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Research Report

Effects of firebricks for industrial process heat on the cost of matching all-sector energy demand with 100% wind–water–solar supply in 149 countries

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Abstract

Refractory bricks are bricks that can withstand high temperatures without damage to their structures. They have been used to insulate kilns, furnaces, and other hot enclosures for thousands of years. Firebricks are refractory bricks that can, with one composition, store heat, and with another, insulate the firebricks that store the heat. Because firebricks are made from common materials, the cost per kilowatt-hour-thermal of a firebrick storage system is less than one-tenth the cost per kilowatt-hour-electricity of a battery system. It has thus been hypothesized that using excess renewable electricity to produce and store industrial process heat in firebricks can provide a low-cost source of continuous heat for industry. Here, it is hypothesized further that, upon a transition to 100% clean, renewable energy worldwide, using firebricks to store industrial process heat can reduce electricity generator, electricity storage, and low-temperature heat storage needs, thereby reducing overall energy cost. Both hypotheses are tested across 149 countries combined into 29 world regions. Results suggest, relative to a base case with no firebricks, using firebricks may reduce, among all 149 countries, 2050 battery capacity by ~14.5%, annual hydrogen production for grid electricity by ~31%, underground low-temperature heat storage capacity by ~27.3%; onshore wind nameplate capacity by ~1.2%, land needs by ~0.4%, and overall annual energy cost by ~1.8%. In sum, the use of firebricks for storing industrial process heat appears to be a remarkable tool in reducing the cost of transitioning to clean, renewable energy across all energy sectors.

Keywords: firebricks, process heat, thermal energy storage, 100% renewable energy, energy transition

Significance Statement

About 17% of all carbon dioxide emissions worldwide comes from burning fossil fuels to produce low-to-high-temperature heat for industrial processes. One way to almost eliminate such emissions is to produce all process heat from electricity, where the electricity comes from clean, renewable sources. However, due to the variability of wind and solar, for example, electricity or heat storage is also needed. The recent commercialization of firebricks, which can store, for a period of time, heat of all temperatures and cost less than one-tenth per unit storage capacity the cost of batteries, suggests a large-scale solution to addressing industrial process heat emissions is possible. Computer simulations across 149 countries indicate firebricks appear to be a remarkable tool in reducing the cost of transitioning the world to clean, renewable energy.

Introduction

The world is undergoing an energy transition to reduce emissions of gases and particles that harm human and animal health, the environment, and the climate. Such a transition involves replacing combustion fuels used to produce electricity, vehicle motion, low-temperature heat for buildings, and low- to high-temperature heat for industrial processes, with clean, renewable electricity, and heat for all four purposes (1). Electrification must occur across all energy sectors: the residential, commercial-government, industrial, transportation, agriculture-forestry-fishing, and military-other sectors (2). The only energy not electrified will be solar and geothermal heat, which will be used to provide some building and industrial heat. Clean, renewable electricity sources include wind (onshore and offshore wind); water (tidal, wave, geothermal reservoir, water reservoir, and river); and solar (sunlight) sources (3). Wind–water–solar (WWS) electricity generators are combined with WWS (solar and geothermal) heat collectors; electricity, heat, cold, and hydrogen storage; electric appliances, machines, and vehicles; and transmission/distribution lines to form a full WWS system (Table S2), to replace the current system (3).

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In 2021, only about 20.6% of annual-average power demand in end-use sectors across 149 countries for which data are available, was provided by electricity (2). Of the electricity generated, 26.0% was generated by WWS sources: 15.5% by hydro, 6.54% by wind, 0.33% by geothermal, 3.63% by solar, and 0.0034% by tides and waves (Table S32). Forty-seven countries, in fact, generated more than 50% of their electricity with WWS and seven generated 99.8–100% of their electricity with WWS (Table S32) in 2021–2022. To date, hydropower has dominated WWS generation, but the growth rates of solar and wind now significantly exceed those of hydropower. If almost all energy worldwide is electrified and if all electricity is provided by WWS, over 90% of all electricity generation may ultimately come from solar and wind (Table S13), which are variable in nature.

One important question, though, is how to provide continuous process heat for industry on demand in a 100% WWS world. Of all fossil fuel and chemical reaction CO_2 emissions worldwide in 2022, about 17% was due to combustion for industrial heat (Table 1). Another 8.38% arose from chemical reaction during the industrial manufacturing of steel, cement, and other products (Table 1). Some individual-country industrial combustion emissions as a percent of total all-sector emissions were 0.10% in the Democratic Republic of the Congo; 9.6% in the United States; 10.4% in Australia; 13.9% in Germany; 14.4% in Russia; 17.2% in Brazil; 21.7% in India; 23.9% in China; and 58.5% in North Korea (Table S31). Heat is needed in industry for many processes. Temperatures of 1,300–1,800 °C are needed for ordinary Portland cement (OPC) and lime production (4). Temperatures of 1,000–1,500 °C are needed for glass and fused silica production and traditional iron and steel making (4). Inorganic mineral production needs temperatures of 150–500 °C (4). Alcohol and basic chemical manufacturing need temperatures of 100–300 °C (5). Paper, paperboard, and pulp mills need temperatures <100 °C (5). Grid electricity, which is not included in the industrial process heat sector by IEA (2), needs temperatures >200 °C with a steam turbine (4, 6, 7) or 1,000–2,000 °C with a thermophotovoltaic cell (8, 9).

Factories today produce heat for manufacturing, largely by burning coal, oil, fossil gas, or biomass continuously, but also by running electric resistance furnaces and boilers, electric arc furnaces, electric induction furnaces, electron beam heaters, dielectric heaters, and electric heat pumps. Upon a transition to 100% WWS, though, all industrial process heat is proposed to come from electricity, geothermal heat, or solar heat. Common solar heat technologies that potentially can provide some low- to moderate-temperature heat for industry include flat plate solar collectors with hot water storage, parabolic trough collectors with and without thermal storage, and linear Fresnel direct steam generation collectors without storage (5, 11). An advantage of solar-to-heat over electricity-to-heat technologies is that sunlight-to-heat conversion efficiencies are higher than wind- or sunlight-to-electricity-to-heat conversion efficiencies. On the other hand, solar heat is available during the day only, whereas WWS electricity may be available during day or night.

Table 1. World 2022 carbon dioxide emissions by source from fossil fuels and industrial process chemical reaction and the percent of world total emissions by source.

Sector	Emissions ($Mt\text{-}CO_2$/year)	Percent of total
Agriculture	150.6	0.39
Buildings	3,422	8.88
Fuel exploitation	2,532	6.57
Industrial combustion for heat	6,538	16.97
Industrial process chemical reaction	3,226	8.38
Power industry	14,669	38.08
Transportation	7,968	20.68
Waste	17,203	0.04
Total	38,522	100

Source: Crippa et al. (10) Agriculture, agricultural soils, crop residues burning, enteric fermentation, and manure management; Buildings, small scale nonindustrial stationary combustion in buildings; Fuel exploitation, production, transformation, and refining of fuels; Industrial combustion for heat, combustion for heat for industrial manufacturing; Industrial processes chem reaction, emissions from chemical reaction, not combustion, during industrial manufacturing, such as during the production of cement, iron, steel, aluminum, chemicals, solvents, etc.; Power industry, electricity and heat generation plants (public and private); Transport, mobile combustion from road, rail, ship, and aviation sources; and Waste, solid waste disposal and wastewater treatment. See Table S31 for total and industrial combustion emissions by country.

Geothermal heat and solar collectors are also used today to provide low-temperature air and water heat for use in buildings. In this study, we assume this but, for simplicity, also assume that only electricity is used to produce heat for industrial processes. Such heat is either stored or used immediately.

Whereas some propose the use of nuclear reactors to provide electricity and heat for industry, newly-planned nuclear is not included here for several reasons. First, newly-planned nuclear reactors will unlikely compete with WWS because the time-lag between planning and operation of a new conventional nuclear reactor today is 12–22 years, too long to help solve world climate and air pollution problems, vs. 1–5 years for new wind and solar farms (12, 13). Second, the levelized cost of newly-planned conventional nuclear reactors is 3–14 times that of new onshore wind (12, 13). Nuclear also faces several well-known energy security risks (12). Small modular nuclear reactors are expected to face similar time-lag, cost, and security risks (12, 14). As such, nuclear is not considered further here.

Given the variability of wind and solar, significant electricity storage will be required upon electrification of most energy. Such storage may consist of a combination of conventional hydropower storage (CHS), battery storage (BS), green hydrogen storage (GHS), pumped hydropower storage (PHS), and concentrated solar power (CSP) with storage (CSPS) (3), among other options. Of these, BS and GHS may grow the most, but both are still relatively expensive today.

An alternative to using high-cost BS and GHS to store electricity for continuous low-to-high-temperature industrial process heat is to use variable WWS electricity, whenever it is available, to generate heat, and then store the heat in firebricks (4, 6, 8, 9, 15–17). Electricity may be converted to heat with metallic electric-resistance heaters connected to the firebricks (15, 17) or with direct resistance heating (DRH) of the firebricks themselves (18, 19). The firebricks may be organized in a pattern that allows air to flow through channels in them (15, 17–19). Firebricks are low cost because they can be made of inexpensive heat-storage materials and because no heat exchanger is needed.

Heat-storing firebricks have high specific heats and densities so that they can absorb a lot of energy with little temperature increase, and they have high melting points. They are surrounded either by another type of firebrick that is more insulating, and then by steel to reduce heat loss further (15) or simply by a thick steel container (9). The process heat may be drawn from the firebricks on demand by passing ambient or recycled air through the channels in the bricks, yielding low-to-high-temperature air (15, 17), or it may be obtained from the emission of infrared radiation directly from the red-hot bricks (9). The use of firebricks avoids the need for BS and GHS to store renewable electricity, replacing electricity storage with firebrick storage. This should be a good tradeoff, because a firebrick system is less than one-tenth the cost per kWh-thermal of a battery system per kWh-electricity (9, 15, 17).

Firebricks are similar to refractory bricks, which are bricks that have high melting points and good insulating properties. Refractory bricks are used to line furnaces, kilns, fireplaces, fireboxes, and ovens. They are usually made of ceramic material containing a combination of alumina (Al_2O_3), silica (SiO_2), magnesia (MgO), and chromia (Cr_2O_3). The portions of each constituent depend on the desired peak temperature, insulating properties, mechanical properties, and resistance to corrosion. Alumina is used to increase the melting point, and silica is used for its insulating properties. The high melting point is needed so that the material can withstand high temperatures; the insulating property, so that the material does not lose heat to the outside rapidly.

Refractory materials were likely used to line primitive kilns dug into the ground during the early Bronze Age (4,000–3,000 BC), iron-making furnaces during the Iron Age (1,500–500 BC), crucibles for molten glass since the early 1600s, and steel-making furnaces since the mid-1850s (20). Refractory bricks containing high percentages of silica and alumina, with trace amounts of iron oxide (Fe_2O_3), calcium oxide (CaO), and magnesia (MgO), were used to line copper smelters in the 1800s in Chile (21). Today, low-cost refractory bricks are also made with chromia and/or mullite (an aluminum silicate mineral). High-cost firebricks mixtures may also contain silicon carbide (SiC), zirconia (ZrO_2), and zircon ($ZrSiO_4$).

In a heat storage enclosure, some firebricks may be used for heat storage and others, for insulation. Those used for storage should have a high specific heat, high density, and high melting point. Ideal low-cost firebrick materials with these properties include, for example, alumina (specific heat at 25 °C: 840 J/kg-K; density: 3,987 kg/m^3; melting point: 2,072 °C) and magnesia, MgO (960 J/kg-K; 3,581 kg/m^3; 2,852 °C) (15).

Another potential firebrick option is pure low-grade solid carbon (graphite) (~707 J/kg-K; 2,260 kg/m^3; 3,550 °C), which can be heated to 2,400 °C (9). This technology has several challenges associated with keeping its cost low, including the fact that graphite slowly vaporizes and its use of radiant heating limits its ability to transfer heat for many applications without additional heat-transfer technology.

The temperature of firebricks is not the same as the temperature achieved in the material heated. The temperature of the material heated depends on the specific heats and masses of both the firebricks and the material and on heat loss between the two. For example, graphite firebricks supplying 1,500 °C heat to a material may need the graphite heated to 1,800–2,000 °C (9) to account for both the material's properties and heat loss.

Firebricks used for insulation must withstand high temperatures yet have low thermal conductivities. Silica has a low thermal conductivity (0.3 W/m-K), so is regularly used in insulating firebricks. Common types of insulating firebricks include alumina silicate bricks (mostly alumina and sand) and calcium silicate bricks (mostly limestone and sand).

Firebricks have been applied previously for heat storage in heat regenerators used in glass making (22) and steel making (15). Regenerators are heat interchangers that receive heat from a high-temperature flue gas, store the heat for 20–30 min, then use the heat to preheat air for combustion. In this study, the heat may be stored for hours to days or even weeks. Even before 2018, firebricks, storing 10 MWh of heat, were deployed in China for commercial complexes and district heating projects (15).

Stack et al. (15) performed computational experiments with firebricks storing electricity as high-temperature heat (1,000–1,700 °C). The firebricks were arranged in a pattern and insulated. When heat was needed, it was transferred to a cold air stream, then used for either industrial processes or to reproduce electricity through a steam turbine. The study found that charging and discharging the firebricks could occur over a few hours, implying that systems of hundreds to thousands of megawatt-hours could be cycled daily.

In Stack et al. (15), electricity was converted to heat with metallic alloy and ceramic electric resistance heaters connected to the firebricks, which were made of either alumina, magnesia, or silicon carbide. However, the electric resistance heaters that produced the highest temperatures, silicon carbide (SiC) and molybdenum disilicide ($MoSi_2$) heaters, could not easily deliver heat to the center of a firebrick array. In addition, whereas such heaters are well suited for 1,100 °C and produce much higher temperatures, they fail relatively quickly at 1,500 °C because oxygen diffuses through their outer protective coating at such temperatures.

Stack et al. (15) proposed instead that direct resistance heating (DRH) be used to heat firebricks. With DRH, an electric current fed to an electrically conductive firebrick dissipates to heat, permitting firebrick temperatures to rise to 1,800 °C (18, 19). An electrically conductive firebrick contains a conductive metal oxide, such as chromia, that is doped with, for example, 2–5% nickel oxide or magnesium. The dopant allows the firebrick to reach a desired temperature of up to 1,800 °C. The doped chromia itself may be molded into a firebrick or molded together with alumni, silica, and/or magnesia into a firebrick (18). Only a fraction of all firebricks used in this heating solution are electrically conductive; the rest are insulating bricks. Aside from reaching higher temperatures, another advantage of DRH over external heaters is that DRH results in no temperature drop between the heating element and firebrick because the firebrick itself is the heating element. Finally, DRH is insensitive to voltage, current, or frequency thus does not require expensive power electronics, or no electronics if connected directly to a photovoltaic array.

With external heating, Stack et al. (15) estimated the overall cost of a 250-MWh alumina firebrick system with peak charge and discharge rates of 75 MW-electricity and 50 MW-thermal, respectively, as ~$10.75/kWh-thermal-storage in 2018. This cost is broken down into the cost of firebricks (18.4%), insulation (1.6%), transformer (52.2%), blower (11.9%), containment vessel (7.2%), and metallic heater wire (8.7%). Whereas the aluminum oxide firebrick itself was ~$2.12/kWh, magnesium oxide would have been less expensive (~$1.87/kWh), and silicon carbide, more expensive (~$7.18/kWh) (15). The cost in all cases per kWh-thermal-storage was less than one-tenth that of batteries per kWh-electricity-storage, which were $250-$500/kWh at the time.

The purpose of this study is to examine the impact of using firebricks to store most industrial process heat, on overall energy cost and grid stability in 149 countries, assuming that each country has transitioned to 100% WWS for all energy purposes. The 149 countries are responsible for 99.75% of world fossil-fuel CO_2 emissions (Table S26). Recently, 2050 plans were developed to transition 149 countries from 100% business-as-usual (BAU) energy to electricity and heat powered by 100% WWS sources (23). Several earlier studies have also examined transitioning to WWS in countries or states (3, 24–30). Hundreds of additional studies have examined the ability of countries, states, provinces, cities, or towns to transition entirely to renewable electricity and/or heat in one or more energy sectors (31).

In this study, electricity is used to heat firebricks through electric resistance heating. The heat is stored until it is needed for an industrial process. This reduces the need for electricity storage, low-temperature heat storage, and/or electricity generation.

Simulations of matching electricity and heat demand with supply, storage, and demand response are performed in each of 29 world regions encompassing the 149 countries. Results are compared with results from simulations in which no firebricks are used. We are not aware of any previous study analyzing the impact of using firebricks for industrial heat on the cost of grid stability with either high or low penetrations of renewables on the grid.

Results

The study involves the use of three types of models (see Methods). The first is a spreadsheet model used to estimate 2050 BAU and WWS energy demand from current BAU demand, and then to estimate WWS generator nameplate capacities needed to satisfy 2050 WWS demand (Note S2). Results from the spreadsheet model are fed into GATOR-GCMOM (Note S3), a global weather-climate-air pollution model. That model predicts wind electricity supply solar electricity supply, solar heat supply (used here for air and water heating in buildings), wave electricity supply, and building heating and cooling demands worldwide every 30 s for multiple years based on wind, solar, and air temperature predictions by the model and given generator nameplate capacity inputs from the spreadsheet model. GATOR-GCMOM output is then fed into LOADMATCH (Notes S4–S7), which matches demand with supply, storage, and demand response every 30 s for multiple years.

Simulations with LOADMATCH are run for 3 years (2050–2052) with a 30-s time step. Two sets of simulations are compared: one with firebricks ("firebrick case") and the other with no firebricks ("base case"). Table S2 lists the electricity and heat generators, storage technologies, electric machines, electric appliances, hydrogen system components, and grid characteristics in both cases. Detailed base-case WWS results for 2050 and a comparison of 2050 base-case WWS results with BAU estimates are provided in Ref. (23) but also presented here where relevant. The WWS base-case results in Ref. (23) use the same spreadsheet (32) and GATOR-GCMOM outputs as the WWS firebrick-case results presented here. The only difference between the base and firebrick cases is the added treatment of firebricks in the firebrick case for industrial process heat storage in LOADMATCH (Methods).

LOADMATCH simulations are carried out in 29 regions encompassing the 149 countries treated (Table S1). Grid stability is obtained in all 29 regions in the firebrick case, just as in the base case. Table 2 and Fig. 1 summarize some of the key differences in results between the firebrick and base cases, averaged over all 29 regions/149 countries. Of note, the use of firebricks decreased battery storage capacity requirements by 14.5%, green hydrogen storage fuel cell size by 3.9%, hydrogen tank size by 18.3%, hydrogen production needed for grid electricity by 31.4%, underground thermal energy maximum discharge rate by 1%, underground thermal energy storage capacity by 27.3%, onshore wind nameplate capacity by 1.2%, offshore wind nameplate capacity by 0.54%, utility PV nameplate capacity by 0.54%, and CSP nameplate capacity by 0.84%. In sum, adding firebricks increased firebrick storage maximum discharge rates and capacities but decreased electricity storage and low-temperature heat storage maximum discharge rates and capacities as well as generator nameplate capacities. The overall impact of adding firebricks was to increase the all-storage maximum discharge rate but decrease the all-storage maximum capacity (Fig. 1).

Tables 2 and 3 and Fig. 2 indicate that the benefits of reducing electricity- and low-temperature-heat-storage and generator capacities with firebricks outweigh the costs of using firebricks across the 149 countries. Using firebricks reduces the capital cost of transitioning the 149 countries to WWS by $1.27 trillion (2.2%), from $58.24 to $56.97 trillion (2020 USD). Capital costs decrease in all regions aside from Iceland and Canada (Table 3), which have such abundant and regular hydropower and wind resources that firebrick storage is not necessary (although still installed). Firebricks also reduce the levelized cost of energy (LCOE) by 0.15 ¢/kWh (1.7%) and the annual energy cost by $119 billion/years (1.78%) across the 149 countries (Tables 2 and 3). The lower LCOE with firebricks is due mostly to reducing grid hydrogen costs, battery costs, underground thermal-energy storage costs, and electricity generation costs (Fig. 2).

The lower annual energy cost with firebricks increases the annual energy cost difference between the BAU and WWS firebrick cases relative to the BAU and WWS base cases (Table 3). This higher difference combined with the lower capital cost with firebricks contribute to the 3.2% decrease (from 5.9 to 5.7 years) in the 149-country energy cost payback time with firebricks of transitioning to 100% WWS (Tables 2 and 3). In two regions (New Zealand and Southeast Asia), the payback time decreases by more than a year (Table 3).

Table 2. Comparison of selected inputs and results among all 29 regions (encompassing 149 countries) between the firebrick case and the base case. Percentage differences between the firebrick case and the base case are also shown. All costs are in 2020 USD.

Parameter	(a) Firebrick case	(b) Base case	(c) Percent difference = 100% × (a – b)/b
Capital cost for an all-sector transition ($ trillion, 2020)	56.97	58.24	−2.18
WWS levelized cost of energy (¢/kWh-all energy)	8.67	8.82	−1.70
WWS annual energy cost ($ trillion/year)	6.549	6.668	−1.78
Capital cost payback time (years) (based on a BAU cost of $16.519/year)	5.72	5.91	−3.21
Battery storage peak discharge rate/storage capacity (GW/TWh)	8,055/32.22	9,426/37.71	−14.5/−14.5
Green hydrogen storage fuel cell size/tank size (GW/Tg-H_2)	1,566/11.59	1,630/14.18	−3.93/−18.3
UTES heat storage peak discharge rate/storage capacity (GW/TWh)	2,283/405.0	2,306/557.1	−1.00/−27.3
Firebrick storage peak discharge rate/storage capacity (GW/TWh)	2,142/32.13	0/0	Inf./Inf.
Hydrogen for grid electricity storage produced (Tg-H_2/year)	26.65	38.87	−31.44
Onshore wind nameplate capacity (GW)	9,981	10,105	−1.23
Offshore wind nameplate capacity (GW)	4,079	4,094	−0.37
Utility PV nameplate capacity (GW)	13,299	13,371	−0.54
CSP nameplate capacity (GW)	141.7	142.9	−0.84
Footprint plus spacing land requirement over 149 countries (km^2)	621,194	623,864	−0.43
Long-term full-time jobs created minus lost	22,782,124	22,900,033	−0.51

Table S10 provides generator nameplate capacities, Table S14 provides storage capacities, Table S25 provides levelized costs, Table S28 provides land area requirements, and Table S30 provides job creation minus loss in both the firebrick case and the base case in each region.

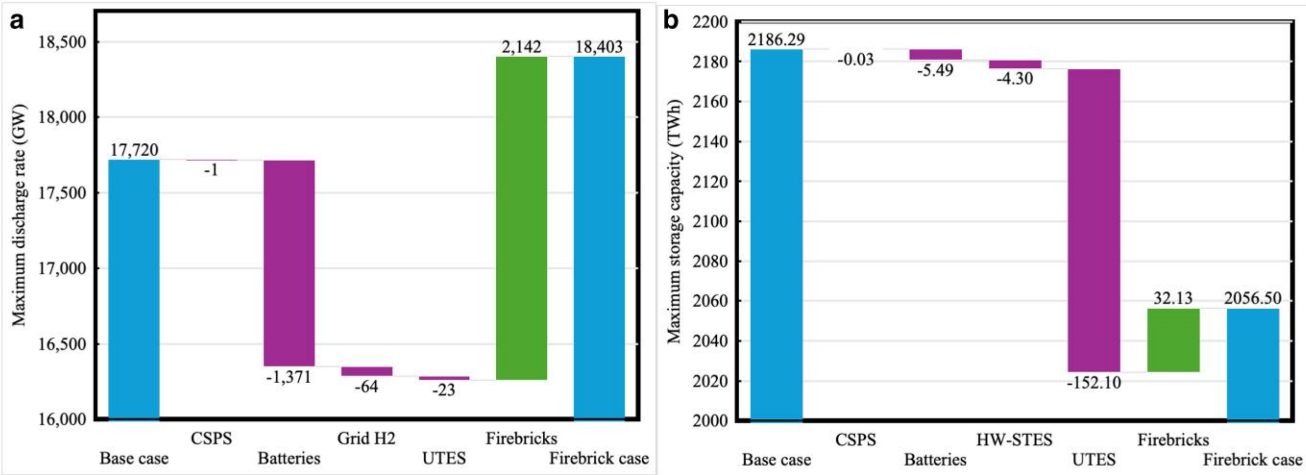

Fig. 1. Base case and firebrick case (a) maximum storage discharge rates (GW) and (b) maximum storage capacities (TWh) among the 149 countries here, and the changes in the storage components between the base and firebrick cases. Data from Table S14. CSPS, concentrated solar power with storage; batteries, battery storage (BS); Grid H2, grid hydrogen fuel cell size; UTES, underground thermal energy storage; and firebricks, firebrick storage. No changes in conventional hydropower storage (CHS), PHS, or other storage listed in Table S14 occurred. This table does not show the change in the maximum storage capacity of hydrogen because hydrogen storage for grid purposes is merged with that for nongrid purposes in this study. However, the overall reduction in hydrogen storage mass among the 149 countries between the firebrick and base cases is 2.587 Tg (11.592 Tg in the firebrick case minus 14.179 Tg in the base case, from Tables 2 and S17).

Using firebricks also reduces the land needed for electricity generators by 2,700 km^2 (0.43%) across 149 countries. The one downside of firebricks is that ~0.51% (118,000) fewer jobs are created with firebricks due to the reductions in electricity- and low-temperature-heat-storage capacities and generator nameplate capacities needed in the firebrick case vs. the base case (Table 2).

A large part of the reason for the lower overall energy cost in the firebrick case is the lower cost of firebrick storage than battery storage. The firebrick case requires 14.5% less (32.2 TWh rather than 37.7 TWh) battery storage capacity than the base case among all 149 countries (Tables 2, 4, and S14). Conversely, the firebrick storage capacity increases from 0 TWh in the base case to 32.1 TWh in the firebrick case (Tables 2, 4, and S14). Although 5.8 times the firebrick storage capacity is added compared with the battery-storage capacity reduced in the firebrick case, the cost per kWh of firebrick storage is one-tenth that of battery storage (15, 17) (Table S22), indicating that replacing batteries with firebricks should reduce cost.

Table 4 shows that firebricks are used quite efficiently in all regions except Iceland. The storage capacity factor here is defined as the energy actually discharged from a storage medium over a simulation divided by the product of the maximum discharge rate and the number of hours of simulation. Averaged over all world regions, the storage capacity factor of firebricks is 78.4%. This suggests firebrick storage is regularly discharged, thus regularly charged as well. The average capacity factor of battery storage among all regions, on the other hand, is only 3.76% (Table 4). Thus, batteries are being used primarily for peaking power, providing short bursts of electricity, but much less so for long-term (>24 h) energy storage. In other words, batteries need high maximum discharge rates to meet short bursts in power, but they do not need such high discharge rates for the long-term storage services they provide. The firebrick storage capacity factor in Iceland is very low, only 0.17%. No other region has a firebrick storage capacity factor less than 50%. The reason is that industrial heat in Iceland, upon a transition to WWS, is satisfied primarily with current electricity (mostly hydro and geothermal), and excess electricity is used primarily to produce hydrogen for nongrid purposes (hydrogen is not needed for grid electricity backup in Iceland), so little electricity remains or is needed for firebrick storage. In sum, the use of firebrick storage in Iceland may not be necessary.

Discussion/Conclusions

The use of firebricks for storing industrial process heat appears to be a remarkable tool in reducing the cost of transitioning to 100% clean, renewable energy across all energy sectors. Firebricks reduce the need for grid electricity storage, low-temperature heat storage, and electricity generator nameplate capacity. Since a firebrick system cost per kWh-thermal-storage is much less than battery cost per kWh-electricity-storage, using firebricks instead of batteries reduces the overall cost of 100% WWS energy worldwide. Firebricks for storing high temperature heat are already commercialized and have potential to be used for up to 90% of industrial process heat applications (15, 17).

Uncertainties still exist as to the performance of firebricks. One such uncertainty is the daily loss rate of heat. Rondo (17) states that the loss rate is 1% per day due to insulating the firebricks and recycling air after it is used to heat a material. A 1% loss rate per day was the default assumption made here in the firebrick case. To test the sensitivity of results to this assumption, additional simulations were performed for loss rates of 2, 3, 4, and 5%, instead of 1%, for the United States. Results indicate that even with a 5% daily heat loss rate, firebricks still reduce the LCOE by ~1.1% relative to the base case (vs. a 1.5% lower LCOE than the base case at a 1% loss rate) (Fig. 3a).

A second uncertainty arises when insufficient firebrick storage is available to meet industrial process heat demand. In the simulations here, the default assumption in that case is that half the remaining demand becomes inflexible and must be met immediately with current electricity generation or electricity storage. The other half may be met immediately, but if sufficient electricity is currently unavailable, the remaining heat demand may be shifted forward in time one time step at a time, for up to 8 h, through demand response. Sensitivity tests are run here to test whether this

Table 3. 2050 annual-average end-use (a) BAU demand and (b) WWS demand; (c) percentage difference between WWS and BAU demands; (d) mean value of capital cost, averaged between 2020 and 2050, of new WWS energy in the firebrick case; (e) same as (d) but for the base case; (f)–(h) mean levelized private costs (¢/kWh-all-energy-sectors, averaged between 2020 and 2050) of all BAU energy, WWS energy in the firebrick case, and WWS energy in the base case, respectively; (i) BAU health cost; (j) BAU climate cost; (k) BAU private energy cost; (l) BAU total social cost; (m) WWS private (equals social) energy cost in the firebrick case; (n) WWS private energy cost in the base case; (o), (p) WWS minus BAU private energy cost difference in the firebrick and base cases, respectively; (q), (r) private energy cost payback time in the WWS firebrick and base cases, respectively; (s), (t) WWS minus BAU social energy cost difference in the firebrick and base cases, respectively; and (u), (v) social energy cost payback time in the WWS firebrick and base cases, respectively.

Region	2050 Annual-average end-use demand (GW)		Percent diff. (%)	2050 mean total WWS capital cost ($trillion)		2050 mean private energy cost (¢/kWh-all energy)			2050 BAU mean annual costs ($billion/year)	
	(a)[a] BAU	(b)[a] WWS firebrick and base	(c) WWS minus BAU demand = 100% × (b – a)/a	(d)[b] Firebrick	(e)[b] Base	(f)[c] BAU	(g)[d] WWS firebrick	(h)[d] WWS base	(i)[e] Health cost	(j)[f] Climate cost
Africa-East	224	64.2	−71.4	0.593	0.609	7.82	10.01	10.24	755	102
Africa-North	380	153.1	−59.7	0.989	0.999	11.34	7.94	8.00	613	725
Africa-South	278	118.5	−57.4	0.788	0.810	9.29	8.31	8.50	333	601
Africa-West	409	110.7	−72.9	1.257	1.272	9.96	11.76	11.90	2,415	266
Australia	201.5	88.9	−55.9	0.492	0.495	10.26	7.81	7.87	34.6	333.5
Canada	401.9	160.1	−60.2	0.599	0.573	8.09	6.54	6.40	42.2	498.1
Central America	301.0	127.3	−57.7	0.808	0.827	10.50	8.24	8.37	323.7	508.0
Central Asia	391.9	143.3	−63.4	0.914	0.924	10.24	7.93	8.01	1,011	631.0
China region	5,081	2,542.8	−50.0	14.59	14.97	9.53	8.24	8.39	10,756	8,969
Cuba	11.9	6.7	−44.0	0.053	0.055	11.65	9.09	9.33	37.5	24.0
Europe	2,054	876.4	−57.3	4.966	5.064	10.06	8.39	8.50	1,772	2,627
Haiti region	17.2	6.8	−60.4	0.089	0.092	11.00	15.37	15.74	36.2	30.2
Iceland	4.57	2.7	−40.6	0.0012	0.0011	7.43	7.23	7.21	0.4	2.1
India region	1,821	967.2	−46.9	6.947	7.135	9.82	8.65	8.86	9,472	3,604
Israel	24.7	12.4	−49.8	0.109	0.112	11.21	10.64	10.85	15.7	43.8
Jamaica	4.09	1.7	−57.7	0.0160	0.0164	11.40	10.48	10.69	3.4	7.9
Japan	329.1	175.7	−46.6	1.220	1.226	10.48	9.60	9.63	261.5	638.1
Madagascar	12.8	3.4	−73.4	0.036	0.037	9.34	11.68	11.80	51.7	6.4
Mauritius	4.17	1.6	−62.4	0.012	0.013	10.54	10.00	10.62	3.7	5.0
Mideast	1,383	647.5	−53.2	3.731	3.822	11.34	7.58	7.74	858.2	2,730
New Zealand	27.9	14.8	−46.9	0.086	0.093	8.22	8.51	8.91	5.2	29.6
Philippines	79.7	34.7	−56.5	0.271	0.292	10.20	9.08	9.51	677.3	178.4
Russia region	729.9	262.7	−64.0	1.271	1.276	10.14	7.36	7.37	602.0	1,324
South Am-NW	201.7	81.7	−59.5	0.512	0.532	8.30	8.43	8.67	242.6	326
South Am-SE	756.9	344.8	−54.4	2.160	2.210	8.37	8.47	8.56	507.2	781
Southeast Asia	1,180.2	560.3	−52.5	6.481	6.677	10.32	12.01	12.46	1,936	1,915
South Korea	279.8	142.0	−49.2	1.588	1.596	10.69	12.52	12.54	104.4	503.4
Taiwan	154.6	85.2	−44.9	0.774	0.791	10.70	10.42	10.61	85.9	347.4
United States	2,183.4	890.2	−59.2	5.617	5.722	10.58	8.61	8.75	830.1	3,137
All regions	18,930	8,627	−54.4	56.97	58.24	9.96	8.67	8.82	33,789	30,893

Region	2050 mean annual private or social energy cost ($billion/year)				2050 WWS minus BAU private energy cost diff. (%)		Private energy cost payback time (years)		2050 WWS minus BAU social energy cost diff. (%)		Social energy cost payback time (years)	
	(k)[g] BAU private cost = afH	(l) BAU social cost = i + j + k	(m)[g] WWS firebrick private and social cost = bgH	(n)[g] WWS base private and social cost = bhH	(o) Fire-brick = 100% × (m – k)/k	(p) Base = 100% × (n – k)/k	(q) Fire-brick = d/(k – n)	(r) Base = e/(k – n)	(s) Fire-brick = 100% × (m – l)/l	(t) Base = 100% × (n – l)/l	(u) Fire-brick = d/(l – m)	(v) Base = e/(l – n)
Africa-East	154	1,012	56.3	57.6	−63.4	−62.5	6.1	6.3	−94.4	−94.3	0.62	0.64
Africa-North	378	1,716	106.4	107.3	−71.8	−71.6	3.6	3.7	−93.8	−93.7	0.61	0.62
Africa-South	227	1,161	86.2	88.2	−61.9	−61.1	5.6	5.9	−92.6	−92.4	0.73	0.76

(continued)

Table 3. Continued

Region	2050 mean annual private or social energy cost ($billion/year)				2050 WWS minus BAU private energy cost diff. (%)		Private energy cost payback time (years)		2050 WWS minus BAU social energy cost diff. (%)		Social energy cost payback time (years)	
	(k)[g] BAU private cost = afH	(l) BAU social cost = i + j + k	(m)[g] WWS firebrick private and social cost = bgH	(n)[g] WWS base private and social cost = bhH	(o) Fire-brick = 100% × (m – k)/k	(p) Base = 100% × (n – k)/k	(q) Fire-brick = d/(k – n)	(r) Base = e/(k – n)	(s) Fire-brick = 100% × (m – l)/l	(t) Base = 100% × (n – l)/l	(u) Fire-brick = d/(l – m)	(v) Base = e/(l – n)
Africa-West	357	3,038	114.0	115.4	−68.1	−67.7	5.2	5.3	−96.2	−96.2	0.43	0.44
Australia	181.1	549.2	60.8	61.2	−66.4	−66.2	4.1	4.1	−88.9	−88.8	1.01	1.01
Canada	284.8	825.2	91.8	89.7	−67.8	−68.5	3.1	2.9	−88.9	−89.1	0.82	0.78
Central America	276.8	1,108	92.0	93.4	−66.8	−66.3	4.4	4.5	−91.7	−91.6	0.79	0.81
Central Asia	351.7	1,994	99.6	100.6	−71.7	−71.4	3.6	3.7	−95.0	−95.0	0.48	0.49
China region	4,243	23,969	1,834	1,870	−56.8	−55.9	6.1	6.3	−92.3	−92.2	0.66	0.68
Cuba	12.2	73.6	5.3	5.5	−56.2	−55.1	7.8	8.2	−92.8	−92.6	0.78	0.81
Europe	1,810	6,209	644.5	652.8	−64.4	−63.9	4.3	4.4	−89.6	−89.5	0.89	0.91
Haiti region	16.5	83.0	9.1	9.4	−44.7	−43.4	12.1	12.9	−89.0	−88.7	1.21	1.25
Iceland	3.0	5.5	1.7	1.7	−43.1	−43.2	1.1	1.1	−69.4	−69.5	0.36	0.36
India region	1,567	14,642	732.7	750.7	−53.2	−52.1	8.3	8.7	−95.0	−94.9	0.50	0.51
Israel	24.3	83.8	11.6	11.8	−52.3	−51.4	8.6	9.0	−86.2	−85.9	1.51	1.56
Jamaica	4.1	15.4	1.6	1.6	−61.1	−60.3	6.4	6.7	−89.7	−89.5	1.16	1.19
Japan	302.2	1,202	147.7	148.2	−51.1	−50.9	7.9	8.0	−87.7	−87.7	1.16	1.16
Madagascar	10.4	69	3.5	3.5	−66.7	−66.4	5.2	5.3	−94.9	−94.9	0.56	0.56
Mauritius	3.9	12.5	1.4	1.5	−64.3	−62.1	4.8	5.4	−89.0	−88.3	1.08	1.17
Mideast	1,374	4,962	429.8	439.1	−68.7	−68.0	3.9	4.1	−91.3	−91.2	0.82	0.85
New Zealand	20.1	54.8	11.0	11.6	−45.1	−42.5	9.5	10.9	−79.9	−78.9	1.97	2.14
Philippines	71.2	926.9	27.6	28.9	−61.3	−59.5	6.2	6.9	−97.0	−96.9	0.30	0.33
Russia region	648.5	2,574	169.3	169.7	−73.9	−73.8	2.7	2.7	−93.4	−93.4	0.53	0.53
South Am-NW	146.7	716	60.4	62.1	−58.8	−57.7	5.9	6.3	−91.6	−91.3	0.78	0.81
South Am-SE	554.9	1,843	255.9	258.5	−53.9	−53.4	7.2	7.5	−86.1	−86.0	1.36	1.39
Southeast Asia	1,067	4,918	589.2	611.5	−44.8	−42.7	13.6	14.7	−88.0	−87.6	1.50	1.55
South Korea	262.0	869.7	155.8	156.0	−40.5	−40.5	14.9	15.1	−82.1	−82.1	2.22	2.24
Taiwan	144.9	578.3	77.8	79.2	−46.3	−45.4	11.5	12.0	−86.5	−86.3	1.55	1.58
United States	2,024	5,991	671.5	682.0	−66.8	−66.3	4.2	4.3	−88.8	−88.6	1.06	1.08
All regions	16,519	81,200	6,549	6,668	−60.36	−59.63	5.7	5.9	−91.93	−91.79	0.76	0.78

All costs are in 2020 USD. Tables S20–S23 give cost parameters. A social discount rate of 2 (1–3)% is used. H = 8,760 h/year.
[a]From Table S4.
[b]The total capital cost includes the capital cost of new WWS electricity and heat generators; new equipment for electricity storage, low-temperature building heat storage, industrial process heat storage, cold storage, and hydrogen storage; hydrogen electrolyzers and compressors; heat pumps for district heating/cooling, and long-distance (HVDC) transmission lines. Capital costs are an average between 2020 and 2050.
[c]This is the BAU electricity-sector cost per unit energy. It is assumed to equal the BAU all-energy cost per unit energy and is an average between 2020 and 2050.
[d]The WWS cost per unit energy is for all energy, which is almost all electricity (plus a small amount of direct heat). It is an average between 2020 and 2050.
[e]The 2050 annual BAU health cost equals the number of total air pollution deaths per year in 2050 from Table S26, multiplied by 90% (the estimated percentage of total air pollution mortalities that are due to energy) and by a VOSL calculated for each country, and multipliers for morbidities and nonhealth, nonclimate environmental impacts (see Note S8).
[f]The 2050 annual BAU climate cost equals the 2050 CO_2e emissions from Table S26, multiplied by the mean social cost of carbon in 2050 from Table S26 (in 2020 USD). See Note S8 for a discussion.
[g]The annual private cost of WWS or BAU energy equals the cost per unit energy multiplied by the energy consumed per year, which equals the end-use demand multiplied by H = 8,760 h/year.

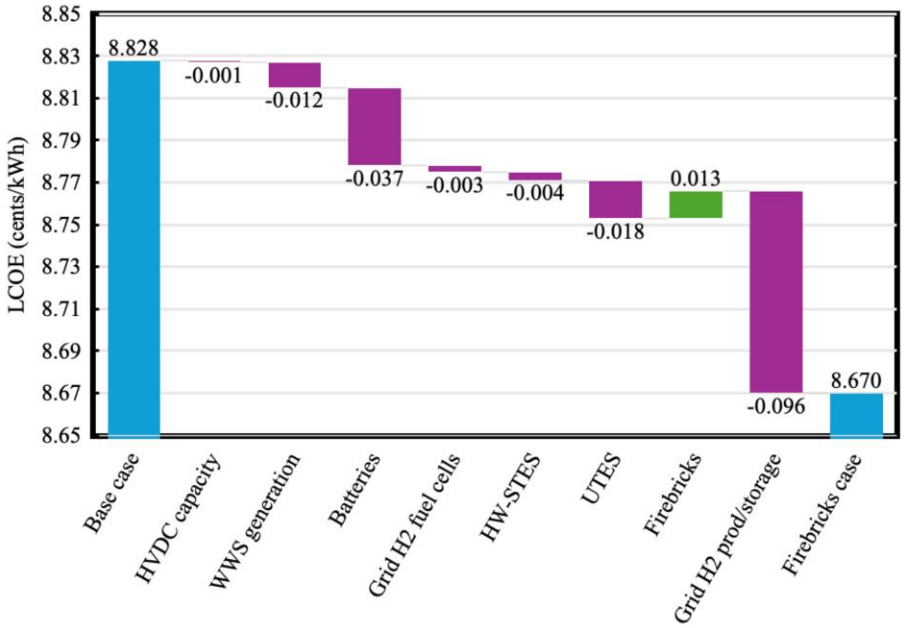

Fig. 2. Base case and firebrick case levelized cost of energy (LCOE) in 2020 USD, averaged over all 149 countries, and the components of LCOE that changed between the base and firebrick cases. Data from Table S24. HVDC capacity, high-voltage direct current transmission line capacity; WWS generation, the generation of WWS electricity; Batteries, battery electricity storage; Grid H2 fuel cells, fuel cells used to produce grid electricity from hydrogen; HW-STES, hot water sensible heat thermal energy storage UTES, underground thermal energy storage; Firebricks, firebrick storage; and Grid H2 prod/storage, rectifiers, water, electrolyzers, compressors, and storage used for grid hydrogen.

Table 4. Battery and firebrick storage capacity and capacity factor by region. The storage capacity factor is the energy discharged from the storage medium over the entire simulation divided by the product of the maximum discharge rate and the number of hours of simulation. Batteries discharge their full storage capacity in 4 h; firebricks, in 15 h.

	Battery			Firebrick		
Region	(a) Peak discharge rate (GW)	(b) Storage capacity (TWh)	(c) Capacity factor (%)	(d) Peak discharge rate (GW)	(e) Storage capacity (TWh)	(f) Capacity factor (%)
Africa-East	340	1.36	1.09	15.69	0.24	96.4
Africa-North	130	0.52	2.83	30.37	0.46	89.4
Africa-South	250	1.00	2.05	26.84	0.40	86.1
Africa-West	400	1.60	0.92	24.92	0.37	95.9
Australia	110	0.44	2.42	21.70	0.33	79.0
Canada	0	0	0	35.02	0.53	75.3
Central America	148	0.59	4.02	33.19	0.50	93.7
Central Asia	35	0.14	3.43	31.83	0.48	98.1
China region	980	3.92	5.29	631.3	9.5	68.8
Cuba	41	0.16	2.24	2.11	0.032	86.9
Europe	15	0.060	8.89	141.4	2.1	67.1
Haiti region	0	0	0	1.54	0.023	94.4
Iceland	0	0	0	1.13	0.017	0.17
India region	1,850	7.40	4.44	347.1	5.2	79.4
Israel	103	0.41	2.78	1.91	0.029	78.3
Jamaica	14.5	0.058	1.53	0.45	0.007	89.7
Japan	170	0.68	3.20	22.85	0.34	53.6
Madagascar	15	0.060	2.45	0.61	0.009	84.4
Mauritius	3.6	0.014	2.95	0.25	0.0038	68.3
Mideast	600	2.40	1.47	192.5	2.9	94.0
New Zealand	0	0	0	3.83	0.058	98.9
Philippines	60	0.24	4.54	7.22	0.11	96.6
Russia region	0	0	0	51.54	0.77	99.7
South Am-NW	0	0	0	16.68	0.25	99.9
South Am-SE	0	0	0	103.8	1.6	100.0
Southeast Asia	1,100	4.40	6.77	169.7	2.5	67.2
South Korea	270	1.08	2.75	28.24	0.42	79.7
Taiwan	250	1.00	2.08	25.92	0.39	70.2
United States	1,170	4.68	2.81	172.6	2.6	83.3
All regions	8,055.1	32.22	3.76	2,142.1	32.13	78.4

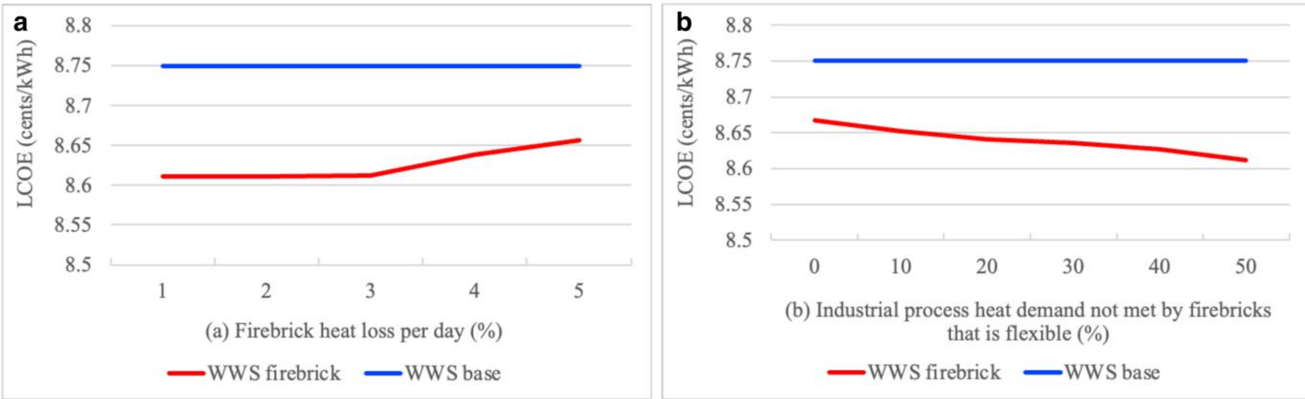

Fig. 3. a) Sensitivity in the United States region of the modeled overall levelized cost of energy (LCOE) in 2050 (2020 USD) to the assumed firebrick storage heat loss per day in the firebrick case. The default assumed heat loss rate for the firebrick simulations here was 1% per day. Also shown is the LCOE in the base case for comparison. b) Same as a), but sensitivity of the LCOE to the assumed percentage of industrial process heat demand that is not met with firebrick heat storage, because the storage is temporarily empty, that is considered flexible and thus subject to demand response. The rest of the unmet heat demand is assumed to be inflexible and must be met immediately with current electricity or electricity storage. A 0% value means 100% is inflexible. The default for the simulations in this study is 50% of the unmet demand is flexible. Also shown is the LCOE in the base case for comparison.

assumption makes much difference to the overall LCOE. Tests are run for the United States with 0, 10, 20, 30, or 40% (instead of 50%) of the unmet demand being subject to demand response. Figure 3b indicates that, even with 100% of the unmet demand becoming inflexible (0% subject to demand response), the LCOE is still ~1% lower than in the base case.

An additional question is how to address industrial manufacturing emissions that firebricks do not address. Such emissions include emissions of many gases and particles from at least 10% of industrial combustion not covered by firebricks and emissions of CO_2 from industrial process chemical reaction, primarily from steel and cement manufacturing. Industrial combustion not covered by firebricks is proposed to be covered by electric arc furnaces, resistance furnaces and boilers, induction furnaces, electron beam heaters, and dielectric heaters (24–30). CO_2 from steel manufacturing is proposed to be addressed by using green hydrogen instead of coke or coal for reducing iron ore to pure iron (30). CO_2 from cement production is proposed to be eliminated by using basalt (calcium silicate rock with no carbon) instead of limestone during OPC production (33) and geopolymer cement instead of OPC (34). With these and similar techniques for other processes, together with firebricks, it may be possible to eliminate most if not all air pollution and CO_2 from industrial manufacturing without the need for carbon capture.

However, combustion heating for industrial processes is deeply ingrained worldwide in industrial facilities today. Little incentive exists for businesses to invest large amounts of capital in firebricks until existing combustion heaters have been naturally retired. As such, incentives and policies are likely needed to affect a transition to firebricks in the time required to address the climate, air pollution, and energy security problems that the world faces. Such time is short. An 80% transition of all energy by 2030 and 100% by 2035–2050 may be needed to avoid sustained 1.5°C global warming (23). An even faster transition is needed to avoid the 7.4 million air pollution deaths that occur each year (23). Based on the findings in this study, installing firebrick storage for industry will benefit a transition in multiple ways.

Methods

Table S2 summarizes the components of the WWS system modeled here. WWS consists of clean, renewable electricity and heat generators, storage devices, electric appliances and machines, and a transmission/distribution system. WWS electricity and heat sources are provided in the Introduction. WWS electricity storage technologies include CHS, BS, GHS, PHS, and CSPS. Low-temperature heat for buildings is stored in water tanks, soil, and water pits. Low- to high-temperature process heat for industry is stored in firebricks. Cold water and ice for cooling buildings is stored in water tanks and ice, respectively. Green hydrogen is produced using electrolyzers running on WWS electricity and stored in tanks for both nongrid (steel and ammonia manufacturing and extra long-distance transport) and grid purposes. Table S21 provides specifications of the hydrogen production, storage, and use technologies.

Building temperatures are controlled with heating/cooling units in individual building or with district heating/cooling systems. Heat pumps running on WWS electricity are used to provide (i) air and water heating, air conditioning, and drying clothes in buildings; (ii) heating and cooling water for district heating/cooling systems; and (iii) low-temperature heat for industry. High- and medium-temperature heat for industry not provided by firebricks come from electric arc furnaces, induction furnaces, resistance furnaces and boilers, electron beam heaters, and dielectric heaters running on WWS electricity. Transport relies on battery-electric vehicles for all but very-long-distance trucks, airplanes, ships, and trains, which run on hydrogen fuel cell-electric propulsion. Electric appliances and machines replace all combustion. For example, electric induction cooktops replace gas stoves (Table S2). WWS electricity flows through alternating current (AC), high-voltage AC (HVAC), and/or high-voltage direct current (HVDC) transmission lines and AC distribution lines.

The study requires the use of three types of models: a spreadsheet model (Note S2) that feeds its output into GATOR-GCMOM (Note S3), a global weather-climate-air pollution model, which in turn feeds its output into LOADMATCH (Notes S4–S7), which is a model that matches demand with supply, storage, and demand response. In LOADMATCH, the 149 countries are combined into 29 regions (Table S1), including 13 multicountry regions (East Africa, North Africa, Southern Africa, West Africa, Central America, Central Asia, China region, Europe, India region, the Middle East, Northwest South America, Southeast South America, and Southeast Asia) and 16 individual countries or pairs of countries

(Australia, Canada, Cuba, Haiti-Dominican Republic, Israel, Iceland, Jamaica, Japan, Madagascar, Mauritius, New Zealand, the Philippines, Russia-Georgia, South Korea, Taiwan, and the United States). Grid analyses are performed with LOADMATCH in each region.

Spreadsheet model

The spreadsheet model (32) is used first to project 2020 energy consumption in end-use sectors (also called total final consumption) from IEA (2) for 149 countries to 2050 in a BAU scenario, and then to estimate nameplate capacities of WWS generators needed to meet such demand in the annual average (Table S8). IEA data include data for each of seven fuel types (oil, fossil gas, coal, electricity, heat for sale, solar and geothermal heat, and wood and waste heat) in each of six end-use energy sectors (residential, commercial, transportation, industrial, agriculture-forestry-fishing, and military-other), and for each of 149 countries (Note S2). The projections (Note S2) are by fuel type, energy sector, and region of the world. They assume moderate economic growth, policy changes by world region, population growth, energy growth, use of some renewable energy, and modest energy efficiency measures.

The spreadsheet model is then used to estimate 2050 reductions in BAU energy demand by country due to converting each fuel type in each end-use sector to electricity, electrolytic hydrogen, or heat, and providing the electricity, hydrogen, and heat with WWS technologies (Note S2). The reductions in end-use demand are calculated with the conversion factors by fuel type and energy sector given in Table S3. Such conversion factors assume the use of vehicles, equipment, and machines running primarily on electricity (Note S2). Overall, about 95% of the technologies needed for a transition are already commercial. Those not commercial include long-distance aircraft and ships, which are proposed to be powered by near-term-technology hydrogen fuel cells (35), and some industrial processes.

Finally, the spreadsheet model is used to estimate nameplate capacities of WWS electricity and low-temperature heat generators that can meet the annual-average demand in each country (Note S2; Table S8). Table S4 provides the 2020 end-use demands, the 2050 BAU end-use demands projected from 2020, and the 2050 WWS end-use demands converted from 2050 BAU demands, for each energy sector in each country.

GATOR-GCMOM

2050 nameplate capacities from the spreadsheet model for most WWS energy generators in each country are input into GATOR-GCMOM (Gas, Aerosol, Transport, Radiation, General Circulation, Mesoscale, and Ocean Model), which is a global air pollution-weather-climate model (Note S3). GATOR-GCMOM is used here to predict wind, solar, and wave production and building heating and cooling requirements at a 30-s time resolution, a 2- by 2.5-degree horizontal space resolution, and a 30-m vertical resolution in the bottom 150 m globally. Output parameters include onshore and offshore near-surface wind electricity supply, rooftop solar PV electricity supply, utility PV electricity supply, CSP electricity supply, solar heat supply for buildings, building cooling demand, and building heating demand in each of 149 countries from 2050 to 2052. The model is initialized under 2050 climate conditions. Wind calculations assume a hub height of 100 m, but turbine blades span multiple model layers (thus heights) in the vertical (Note S3). The model accounts for competition among wind turbines for available kinetic energy in all three spatial dimensions. It also calculates changes in air temperature due to wind turbine extraction of kinetic energy, PV extraction of solar radiation, CSP extraction of solar radiation, and extraction of solar radiation by solar thermal devices. Time- and space-dependent wave electricity output is calculated proportionately to time-dependent offshore wind output. GATOR-GCMOM calculates building cooling and heating demands by comparing modeled temperatures every 30-s time step in each near-surface model grid cell within each country with an assumed comfort temperature for buildings while accounting for building characteristics (Note S3). GATOR-GCMOM output is fed offline into LOADMATCH.

LOADMATCH

LOADMATCH (Notes S4–S7) (3, 24–30) uses GATOR-GCMOM output as input to simulate matching time-dependent electricity, heat, cold, and hydrogen demand (Table S4) with generation, storage, and demand response in each of the 29 regions. LOADMATCH is a trial-and-error simulation model. It works by running multiple simulations for each region, one at a time. Each simulation advances one timestep at a time, just as the real world does, for any number of years. The main constraints are that electricity, heat, cold, and hydrogen demands plus losses, adjusted by demand response, must each meet WWS supply and storage every 30-s timestep of a simulation. The simulation stops if a demand is not met during a timestep. Inputs (either the nameplate capacity of one or more generators; the peak charge rate, peak discharge rate, or peak energy capacity of a storage device; or characteristics of demand response) are then adjusted one at a time after examining what caused the demand mismatch (hence the description "trial-and-error" model). Another simulation is then run from the beginning. New simulations (usually less than 10) are run until demand is met during each time step of the entire simulation. After demand is met once, another 4–20 simulations are generally performed with further-adjusted inputs based on user intuition and experience to generate a set of solutions that match demand during every timestep. From the set, the lowest-cost solution is then selected. Because LOADMATCH does not permit load loss at any time, it is designed to exceed the utility industry standard of load loss once every 10 years.

LOADMATCH is not an optimization model, so it does not find the lowest-cost solution. Instead, it produces a set of low-cost solutions from which the lowest cost is determined. Its advantage is that it treats many more processes while taking orders of magnitude less computer time at a much shorter time step than an optimization model, requiring only minutes to solve multiyear simulations with a 30-s time step (Note S4).

Table S2 summarizes the processes in LOADMATCH. Note S4 describes many of the model's inputs. LOADMATCH treats several electricity storage options: CHS, BS, GHS, PHS, and CSPS (Table S2), with maximum charge rates, discharge rates, storage capacities, and storage times given in Table S14. Note S6 discusses the time-dependent demand profiles, maximum storage sizes, flexible and inflexible demand treatments, and the treatment of demand response in LOADMATCH. Note S7 describes the model's order of operation, including how it treats excess generation over demand and excess demand over generation. Note S7 also provides additional details of how LOADMATCH treats demand response. Once LOADMATCH simulations are complete, energy costs, health costs, climate costs, and employment numbers between WWS and BAU are calculated (Notes S8 and S10), and new land requirements of WWS generators are estimated (Note S9).

Grid stability is obtained in LOADMATCH in at least eight ways (23). These include overbuilding electricity generation, electrifying nonelectricity sectors, storing excess electricity in electricity storage, using excess electricity to produce cold and low-temperature heat that are stored, using excess electricity to produce nongrid hydrogen that is stored, using demand response, interconnecting geographically dispersed and complementary WWS resources on the grid, and importing/exporting electricity when necessary. Table S8 provides an example of the amount of overbuilding needed. It indicates that, on average among all regions, the nameplate capacity of WWS generators required to keep the grid stable continuously was 9.2% larger than that required to meet annual average load. Whereas transmission costs and losses are accounted for, this study assumes perfect transmission within each region simulated. Since the cost of grid stability is only slightly lower when countries or states are islanded vs. interconnected (27, 29), the assumption here of perfect transmission among countries in regions with multiple countries should not impact conclusions.

New treatment of firebricks in LOADMATCH

For this study, firebricks are added as an industrial process heat storage option. The firebrick system in LOADMATCH is largely patterned after that of Rondo (17). Rondo states that firebricks can address 90% of industrial process heat applications. Their RHB300 system has the following characteristics, which are assumed here as well: an energy storage capacity of 300 MWh; a maximum electricity charge rate of 70 MW (AC); a maximum heat discharge rate of 20 MW-thermal (thus 15 h of storage at the peak discharge rate); a maximum depth of discharge of 100%; any number of full charge–discharge cycles within its expected lifetime of ~40 years; a round-trip efficiency of 98% (thus, there is a 2% energy loss converting electricity to heat for storage then using the stored heat to heat a material); and an additional daily heat loss rate from storage of 1%. Stack et al. (15) estimated that the loss rate of heat from heating firebricks that attain a peak temperature of 1,200 °C can be limited to 1.25% per day if the volume of insulating firebricks is 14.5% that of the heating firebricks and that more insulation can reduce losses further. Such insulation comprises only a modest part of a firebrick system cost (15).

Rondo's firebrick battery system assumes the use of external resistance heaters thus assumes a typical temperature range of heat discharge of 80–1,100 °C, with temperatures of up to 1,500 °C, subject to the limitations discussed in the Introduction. Here, we assume that direct resistance heating technology will extend the temperature range for low-cost firebricks to 1,800°C within the next few years (18, 19). This assumption appears reasonable since this study applies to the years 2024–2050. Finally, like with Stack et al. (15), Rondo (17) indicates the cost per kWh-thermal of the firebrick battery system to be about one-tenth the cost per kWh-electricity of a battery system. That assumption is also made here (Table S22).

In both the firebrick and base cases, overall industrial process heat demand is first reduced relative to the data base of IEA (2) due to using green hydrogen for ammonia and steel manufacturing (30). This is because an electrolzyer reduces heat demand vs. a fossil gas steam reformer for producing hydrogen needed for ammonia manufacturing, and hydrogen reduction of iron ore to pure iron during steel manufacturing requires a much lower temperature than does coke or coal reduction.

In the base case, 30% of all resulting industrial process demand is assumed to be inflexible industrial process heat demand that is met immediately with either current electricity or electricity storage (23). The time profile during a day of the electricity demand for industrial process heat is assumed to be the same as that of all electricity demand in the country (Note S6). Industrial process heat demand subject to demand response is then calculated as the total industrial process demand minus the inflexible industrial process heat demand and minus the electricity demand for producing hydrogen needed for ammonia and steel manufacturing. The industrial process heat demand subject to demand response is assumed to be flexible thus can either be met with current electricity or electricity storage or pushed forward in time due to demand response 30-s at a time, but by no more than 8 h. At that point, it becomes an inflexible demand that needs to be met by current electricity or electricity storage.

In the firebrick case here, 10% of the industrial process demand is assumed to be inflexible heat demand that must be met by current or stored electricity. The time profile for that electricity demand is assumed to be the same as that of all electricity in the country. The industrial process heat demand subject to firebrick storage is then calculated as the total industrial process demand minus the inflexible industrial process heat demand and minus the electricity demand for hydrogen needed for ammonia and steel manufacturing. This distribution of total industrial process demand is in line with Rondo (17), who state that ~90% of industrial process heat applications can be met with firebrick storage. The heat demand subject to firebrick storage is assumed to be constant during each hour of each day, since it is assumed industrial plants will prefer a constant source of heat if it is available.

Each time step in LOADMATCH, firebrick storage is used first to satisfy industrial process heat demand subject to storage. If firebrick storage depletes, 50% of the remaining demand becomes an inflexible demand that must be met immediately by current electricity or electricity storage. The remaining 50% can be met either immediately or, if no current electricity or electricity storage is available, be pushed forward in time due to demand response by up to 8 h. After that time, the demand becomes inflexible and must be met immediately; otherwise, a grid failure occurs and the system must be reconfigured. Some industrial loads that can be shifted readily include air liquefaction; induction and ladle metallurgy; water pumping with variable speed drives; and production by electrolysis of aluminum, chlor-alkali, potassium hydroxide, magnesium, sodium chlorate, and copper (36). U.S. National Research Council (37) states that industrial customers have strong financial incentives to engage in demand response: "The ability of industry to cut peak electric loads is a motivator for utilities to incentivize demand response (shifting loads to off-peak periods) in industry" and "In combination with peak-load pricing for electricity, energy efficiency and demand response can be a lucrative enterprise for industrial customers." A sensitivity study (Discussion/Conclusions section) indicates that even if 100% of industrial heat demand becomes inflexible after firebrick storage is depleted, overall energy costs are still less with firebricks than with no firebricks.

Firebrick storage in LOADMATCH is charged primarily with excess WWS electricity. However, firebrick storage competes with other types of storage for excess WWS electricity. Excess WWS electricity is used first to charge battery storage. If battery storage is full, remaining electricity is next used to produce hydrogen that can later be used to regenerate electricity in a fuel cell or for nongrid purposes. If either hydrogen storage is full or the excess power available exceeds the electrolyzer plus compressor nameplate capacity for grid plus nongrid hydrogen, the remaining electricity is used to fill pumped hydropower storage. Only after PHS is filled is excess electricity used, through resistance heating, to fill industrial process heat storage in firebricks. After that, excess electricity fills cold water storage, then ice storage, then hot water tank storage, and then underground thermal energy storage, respectively. Any residual after that is curtailed.

Another source of excess electricity is excess CSP heat. Excess CSP high-temperature heat is first put into CSP thermal energy storage. If CSP heat storage is full, remaining high-temperature CSP heat is used to produce electricity immediately. That electricity, if not needed for current demand, is then used to fill storage in the same order as with excess electricity just discussed, starting with filling battery storage. Hydropower dam storage is filled naturally with rainfall and runoff as described in Note S5.

Firebrick storage is sized such that the maximum power discharge rate of storage equals the annual-average industrial process heat power demand subject to firebrick storage (Table S14). For example, the sum of the maximum firebrick discharge rates among all world regions in Table S14 is 2,142 GW, which equals the summed industrial process heat demand subject to firebrick storage in Table S7a. Process heat demand subject to storage here thus represents ~46.0% of all annual-average industrial power demand across 149 countries, which is 4,653 GW (Table S6), and 24.8% of all annual-average all-sector power demand across the countries, which is 8,628 GW (Table S7a).

The maximum charge rate of firebrick storage (7,497 GW from Table S14) is 3.5 times the maximum discharge rate of such storage (2,142 GW), consistent with the specifications of the Rondo RHB300 heat battery (17). Since storage duration at the maximum discharge rate of the Rondo RHB300 heat battery is 15 h, the storage capacity globally in LOADMATCH is 32.13 TWh-thermal.

Supplementary Material

Supplementary material is available at *PNAS Nexus* online.

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Author Contributions

Conceptualization: M.Z.J.; Methodology: M.Z.J.; Investigation: M.Z.J., D.J.S, Y.F.F, and A.M.; Software: M.Z.J.; Writing—Original Draft: M.Z.J.; Visualization: M.Z.J. and A.M.; Writing—Review & Editing: M.Z.J., D.J.S., Y.F.F., and A.M.

Data Availability

The Supplementary Material and the tables and figures in the main text contain most results. The spreadsheet model used for this study is publicly available online (32). This study did not develop the original GATOR-GCMOM code. The LOADMATCH source code used for this study is available at https://web.stanford.edu/group/efmh/jacobson/Articles/I/CombiningRenew/24-05-03-LOADMATCH.pdf.

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