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Review Article

Reversible solid oxide cells applications to the building sector

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HIGHLIGHTS

- Reversible solid oxide cell application review as energy system in the building sector.
- Interest in reversible solid oxide cell technology has been constantly increasing in the last decade.
- 17 large research and development projects concerning the technology have been identified, analysed and compared.
- Projects are compared in size, objective, budget, technology readiness level and manufacturer.
- Terminology must emphasize the ability of this solution to work bi-directionally as electrolyser and fuel cell.

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ABSTRACT

Hydrogen can manage intermittent Renewable Energy Sources (RES), especially in high-RES share systems. The energy transition calls for mature, low cost, low space solutions bringing the attention to unitized items such as the reversible Solid Oxide Cell (rSOC). This device, made of a single unit, can work as an electrolyzer and as fuel cell with high efficiency, fuel flexibility and producing combined heat. The objective of this review is to identify and classify rSOC applications to the building sector as an effective solution and to show how much this technology is near to its commercialisation. Research & Development projects were analysed and discussed for a comprehensive overview. Conclusions show an increasing interest in the reversible technology, although it is still at pre industrialisation stage with few real applications in the building sector, of which, the majority is reported, commented, and compared in this paper for the first time.

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Abbreviations

Chemical Symbols

B Boron
Ce Cerium
CO Carbon Monoxide
CO_2 Carbon Dioxide
Cr Chromium
Fe Iron
GDC Gadolinium-Doped Ceria
H_2 Hydrogen
H_2O Water
La Lanthanum
LSCF Lanthanum Strontium Cobalt Ferrite perovskite
Ni Nickel
W Tungsten
Y Yttrium
Zr Zirconium

Acronyms

ADASTRA HArnessing Degradation mechanisms to prescribe Accelerated Stress Tests for the Realization of SOC lifetime prediction Algorithms
ALK Alkaline
AST Accelerated Stress Testing
B€ Billions of Euros
BALANCE Increasing penetration of renewable power, alternative fuels and grid flexibility by cross-vector electrochemical processes
BMWi German Federal Ministry of Economic Affairs and Energy
CHP Combined Heat and Power
CTESTNET Fuel Cell Systems Performance Testing and Standardization
EC EleCtrolyzer
EIS Electrochemical Impedance Spectroscopy
EU European Union
FC Fuel Cell
FCH JU Fuel Cells and Hydrogen Joint Undertaking
FCTESQA Fuel Cell Testing, Safety, Quality Assurance
FGG Austrian Research Promotion Agency
GIFT Geographic islands FlexibiliTy
GrInHy2.0 Green Industrial Hydrogen via Reversible High-Temperature Electrolysis 2.0
HERMES High Efficiency Reversible technologies in fully renewable Multi-Energy System
HI2H2 Highly efficient, High temperature, Hydrogen Production by Water Electrolysis
HYPOS Hydrogen Power Storage & Solutions East Germany
IEA International Energy Agency
IPCEI Important Projects of Common European Interest
IT Intermediate Temperature
LCA Life Cycle Assessment
LOHC Liquid Organic Hydrogen Carrier
MOXIE Mars Oxygen ISRU Experiment
NAVFAC EXWC Naval Facilities Engineering Command Expeditionary Warfare centre
NewSOC Next Generation solid oxide fuel cell and electrolysis technology
NG Natural Gas
OCV Open Circuit Voltage
PEM Proton Exchange Membrane
PRIN Progetti di Rilevante Interesse Nazionale
R&D Research and Development
REAL-SOFC Realising Reliable, Durable, Energy Efficient and Cost Effective SOFC Systems
REFLEX Reversible solid oxide Electrolyzer and Fuel cell for optimized Local Energy miX
RELHY Innovative Solid Oxide Electrolyser Stacks for Efficient and Reliable Hydrogen Production
RES Renewable Energy Source
rSOC reversible Solid Oxide Cell
rPCE reversible Proton Ceramic Cell
SOCTESQA Solid Oxide Cell and Stack Testing, Safety and Quality Assurance
SOEC Solid Oxide EleCtrolyzer
SOFC Solid Oxide fuel Cell
SOFC600 Demonstration of SOFC stack technology for operation at 600C
SOWE Solid Oxide Water Electrolysis
SrSOC Symmetric reversible Solid Oxide Cell
SSOC Symmetric reversible Solid Oxide Cell
SWITCH Smart Ways for In-situ Totally Integrated and Continuous multisourCe generation of Hydrogen
TRL Technology Readiness Level
U.S. United States
W2G WASTE to offer flexible GRID balancing Services
W2W Waste2Watt
WASTE2GRIDS Converting WASTE to offer flexible GRID balancing Services with highly integrated-integrated efficient solid-oxide plants

Contents

Introduction

Climate change is identified as one of the greatest exposures to the world [1] and decarbonization is the key action to handle it [2]. The main culprits can be individuated in the transport sector, responsible for 23% of total global emissions, the industry sector for 32%, and on the top of the list, the building sector for 39% of energy and process-related emissions [3]. In Europe, this will lead to an intensive sector upgrading to meet the mandatory renewable energy target for 2030 [4], represented by at least 40% of the final energy consumption satisfied from Renewable Energy Sources (RES), and by 39% of energy efficiency achieved collectively [5]. Those objectives conceal important implications as energy systems retrofitting and RES penetration in buildings, this latter affected by non-programmable production. The variable production distresses grid stability [6] and security [7], system operations [8], market economics [9] and the service continuity [10], representing an obstacle to their dissemination and uptake. Energy vectors, and recently with a strong consideration Hydrogen [11], are seen as a pathway to efficiently manage intermittent renewable electricity in systems with high-RES share [12] as foreseen by different plans [13]. Additionally, hydrogen is seen as a valuable vector to be used in all sectors, even in the hard to abate [14]. The decarbonization effect achievable by means of hydrogen can be seen as well in the mobility [15], as maritime [16] and rails sectors [17], the iron industry [18], and as said in the RES sector to provide seasonal storage [19] and grid balancing [20]. Also Domestic hydrogen [21] is an investigated topic, focusing the Fuel Cell (FC) applications, for example as CHP [22] and micro-CHP units [23], silent operations [24], cost-effectiveness [25], and to reduce the CO_2 impact [26]. Similarly, Electrolyser (EC) systems are investigated to integrate different energy carriers [27], to offer a storage solution [28], or transforming the residents in prosumers [29].

The reported studies are based on the single installation of a device, however, for such transition to occur effectively in the building sector as desired, mature, low cost and low space solutions are needed [30] thus bringing the light on unitized systems, i.e. the reversible solid oxide cell (rSOC). This machinery unitizes in one single device its EC version called Solid Oxide EleCtrolyzer (SOEC) and its FC version named Solid Oxide Fuel Cell (SOFC) [31]. Similarly to its separated component, the rSOC works in combined heat and power production (CHP), guaranteeing high efficiencies and lower emission than traditional CHP systems supplied by fossil fuels [32], while also offering a storage solution for excess [33]. Those capabilities were shown in the industrial framework of a paper mill in Italy [34] already.

Besides the rSOC technology, also the alkaline (ALK) and proton exchange membrane (PEM) can work in a reversible way, but at low temperature. Since there are very few reversible applications worldwide, underlying the importance to review those cases, the ALK and PEM solution roundtrip efficiency is not identified yet, while for the rSOC this value oscillates around 37%. Considering the roundtrip ultimate target, beyond 2030, is expected a value of 50% for PEM and ALK while for the rSOC is estimated in 65%, hence the rSOC represents the most efficient option also in the long term [35] among these reversible solutions. Another reversible solution is represented by the Proton Ceramic Cell (rPCE), which can provide similar outputs as an rSOC but a lower temperature, significantly simplifying their management, lowering the startup process, and reducing the long-term degradation. Despite those advantages, the rPCE technology has different barriers to overcome, such us the lower efficiency, impaired electrode performances, and poor electrolyte sinterability [36].

Moreover, a single unit (a FC or EC) will need a dedicate infrastructure to properly work, i.e. a grid connection or a supply chain to dispatch and or purchase hydrogen for its functioning [37]. Although the worldwide strong political interest in the topic, as demonstrated by many strategies in the Asia [38], and Pacific areas [39], in North [40] and South America [41], and as tested also by many European initiatives designed to develop the back-bone [42] of a pan-European hydrogen grid [43], nowadays, there is not an infrastructure able to support the use of single units in buildings [44]. In the actual framework, considering an energy system where hydrogen is involved directly, the possibility to use in situ production is more realistic [45]. In this regard, considering an energy scheme with a rSOC, only one machine would be needed to manage autonomously the system, with relative saving in economics and space terms [46]. Furthermore, according to International energy Agency (IEA) on hydrogen today's opportunity [47], the greatest near-term prospect in building to use hydrogen is represented by blending it into the existing natural gas network, and only in the long term is prospected the hydrogen direct distribution [48]. It is worth noting that the blending will not be an effective solution for all FC, since most of them are not designed to work with blended hydrogen, instead the rSOC can work already with blended fuels [49] or directly with Natural Gas (NG) [50], representing a significant advantage.

Thus, although from an environmental perspective the use of NG or blend is less effective compared to the pure hydrogen use [51], this solution could be a probable starting point to establish the future affordable and efficient hydrogen supply chain [52] in our cities.

In light of the above, rSOCs seem to have all the necessary characteristics to increase RES penetration [53], improve energy efficiency [54] and establish an enabler hydrogen value chain [55] for the residential and building sector.

The hydrogen uptake in buildings also involves a manufacturing challenge. To satisfy the EC and FC demand their production must increase significantly. Using unitized solutions can be a first step to solve this bottleneck. Additionally PEM needs for specific and rare materials which could compromise its uptake at large scale [56], while ALK technologies are susceptible to fluctuating working loads, which is not compatible with RES [57]. Moreover, ALK could lead to corrosive dangerous conditions [58], especially in a domestic scenario. Overall, considering their Life cycle assessment (LCA), the equivalent CO_2 emission for a PEM are 16 and 15 times higher than the SOC and ALK respectively. While considering the mineral resource scarcity the PEM has a need for material (in copper equivalent) 76 time higher than SOC and 22 times higher than ALK [59].

Those advantages, plus the ability to work in CHP mode, the fuel flexibility and the higher efficiency put the rSOC in the spotlight among the hydrogen solution.

Thus, the goal of the review is to identify and classify the available rSOC applications in the residential sector to outline the actual development of what is so far just a technology with promising technical characteristics to be applied to the investigated sector.

Since this technology it is still a precommercial stage, reviewing Research and Development (R&D) projects, and related scientific contribution, will lead to pointing out targets already achieved, pathways chosen by policymakers and industrial stakeholders, the expected outcomes and solutions available on the market. From reading this review, the reader can receive a more detailed vision about the rSOC use and synergies within buildings rather than a description of constituent materials, modelling, degradation, or possible futuristic applicative scenarios as presented by most of the few available reviews on the topic.

Literature review

The literature review is focused on identifying other reviews that addressed the rSOC topic. Thus, this part will be focused primarily on those works that investigated the rSOC use in the building sector, to identify the actual literature gaps. Other works, that analyse a specific application will be discussed while introducing and discussing the technology in the upcoming sections.

First of all, the interest towards rSOC technologies along the years was analysed. The analysis has been carried out on Scopus, the values reported identify the researches attributable to the key words “reversible solid oxide cell and hydrogen” and “reversible solid oxide cell”. These two key words were selected to underline in the first case a connection to an rSOC operational case where hydrogen use is involved, while in the second case the attention is merely focused on the rSOC technology.

The interest on such technology has increased from 2012, as it is possible to appreciate from the rising trend as shown in Fig. 1. This latter is meant only as a pure figure of merit on the research conducted on these keywords rather than examining the entire rSOC field of investigations.

Nonetheless, although a rising trend, from this comparison it emerges already how the available literature mostly addresses theorical and technical aspects rather than applicative cases.

Analysing the majority of reviews on the topic, trend topics can be identified, and they are distant from showing the rSOC actual use, underlying the novelty and the added value to the

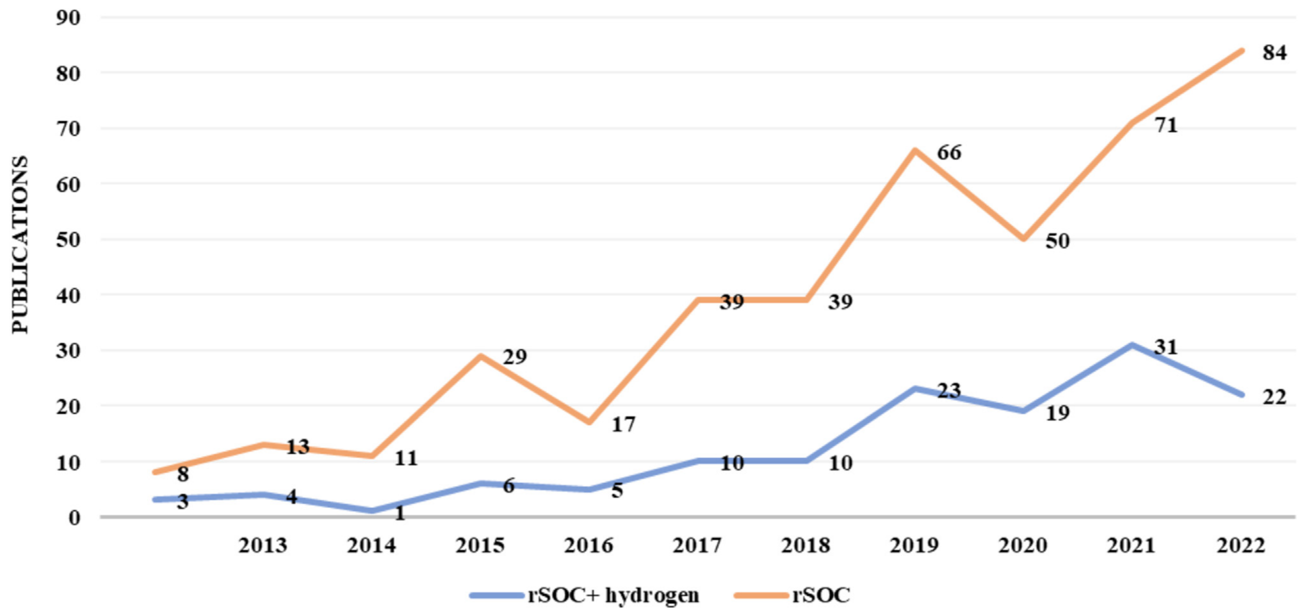

Fig. 1 – Scopus results regarding the key words "rSOC, hydrogen" and "rSOC".

scientific literature of this review. Actually, no review specifically addressing rSOC applications in the building or any other sector was available in literature.

The most addressed subject is indisputably the materials analysis, also including reversible Proton Exchange Membrane (PEM) and Alkaline (ALK) technologies as described in Refs. [53,61]. The material analysis is still a flourishing topic, and it is possible to find advances and innovation in the adopted materials as reported for the years 2019 [62], 2020 [63] and 2021 [64]. Similarly, in Refs. [65,66], the focus was to review the material used for electrodes but with a focus on only one specific solution, nickel (Ni) and lanthanum strontium cobalt ferrite perovskite (LSCF) respectively. Considering electrodes, it is possible to mase a symmetric configuration (SSOC or SrSOC) when the cathode and anode are made by the same materials, as explained and reviewed in Ref. [67], where different symmetric materials combination are reported.

From the material analysis, many other subtopics can be detected such as the degradation performances studied in Refs. [68,69] and especially in Ref. [70] by means of Electrochemical Impedance Spectroscopy (EIS) methodology. Although still focused on materials issues, in Ref. [71], the analysis was performed with an additional focus on the economic performances, and in Ref. [72] the attention was moved on how to establish a market ready chain for rSOCs components and stack. This latter is the core of the rSOC technology, where the chemical reactions take place, hence it is also important to analyse the impact of the overall result according to the system connection and architecture [73] in terms of metallic interconnects and distributions [74]. Another identified subtopic is related to the focus on Intermediate Temperature (IT) rSOC materials, hence working between 500 °C and 600 °C instead of 900 °C, with two examples offered by Ref. [75] where chromium (Cr) deposition is studied and by Ref. [76] where composite cathodes are studied. Completely different aspects were studied in Ref. [77] where 32 Life Cycle Assessments (LCAs) from Power-to-X projects are reviewed, and among those, just 3 are referred to SOC technology, which do not ensure the use of the reversible solution.

Moving from the material topic and seeking for information about the rSOC use in a real context, the available literature amount decreases drastically. Apparently, in Ref. [78], this issue is addressed by the authors, although an extensive hydrogen technologies integration with different devices is reported, the use of rSOC in those processes is not mentioned. Instead, in Ref. [79] and [80], different methodologies to model the rSOC and simulate its functioning are reported while in Ref. [81] the modelling was focused to simulate the degradation mechanism. The simulation phase can be considered preparatory to the subsequent installation in real context. In Ref. [82], the objective was to review and compare different energy storage systems, including storage system based on rSOC technology but no real cases or projects were reported. Similarly, in Ref. [83], a review on the current status of water electrolysis was done, comparing PEM, ALK and SOC solutions. Considering SOC technology, just one technology provider is identified and the rSOC concept is overlapped with the SOEC, defined in the reported literature as SOEL. Alike, in Ref. [84], the authors reviewed the water electrolysis technologies involved in different projects, from the 128 reported projects only 9 cases refer to SOCs, and also in this case the rSOC and SOEC concepts are not clearly distinguished again.

In Fig. 2 is reported the presented reviews breakdown as percentage, an overall 64% is focused on materials and related aspects (all reported in blue shades). The integration, which is also the broader topic of this review, represents just 14%. Additionally, inside this 14% the direct rSOC mentioning, or better the SOC, cover even a smaller percentage, varying between 7% and 9% according to studies reported in Ref. [77] and in Ref. [84] hence representing less than 1% of available literature, underline the literature gap on the topic.

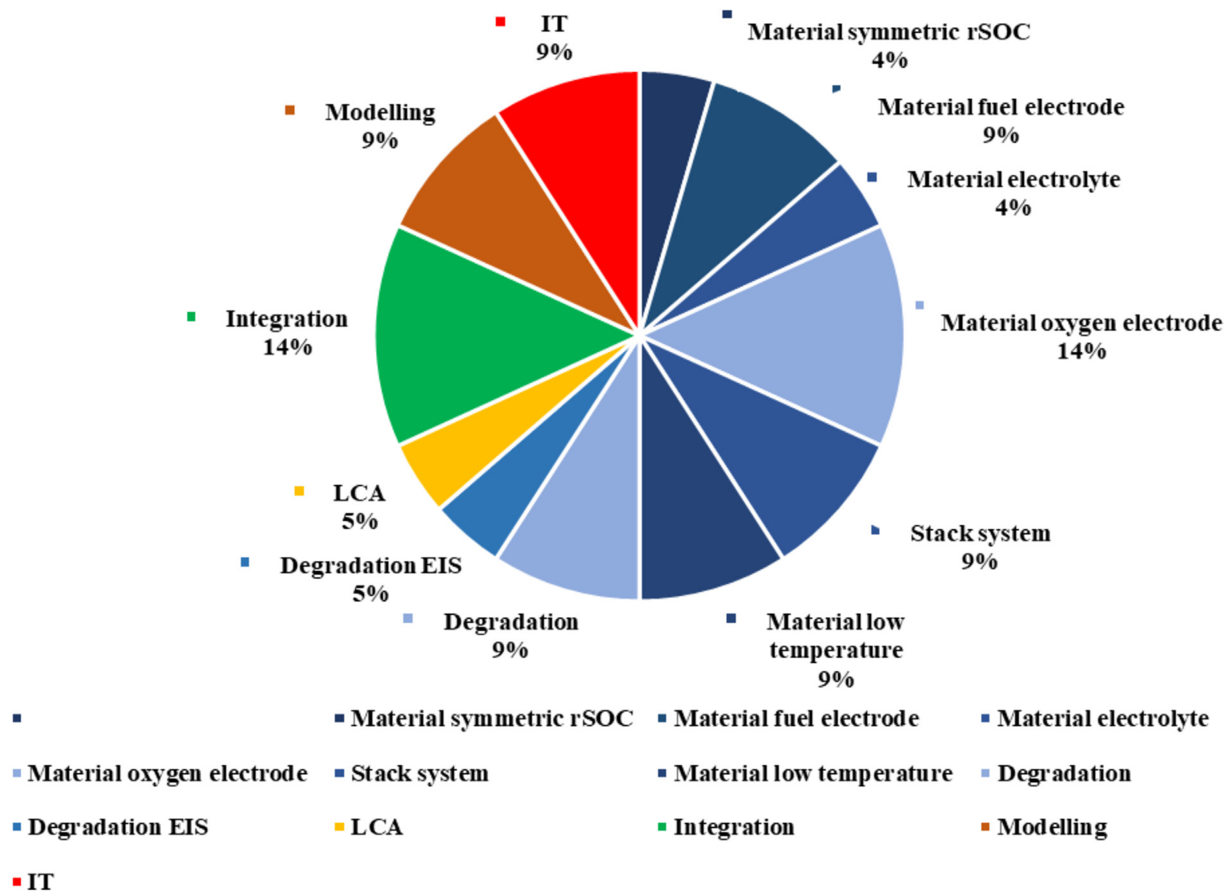

Fig. 2 – Identification of reviews addressing the rSOC technology in different topics coming from the reviewed literature.

From these works, which give a picture of the most explored subjects until now, it is difficult to understand how much of the rSOC technological advances are already transferred in practical use. Instead, this review wants to fill this gap presenting the most prominent results achieved in the investigated topic. Undeniably, the presented work cannot be considered as an exhaustive source for all the projects in progress or completed at all levels, nevertheless, the authors tried to present the most updated and complete framework to date. After a concise introduction on the solid oxide technologies, the review will follow with an overlook on the ongoing or finished projects, focusing on the Technology Readiness Level (TRL) and technical features, relevant project partners identification, targets, financing, and the project duration.

Solid oxide technologies

In this section, the single solid oxide cells, i.e. SOFC and SOEC versions and the unitized rSOC are presented. In Fig. 3, an rSOC representation is schematically reported; in addition, from the figure, it is possible to appreciate its reversible behaviour. It should also be noted that this technology generally consists of two main components represented by the two porous electrodes and the dense ceramic electrolyte. Additionally, the manufacturing materials needed for its components are mostly based on easy to find metals and ceramic [85], with a strategic value in the optic of mass manufacturing. The fuel electrodes are mostly made by nickel–yttria stabilized zirconia (NI-8YSZ), the electrolytes as well are made by yttria stabilized zirconia (8ysz) [86], while the oxygen electrode are based on Lanthanum Strontium ((La0.6Sr0.4) Cobalt Ferrite perovskite (0.98CoO3), also simplified in LSCF [87].

The ceramic electrolyte allows to reduce construction costs since it does not rely on expensive material to cope with the high temperatures needed to enable the chemical reactions. Another common point to the three solutions is the high working temperature varying between 650 and 1000 °C.

As inferable from the abundant literature reviews, there are many available constituent material options from which to choose. Within this topic, also the material disposition was investigated as in the case of the symmetric electrode configuration [73], where the two electrodes are made by the same material. Some interesting studies about this topic were also conducted by NASA in the early 2010s [88]. The rSOC solution stems from the studies made on SOEC and SOFC, where the regenerative or reversible nature of the process was clear from the initial stage of investigation. It must be clarified that with the term reversible it is possible to identify also a system made by an individual EC and FC working together, otherwise, using the term unitized it is elucidated that only one machine is installed [53,61], similarly the word

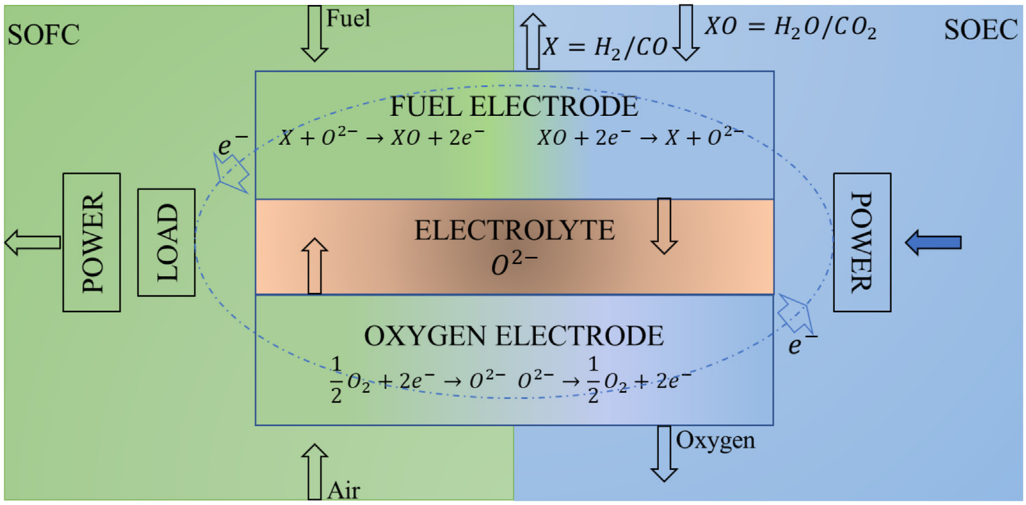

Fig. 3 – Simplified rSOC layout, divided in SOFC (left) and SOEC (right).

regenerative [53,61,89,90] has been used to underline the difference from the use of two machines.

The solid oxide electrolyzer

The first reported results from a SOEC were presented in the 1980s by Dönitz and Erdle [91]. Since the beginning of its history, SOEC showed attractive features such as high efficiency, high purity hydrogen production and syngas co-electrolysis [92]. As matter of fact, they use steam for electrolysis, hence a heat source at a high temperature (between 650 and 1000 °C) is needed, otherwise a thermoneutral cell voltage can be applied. This latter solution represents the minimum voltage to obtain hydrogen from water in an ideal electrolysis cell, without external heat integration. This solution implies a greater electrical consumption and hence a reduced total efficiency. Nonetheless, its high operating temperature is a fascinating management challenge since part of the heat waste can be recycled for further processes at lower temperatures. In this regard, coupling with different heat sources has been tested, aiming at increasing the overall operational efficiency. It is possible to find in literature many coupling examples with nuclear power plants [93], solar thermal [94] or geothermal [83] heat systems. Additionally to the heat source, also electricity and water must be provided to the SOEC to obtain hydrogen, as schematically represented in Fig. 4.

It is worth noticing that research on the SOEC technology is a relatively new field, also its name is changing during these past years since in 2004 it was referred to as SOWE (solid oxide water electrolysis) or in other works as SOEL. Currently, most of the projects are preliminary lab-scale studies, mainly focused on the advancement in the efficient manufacturing of materials and processes instead of the deployment for a market ready solution. For its future deployment in large scale projects, it will be essential to maximize the ceramic materials durability at high temperature and the long-term operations, thus its components structure and electrochemistry [70,83].

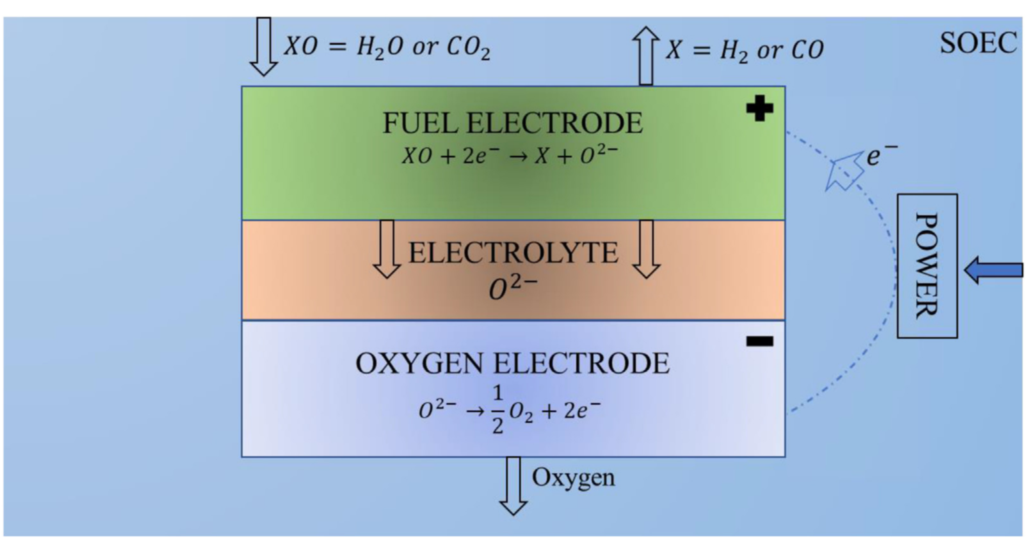

Fig. 4 – Simplified SOEC layout reporting the reactions at the electrodes.

Table 1 – Comparison between unitized and single unit solid oxide cells.

Specification	SOEC	SOFC	rSOC
Cell temperature (°C)	650–1000	650–1000	650–1000
Cell pressure (bar)	1–20	1	1
Power density (W/cm^2)	0.65–1.3	1.5–2	0.65–2
Specific energy consumption stack (kWh/Nm^3)	2.5–3.5	none	2.5–3.5
Nominal system efficiency (%, LHV)	74–81	>60	80
partial load range (%)	20–100	n/a	20–100
H_2 production rate: Stack-system (Nm^3/h)	<10	n/a	<10
Hydrogen Purity (%)	99.99	Fuel flexibility	99.99
Lifetime stack (kh)	10–30	10–30	10
Voltage Degradation rate (%/1000)	2–6	≈1	1.5
Investment costs small-scale (€/kW)	5600	3000	8400

Several projects, starting from the Hot Elly [95] developed by Dornier System GmbH aimed to improve the SOEC outcomings. Successively, the European Commission financed different projects aimed at enhancing knowledge and expertise around this technology, such as the RelHy [96] and the HI2H2 [97]. Also in the US, research activities are still ongoing in this field, and the NASA is an active player since the co-electrolyse could be key to achieve the realization of human settlements on Mars, as studied in the project MOXIE [98]. The actual performances reached by this technology are summarised and reported in Table 1, in a comparative way with the rSOC and SOFC statistics.

The Solid Oxide Fuel Cell

Emil Baur and H. Preis were the first to report the use of a SOFC in 1937, using materials such as zirconium (Zr), yttrium (Y), cerium (Ce), lanthanum (La), and tungsten (W) oxides [99]. This first publication pathed the way for a series of investigations around this topic, with ups and downs, until today. The high operating temperature allows internal reforming, produces high quality by-product heat (CHP mode), and promotes fast electrocatalysis even if non-precious metals are used. Its schematic functioning and component are reported in Fig. 5.

Efficiencies for this type of FC are around 48% with a peak of 70%. Additionally, considering the heat recovery that can be achieved installing thermal systems in parallel, the efficiency can reach an average value of 80% [100]. Until a few years ago, the SOFC role was relegated to the provision of power in utility scale applications due to the significant time required to reach the operating temperatures. Nonetheless, the high working temperature allows to work not only with pure hydrogen but also with any king of rich hydrocarbon fuels such as natural gas or syngas.

Likewise, the thermal management of high temperature outside the industrial context was seen as a further challenge to cope with [101]. Nevertheless, thanks to the progresses recorded during those past years of research activities, this technology is now experimenting also a miniaturisation process, with a total size varying between few kW to MW. Additionally, some FC developers see opportunities for SOFC employed in motor vehicles [102,103]. Because of its high efficiency, cheaper manufacturing materials and co-generative operation, the European Union has financed several projects in the recent years aimed at enhancing SOFC performances and widen its applications as testified by the funded projects: Waste2Watt [104], SOFC600 [105] and REAL-SOFC [106].

The unitized reversible solid oxide cell

rSOCs can operate in both power production and energy storage modes and are a promising way to store the non-programmable RES overproduction. The water splitting process, performed during the electrolysis process, can be thought as equivalent to charging a battery. In FC mode, the stored hydrogen is sent through the same electrochemical stack used for the EC to generate electricity, similar to the discharging process in a battery, hence reversing the previous

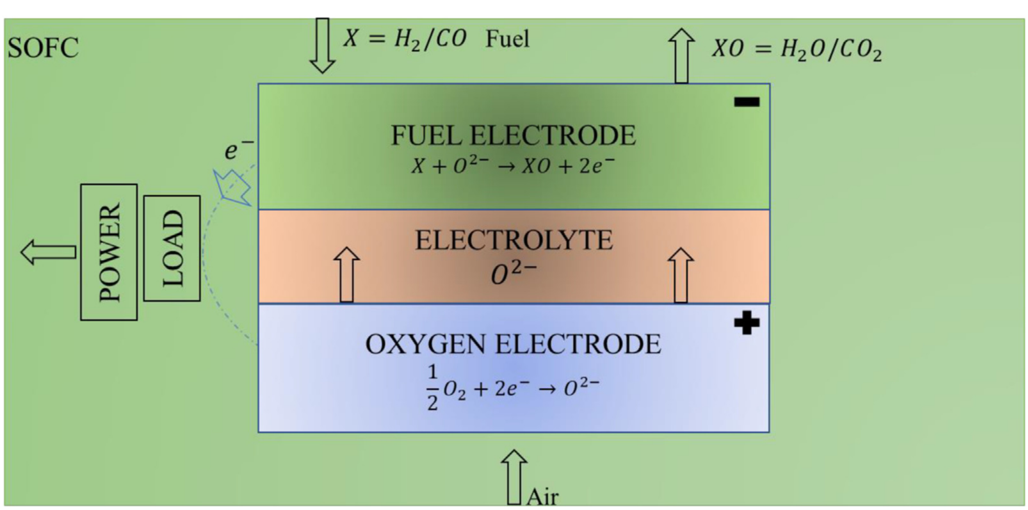

Fig. 5 – Simplified SOFC layout reporting the reactions at the electrodes.

process. Electricity, water, and in addition heat will be the only process outcomes when hydrogen is used as fuel.

The preliminary studies in this sector were carried out at the beginning of the '90s by Erdle et al. [107] for tubular cells, and in Refs. [108,109] for planar cells. Nowadays, the cells design majority is based on a planar configuration, and significant variations associated with the cell structure are not registered [110]. Another way to classify a rSOC is to identify its electrolyte functioning which can be classified in oxygen ion-conducting or proton-conducting [61].

Nevertheless, numerous incognita are waiting for their answers, which are specific to the reversible nature of the working flow, such as the electrode performances, materials, cell/stack designs, operating parameters, and its integration in real cases to establish its feasibility [111]. From this latter consideration, due to the lack of information in literature, it continues our review to present the possible most complete framework regarding the rSOC integration in real case, looking especially for building cases.

The values reported in Table 1 are extrapolated from all the works presented in the previous sections regarding the SOEC, SOFC, and rSOC. The table represents the most generic values for the technologies, slight differences can be found in edge research projects [112,113] or in specific application in the industrial [114] or aerospace [115] sectors, which our outside from the scope of this research.

The unitized reversible solid oxide cell advancements

As reflected by the previous chapter and from Table 1, where it is possible to appreciate the SOC solutions principal parameters, the rSOC state-of-art already offers a promising deployable solution. Nowadays, there are many projects currently ongoing or recently finished that installed, tested, and verified the SOC performances in real contexts. Most of these projects rely on research funding to accelerate expertise growth. To do so, Europe created in 2008 also a dedicated funding program called the Fuel Cells and Hydrogen Joint Undertaking (FCH JU), and in ten years 180 M€ were allocated to SOFC and SOEC development, with a total of 49 founded projects representing approximately the 50% of the energy type projects [116].

Fig. 6 – GrInHy logo.

In the next sections, the projects related to the rSOC deployment, with a special focus on the building sector will be presented and briefly described.

Green Industrial Hydrogen via reversible high-temperature electrolysis

The project GrInHy [117] (Fig. 6) studied a multi-stack module design with 6 stacks modules in parallel, with a 150 kW in SOEC and 30 kW in SOFC [118], as reported in Table 2 with the investigated aspects summary.

During the project, the tests were run for more than 7000 h analysing lifetime [119] and integrity [120]. The bench test took place in the environment of an integrated iron and steel works. The metalworking processes and offered the required waste heat, increasing the overall process cost-effectiveness and minimizing the energy demand. During the project, an electrical efficiency of 80% was achieved in SOEC mode and 50% in SOFC [121]. Other interesting information regarding the material test and design can be found in Refs. [122,123], while in Ref. [124] the attention was focused on the cycling effects on the rSOC output conducting 80,000 current on/off cycles in a one year long experiment.

As evidenced also in the project name, the rSOC functioning is studied in an industrial context, nevertheless, due to the modularity of the analysed solution, the project size can be also comparable with domestic or office buildings consumptions, although it could be less efficient since it would not be guaranteed an external heat source. Additionally, the GrinHy2.0 project [125] was funded as well by the EU, but this latter as inferable from the name, Green Industrial Hydrogen via steam electrolysis, is focused on SOEC technology. Nonetheless, as reported in Ref. [101], the new implemented SOEC comes from the experiences developed during the previous project and the experience brought by new partners [126].

Reversible solid oxide electrolyzer and fuel cell for optimized local energy miX

The REFLEX project [127] (Fig. 7) aims at developing an innovative renewable energies storage solution, the "Smart Energy Hub", based on rSOC technology. The challenging issue of achieving simultaneously high efficiency, high flexibility in operation and cost optimum is duly addressed through rSOC components and systems development, and the definition of innovative management strategies. An in-field demonstration will be performed in Turin at Environmental Park facilities, where the Smart Energy Hub will be combined to the local solar and hydro RESs and will provide electricity and heat to the headquarters of the park. It will demonstrate, in a real

Table 2 – GrInHy project summary.

Duration	Overall budget	TRL	Size SOFC/SOEC	Technology Partners	Targets
2016–2019	4,498,150 €	8	30/150 kW (6 modules)	- Boeing - Sunfire	- Overall electrical efficiency of at least 80% LHV (ca. 95 %HHV) - Reaching a lifetime of greater 10,000 h with a degradation rate below 1%/1000 h - Integration and operation for at least 7000 h

Fig. 7 – REFLEX logo.

environment, the high power-to-power round-trip efficiency of this technology and its flexibility in dynamic operation, thus moving the technology from TRL 3 to 6.

The Smart Energy Hub developed by Sylfen, will be used to assess a sensibility analysis to evaluate its techno-economic performance at different scales. Based on the REFLEX Description of Action (DoA), the impacts can be organized into four main aspects: i) technical, ii) economic, iii) network and research, and iv) environmental. A summary of REFLEX objective and module characteristics is reported in Table 3. It is possible to gather more information regarding stack testing in Ref. [128], while in Ref. [129] is presented an optimized stack design concerning the internal pressure drop (reduced by a factor of 2) and sealing resistances allowing to reach a better electrochemical performance. Regarding Stacks degradation, tests have been performed to explore the current density, steam content and degree of utilization effects [130].

Geographic islands flexibility

The GIFT project [131] (Fig. 8) aims at decarbonising the energy mix of European islands integrating renewable production through the development of several innovative solutions enhancing the grid flexibility, a project summary is provided in Table 4.

Among the proposed solutions, hydrogen will play a leading role, and the rSOC system proposed by Sylfen, coupled with li-ion batteries, will be deployed, and tested on the island of Procida, Italy.

The implementation will test in a real case study the rSOC ability to harmonise production and demand, at building scale while also providing flexibility services to the grid. The GIFT project will allow improving the rSOC integration in an extended energy management system to deliver both valuable electricity and heat to the consumers as well as grid services by testing it in real conditions and converting it into a market-ready product. In literature, it is possible to find different studies related to this project, presenting flexibility and load analyses [132,133], the Hydrogen–Bromine Flow Battery System deployment [134] or the rSOC feasibility study [135] and the sensitive analysis of its outputs according to storage size, PV availability and building end-use [136].

Fig. 8 – GIFT logo.

Next generation solid oxide fuel cell and electrolysis technology

The NewSOC project [137] (Fig. 9) aims at considerably enhancing performances, durability, and cost competitiveness of solid oxide cells compared to the actual technology advancement. Within the project, twelve innovative concepts will be proposed and studied by the consortium concerning structural optimisation and innovative architectures, alternative materials, advanced engineering to reduce critical raw materials, which will lead to a lessening of environmental footprint while obtaining better lifetime and performance.

The NewSOC consortium final objective is to validate the new cells and stacks at the level of large cells with >50 cm^2 active area and short stacks in close collaboration with industry, thereby moving the TRL from 2 to 4. Six majors European SOC manufacturers are involved directly during the R&D activities with the objective to reach TRL 6, their names and the project summary are reported in Table 5. The project will assess the new SOC materials and fabrication methods considering the life cycle impacts and cost assessment. This project recently started, however some results are already published regarding the modification of commercial Ni/GDC (Nickel and gadolinium-doped alloy) powder used in the fuel electrode with iron (Fe) [138] and it was published holistic study to analyse the dominant reaction involving the CO production in H_2–H_2O–CO_2 feed mixtures, by differentiating the catalytic and electrochemical reactions [139].

Increasing penetration of renewable power, alternative fuels and grid flexibility by cross-vector electrochemical processes

BALANCE [140] project (Fig. 10) aimed to gather leading research centres in Europe involved in the Solid Oxide technologies topic, with the final objective to enhance the development of a European value chain suited to the rSOC theme primarily. The experimental work was performed by means of modelling [141] and simulate from small (50–400 kW) to large (40 MW) scale [142], also performing the techno-economic analysis [143], with distinct rSOC technologies integration in different applications such as methane reforming [144], water

Table 3 – REFLEX project summary.

Duration	Overall budget	TRL	Size SOFC/SOEC	Technology Partners	Targets
2018–2021	2,999,575 €	6	15/120 kW	- CEA	- Improvement in manufacturing processes, costs, and efficiencies
				- Sylfen	- New human resource opportunity - Piloting strategies for rSOC - Durability and integrability test on field - coupling with PV and hydropower plant

Table 4 – GIFT project summary.

Duration	Overall budget	TRL	Size SOFC/SOEC	Technology Partners	Targets
2019–2023	12,151,534 €	7	6.7/40 kW	- Sylfen	- Allow a high level of local renewable energy sources penetration - Provide visibility to the energy grid to better manage its flexibility and plan its evolution - Develop synergies between the electricity, heating, cooling, water and, transport networks - Reduce the use of hydrocarbon-based energies - Ensure the sustainability of the solutions and their replicability in other islands

Fig. 9 – NewSOC logo.

Fig. 10 – BALANCE logo.

electrolyse and co-electrolysis [145] and compared to lithium battery [146].

Nonetheless, during the project two partners developed and installed in Finland two 10 kWe SOEC/2 kWe SOFC rSOCs for real tests [147]. This latter work also availed funding from the Finnish national Smart Otaniemi project [148], and similar studies were conducted in Ref. [149] where different rSOC sizes were virtually simulated during the optimisation processes. Similarly, different researches were conducted in conjointly with the project PENTAGON, Unlocking European grid local flexibility trough augmented energy conversion capabilities at district-level [150], mostly based on SOEC topics [143,145]. Another issue investigated by the project was the fragmented national research efforts. Those latter are currently obstructing a faster expansion of next-generation technologies [151]. Therefore, besides the research activity, they have been studying the national initiatives concerning the topic. The overall project summary is reported in Table 6.

Harnessing degradation mechanisms to prescribe accelerated stress tests for the realization of SOC lifetime prediction algorithms

ADASTRA [152] (Fig. 11) wants to depict Accelerated Stress Testing (AST) protocols [153] determined from a systematic analysis coming from the previous FCH JU projects experience related to degradation mechanisms of aged components in solid oxide cell stacks [154,155].

Especially, electrodes concerns and interconnection losses will be faced, similarly, the other targets reported in Table 7 are going to be addressed.

The obtained results will be used to create and validate test protocols that will evaluate and foresee degradation in SOCs, by means of Lock-in Thermography [156] or identifying the correlation between stress-accelerating tests and real-world conditions [157].

Converting WASTE to offer flexible GRID balancing services with highly-integrated, efficient solid-oxide plants

Waste2GridS [158] (Fig. 12) project wants to identify efficient industrial waste gasification strategies [159] and SOC integrated power-balancing plants (W2G) [160].

In Table 8 the project objectives to be explored are reported, the range varies between the long-term techno-economic of W2G plants to meet different grid-balancing needs and to identify several promising business cases [146].

The consortium is composed of leading research bodies and companies in Europe in the fields of rSOC, waste classification, gasification and syngas [161], grid operation [162], and energy/process systems engineering [163]. The project outcomes want to improve the cooperation and network between different players (manufacturers, investors, and research institutions), provide roadmaps/procedures for technology

Table 5 – NewSOC project summary.

Duration	Overall budget	TRL	Size SOFC/SOEC	Technology Partners	Targets
2020–2023	4,999,726 €	2–6	50 cm^2 active area	- CEA - Solid power - Sunfire - Elcogel - Ceres power - Hexisss	- Better performances by mean of structural optimisation and innovative architecture - Alternative materials investigation to increase the stack durability and overall cost competitiveness - Advanced engineering to reduce critical raw materials and reduction of environmental footprint

Table 6 – BALANCE project summary.

Duration	Overall budget	TRL	Size SOFC/SOEC	Technology Partners	Targets
2016–2019	2,856,096 €	8	2/10 kW	CEA DTU	- Area specific resistance of 0.2 Ω cm^2 in SOEC mode. - Stability targets are of <0.5%/1000 h - To have less than 20% of performance loss between cell and stack - degradation rate less than 2%/1000 h in SOEC mode. –50% efficiency in SOFC and 90% in SOEC mode at multi-kW scale. - The reversibility and flexible operation 2500 h test. - System modelling, exergy analysis and techno-economic analysis up to MW scale

development/deployment and market positioning, enhance industries competitiveness and leadership, as well as holistic knowledge to develop a circular economy for the energy system decarbonization. In fact, many publications share fundings coming from different EU projects especially with: BALANCE [140] CH2P [164] and W2W [104].

Unfortunately, this project does not refer directly to the use of rSOC in the building sector although its activities concerning networking and market positioning will be helpful for the technology application in different sectors, furthermore the project CH2P directly address the topic exploring the use of SOFC in buildings only.

Smart ways for in-situ totally integrated and continuous multisourCe generation of hydrogen

SWITCH [165] (Fig. 13) focuses on three key elements: a reversible solid oxide module based on anode-supported electrolytes, a fuel processing unit that can efficiently accomplish steam generation and methane-reforming reactions, and finally a purification unit to produce highly pure hydrogen in compliance with the stringent automotive regulations.

The goal is to demonstrate operating rSOC system in an industrial environment for at least 5000 h. The project will take advantage of rSOC fuel flexibility, focusing on the development of this specific solution and realizing a mostly green and pure hydrogen, heat and power source (Table 9).

Relevant will be also the topic regarding cost attractiveness and eco-friendly score, with hydrogen target price lower than 5 €/kg. This system was meant to be scalable to various sizes, low transient times, and thus able to reach target applications in other different sectors. The information available in literature concerning this project are all related to AdAstra initiative [152] such as [156,166,167] all focusing on material aspects and degradation rather than an applicative scenario, which is expected in the next years. In addition, although real tests will be performed, they are thought to take place in an industrial context [168]. Nevertheless, due to the reduced size, and the integration with the civil transport sector, this project can have a beneficial impact also on the building sector, especially at the neighbour scale.

Solid oxide cell and stack testing, safety and quality assurance

The main SOCTESQA [169] (Fig. 14) project objective was to develop procedures for SOC cell/stack assembly tests [170]. The operations were thought of as the continuation of previous works such as the FCTESTNET [171,172] and FCTESQA

Fig. 11 – AdAstra logo.

Fig. 12 – W2G logo.

Table 7 – AdAstra project summary.

Duration	Overall budget	TRL	Size SOFC/SOEC	Technology Partners	Targets
2019–2022	3,008,426 €	4	Lab tests	- CEA - ENEA - Solid power - Sunfire - EIFER	- Previous project review in terms of electrodes ageing and degradation - Stress Testing protocols procedures determination - Methodology validation - Formalise the adoption of relevant standards in industry

Table 8 – Waste2Grids project summary.

Duration	Overall budget	TRL	Size SOFC/SOEC	Technology Partners	Targets
2019–2020	528,750 €	6	modelling	- Enea - Solid Power - DTU - EPFL	- Explore long-term techno-economic feasibility of W2G plants - Meet different grid-balancing needs - Identify promising business cases - provide knowledge for policy support on W2G topic

[173]. SOCTESQA investigated new application fields based on the operation of the SOFC/SOEC assembly [174].

The project partners are experts in the development, testing, and harmonization of solid oxide cells/stacks. A round robin test was conducted to validate the models developed. Additionally, alongside the cell/stack operation, also safety and industrial standardization were analysed, trying to help the European market to foster the growth and dissemination of hydrogen technologies in the actual energy sector. This project, as summarised in Table 10, can be considered the foundation of the industrial value chain able to deliver a product to the market with established quality standards and procedures, enabling its consequent uptake as a deployable solution in everyday life.

Fast, reliable and cost-effective boron hydride based high-capacity solid state hydrogen storage materials

The project BOR4STORE [175] (Fig. 15) analysed the possible use of boron hydride-based storage materials and their suitable properties for hydrogen storage in SOEC/SOFC systems.

In Table 11 a short project presentation is reported. Additionally to the critical points on these materials [176], focusing on B (boron) supply safety, costs, use of metal waste as raw materials, the thermal integration at 650 °C was investigated as well [177].

The exploitable heat reaction coming from metal hydrides can be used for rSOC heat management to increase the overall energy system efficiency and independence from external heat sources [178].

High energy density Mg-based metal hydrides storage system

The project EDEN [179] (Fig. 16) developed new storage materials with high hydrogen storage capacity, manageable in real-time, for distributed applications [180].

This dynamic storage, based on Mg-based metal hydrides, was thought to be interlinked to an energy provision system able to match intermittent and especially with the recovery heat system for enhancing SOFC performances as reported in Table 12.

Additionally, as a perspective, the consortium realized a prototype coupling rSOC with hydrogen storage tank Mg-based with a system efficiency of 25% and a 1,5 kW power production.

White Dragon

The proposal project White Dragon [181] (Fig. 17), summarised in Table 13, aims to integrate and partially substitute the actual energy production and district heating systems based on lignite with a rSOC in western Macedonia (Greece) (see Table 14).

The rSOC was selected for its highly valuable thermal output and will be coupled with 1 GW of newly installed PV power to ensure a sustainable energy production [182].

The PV overproduction will be stored in form of hydrogen and collected as compressed gaseous hydrogen, liquid organic hydrogen carrier (LOHC), or exported via pipeline towards Italy. In this project the rSOC will be coordinated with the PV

Fig. 13 – SWITCH logo.

Fig. 14 – SOCTESQA logo.

Table 9 – SWITCH project summary.

Duration	Overall budget	TRL	Size SOFC/SOEC	Technology Partners	Targets
2020–2022	3,746,753 €	6	25/75 kW	- Solid power - Hygear - DLR - Bruno Kessler - Hygear	- 5000 h functioning test - Hydrogen cost of 5 €/kgH_2 - Multisource generation in terms of heat, power, water, oxygen and hydrogen - Hydrogen production with high purity standard - Refuelling station design for hydrogen mobility system

Table 10 – SOCTESQA project summary.

Duration	Overall budget	TRL	Size SOFC/SOEC	Technology Partners	Targets
2014–2017	3,212,186 €		Procedures/lab test	- CEA - Enea - DLR - EIFER	- Assembly test and its validation for SOC technology - Temperature sensitivity and thermal cycling - Robin test campaigns

Fig. 15 – BORE4STORE logo.

Fig. 16 – Eden logo.

production and Power Grid dispatching orders, additionally, its thermal production will be used in the district heating for the nearby houses and building blocks, the prospected billionaire investment could strongly impulse the rSOC technology to develop faster.

Reversible solid oxide cell for industry

The project RSOC [183] aims to conduct a feasibility study for the technical and economic assessment inherent the rSOC implementation at the grid management level. During the project, a system with an output of 180 kW (approx. 50 Nm^3/h_2) was developed and operated under market-related conditions. This project was not funded by the EU, instead, it represents national research conducted by the Hydrogen Power Storage & Solutions East Germany (HYPOS) initiative [184]. In Ref. [185] it is possible to read the results coming from long term operation behaviour in SOEC and reversible operation, for a total time exceeding 5000 h.

The project, funded by the German government, explicitly aims to integrate the rSOC within the industrial sector, as reported with the other objectives in Table 13, not considering the building sector, however, as considered also in the previous cases the system size is comparable with the building blocks or collective housing needs or offices, and for these reasons is reported in the review.

High efficiency reversible technologies in fully renewable multi-energy system

The HERMES [186] project aims to evaluate experimentally the performances of short stacks and button cells constituting an rSOC system. A broad performance evaluation campaign was carried out between 2017 and 2021 as summarised in Table 15, with a multidisciplinary approach detailing a multidimensional computational fluid dynamics model [187], and out of design thermodynamic model and a transient model [188,189], to fully describe the rSOC behaviour [190] and degradation [191]. This project funded by the Italian Progetti di Rilevante Interesse Nazionale (PRIN), is supporting the research activities of seven Italian universities to increase their knowhow in this topic, with the final aim to translate the acquired knowledge in a practical benefit for the national hydrogen industry.

Naval facilities engineering command rSOC

The NAVFAC EXWC [192] project addressed the RES storage topic in micro-grid in context of an army base, with the final aim to enhance its grid independence and energy security in cases of emergencies. During this collaboration, the rSOC manufactured by Sunfire was integrated with the Boeing's handling subsystem to build an integrated, containerized,

Table 11 – BORE4STORE project summary.

Duration	Overall budget	TRL	Size SOFC/SOEC	Technology Partners	Targets
2012–2015	4,070,711 €	N.A.	Storage analysis	- Helmholtz Centrum - Abengoa - Aarhus university - ZOZ - Katchem	- B hydride-based compounds for H_2 storage. - Focus on microstructures and hydrogenation properties. - Selection of the most suitable material for use in H_2 storage tank - Heat management system for heat transfer from an SOFC to the metal hydride store. - Development of B hydride-based solid state H_2 storage tank, thermally integrated with a SOFC, to demonstrate energy-efficient operation using SOFC off-heat only for H_2 release.

Table 12 – EDEN project summary.

Duration	Overall budget	TRL	Size SOFC/SOEC	Technology Partners	Targets
2012–2016	2,653,574 €	5	1.5/N.A Storage Analysis	- MBN nano-materialia SPA - Ranco GmbH - JRC - Cidete Ingenieros societad limitas - Bruno Kesler foundation	- Material: Storage capacity: >6,0 wt%, Density: >80 g/l, Desorption rate: >3 g/min, Cost: <€ 30/kg. - Tank: Storage capacity: 4,0 wt%, Density: 40 g/l, Absorption heat recovery: 25%, H_2 stored: 600 , Desorption rate: 1,5 g/min. - System: Heat recovery, Safety, SOFC performance: >300 mW/cm^2, - Performance loss: <10%/year.

automated, self-sustained, and grid tied system, which characteristics are summarised in Table 16. This latter system was delivered in January 2016 for testing and the results are reported in Ref. [193].

AURORA

The project Aurora received funding from the Austrian Research Promotion Agency (FGG) [194] and it is focused on the functional verification of a rSOC prototype whose characteristics are summarised in Table 17.

The project began with a stack performance characterization considering different operation modes and temperatures [195] and then defining its electrochemical characterization performing electrochemical impedance spectroscopy (EIS) at elevated current densities and open circuit voltage (OCV) [196]. This phase was extended then including the study of varying current densities and the gas inlet [197]. Finally, tests were conducted to appreciate the stack fuel utilization in steady state and transient operation regimes [198] until introducing more units in the stacks. Those results hence produced suggestions and proposals for stack improvement [199].

Fig. 17 – White Dragon logo.

Synthetic e-fuels as key enabler for sector linking

The Synlink project [200] explores the possibility to exploit the RES to produce renewable fuels. The entire value chain from the production until the application tests in cars and trucks is investigated technically and economically. At the production core a 150 kW SOEC is placed [201], but it has been also used in reversible mode, hence in SOFC mode [202]. The project does not address the rSOC application in buildings directly, as reported in Table 18, nonetheless the size can be comparable with building demand, and it demonstrates the different opportunities offered by this versatile technology.

Also this initiative is funded under national program, in this particular case by the German Federal Ministry of Economic Affairs and Energy (BMWi).

Discussion

In Fig. 18, the systems sizes encountered in all the presented projects, except for the White Dragon whose size is off scale and there are no data available yet, are reported. From the Fig. 18, it can be appreciated how the currently studied sizes are chosen with a preference towards a solution able to

Table 13 – White Dragon project summary.

Duration	Overall budget	TRL	Size SOFC/SOEC	Technology Partners	Targets
2022–2029	8 B€	8/9	167/670 MW	Solid power	- Replace lignite by photovoltaics, reversible solid oxide Cells producing hydrogen, power and heat - Feeding heat into the existing district heating system - Storing hydrogen using technologies like hydrides, LOHC and compressed hydrogen - Transporting excess hydrogen through the close-by Transadriatic Gas Pipeline for further uses - Using active fuel cell power (combined electrolyser and fuel cell)

produce between 20 and 30 kW in SOFC mode, while absorbing in SOEC approximately between 80 and 120 kW.

It is worth noting that 1 kW SOFC equals almost 4 kW in SOEC as a general trend, this is due particularly to the voltage appliable at the electrodes in both modes. Only two reported projects are not close to this evidenced trend (REFLEX and EXWC), but this could be attributable to special design choices to better adapt the system to the specific scenario, i.e. to cover an excess of RES production or a continuous demand to be supplied. Additionally, thanks to its modularity, the rSOC can be adapted to many scenarios. Considering the minimum sizes found during this review, it could be difficult to find rSOC systems smaller than 1 kW (SOFC).

Table 14 – RSOC project summary.

Duration	Overall budget	TRL	Size SOFC/SOEC	Technology Partners	Targets
2016–2020	3,200,000 €	6	180/36 kW	- Sunfire - DLR	- Technical and economic assessment of hydrogen production - Obtaining a higher capacity factor when compared to SOEC or SOFC single unit - System integration in the actual industrial sector

Table 15 – HERMES project summary.

Duration	Overall budget	TRL	Size SOFC/SOEC	Technology Partners	Targets
2017–2021	822,306 €	4–5	tests at stack level	Italian Universities Consortium	- Performance evaluation - Auxiliaries system design and innovation - LCA Cyber-physical pilot implementation, to test complex system with reduced hardware cost and damage risk

Table 16 – NAVFAC EXWC project summary.

Duration	Overall budget	TRL	Size SOFC/SOEC	Technology Partners	Targets
2016–2019	n/a	7	120/50 kW	- Sunfire - Boeing	- Technical assessment of an rSOC integrated system with compression and desalination auxiliaries - Resiliency and self-sufficiency of the proposed system in an islanded Power grid - Renewable energy storage and Power-to-Gas analysis

Table 17 – AURORA Project summary.

Duration	Overall budget	TRL	Size SOFC/SOEC	Technology Partners	Targets
2016–2019	N.A.	N.A.	1 kW/3 kW	- TU Gratz - AVL	- Modelling, design and testing of a reversible SOC System (rSOC) - H_2O electrolysis and CO_2 Co-electrolysis for syngas Production - Fuel flexibility, i.e. H_2 and CH_4 use - Final System with 33 kWFC and 100kWEC of total power is designed

Table 18 – Synlink project summary.

Duration	Overall budget	TRL	Size SOFC/SOEC	Technology Partners	Targets
2019–2022	493,484€	5–6	30 kW/150 kW	- Sunfire - DLR - Fraunhofer - EIFER	- substitution of molecules previously obtained from crude oil and natural by chemically identical molecules obtained from CO2, water and renewable energy - The production of synthesis gas using Co-SOEC-Fuel flexibility - The synthesis gas is converted via methanol synthesis or Fischer-Tropsch synthesis

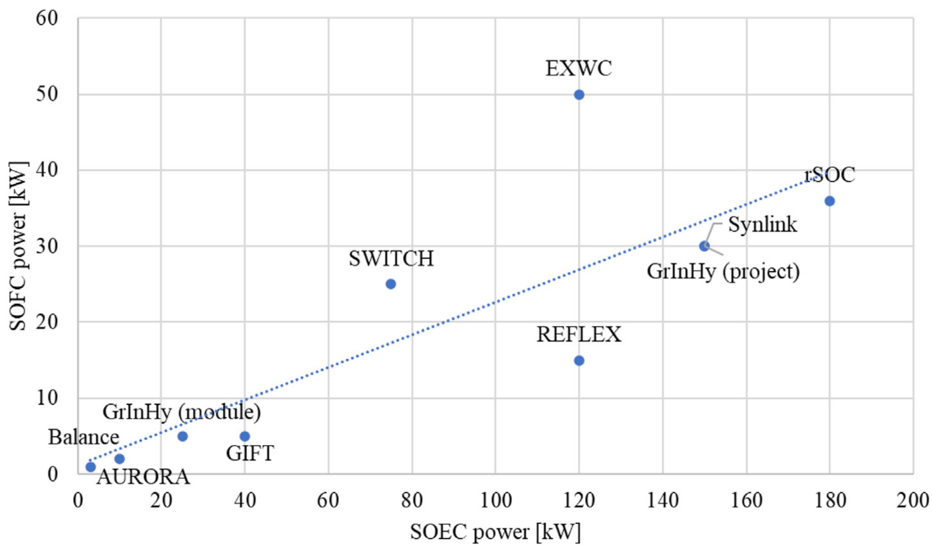

Fig. 18 – rSOC sizes in the different reported projects, with overall trend curve.

Project timetables

As presented, from 2012 until now, one submitted proposal and 16 research projects were identified addressing the rSOC topic, directly or indirectly, connected with the building sector. Their development along this last decade is reported in Table 19, due to the Covid-19 pandemic many of them obtained time extensions, and so far, only the proposal White Dragon could last longer than 2023.

The projects majority lasts for 36 months, and the year 2019 can be considered the most active until now concerning research activities, with 4 projects concluded, 2 ongoing, and 4 projects started from which the results are expected by the end of 2022.

Project objectives

In the light of the above, it is interesting also to compare the reported projects underlying their main application sectors and then the advantages and disadvantages to apply the same solution to the residential one. This latter analysis is reported in Table 20.

From the analysis emerges how only two projects were meant to address the residential sector (REFLEX and GIFT), both conceptualised in the same period, just after a first phase of projects dedicated to materials and procedures. After this phase, a new series of research projects were launched, investigating in a wider way the rSOC applications integrated in more complex processes. Although the new projects address different topics, rSOCs are studied and developed, and the investigates sizes are comparable with residential expectations.

Projects fundings

Regarding the fundings, except for EXWC financed by the U.S. Navy, the other researches are centred in Europe and excluding the projects RSOC, HERMES, AURORA funded by the

Table 19 – Projects timetable 2012–2023.

Project	start	end	Months	'12	'13	'14	'15	'16	'17	'18	'19	'20	'21	'22	'23	'24	29'
BOR4STORE	2012	2015	36														
EDEN	2012	2016	48														
SOCTESQA	2014	2017	36														
EXWC	2016	2019	36														
GrInHy	2016	2019	36														
rSOC	2016	2020	48														
AURORA	2016	2019	36														
Balance	2016	2019	36														
HERMES	2017	2021	60														
REFLEX	2018	2021	36														
SYNLINK	2019	2022	36														
GIFT	2019	2023	56														
AdAstra	2019	2022	36														
W2G	2019	2020	12														
SWITCH	2020	2022	24														
NewSOC	2020	2023	36														
WhiteDragon	2022	2029	84														

Table 20 – Projects application comparison referred to the building sector uptake.

Project	Application	Advantages	Disadvantages
BOR4STORE	Storage	The exploitable heat reaction coming from metal hydrides storage system can be used for rSOC heat management to increase the overall efficiency and independence from external heat sources	The rSOC is studied as integration and not as project focus, no information about tests and sizes were disclosed
EDEN	Storage	Hydrogen tank storage Mg based, with heat recovery used to enhancing SOFC and then rSOC outputs.	The rSOC is studied as integration and not as project focus, few information about tests and sizes were disclosed
SOCTESQA	Research	Cell/stack assembly tests	No direct use in real conditions
EXWC	Military	An rSOC able to sustain a small military base was tasted in real condition and using salt water	Being a military project some information are not available.
GrInHy	Industrial	the size of one module is comparable with residential needs	Industrial heat waste is used to increase the overall efficiency
rSOC	Industrial	rSOC tested in a real environment, with a size comparable to residential needs	Tested in an industrial environment, hence with possible access to external heat sources
AURORA	Research	Real rSOC prototype development with a size comparable to a flat consumption	It is not clear if or how this prototype will be launched on the market
Balance	Power Grid	Techno economic analyses of small scale rSOC to increase RES penetration, produce alternative fuels and provide grid flexibility. Two reals small rSOCs were used for real tests in buildings.	Alternative fuel production is not envisaged to be applied to the residential sector. Additionally, more than grid flexibility at residential level, with smaller sizes, it would be possible to offer ancillary services
HERMES	Research	A broad campaign of rSOC testing in different environments	The test were almost lab tests with many simulations done only on software
REFLEX	Residential	The analysis is conducted in an office in a real environment	N/A
SYNLINK	Sustainable fuels	A real rSOC is used with a size comparable to the residential sector needs	the rSOC outputs are used to produce synthetic e-fuels rather than supply a residential building
GIFT	Residential	The module will work at building level but with also works with the grid to provide ancillary services	N/A
AdAstra	Research	Accelerated Stress Testing protocols procedures determination	Being an accelerated test, the system was not studied in a real environment
W2G	Industry	Activities concerning players networking and market positioning will be helpful for the technology application in different sectors	No clear statement about rSOC use, additionally gasification processes will be used, which are not likely to be replicated in the residential sector
SWITCH	Industrial	rSOC used in real condition. Also a purifier is studied to provide hydrogen for mobility	Tests in the industrial context. Nevertheless, beneficial impact also for the building sector, especially at the neighbour scale.
NewSOC	Research	Alternative materials investigation to increase the stack durability, overall cost competitiveness while reducing critical raw materials	no test or applications in real conditions are foreseen in the project description, it is not clear if reversible process will be tested as well
White Dragon	Power Grid	Extensive funding for the sector	It is just a proposal waiting for approval. The rSOC will be used directly only connected to the power grid and district heating systems

German, Italian and Austrian governments respectively, the reaming projects were supported by EU research funds. The overall reported budget allocated to the rSOC exceeds 49 M€, while in Fig. 19 is possible to compare the contribution coming from each project.

Although GIFT represents the biggest fund among the encountered ones, it must be specified that other different technologies are being studied, hence the total amount is not dedicated exclusively to rSOC development and integration.

Additionally, if it is considered the grant that could be assigned to White Dragon, funded under the program Important Projects of Common European Interest (IPCEI), for this case only is expected a total budget of over 8 B€ that will represent a boost for the entire technological sector.

Todays, those budgets are mainly allocated for two different objectives which define the main trends for the rSOC development: materials research, and test in real environment. Their junction point can be found in the cycling effect study, which is a crucial point in all the presented projects. Instead, in the past, attention was given to assembly and industrial standard definition (FCTESTNET, FCTESQA, and SOCTESQA).

Next challenges

Considering the gaps reported for this technology, the goal to be achieved to see a consistent penetration in the building sector could be summarised as follow:

- Study new material that might increase energy density, reduce degradation, which is translated in higher efficiencies, longer lifetime, and a more compact size;
- Reducing the working temperature, from one side could reduce the CHP appeal of this solution, but it will lower the machine thermal momentum, with benefit in terms of start-up waiting time, maintenance and reducing the time to switch from one mode to another;
- Industrialise the rSOC manufacturing for lowering the costs;
- Standardised quality tests to allow customers to easily compare different rSOC products and familiarise with it;
- Analyse different operation strategies and solutions to open new business opportunities in buildings, such as storage, remunerated ancillary services to the power grid, compact refuelling station for local micro mobility, and energy communities.

All 17 projects included in this review article are related to the rSOC application and development in the building sector. By reviewing the projects, the salient literature concerning the technology application has been presented, reporting more than 120 papers, to take stock of the real case studies situation. Those cases represent the most advanced results achieved by rSOC, with their sizes reported in Fig. 18, their budgets in Fig. 19, their applications in Table 20. The information reported, can be used by the reader to obtain an overview of the progress attained by this technology especially outside the laboratories, creating a clear distinction between this work and the others available in literature, as reported in section Literature Review. and summarised in Fig. 2.

Conclusion

A comparison between the available SOC technologies has been presented. According to the reported literature, the reversible solution is the least mature, with uncertainties

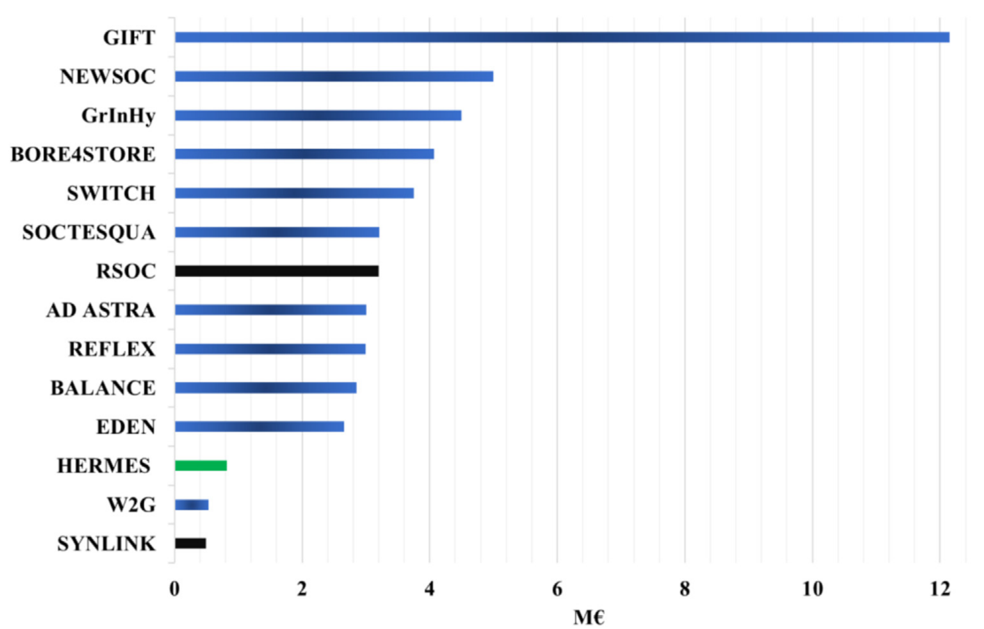

Fig. 19 – Budget repartition per project in blue EU fundings, black German fundings, green Italian funding. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

mostly deriving from the SOEC side development, which still needs further investigations. Furthermore, the current terminology ambivalence concerning the rSOC adjective: reversible, regenerative, unitized. In this regard, it could be advantageous to support the diffusion of the term “unitised”, which according to the authors, exemplifies with enough precision a single device able to interact bi-directionally with the energy system, removing all doubt about single FC and EC working in an integrated way together, but separately. Besides the SOEC investigation and terminology, which are outside the scope of this review, the attention was moved towards rSOC applications to examine its actual application and capabilities, with a special focus concerning the synergies with the building sector.

To sum up:

- 17 projects have been identified outlining, when possible, the funding, duration, TRL, rSOC size, technology partners, objectives, and related scientific publications. This process was used to define an operative framework around the technology, which was just sketched in previous works or overlapped in a combination between SOFC or SOEC single applications. Actually, due to the SOC intrinsic reversible ability, it could be difficult to understand if the machine is used or not reversibly, thus complicating the classification in well-defined use cases.
- Besides two projects addressing the specific topic of the review, the rSOC integration in the building and residential sector, most of the presented works are now exploring the rSOC integration with industrial processes. However, considering the sizes stated and their modularity, it is allowed to broaden the scenario also to its possible application in buildings.
- Several projects declared their intention to investigate greater sizes in future instead of smaller one, in a way to exploit the scale effect to reach the lowest forecastable hydrogen price and greatest efficiency. In this optic, the final aim is to explore the opportunity to use the rSOC as a grid controller to flatten the natural RES production fluctuations or in synergies with the heavy industry operations. Indeed, since the technology has not reached the commercialization phase yet, the costs are still high and for this reason the R&D is moving to bigger sizes and toward the industrial sector to exploit low-cost waste heat to increase the overall efficiency and decrease operation costs.
- Looking at the financed projects from 2012, it is undeniable that the rSOC and its application is gaining momentum following the entire hydrogen subject expansion. This fact should be further stressed, bearing in mind that the SOC technology started in a backward position considering the technology maturity and subsequent market deployment when compared to PEM and ALK technologies. The SOCs are regain the lost ground, and from a hypothetical solution, now they are seen as one the three most affirmed technologies with PEM and ALK.

To conclude, this review investigated on the rSOC as an effective solution to guarantee energy efficiency and emissions reduction in buildings, also considering the need to trust on a mature, low cost and low space solutions. Although the technology still needs to reach a TRL higher than 8 outside the industrial sector, the rSOC has already showed high performances, and the new projects are pushing these values even furthers, arriving at the end of its maturing process. In the next years, several applicative projects, also inherent to building context, will come to their end, and their results will be valuable to better define rSOC applicability and its cost. From the current perspective, rSOC application in small single building does not seem the most investigated solution, and in future, the use of rSOC outside the industrial sector seems to be more suitable, in terms of sizes, for large building or blocks.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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