Seasonal Energy Storage in Aluminium for 100 Percent Solar Space Heat, DHW and Electricity

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Abstract

For climates with large amounts of solar energy in summer and buildings with significant energy consumption for space heating in winter, solutions are needed to store and transfer solar energy from summer to winter. In this paper, a seasonal energy storage based on the aluminium redox cycle (chemical reduction and oxidation of aluminium) is proposed. For charging, electricity from solar or other renewable sources is used to convert aluminium oxide or aluminium hydroxide to elementary aluminium (chemical reduction: $Al^{3+}\rightarrow Al$). In the discharging process, aluminium is oxidized (chemical oxidation: $Al\rightarrow Al^{3+}$), releasing hydrogen, aluminium hydroxide and heat. Hydrogen is used in a fuel cell to produce electricity. The heat produced in the fuel cell and in the aluminium oxidation process is used for domestic hot water production (DHW) and space heating. The system proposed uses 480 kg of aluminium, 11 kWp of photovoltaics and a battery of 11 kWh useable capacity to achieve 100% solar heat and electricity coverage of a single family home with a total heat demand of 5.2 MWh and an electricity demand of 3.3 MWh for all seasons of the year.

Keywords: seasonal energy storage, power-to-X, aluminium redox cycle

1 Introduction

In central European countries, about 50% of the final energy demand is used in buildings as electricity or for heating purposes. Whereas the electric energy demand for household appliances is fairly even over the year, more electricity is needed in summer for cooling load dominated climates, while for heating load dominated climates more energy is needed in winter. For the latter, the peak heat demand is in winter when little solar energy is available, and little heat is needed in summer, when solar energy is available in abundance. Therefore, seasonal energy storage solutions are needed especially for covering heating demand in these climates.

Different materials have been proposed for sensible, latent and thermochemical storage of heat or for converting renewable electricity to an energy vector (Krajačić et al., 2008; Li, 2016; Reddy et al., 2018). These power-to-X technologies usually start with the electrolysis of water and the production of hydrogen ($X = H_2$). Hydrogen has the largest gravimetric energy density (a factor of 3 higher than gasoline); however, its density is very low. The density of gaseous hydrogen is only 7% of the density of air. The density of liquid hydrogen is 70.8 g/L at -253 °C, which represents 7% of the density of water density (Ley et al., 2014). Therefore, the volumetric energy density of hydrogen is very low. Moreover, hydrogen is the lightest element from all and being so small it diffuses very easily through metals or other materials (Barrera et al., 2016). For these reasons, hydrogen is not well suited for storing large amounts of energy over long time-periods.

Research and development effort is dedicated to producing other gases or liquids such as methane or methanol (X = methane or X = methanol), or to use materials that can store hydrogen such as metal-organic frameworks, hydrides, alloys, carbon nanotubes or graphene (Chanchetti et al., 2019). Each conversion step is requiring energy, i.e. contributing to conversion losses, and most of the proposed solutions require a carbon source in order to produce a hydrocarbon fuel from H_2. Compared to these technologies, aluminium (Al) is a very promising candidate for storing energy due to its high energy density, both gravimetric (8.7 kWh/kg) and volumetric: (23.5 MWh/m^3), as shown section 2. The volumetric energy density of Al outperforms the energy density of hydrogen or hydrocarbons, including heating oil, by a factor of two (Fig. 1). Elementary Al is easy to handle and it is inert in ambient conditions due to the protective oxide layer. From Al, heat and electricity can be produced on demand by aluminium oxidation in aqueous alkaline solutions (Soler et al., 2007; Dudita et al., 2019).

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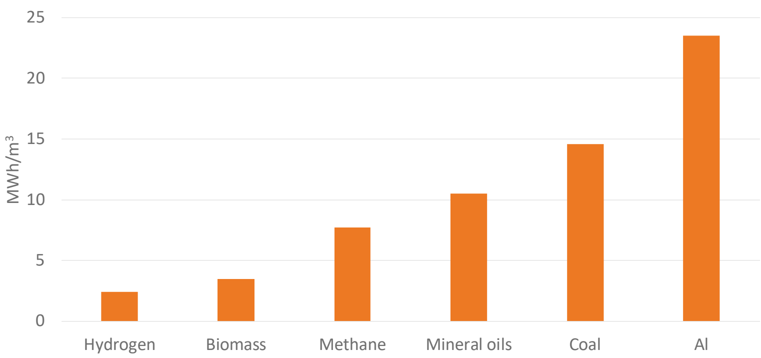

Fig. 1: Volumetric energy storage densities of different solutions proposed for seasonal energy storage.

2 System Concept and Methodology

2.1 The Aluminium Redox Cycle

Aluminium is used as an energy carrier already today, e.g. for rocket propulsion (Baschung et al., 2002), and it has been proposed for the storage of renewable energy as well (Wochele and Ludwig, 2004; Shkolnikov et al., 2011). However, to the authors' knowledge, it has not been used yet to supply heat and electricity in residential buildings. The storage of energy in Al is based on the redox cycle Al^{3+}→Al→Al^{3+}. In conventional Al smelter plants, the Hall-Héroult process is used in order to produce Al from alumina (Al_2O_3). The efficiency of this process is currently at about 50%, and it is estimated that it may be increased to about 65% with non-consumable electrodes, wetted cathodes, lower temperature electrolysis cells, and reduction of heat losses (Galasiu et al., 2007). With this process, a solid material is obtained directly and can be stored without losses as long as desired, with much less safety concerns than for hydrogen or hydrocarbons.

The Al smelter plants are currently using carbon anodes. During the process of obtaining Al, the solid carbon from these anodes is oxidized to carbon dioxide gas (CO_2) and released to the atmosphere. At the cathode, aluminium ions are reduced to elementary aluminium. The overall reaction from the Hall-Héroult cell is presented in eq. 1. Since carbon anodes are made from fossil carbon sources, this process contributes to global warming.

$$2Al_2O_3 + 3C \rightarrow 4Al + 3CO_{2\,(\uparrow)} \qquad \text{(eq. 1)}$$

Electrolysis cells based on inert or non-consumable anodes have been proposed and investigated by many research institutions as well as the aluminium industry (von Kaenel, 2006; Galasiu et al., 2007; Beck, 2013; Hotter, 2018). In this alternative Al production process, O_2 is released instead of CO_2 (eq. 2). However, despite of tremendous efforts in this direction and despite the fact that its feasibility has been demonstrated on a small lab scale, this more environmental friendly path has not reached commercial stage yet.

$$2Al_2O_3 \rightarrow 4Al + 3O_2 \qquad \text{(eq. 2)}$$

Aluminium can be converted to heat and hydrogen either by reacting with steam at high temperature (> 480 °C), producing alumina directly (eq. 3), or with a low temperature reaction in aqueous solution where the resulting product is aluminium hydroxide (eq. 4) (Belitskus, 1970; Franzoni et al., 2010).

$$2Al + 3H_2O_{(g)} \rightarrow 2Al_2O_3 + 3H_2 \qquad \text{(eq. 3)}$$

$$2Al + 6H_2O_{(l)} \rightarrow 2Al(OH)_3 + 3H_2 \qquad \text{(eq. 4)}$$

Due to the different temperature levels, a process based on eq. 3 is more suitable for an industrial application, while a process based on eq. 4 is more suitable for the residential sector and thus it is the path used in this paper.

Fig. 2 shows that under ideal conditions the low temperature reaction path (eq. 4) in combination with a fuel cell (50% electric efficiency) yields about 2.2 kWh of electricity and 6.5 kWh of heat per kg of Al in an ideal case where all heat can be used. Thus, the energy density of Al is 8.7 kWh/kg or 23.5 MWh/m³ (ρ = 2700 kg/m³).

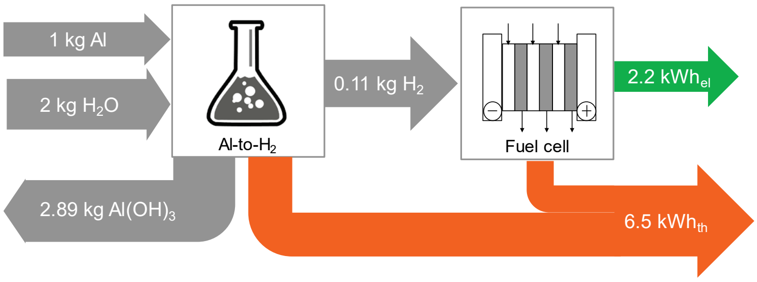

Fig. 2: Production of heat (ht) and electricity (el) from hydrogen - idealized.

For the low temperature path, aluminium hydroxide is formed and a calcination step is needed in order to obtain alumina that can be used for the electrolysis smelter process (eq. 5).

$$2Al(OH)_3 \rightarrow Al_2O_3 + 3H_2O \qquad \text{(eq. 5)}$$

2.2 System for providing heat and electricity for buildings

Photovoltaics in combination with heat pumps can provide heat and electricity for buildings. In these systems, electric final nergy is purchased from the utility when PV yield is not enough, and fed-in when PV is delivering more electricity than needed. A net-zero concept can be achieved by sizing the PV field such that the amount of generated electricity matches the demand on an annual base. Purchased electricity can be reduced by smart control in combination with electric batteries and thermal storages. However, the net-zero concept leads to surplus of PV electricity in summer and grid-purchase in winter. It has been shown in several studies (e.g. Battaglia et al., 2017) that roughly 50% of the electric final energy demand can be covered without purchase from the grid, and that the grid purchase can be as low as one fifth of the total useful energy (heat and electricity) that is delivered to the consumers. In order to overcome the seasonal mismatch between PV production and electricity consumption, a system combining PV and air source heat pump with thermal and electrical storages and the Al seasonal storage as shown in Fig. 3 has been simulated in TRNSYS. Key data of the simulated single family house (SFH) load "SFH15" (Dott et al., 2012; Haller et al., 2013) in combination with electricity profile for household appliances (from LoadProfileGenerator https://www.loadprofilegenerator.de/) and components are given in Table 1.

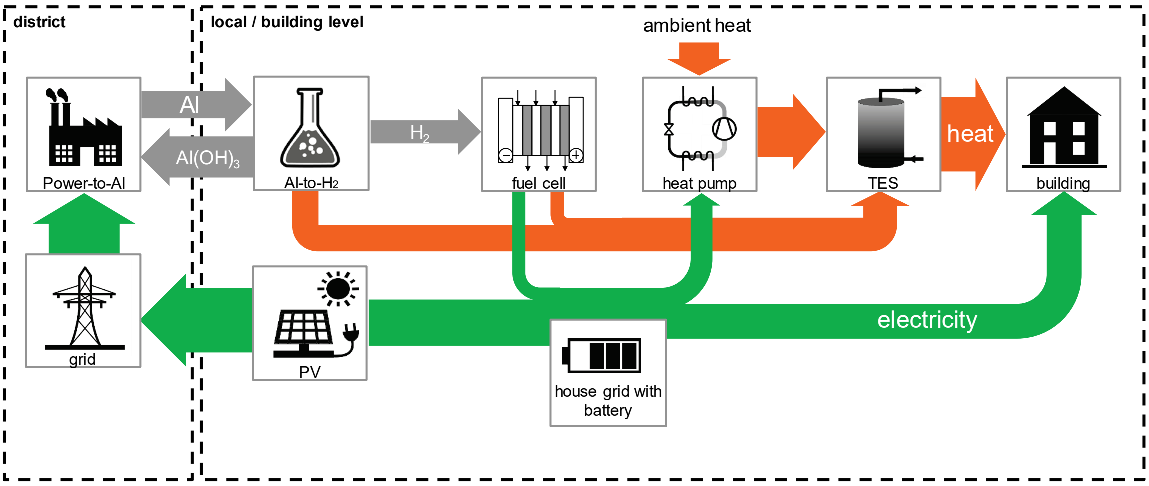

Fig. 3: Solar and heat pump system concept with seasonal Al redox storage cycle.

Tab. 1: Key data of the simulated system and loads.

Parameter	Value	Parameter	Value
Climate	Zurich, Switzerland	Thermal storage	1.8 m^3
Space heat	3'029 kWh_{th}	Battery capacity (usable)	11 kWh_{el}
Domestic hot water	2'186 kWh_{th}	Aluminium converter	0.5 kg/h
Household appliances	3'289 kWh_{el}	Fuel cell	1.0 kW_{el}
PV generation (11 kW_p) south 45°)	11'232 kWh_{el}	Heat pump	12 kW_{th}

The assumptions for efficiencies and cost of components are given in Table 2. Cost assumptions are projected costs to 2030 according to industry targets and market analysts. TRNSYS Type 203 has been used for the simulation of the PV array, and rectifier losses have been matched to the efficiency curve of data provided by the manufacturer for Fronius Symo 4.5-3.5. It has been assumed that the electricity grid operator charges 0.07 €/kWh for grid transmission of electricity from the PV system to the central smelter (corresponding to current practice in Switzerland for delivery to homes with > 4'500 kWh/a consumption). For the service of transporting aluminium hydroxide from homes to the industrial facility, converting it to Al with solar energy in summer, and transporting it back to the consumer, a cost of 1.2 €/kg has been assumed. An interest rate of 1% has been used for annuity calculation – corresponding to current mortgage rates in Switzerland.

Tab. 2: Assumptions for efficiency and cost of components.

Device	Process	Efficiency	Cost
photovoltaics	solar to AC	efficiency of module: 16.8%, temperature coefficient: -0.391/K, loss of rectifier 4.7%[a)]	1'400 € + 700 €/kWp [h)]
Al-to-Energy	Al to H_2, heat and $Al(OH)_3$	95% of stoichiometric value for H_2 production, 95%[b)] total (H_2 or heat)	1'500 € + 1'300 €/(kg/h)[c)]
Fuel cell	H_2 to electricity and heat	50% of HHV for electricity, 95% of HHV total	1'000 € + 1'000 €/kW_{el}
Power-to-Al	$Al(OH)_3$ to Al	58.7% calcination + smelter[d)]	1.2 €/kg Al[e)]
Home battery	Storage of electricity	76.6% roundtrip on annual base[f)]	450 € + 230 €/kWh
Heat pump	El. and ambient heat to useful heat	SPF = 3.5[g)]	6'000 € + 450 €/kW_{th}
TES	Storage of heat	87.5%[g)]	700 € + 700 €/m^3

a) rectifier losses have been assumed as depending on the DC power from the PV field, matched to the efficiency curve of Fronius Symo 4.5-3-S
b) based on 8.7 kWh/kg for Al and HHV(Higher Heating Value) of H_2
c) value is extremely uncertain since there are no such devices on the market yet
d) 1.6 kWh/kg Al for calcination and 13.2 kWh/kg Al (65% efficiency) for the inert electrode smelter process
e) including cost of transport between industrial site and end-consumer
f) 8% rectifier losses (each way), 5% / month cell loss (relative to nominal capacity), 5 W standby consumption
g) results from TRNSYS simulations
h) A study of the EU PV Platform (Vartiainen et al., 2015) predicts a cost of 900 €/kWp for 5 kWp, and 700 €/kWp for 50 kWp in 2030

3 Results

3.1 Annual energy balance

The overall annual energy balance of the simulated system is shown in Fig. 4. From the 11.2 MWh electricity that is produced by the PV system, 4.7 MWh are used locally either directly for the heat pump, the heating system in general, or for household appliances. Part of this energy is also going to the battery and eventually lost due to parasitic electricity consumption of components and battery standby consumption and losses. The fuel cell contributes only with roughly 1 MWh to the local electricity consumption and is thus only running with 1000 full-load hours per year. A small fraction of electricity is drawn from the grid (1%) because of short-term imbalances that might be solved with better control of the system dynamics. Heat that is produced from the aluminium reaction and by the fuel cell contribute to the heating demand 2.9 MWh/a, and 2.2 MWh/a of ambient heat is used by the heat pump.

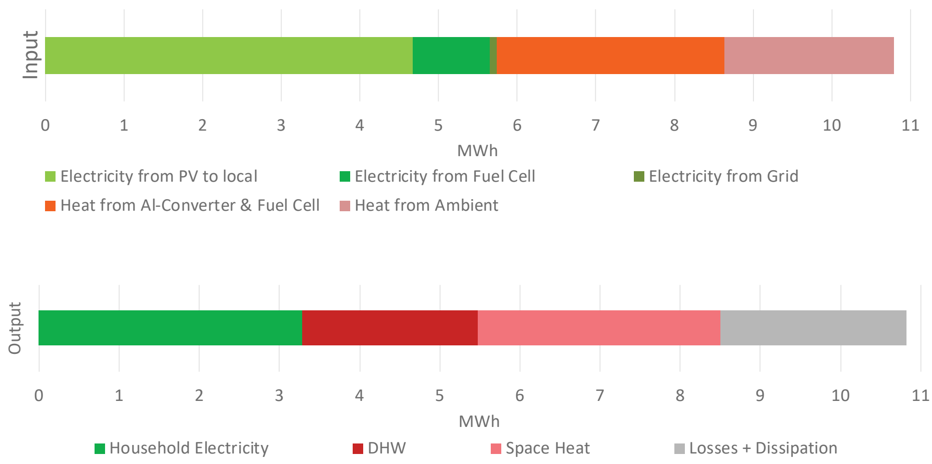

Fig. 4: Overall energy balance of the 100% solar heat and electricity supply.

The amount of PV electricity that is fed to the grid is 6.7 MWh (see Fig. 4) and corresponds to 59% of the PV production. At the industrial site, 480 kg of Al are produced from $Al(OH)_3$, using 6.6 MWh and transferred back to the decentralized customer and end-user from which it takes the $Al(OH)_3$ product back. More precisely, the PV energy that is fed to the grid is 170 kWh more than needed for the smelter, and 80 kWh are in turn drawn from the grid for system balancing.

The total energy output of the decentralized heat and electricity system is shown in Fig. 4 (bottom). The largest fractions in terms of useful energy delivered are space heat and electricity for household appliances, while energy for DHW is in the same order as losses and dissipation of the system.

Fig. 5 shows the simulated monthly consumption of Al-fuel and the electricity from the PV system that is fed to the grid. Interestingly, the short term storages (thermal and battery) are not able to store energy long enough to avoid Al consumption in summer completely for this climate, or to avoid PV feed in to the grid in a month where Al fuel is consumed. This might indicate that there is still room for optimization of control and sizing of components in this respect.

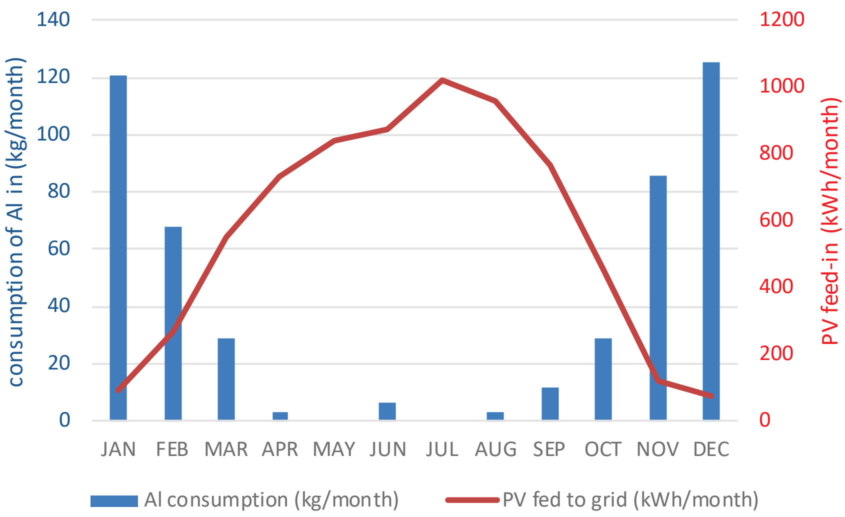

Fig. 5: Overall energy balance of the 100% solar heat and electricity supply.

3.2 System cost

The cost estimation for the production of heat and electricity of a private home with the assumptions from section 2.2 and the results of section 3.1 is shown in Table 3. Cost estimation has been based on the annuity cost of the investment with the given life times of the components and an interest rate of 1% that corresponds to current Swiss mortgage rates, plus maintenance and operation cost as indicated in the table. With the assumptions made, a mixed (electricity and heat) end-consumer energy cost of 0.32 €/kWh is calculated, including CAPEX (system installed) and OPEX (services and maintenance).

As can be seen from Fig. 6 left, the largest share of the investment cost estimation for year 2030, under the assumption of further cost decrease for PV, fuel cell and battery systems, may be the heat pump. However, the cost estimations, in particular the cost decrease and the cost estimation for the not-yet-built Al-to-H_2 converter, are quite uncertain.

Tab. 3: Cost estimation table.

	Major Component	Size	Unit	Life time [years]	Total Costs [€]	
Investment Cost, CAPEX	**PV**	10.8	kW_p	25	8926	**30%**
	Battery	11	kWh	15	2980	**10%**
	Thermal Storage	1.8	m^3	40	1960	**7%**
	Heat pump	12	kW_{th}	25	11400	**39%**
	Fuel Cell	1	kW_{el}	20	2000	**7%**
	Al-to-H_2 converter	0.5	kg/h	25	2150	**7%**
	Total Investment Cost				***29416***	**100%**
Annuity Cost	**Type of Cost**		**Unit**	**Amount**	**Annual cost [€/a]**	
	Investment Cost				1406	**51%**
	Al Smeltering & Transport (1.2 €/kg)		kg	482	578	**21%**
	Maintenance (1% investment cost)		CHF	29416	294	**11%**
	Electricity transmission (0.07 €/kWh)		kWh	6737	472	**17%**
	Total annual cost				***2750***	***100%***
Energy Delivered	**Type of Useful Energy to Consumer**					
Electricity	Electricity			3289	kWh	
Heat	Heat			5215	kWh	
Energy generation cost (including CAPEX + OPEX)				**0.32**	**€/kWh**	

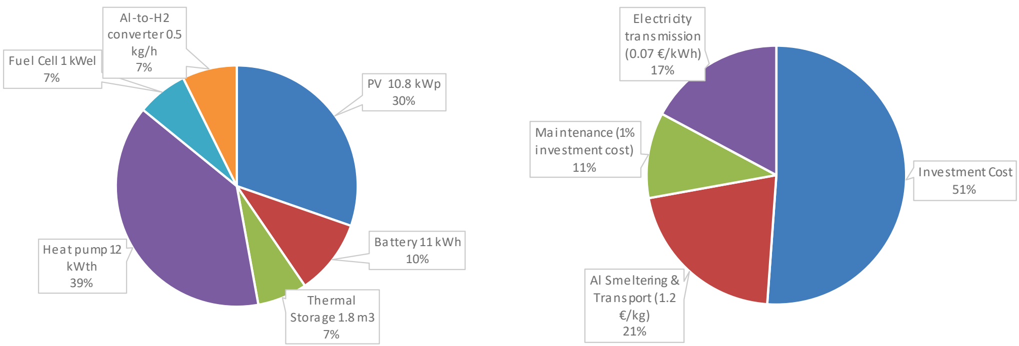

Fig. 6: Investment cost (left) and annuity cost (right) breakdown.

Results for multi-family buildings have been simulated and an estimated mixed end-consumer cost in the range of 0.20 €/kWh for a similar climate has been obtained[1].

4 Conclusion

Residential buildings consume a significant amount of energy in European countries, particularly for heating purpose. Solar energy is a promising technology to reduce the dependence of fossil fuels and decrease emissions to the environment. However, the main drawback of solar energy is the temporal mismatch between its availability and the total energy demand of buildings. Therefore, seasonal energy storage solutions are needed especially for covering heating demands.

This paper shows that a seasonal energy storage concept based on an aluminium redox cycle is feasible, and that a single family home in Switzerland built according to current building standards could provide all its energy needs for space heat, domestic hot water and electricity based on solar energy with the help of this concept. The proposed energy system includes, besides an 11 kWp PV system, the seasonal Al-storage concept, a heat pump, a fuel cell, and short term thermal and electrical storage.

Preliminary cost calculations with cost projections for 2030 show that a mixed energy price of 0.32 €/kWh is feasible, including CAPEX and OPEX. This is comparable to the electricity price in many countries and thus may be cost competitive. However, it is foreseen that larger residential buildings that will allow to achieve much lower costs, will be the main application of this concept.

The proposed system that is based on a seasonal aluminium storage is not autarkic, since it relies on feeding electricity from decentralized PV systems through the grid to the energy service provider (ESCO) that runs the centralized Power-to-Al process (calcination and smelter). The energy service provider is also envisaged to organize the transport of Al solar fuel to the consumer as well as the transport of reacted Al in the form of aluminium hydroxide back to the Power-to-Al process. Thus, the new proposed system concept offers also new business models for ESCOs. Interestingly, the amount of electricity transported by the ESCO for this single family home is roughly double the amount it would transport in a normal case today, just that it is not transported to the end consumer, but rather from the end consumer or rather prosumer to the centralized industrial site of the Power-to-Al process. Furthermore, this concept relieves the electricity grid in winter since the amount of electricity that needs to be transported in winter is negligible, and it offers the possibility to even produce more electricity in winter than needed for this prosumer and thus contribute to power balancing of the grid.

5 Outlook

At the SPF Institute for Solar Technology, a small scale demonstrator for the conversion of Al to hydrogen and heat has been built and validated, and it is envisaged that this process is automated and scaled up to a power of 400 Watt (100 W_{el}) and then to 4 kW (1 kW_{el}). At the same time, SPF is collaborating with partners that are able to validate and possibly demonstrate Al production with inert anode smelter processes.

[1] paper under review at "Energy Conversion and Management".

6 Acknowledgments

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7 References

Barrera, O., Tarleton, E., Tang, H.W., and Cocks, A.C.F. (2016). Modelling the coupling between hydrogen diffusion and the mechanical behaviour of metals. Comput. Mater. Sci. *122*, 219–228.

Baschung, B., Grune, D., Licht, H.H., and Samirant, M. (2002). Combustion Phenomena of a Solid Propellant Based on Aluminium Powder. Int. J. Energ. Mater. Chem. Propuls. *5*.

Battaglia, M., Haberl, R., Bamberger, E., and Haller, M. (2017). Increased self-consumption and grid flexibility of PV and heat pump systems with thermal and electrical storage. Energy Procedia *135*, 358–366.

Beck, T.R. (2013). A New Energy-Efficient and Environmentally Friendly Process to Produce Aluminum. JOM *65*, 267–271.

Belitskus, D. (1970). Reaction of aluminum with sodium hydroxide solution as a source of hydrogen. J. Electrochem. Soc. *117*, 1097–1099.

Chanchetti, L.F., Leiva, D.R., Lopes de Faria, L.I., and Ishikawa, T.T. (2019). A scientometric review of research in hydrogen storage materials. Int. J. Hydrog. Energy.

Dott, R., Haller, M.Y., Ruschenburg, J., Ochs, F., and Bony, J. (2012). The Reference Framework for System Simulations of the IEA SHC Task 44 / HPP Annex 38 - Report C1 Part B - Final: Buildings and Space Heat Load - A technical report of subtask C (Muttenz, Switzerland: FHNW).

Dudita, M., Farchado, M., Englert, A., Carbonell, D., and Haller, M. (2019). Heat and power storage using aluminium for low and zero energy buildings. In Proceedings CLIMA 2019 -13th REHVA World Congress, (Bucharest, Romania), pp. 1–6, accepted for publication.

Franzoni, F., Milani, M., Montorsi, L., and Golovitchev, V. (2010). Combined hydrogen production and power generation from aluminum combustion with water: Analysis of the concept. Int. J. Hydrog. Energy *35*, 1548–1559.

Galasiu, I., Galasiu, R., and Thonstad, J. (2007). Inert anodes for aluminium electrolysis (Düsseldorf, Germany: Aluminium-Verlag).

Haller, M.Y., Dott, R., Ruschenburg, J., Ochs, F., and Bony, J. (2013). The Reference Framework for System Simulations of the IEA SHC Task 44 / HPP Annex 38 - Report C1 Part A: General Boundary Conditions - Final Revised (Rapperswil, Switzerland: Institut für Solartechnik SPF, Hochschule für Technik HSR).

Hotter, A. (2018). HOTTER ON METALS: Elysis could revolutionize aluminium smelting technology.

von Kaenel, R. (2006). Technical and economical evaluation of the de NORA inert metallic anode in aluminum reduction cells. In Light Metals, T.J. Galloway, ed. (TMS (The Minerals, Metals & Materials Society)), pp. 397–402.

Krajačić, G., Martins, R., Busuttil, A., Duić, N., and da Graça Carvalho, M. (2008). Hydrogen as an energy vector in the islands' energy supply. Int. J. Hydrog. Energy *33*, 1091–1103.

Ley, M.B., Jepsen, L.H., Lee, Y.-S., Cho, Y.W., Bellosta von Colbe, J.M., Dornheim, M., Rokni, M., Jensen, J.O., Sloth, M., Filinchuk, Y., et al. (2014). Complex hydrides for hydrogen storage – new perspectives. Mater. Today *17*, 122–128.

Li, G. (2016). Sensible heat thermal storage energy and exergy performance evaluations. Renew. Sustain. Energy Rev. *53*, 897–923.

Reddy, K.S., Mudgal, V., and Mallick, T.K. (2018). Review of latent heat thermal energy storage for improved material stability and effective load management. J. Energy Storage *15*, 205–227.

Shkolnikov, E.I., Zhuk, A.Z., and Vlaskin, M.S. (2011). Aluminum as energy carrier: Feasibility analysis and current technologies overview. Renew. Sustain. Energy Rev. *15*, 4611–4623.

Soler, L., Macanás, J., Munoz, M., and Casado, J. (2007). Aluminum and aluminum alloys as sources of hydrogen for fuel cell applications. J. Power Sources *169*, 144–149.

Vartiainen, E., Masson, G., and Breyer, C. (2015). PV LCOE in Europe 2014-2030 - Final Report (European PV Technology Platfrom Steering Committee - PV LCOE Working Group).

Wochele, J., and Ludwig, Chr. (2004). Aluminium als Brennstoff und Speicher (Paul Scherrer Institut, im Auftrag des Bundesamtes für Energie).