuels such as methanol or dimethyl ether. In the

---

[*] Corresponding author. Place du Levant, 2, B-1348 Louvain-la-Neuve, Belgium.
E-mail address: gauthier.limpens@uclouvain.be (G. Limpens).

https://doi.org/10.1016/j.energy.2018.03.180

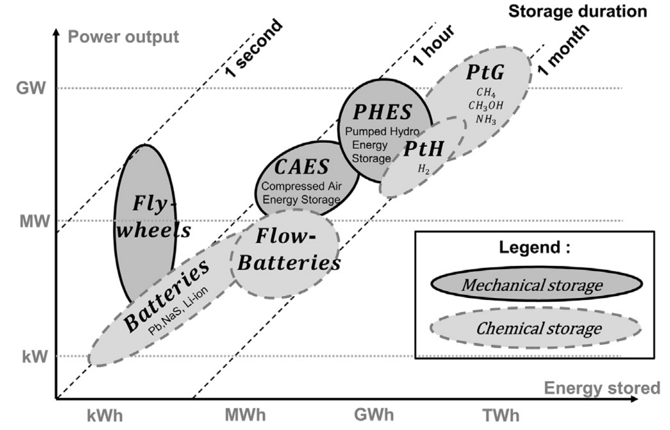

Fig. 1. Overview of energy storage capacity of different storage systems including PtG. There are 2 families: mechanical and chemical storage. Adapted from Ibrahim et al. [8].

”mechanical” family, energy can be stored into inertia form as in flywheels, gas potential energy as in Compressed Air Energy Storage (CAES) or based on gravity as in Pumped Hydro Energy Storage (PHES).

Each technology is suitable for a specific time scale. Short and long-term are defined as periods shorter than a couple of hours or longer than weeks, respectively. Fig. 1 sorts storage technologies by power and energy capacity for a typical unit. The duration is the time required to empty the storage at full load. The competitive edge between the technologies should be the round trip efficiency. Indeed, short-term storage is used very often throughout the year and must have a high round trip efficiency. This requires large numbers of batteries and flow batteries (bottom left of Fig. 1) with limited unit capacity. However, the efficiency of long-term storage is less relevant. In that case, the size of the reservoir becomes the key parameters. These large reservoir are used for seasonal storage or to backup production during a lack of RE for a couple of days or even weeks. PHES and PtG have naturally this specification (top right in Fig. 1).

Some technologies are geographically dependent such as CAES that needs caves or PHES that needs a significant difference in height.

Power to gas exists at demonstration scale and can produce hydrogen, methane, methanol, dimethyl ether or ammoniac [12,13]. Storing these molecules is industrially mature, at low cost and at an energy denisty of the same order of magnitude as fuel oil.

An ideal storage mix is composed of an efficient daily storage and a large energy reservoir seasonal or backup storage. A mix of PHES, batteries and PtG is promising with high efficiency batteries for short-term, PHES depending on geography for mid term and PtG for large energy storage and seasonal needs. This storage mix is relevant and used in other works studying high RE share in Germany or Europe [14–16]. Still such a mix has never been optimized regarding the EROI.

This paper estimates the storage needs for energy management. It focuses on time scales ranging from 1 h to one year. At very small time scales, energy storage is also required for power quality management but that will not be investigated in this study. Energy storage taken into account in this study is used for different applications as listed in Refs. [17,18]. Applications are sorted in seven categories. (1) Renewable energy support, small scale storage is installed close to the RE device and buffers production (as solar panels in dwellings). (2) Commodity arbitrage, large scale storage absorbs excess during peaks and provides power during deficit. It ensures a production and consumption match at large time scale and decreases the spread in electricity prices. (3) Transmission support, storage avoids congestion on the transmission grid. (4) Distribution deferral, storage is used to arbitrage at distribution grid level (similar to (2) but at the distribution level). (5) Power quality, storage is used to control the frequency. This is equivalent to matching the production and consumption at a small time scale. (6) Distribution grid support, which avoids congestion on the distribution grid (similar to (3) but at the distribution level). (7) Off grid, system is not connected to the grid.

Common metrics used to evaluate energy systems are the Levelized Cost Of Energy (LCOE) and the financial investment (the money Return On Investment, ROI). Analysing an energy system based on ROI requires to take into account economical assumptions such as inflation and growth. Moreover, some energy source prices are biased by subsidies, policies and lobbies. To avoid these problems, this study uses the Energy Return On Investment (EROI).

EROI is the ratio between the energy produced throughout the lifetime of an energy system and the energy mobilized to produce, maintain and dismantle the same energy system. This dimensionless factor allows a comparison between energy sources, if the same boundaries for calculating inputs and outputs are used.

A high EROI is desirable because it is directly correlated to the standard of living in our society, which is based on energy-intensive machines. It is an indicator of society welfare and economy development [19–21]. The quality of energy sources matters because they have different EROI. David Ricardo's first principle is then verified: highest EROI sources are exploited first because they provide the most energy for the less effort. Therefore, the best fossil sources (EROI around 100) have been exploited in the past. Today, these sources are still exploited but with lower EROI (around 15) due to depletion [19,20,22]. Nowadays, wind and solar energies become competitive based on their respective EROI around 10–20 and 2–9 [19–24].

With a lower EROI and a decentralised RE production, the energy sector becomes more asset and worker intensive. Thus, an increasing proportion of the economy has to be devoted to obtain the same amount of energy available for the rest of the economy.

In scientific papers, EROI is a widely used metrics to measure the energy efficiency of energy sources [20,22,24]. To compute the EROI of the society, all actors from the primary energy to the end users must be taken into account. Thus EROI is negatively impacted by energy storage, conversion and transport. The goal of this paper is to estimate the best electricity energy storage mix for the energy transition. The approach is illustrated by the case of Belgium. Similar case studies exist for Europe [16,25], Germany [15] or even Belgium [26,27]. But, they are all focusing on the ROI and not the EROI as the metric. Also, the studies about Belgium [26,27] consider only one type of storage without geographical constraints. In the present work, as explained above, three storage technologies are taken int account. Only one other study analyses the impact of the energy storage on the EROI for the specific case of an isolated RE farm with a limited transmission line [28].

The work is organised as follows. a methodology, presented in Section 2, has been developed in order to analyse an electricity system based on RE and storage capabilities. Then the focus case of Belgium energy transition is detailed in Section 3 and solved in Section 4. Finally, the results are discussed in Section 5 and general trends are highlighted for similar countries.

2. Methodology

In this section, a generic future electricity system and its components are defined. The system is split into several cells that exchange electricity. Cells represent a city, a region or even a country depending on the size of the whole system. This mimics an