Title of the Paper: Savings and Avoided Costs of Living Carbon Negative

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Abstract

In order to prevent the biodiversity losses anticipated under business-as-usual (BAU) conditions, and to prevent the associated enormous financial and human losses, the world has to transition to carbon negative economies, where for decades more CO_2 will be sequestered than emitted. To abate and possibly reverse global warming, we need to both transition from fossil fuels to renewables (mainly photo voltaic or PV, solar and wind) and remove CO_2 from the atmosphere (Direct Air Capture and CO_2 Sequestration or DACCS), preferably to levels close to pre-industrial conditions. This means changing the built environment using carbon negative buildings. Renewable energy (RE) is already cheaper than fossil-fuel-based energy, but based on investments needed for electric utilities and due to increased costs (sunk investment in fossil fuel power plants), the price of electricity paid by end users is likely to rise. End users can save on the cost of energy by installing roof PV solar in combination with the use of heat pumps (HP) and electric cars and trucks (E-cars). For the US, savings vary on PV panel orientation, type of HP and car used. For South facing PV panels, using ground source HPs (GSHP) and E-cars, the savings in the levelized costs of energy (LCOE) are 80 percent compared to the combination of using natural gas (NG) for heating, using utility provided electricity and using fossil fuels for transportation. For areas with on average higher prices for electricity, NG and car fuels and lower prices for roof PV solar (the EU) the savings would be larger. Carbon negative building codes are needed to guarantee that all new buildings have good insulation, 100% South facing (or flat) roofs, are fully covered by PV solar and use HPs (preferably GSHPs) for all heating and cooling needs. For existing buildings, codes should require that fossil fuel energy systems are replaced by carbon neutral or negative ones at the end of their economic life. Based on the 20-year economic life cycle of HVAC and hot water systems, this transition can be completed in 20 years. Buildings typically need major renovations about 50 years after construction. At that time roofs can be adapted to be flat or face mostly South. For the US, the total of roof solar electricity produced by all buildings (South PV azimuth) would be equivalent to 2.6 times the electricity sold in the US in 2022. However, due to intermediate and seasonal storage needs, and the H_2 needs (replacing NG), the total electricity used for a US H_2 based RE economy requires 3.8 – 5.6 times the 2022 consumption, depending on the H_2 system efficiencies reached. If all global RE would be generated using PV solar and installed on cropland (using US per capita energy usage), this would cover 39 – 58% of global croplands for an 8-billion population and 49 - 72% for a 10-billion world population. However, agricultural lands are needed to feed the world and installation of solar farms on lands suitable for agriculture is not sustainable since it would lead to deteriorating human conditions. Remaining RE needs can be covered by wind energy (anywhere, including on agricultural lands) and utility scale solar in areas with no agricultural value (deserts) after the IMACS required fraction of the ecoregion is protected for its biodiversity. In 2021 the total US spending on energy was 5.73% of GDP. Using the combination of most cost effective RE and RE using systems (South facing roof PV solar, GSHP and E-cars), this could be reduced to 2.11% % of GDP, saving 3.62% of GDP. This is a conservative number and actual savings could be larger when GSHPs, Very High Temperature HPs and High Lift HPs are applied in the commercial and industrial sectors. These potential savings are larger than the average annual costs of DACCS (0.7 – 1.8% of global GDP) for a return to pre-industrial atmospheric conditions in 40 years. The 3.6% potential GDP savings only result from roof PV solar and not from field mounted utility scale PV solar or wind energy. These savings are not made if electricity users continue to buy the bulk of their power from electric utilities; in the latter case their cost are expected to go up. Based on the average projected costs of DACCS over 25-year, the societal DACCS costs avoided for PV solar systems are larger than their installation cost; 1.1 -1.3 for utility scale PV solar (South facing), 1.8 – 2.0 for E – W facing roof PV solar and 2.4 – 2.7 for South facing roof PV solar. Governments could pay in full for roof PV solar and still create society wide saving of 1.4 -1.7 times the system costs. In order to speed up the rate of roof PV solar installation over the full roof area available, and allow home and other building owners to reap the savings from roof solar systems, net-metering agreements must be extended to apply to “Roof Solar Production & Use Associations”, where association members invest in PV solar on roofs of members and pay no cost to the power distributing utility for the fractions of power sent to and withdrawn from the grid by members. By focusing on laws and regulations that save energy for building owners, investments made towards a RE future are earned back quickly. If not done so, energy costs will become a drag on economies, the transition to a RE future will be slow and cause large biodiversity, financial and human losses that could have been avoided.

Keywords: Sustainability, Sustainable economy, biodiversity, protection, restoration, carbon neutrality, carbon negativity, Carbon capture engineering, Sustainability sciences, international protection of human rights

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1. Abstract

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This is a conservative number and actual savings could be larger when GSHPs, Very High Temperature HPs and High Lift HPs are applied in the commercial and industrial sectors. These potential savings are larger than the average annual costs of DACCS (0.7 – 1.8% of global GDP) for a return to pre-industrial atmospheric conditions in 40 years. The 3.6% potential GDP savings only result from roof PV solar and not from field mounted utility scale PV solar or wind energy. These savings are not made if electricity users continue to buy the bulk of their power from electric utilities; in the latter case their cost are expected to go up. Based on the average projected costs of DACCS over 25-year, the societal DACCS costs avoided for PV solar systems are larger than their installation cost; 1.1 -1.3 for utility scale PV solar (South facing), 1.8 – 2.0 for E – W facing roof PV solar and 2.4 – 2.7 for South facing roof PV solar. 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building owners, investments made towards a RE future are earned back quickly. If not done so, energy costs will become a drag on economies, the transition to a RE future will be slow and cause large biodiversity, financial and human losses that could have been avoided.

2. Introduction

The world economies continue to emit annually increasing amounts of CO_2 *(126)* and atmospheric CO_2 concentration continues to rise *(119).* The resulting anthropogenic global warming in combination with direct anthropogenic wildlife area loss could lead to large losses in biodiversity *(50, 55, 56).* Global warming forces species to migrate to cooler areas in order to survive. With an increasing fraction of areas cultivated and a diminishing fraction of wildlife areas remaining, such species migrations can only have diminishing success rates. The food supply and other ecosystem services available to humans and other species depend on the biodiversity of the ecosystem they live in *(51).* Ecosystem services include water purification, carbon storage, food production (including fertilization), waste degradation, dust collection, water infiltration, wood & fiber production. Compared to the background extinction rates, current extinction rates are about 35 times higher (for vertebrate genera, excluding fishes) to 100 times higher (for vertebrate species) *(55, 56).* For all species extinction rates are about 100 times higher than background rates *(50).* If all currently endangered genera would go extinct by 2100, the extinction rates would be 511 times higher for mammals and 354 times higher averaged over all species compared to background rates *(56).* Biodiversity losses can result in the loss of ecosystem services for which the annual value is estimated at almost twice the global GDP *(51).* Colossal economic losses outsizing all others are thus expected with loss of biodiversity. More than an economic issue, biodiversity loss is an existential issue; humanity and other species alike cannot survive without a biodiverse environment *(8, 9, 10, 52, 53).* Nature cannot support the current and growing human world population even when all ecosystem services were provided. According to the Global Footprint Network and Statista *(63),* humanity would need about five planets Earth if the entire world population would live like some of the richest countries currently do (4.9 for the USA and 4.8 for Denmark). This is based on 2022 data and a world population of 8 billion. For a world population growing to 10 or 12 billion, humanity would need 6 – 7.5 planets Earth based on this metric. The reduction or loss of ecosystem services would likely lead to even larger scale famine, disease and mass migration than exist today, ultimately leading to societal collapse. Both global warming and loss of wildlife area need to be stopped and where possible be reversed. Currently, governments and the society as a whole treat the investments needed to become sustainable as a cost, with little emphasis on the savings and “cost avoided” resulting from actions preventing damage in the first place. Here I address what can be done to stop and reverse global warming and calculate the associated savings and avoided costs.

3. Transition to a Carbon Negative Society

3.1. General

Two types of sustainability can be defined; *“sustainability in the use”* of products or services and “*manufacturing sustainability of products and services”*. The IMAC system *(1 – 7, 138, 139)* determines the manufacturing sustainability of products and services by first measuring all damaging and conserving impacts and then calculates the sustainability value. “Sustainability in use” reflects the impacts created by using the product or service, not the impacts incurred during its manufacturing. As two distinct differences from Life Cycle Analysis for products and services, IMACS includes all environmental impacts from employees along the supply chain and includes human condition impacts. Currently, essentially all products and services have a very low to zero manufacturing sustainability, but can be sustainable in use. The latter applies to building insulation, PV solar panels, geothermal heating systems and electric traction aspects of electric and plug-in hybrid vehicles. Only by using increasingly more products and services that have no or low damaging impacts in their use, the *manufacturing sustainability of products and services”* can gradually improve. To abate and possibly reverse climate change, we need to both transition from fossil fuels to renewables (mainly PV solar and wind) and to remove CO_2 from the atmosphere, preferably to levels close to pre-industrial conditions. This means changing the built environment using carbon negative buildings. This should apply to new buildings (in all aspects), but should include replacement of HVAC and hot water systems in existing buildings by heat pump-based systems at the end of their economic life cycle. In addition, the atmospheric CO_2 concentration needs to be reduced to levels where global warming drops well below 1.5 ^oC or to pre-industrial levels. This can be done using a combination of increased wildlife area and by using direct air capture (DAC) with permanent underground storage (CS) combined under the acronym DACCS. The costs of capturing CO_2 (DAC) from air depend on the process used and are higher for high temperature compared to low temperature processes. For both types of processes, the costs are expected to drop from high values in 2020 to much lower values in 2050 *(16).* Depending on the rate of change, it can take a few decades to centuries to reduce atmospheric CO2 to pre-industrial concentrations. During the first part of this period global temperatures will continue to rise further, leading to higher death rates of (mostly) the elderly due to heat exposure. About 37% of heat related death are caused by climate change *(120),* but deaths due to cold temperatures are much higher *(121),* indicating that buildings should shelter their inhabitant from both too high and too low temperatures. Even in countries where air conditioning is not typically used in homes, such systems should be installed for health reasons and home activity productivity. The energy used by the building and its users, including heating, cooling and electric driving, should preferably be provided by the building itself. This means changing the built environment to one where buildings are well designed, insulated, with an optimal exposure for PV solar and use high efficiency heat pumps for HVAC and hot water. Currently available heat pumps circulating air, used for space heating also provide cooling and can provide hot water heating for little or no additional investment costs. This transition could best be started by the introduction of new sustainability updated carbon negative building codes. For new construction, fossil fuels using heating and tap water equipment should no longer be allowed per building code. For existing buildings, fossil fuel using equipment would need to be replaced by heat pumps upon system replacement. Damage prevention costs less than damage repair. For all IMACS impact groups, damage prevented now leads to lower future cost. This applies to the energy transition from fossil fuel to renewable energy-based system, since faster reduction of CO_2 emissions combined with CO_2 sequestration (C-sequestration) leading to pre-industrial atmospheric conditions, would reverse climate change. This would allow a faster return of snow deposits on mountains and the resulting melt water flows that are currently disappearing. Most importantly, such a return to pre-industrial conditions minimizes biodiversity losses, limits sea level rise and the associated flooding damage, limits the costs of dike system construction and reduces reverse osmosis (RO) water costs. In addition, the transition to renewable energy systems saves money since PV solar and wind energy are cheaper than fossil fuel-based energy *(32).* The financial savings from the transition to renewable energy can be used (in part) to pay for the costs associated with rendering impact variables in the other impact groups sustainable.

3.2. Levelized Costs of Roof Solar Electricity

How do the electricity costs generated using roof mounted PV solar compare to electricity provided by the local utility? Cost of PV solar are strongly a function of the system owner and sector; homeowners (small), commercial and industrial (medium), community solar (large) and utilities scale (very large). Lazard data (US) show solar PV cost in $/MWh range from $117 – 282 for roof-top residential, from $49 - 185 for Community & Commercial and Industrial and from $ 24- 96 for utility scale systems *(32).* For roof top solar, the costs are not only high due to the small system sizes, but also due to the often-non-optimal system azimuths, shade, multiple roof sections and high soft costs (non-hardware). These soft costs represent about half of the system costs for residential systems and about one quarter for utility-scale PV *(34).* Data from the National Renewable Energy Laboratory (NREL) show *(35)* that utility scale PV solar systems cost about 1/3 of residential roof PV solar power systems ($\$/W_{DC}$) (table 3.2). The cost data for different system sizes allows linear cost interpolation. For small roof mounted systems, US prices vary from 2.57 – 2.54 $\$/W_{DC}$ for 4 – 10 kW systems. While ample price data are available for the US, there is a paucity of official and independent price data for solar system costs in the EU. However, a number of PV solar installer organizations price similar sized system at much lower costs. In Germany, 2024 costs for 4 – 10 kW systems vary from 1.2 - 1.5 per €/W (or 1.32 – 1.62 $/W at 1.10 $/€ for Q1 2024) *(68),* while price offers in the Netherlands vary from 1.06 €/W for 8 $/W to 1.24 €/W for 4 kW (or 1.17 – 1.36 $/W at 1.10 $/€ for Q1 2024) *(69).* Table 3.3 shows data on group size and power use for the four US electric power use sectors (Residential, Commercial, Industrial and Transportation). Using sector size and power use per sector, the average power use (in kWh) can be calculated using data from the U.S. Energy Information Administration (EIA) *(36, 37, 38)*. This in turn allows calculation of the PV system size needed to meet the 2022 electricity needed on an annual basis for the average user in each sector. To provide these amounts of electricity on premises using roof or ground mounted systems for the Residential, Commercial, Industrial sectors, their average system sizes are respectively 8.5, 57.1 and 676 kW. However, most buildings have no PV solar installed and where installed, the typical PV system is smaller than needed to provide the current annual electricity needs. In addition, future electricity requirements are much larger to allow conversion from fossil fuel (heat pumps and electric cars) to renewables (mainly solar and wind). An example of an actual residential house system (12.5 kW) is therefore used instead. The phase out of fossil fuel systems and the transition to heat pumps for space and tap water heating will also lead to a higher than current power use for commercial and industrial users, but since such changes can vary strongly for different users, no corrections were made in electricity use for these sectors. Using these PV system sizes, the levelized costs of electricity (LCOE) are calculated for residential, commercial and industrial scale PV solar power and for utility provided power. The Levelized Cost of Energy Calculator | Energy Analysis | NREL *(25)* was used for this calculation (table 3.4). For residential users, costs are calculated for both East-West and South facing panel orientations. For the US, tax rebates for 30% of the PV system costs are available (with smaller "sunsetting" rebate percentages for geothermal systems). Since similar rebates are not available outside the US, the "Zero tax rebate" case is calculated for all cases. For residential PV system owners, the LCOE for PV solar (LCOE$_{PV}$) varies from 7.7 – 14.3 cent/kWh dropping to 5.6 to 7.9 for industrial PV system owners. A number of US states have Solar Renewable Energy Credits (SRECs) whereby qualifying PV solar system owners receive incentives for each MW of PV solar produced. These incentives are auction based (depend on supply and demand) and vary from 12 $/MWh (Ohio) to 395 $/MWh (Washington DC) *(76).* SREC payment policies vary and it is hard to define an "average" case. However, at SREC incentives of 395 $/MWh, a PV solar system would have paid for itself in 4 years by SREC payments alone (ignoring savings from utility payments no longer purchased). SREC payments can thus have a very large effect on the payback period of PV solar systems, but are excluded from the levelized costs of energy calculation for PV solar. The LCOE$_{PV}$ can be compared with the levelized costs of utility electricity (LCUE), both calculated over the next 25 years. For each of the three user categories, the US average utility electricity price for its category is used. The 2022 average electricity prices are the highest for residential users and the lowest for industrial users. However, electricity prices can vary strongly per state. The lowest cost state (Wyoming) has slightly lower prices (8.24 c/kWh) for residential users than the average US industrial user pays (8.32 c/kWh). To compare "low-cost state" LCUE prices with LCOE$_{PV}$, the residential example LCOE$_{PV}$ and LCUE are calculated for Wyoming.

LCUE prices for residential, commercial and industrial users are respectively 24.4, 17.7 and 11.9 cent/kWh and 11.7 cent/kWh in Wyoming. For the residential example using average US utility costs, the costs savings using self-generated PV solar vary from 33 to 63% depending on tax rebate and PV panel orientation. However, for the lowest cost US state, the savings vary from 11 to 33%. Note that the 22% higher cost for PV solar "without a tax rebate" in Wyoming is theoretical, since Wyoming is a US state and all PV systems being installed there can apply for the standard 30% tax rebate. Commercial and industrial systems can be placed or large roof sections with more choice or panel orientation, typically not available to residential roofs. For that reason, the SW or SE panel orientation is chosen as the "average" orientation for commercial and industrial systems *(122).*

The cost savings for using rooftop PV solar vary from 39% (no tax rebate) to 55% (30% tax rebate). Even for the industrial sector, with already low cost of utility power, the cost savings for PV solar vary from 34% (no tax rebate) to 53% (30% tax rebate). For both commercial and industrial PV systems a pure South panel orientation would result in a further 10 to 15% lower LCOE$_{PV}$. As expected, due South facing PV panels have higher costs savings. Hence, cost savings of PV solar versus utility costs of South facing panels in the US are always significant (33% to 64%), even in low-utility cost states. For US states with higher-than-average utility power costs, the savings from PV solar power are even larger. EU countries have on average higher utility electricity prices (0.289 €/kWh, or 0.318 $/kWh at 1.1 $/€), more than twice the US average, with the highest at 0.55 $/kWh for Denmark. 0.52 $/kWh for Germany and 0.47 $/kWh for the UK *(23, 72).* The solar irradiation in Northern Europe in combination with cloudy weather reduces the PV solar panel output (by ~ 40% for Amsterdam compared to Philadelphia). However, the lower system costs per kW installed and the high cost of utility electricity in Denmark, Germany, the UK and the Netherlands (0.35 $/kWh in March 2023 and 0.49 $/kWh in September 2022), and for the EU in general, brings in most cases even larger savings for roof mounted PV solar electricity in the EU compared to the US average.

User Category (b)	System Size 2022 (a) [kW_{DC}]	MSP 2022 (a, b, c) [$\$/\text{W}_{DC}$]	Installation Type	Slope A for Linear Function y = A.x + B	Constant B for Linear Function y = A.x + B	Calculated Value (Check)	Residuals
	Size	**Price**					
Residential	7.9	2.55	Rooftop	-0.0048	2.5878	2.550	0.000
Residential (example case)	12.47		Rooftop	-0.0048	2.5878	2.528	
Commercial	200	1.63	Rooftop	-0.0048	2.5878	1.628	0.002
Commercial	500	1.71	Ground Mounted	-0.000088	1.754	1.710	0.000
Community	3,000	1.49	Ground Mounted	-0.000088	1.754	1.490	0.000
Utility Scale	100,000	0.87	One-axis-tracking				

Table 3.2: PC system costs and linear regression data as function of system size for different user categories. MSP = Minimum Sustainable Price. See *(132)* sheet PVSystemCosts.
(a). All data are based on U.S. Solar Photovoltaic System and Energy Storage Cost Benchmarks, With Minimum Sustainable Price Analysis: Q1 2022 (nrel.gov).
(b). For the residential example case, the 2022 MSP value is calculated using linear regression. Installed system costs for the NREL average residential system in 2018 and 2022 were respectively 3.22 and 3.16 /W (U.S. Solar Photovoltaic System Cost Benchmark: Q1 2018 (nrel.gov)). The actual June 2018 installation costs for the 12.47 kW example system were $ 29,750, or 2.386 $/W and were thus 26% lower than the average 2018 NREL costs.
(c). For Community Solar, no 2022 NEL data were available and the 2023 data are used.

US Electric Power Use Categories (2022 data)	Number of Users in Category (a)	Group Usage [kWh] (b)	Usage per User [kWh]	Average Usage 2022 [kW]	Average Retail Price (c) (cents/kWh)	Total Utility Revenues [$/y]	PV Orientation (d)	Annual kWh produced / kW installed (e)	Equivalent PV System Size [kW]	PV System Costs [$]
US - Residential (average)	139,854,080	1.509E+12	1.08E+04	1,270	15.04	2.2699E+11	Average ESW	1,264	8.5	21,742
US - Residential (example)									12.47	31,523
US - Commercial	19,257,393	1.391E+12	7.22E+04	8,501	12.41	1.7261E+11	Average ESW	1,264	57.1	132,185
US - Industrial	1,049,921	1.020E+12	9.72E+05	114,400	8.32	8.4903E+10	South	1,438	676	1,145,626
US - Transportation	84	6.599E+09	7.86E+07	9,246,648	11.59	7.6482E+08				
All sectors (c)		**3.927E+12**			**12.36**	**4.8540E+11**				

Table 3.3: US electric power data per user group. PV system size and cost are calculated using slope and constants for linear relations listed in table 5.2. See *(132)* sheet Power_Use.
(a) For 2022 data see Electricity data browser - Number of customer accounts (eia.gov).
(b) See EIA Table 7.1_Electricity Overview d.d. 2-13-24. Electricity data browser - Retail sales of electricity (eia.gov) and Electricity generation, capacity, and sales in the United States - U.S. Energy Information Administration (EIA).
(c) See EIA data Electricity data browser - Average retail price of electricity (eia.gov)
(d) ESW stands for the average orientation between East, South and West and thus corresponding with SW or SE.
(e) The ratio "Annual kWh produced / kW installed" is calculated using the PVWatts Calculator (nrel.gov) for the Philadelphia location, as the average for an East-West and South orientation using the "residential example" house.

Levelized Costs of Electricity		**Residential Example - US Average Utility Costs**				**Residential Example - Lowest Utility Costs US State (Wyoming)**				**Typical US Commercial**		**Typical US Industrial**	
Levelized Cost of Energy Calculator | Energy Analysis | NREL		**E - W Orientation**	**E - W Orientation**	**South Orientation**	**South Orientation**	**E - W Orientation**	**E - W Orientation**	**South Orientation**	**South Orientation**	**Average Orientation**	**Average Orientation**	**Average Orientation**	**Average Orientation**
Case		1	2	3	4	1	2	3	4	1	2	1	2
System Data	Units	Value	Value	Value	Value	Value	Value	Value	Value	Value	Value	Value	Value
Size	[kW]	12.47	12.47	12.47	12.47	12.47	12.47	12.47	12.47	62	62	734	734
Orientation		E - W	E - W	South	South	E - W	E - W	South	South	Average	Average	Average	Average
Annual production	[kWh]	12,380	12,380	16,521	16,521	12,380	12,380	16,521	16,521	72,225	72,225	850,113	850,113
Annual production / kWh installed		993	993	1,325	1,325	993	993	1,325	1,325	1,159	1,159	1,159	1,159
Installation Costs	[$]	31,523	31,523	31,523	31,523	31,523	31,523	31,523	31,523	142,644	142,644	1,239,386	1,239,386
Tax Rebate (30%)		0	9,457	0	9,457	0	9,457	0	9,457	0	42,793	0	371,816
NPV of Solar Renewable Energy Certificates													
Net Installation costs after tax rebate		31523	22066	31523	22066	31,523	22,066	31,523	22,066	142,644	99,850	1,239,386	867,571
PV Panel manufacturer's guaranteed lifespan	[y]	25	25	25	25	25	25	25	25	25	25	25	25
Cost replacement inverter (incl. installation)	[$]	3649	3649	3649	3649	3,649	3,649	3,649	3,649	7,224	7,224	62,768	62,768
NREL LCOE Calculator Inputs		**Using US Average Electricity costs**				**Using Electricity Lowest Cost US State (Wyoming)**				**Using US Average Electricity costs**		**Using US Average Electricity costs**	
Period Years	[y]	25	25	25	25	25	25	25	25	25	25	25	25
Discount rate used		0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
Capital costs	[$/kW]	2,528	1,770	2,528	1,770	2,528	1,770	2,528	1,770	2,288	1,602	1,689	1,182
Capacity factor		0.1133	0.1133	0.1512	0.1512	0.1133	0.1133	0.1512	0.1512	0.1323	0.1323	0.1323	0.1323
Fixed O&M Costs	[$/(kW.yr)]	0	0	0	0	0	0	0	0	0	0	0	0
Variable O&M Costs	[$/kWh]	0.01179	0.01179	0.00883	0.00883	0.01179	0.01179	0.00883	0.00883	0.00400	0.00400	0.00295	0.00295
Heat Rate		0	0	0	0	0	0	0	0	0	0	0	0
Fuel Costs		0	0	0	0	0	0	0	0	0	0	0	0
Electricity Price 2022 (utility)	cents/kWh	15.04	15.04	15.04	15.04	8.24	8.24	8.24	8.24	12.41	12.41	8.32	8.32
Cost Escalation Rate		0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.030	0.030	0.030	0.030
Results using NREL calculator													
Levelized Cost of Utility Electricity	[cents/kWh]	21.4	21.4	21.4	21.4	11.7	11.7	11.7	11.7	17.7	17.1	11.9	11.9
Simple Levelized costs of Renewable Energy	[cents/kWh]	14.3	10.4	10.8	7.8	14.3	10.4	10.8	7.8	10.8	7.7	7.9	5.6
PV Cost Savings compared to Utility		33.2%	51.4%	49.5%	63.6%	-22.2%	11.1%	7.7%	33.3%	39.0%	55.0%	33.6%	52.9%

Table 3.4: Levelized costs of utility and roof mounted PV solar electricity for residential, commercial and industrial users (2022 cost basis) using the Levelized Cost of Energy Calculator | Energy Analysis | NREL (Levelized Cost of Energy Calculator | Energy Analysis | NREL). The annual power production for East-West and South orientations are calculated using the PVWatts Calculator PVWatts Calculator (nrel.gov) for the Philadelphia location. See *(132)* sheet "PV LCOE_E".

(Sub) Sector Info			Current fossil-fuel-based energy society			Future renewable energy society							
US Buildings by Type (2022)	**Building Floor Area per unit [m2] (l)**	**Units (h)**	**Electri-city use per unit (2022) [kWh/y] (i)**	**Group electricity use 2022 [kWh/y] (j)**	**Group electricity use 2022 [%] (k)**	**Roof Solar produced per unit [kWh/y] (n)**	**Roof solar produced all units [kWh/y]**	**Roof solar produced all units [%]**	**Electricity use per unit [kWh/y] (r)**	**Electricity use all units [kWh/y] (q)**	**Electricity use all units [%]**	**Roof Solar available to others [kWh/y] (s)**
SFR (255 m2) (a)	255	8.27E+07	11,609	9.60E+11	24.5%	98312	8.13E+12	207%	16,717	1.38E+12	35%	6.74E+12
MFR (209 m2) (b)	209	4.05E+07	11,609	4.70E+11	12.0%	18999	7.69E+11	20%	13,453	5.44E+11	14%	2.24E+11
Other residences (c)	109	6.88E+06	11,609	7.98E+10	2.0%	57283	3.94E+11	10%	13,899	9.56E+10	2%	2.98E+11
Commercial (d)	467	1.93E+07	72,200	1.39E+12	35.5%	55937	1.08E+12	27%	72,200	1.39E+12	35%	0.00E+00
Industrial (e)	1307	1.05E+06	972,000	1.02E+12	26.0%	34095	3.58E+10	1%	972,000	1.02E+12	26%	0.00E+00
Total				**3.92E+12**	**100.0%**		**1.04E+13**	**265%**		**4.43E+12**	**113%**	**7.27E+12**

Table 3.5: Electricity use by sector (excluding transportation) for 2022 and the potentially available roof solar PV electricity for a future RE society. All percentages are expressed using the 2022 fossil fuel-based society energy use as a basis. The future energy use would be 113% of the 2022 base use, while the roof solar produced would be 265% of the 2022 base use. While roof PV solar systems could produce 2.3 times the RE energy needed, the renewable electricity (RE) requirements to produce H_2, methanol of other synthetic fuels, replacing primary fossil fuels and as needed to provide seasonal energy storage, are excluded. For the future renewable energy society, all homes and other buildings are assumed to reflect the energy efficiency of the SFR and MFR modeled. This will not be the case for a variety of reasons; not all buildings will be replaced by efficient new ones, while the above average use of energy intensive appliances and equipment is likely to continue to some extent (electric radiant heat fireplaces and space heaters, oven use for baking, pottery kilns, etc.). The actual future electricity use is therefore likely to be higher than listed in table 3.5. Commercial floor area can be available in dedicated commercial/office buildings (DCB) or in multi-use buildings (MUBs) with office space and MFRs. For the 19,258 million commercial organizations this would correspond to 5036 sqft (467 m^2) per organization *(74).* All DCBs are assumed to have 4 floors and the same 467 m^2/floor projected surface area. All buildings have roof solar with South azimuth on 100% of the roof area. Industrial buildings are assumed to have one floor. Future energy use and PV solar generated for MFR, other residences and commercial spaces are calculated using the MFR model (Case_B). For SFRs the SFR model is used (Case_A). Even after updating the 2021 residences to 2022 estimates (adding growth), the ~ 130 million residences are significantly less than the ~ 140 million residential electricity accounts reported by the EIA. This could be caused by multiple electricity meters in some residences. To prevent a shortfall in calculated electricity use, the average "electricity use per unit" is increased by the ratio of meter accounts / residences. For “Roof Solar produced per unit” and “Electricity Use per Unit” for SFRs and MFRs (see *(134)* sheet “Case_B”). For additional notes and details see *(134)* sheet “Solar Capacity”.

	Residential Sector			Commercial Sector			Industrial Sector			Totals All Sectors		
US Energy Use 2022	**[TWh] [10^{12} Wh]**	**[%]**	**[%]**	**[TWh] [10^12 Wh]**	**[%]**	**[%]**	**[TWh] [10^12 Wh]**	**[%]**	**[%]**	**[TWh] [10^12 Wh]**	**[%]**	**[%]**
Total energy consumed	5,709	100%		4,843	100%		9,109	100%		19,661	100%	
Thermal losses (power plant)	2,214	39%		2,040	42%		1,497	16%		5,750	29%	
Primary energy (heat & transp.)	1,986	35%	57%	1,412	29%	50%	6,592	72%	87%	9,991	51%	72%
Electricity sold	1,509	26%	43%	1,391	29%	50%	1,020	11%	13%	3,920	20%	28%

Table 3.6: US electricity and primary energy use per sector. The ratios of primary energy over electricity used for the residential and commercial sectors are 56/43 and 50/50, but is 86.6/13.4 = 6.7 for the industrial sector *(73, 136).* In the residential sector, all electricity needs and primary energy needs can be met using rood mounted PV solar and heat pumps. This is not the case for the commercial and industrial sectors. Some of the primary energy needs in the commercial and industrial sectors can be replaced by heat pumps, but for high temperature processes, the use of green H_2 is needed *(135).*

3.3. Carbon Neutral Buildings

Buildings differ greatly in their energy use as affected by size, climate region, insulation, HVAC & hot tap water systems installed and the energy needs of its users. Instead of starting with a global picture of a carbon neutral society and scaling this down to individuals, it is easier and more illustrative to start with an example of a carbon neutral building and scale this up to the overall carbon neutral society. I define a building as carbon neutral when it has no direct fossil fuels emissions but instead provides just enough renewable electricity for the building (HVAC) and all other energy needs of its users as withdrawn on premises, including electricity for E-bikes and E-cars. I define a building carbon negative when it produces electricity in excess of its carbon neutrality needs. To minimize both investments and operational costs, carbon neutral buildings need to be well-insulated, have HVAC and hot tap water systems using heat pumps, have building mounted (roof, façade) or on premises ground mounted and building integrated PV solar panels, well oriented to the sun and with a capacity large enough to be carbon neutral for all building and user needs for the average year. A wind turbine owned by the building owner and electrically intergraded with the building (similar to roof mounted solar) would also qualify. The percentage of US detached single family residences (SFR), multi-family residences (MFR) and “other residences” (mostly manufactured/mobile homes) were respectively 64, 31 and 5% of all residences in 2022 *(84).* Recently built SFRs (2022) have an average floor area of about 214 - 234 m^2 *(86, 87).* MFRs exist in a wide range of sizes. Recent (2022) MFR are about 122 m2, while manufactured/mobile homes have an average size of 109 m2 *(85).* No data are available for the total US inventory of SFR, MFR or mobile homes. I will use a new, well insulated carbon neutral$^+$ single-family residence (SFR) (Case Zero) as an example and derive Cases A and B for carbon negative SFRs and MFRs.

Inputs Case A: Single Family Home (SFH)	Value Used	Units	Outputs Case A	Value	Value	Units	%	%
Conditioned basement area	152.03	m2	Conditioned area including basement		407.17	m2		
Conditioned 1st floor area	152.03	m2	Building footprint incl. garage & porch		196.54	m2		
Conditioned 2nd floor area	103.11	m2	Total building envelope		891.42	m2		
Garage area + covered porch	44.51	m2	Building envelope ex basement		684.01	m2		
Wall length basement and 1st floor	71.6	m	Form factor basement & 1st floor		1.452			
Wall length 2nd floor	59.6	m	Form factor 2nd floor (1)		1.467			
Center-to-center floor distance	2.90	m	Heating flux building envelope		24.21	kWh/m2.y		
Roof overhang	0.50	m	Cooling flux building envelope		11.85	kWh/m2.y		
Roof slope	40	degree	Heat. flux building envelope Ex. Basement		31.55	kWh/m2.y		
Annual space heating load	21,579	kWh/y	Cool. flux building envelope Ex. Basement		15.45	kWh/m2.y		
Annual space cooling load	10,567	kWh/y	Horizontal projected roof surface area		224.58	m2		
Annual hot water heating load / user	1,725	kWh/y	Roof surface area at slope		293.17	m2		
Number of hot water users	2.50		PV system size full roof		66.78	kW		
Other home power use per resident	1,197	kWh/y	Number of PV panels full roof		293			
Electrical car miles driven (household)	22,800	miles/y						
Power use per mile	0.31	kWh/mile						
COP HP space heating	5.00		Solar panel orientation	E - W	South		E - W	South
COP HP space cooling	7.71		PV system sized for SFR only	15.16	11.36	kW		
COP HP hot water heating (average)	4.44		Annual PV Power Production	73.666	98.312	MWh/y	100%	100%
Annual PV Production / W installed (E-W)	1,103	kWh/kW	Building Electricity Use	16,717	16,717	kWh/y	22.7%	17.0%
Annual PV Production / W installed (South)	1,472	kWh/kW	HVAC heating	4,316	4,316	kWh/y	5.9%	4.4%
STC power rating PV panel	440	W	HVAC cooling	1,371	1,371	kWh/y	1.9%	1.4%
Surface area per PV panel	1.93	m2	Hot water power use	971	971	kWh/y	1.3%	1.0%
PV Panel output per unit area	227.80	W/m2	Other home power use	2,992	2,992	kWh/y	4.1%	3.0%
LCOE PV East - West Azimuth	0.11	$/kWh	Electric car power use	7,068	7,068	kWh/y	9.6%	7.2%
LCOE PV East - South Azimuth	0.08	$/kWh	Electricity sold to utility or neighbors	56,949	81,595	kWh/y	77.3%	83.0%

Table 3.8: Floor surface area and energy use aspects of Case A single family residence (SFR). Case A reflects the actual single-family home (Case Zero) as used, but with hot water use set to the national average of 2.5 persons per household, E-miles driven set to the US national household average, while the PV system size was increased from 12.45 to 14.61 to meet all energy demands including E-miles for E-W azimuth. The higher PV power production for South orientation is calculated by multiplying the PV power production for E - W (meaning East or West) orientation with the factor 1.318 as found using the PVWatts Calculator *(25, 77).* PV power is fed into and withdrawn from the utility grid using net metering. The annual space heating and cooling loads are based on builder provided Whole House Building Analysis (Manual J-Calculations) and Philadelphia climate data. COP values for HVAC and hot water use were calculated using GEODESGNER software *(24)* and ClimateMaster technical documents. The field loop consists of four vertical 200 ft deep 1.0” ID U-tubes. The loops are operated as two parallel groups of two loops (“twins”) where the two twins are lined up in series and grouted using bentonite clay mixed with carbon flakes to increase borehole conductivity. In addition, the water flow direction through the field loop is reversed with change of season, resulting in partial heat storage and a permanent 3 - 4 °C difference between the “warmer” and the “colder” loops. In addition to a likely conservative calculation approach of GEODESIGNER, higher heat transfer coefficients are expected from serial loop operation. COP values used are estimated based on system capacity, field water flows, entering and leaving water temperatures and the performance data table for the geothermal heat pump (Geo HP) used *(71).* The Geo HP used is a 2 stage ClimateMaster Tranquility® 30 Digital (TE) Series TE 38 with vFlow. Leaving water temperatures allow for year-round use of fresh water without need for freeze protection. HP stages 1 and 2 provide the design heat loads up to respectively – 8 °C and – 18 °C outside temperatures. HP operation at stage 2 was never needed over the 4 years operational period. See *(134)* sheet “Case_A”.

The Case Zero SFR is conditioned to a temperature of about 72 ºF (22 ºC) in winter and 70 ºF (20 ºC) in summer and has a total conditioned floor area of 407 m^2 (4381 sqft) divided over 152 m^2 1st floor, 103 m^2 2nd floor and a 152 m^2 conditioned basement. Most SFR have no conditioned basements. Excluding the basement, the Case A SFR of 255 m2 is slightly larger than the recently built SFRs. The characteristics of the case A home are listed in table 3.8. For carbon neutrality a 14.61 (E-W facing) or 10.95 kW (South facing) PV solar systems is needed assuming 22,790 annual person miles of travel (PMT) per year per household (2022 average) *(22)*. For a 40-degree roof inclination, only 16% (South azimuth) and 22% (E-W azimuth) of the total roof area needs to be covered with solar panels to provide the electric power needed. Comparing electricity use types (using the Case A SFR as an example of carbon negative residential SFRs), electric driving (E-miles) is the largest electricity user (42%), while heating and cooling add up to 35%. Heating and cooling needs will vary between cold and hot climate areas, but using good building insulation and geothermal heat pumps, the annual HVAC power needs will in most cases be less than the E-mile requirements using the US average national person miles of travel. The Case A SFR needs only 16% of its South facing and 22% of its East or West facing roof to meet carbon neutrality needs. In case the entire roof area would be covered with solar panels, the remainder of the energy produced could be used to provide (sell) power to neighborhood users. The Case A SFR has a full basement and an attached garage as is typical for most SFR in the US. For Case A, the basement is conditioned all year. The average heat fluxes for heating and cooling over the entire building envelope are calculated. To allow comparison with buildings without basements, the heat fluxes (expressed as kWh/m^2.y) are also calculated over the building envelope without basement, such that the full heating and cooling loads for the 406 m2 SFR are assigned to above ground exterior surfaces and the ground floor. This creates higher and more conservative unit heat fluxes (see figure 3.1). The Case A SFR has a form factor (here defined as the circumference of a conditioned floor area compared to that of a square floor area) of 1.45 – 1.46. For multi-family residences (MFR), street level parking lots or basement parking is typical, eliminating garage roof area as well as the potential for PV power generation on garage roofs. For Case B, MFRs can be stacked on top of each other as "2 floor residences", using the same 407 m2 floor plan (203.5 m^2 on two floors) in a square layout (form factor of unity), but using the heat fluxes per unit area for above ground (and floor) exterior surfaces for Case A. How many units can be stacked to just use all roof solar produced? The closest total floor area with 0% residual unused PV solar electricity is 403.2 m^2 for a block of 7 stacked two-floor residences and a total of 14 floors (figure 3.2). If the same floor area would be used for single floor MFRs (201.6 m^2 each), the high electricity requirements for E-miles, hot water and other power use, limits the number of MFRs to ~ 8 (figure 3.3). The closest total floor area with 0% residual unused PV solar electricity is 209 m^2 for a block of 8 stacked single floor MFRs. In the US, MFRs have typically less than 8 floors (no statistical data can be found). Limited to 6 floors, for the 403 m^2 MFR, 40 - 55% of the PV roof solar electricity (depending on the azimuth) can be made available (sold) to neighbors participating in an PV solar exchange plan. For the 209 m^2 MFR this would correspond to 0 – 24%. The floor surface areas for these MFRs were only chosen to facility comparing them with the Case A SFR. Combination of 4 to 40 multi-floor MFR blocks (as is currently more typical) would significantly reduce the construction costs. Such larger MFR complexes

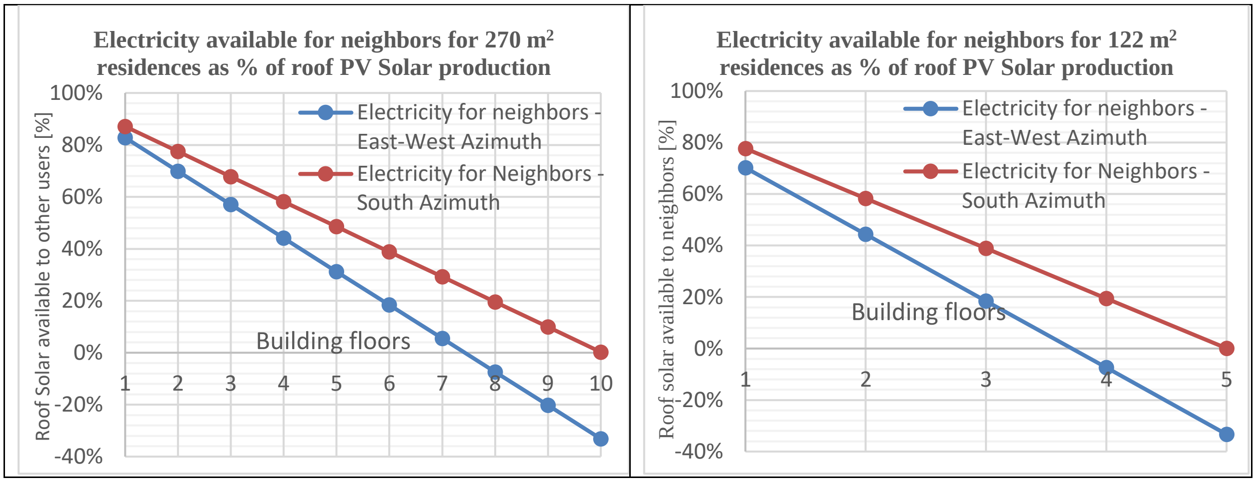

Figure 3.2: Electricity available for neighbors for 270 m^2 (left) and 122 m^2 residences (right) as percentage of roof PV Solar production, for South and East – West solar azimuth. The 2.2 times larger residences have a 2.2 times larger roof area, but the same electricity requirements for E-driving and hot water, allowing twice as many building floors for carbon neutrality *(134)*. See *(134)* sheet "Case_B".

are more affordable, would further reduce the heating and cooling loads per MFR and make more PV roof solar electricity available for neighbors. Since the electricity needs for Case A SFRs and Case B MFRs includes the average car mileage to be driven electric, the combined energy use for driving electric and hot water varies from 48 – 62%, while HVAC varies from 16 to 35%. For well insulated residences, the floor area becomes less important for the energy use, but the associated roof area remains important for the PV solar energy generated. For mixed-use buildings (MUB), combining ground floor stores with upper floor offices and residential spaces, the heating and cooling load would be the same (for same building size, number of floors, window area, insulation and HP use), while the E-miles, hot water requirements and other electricity uses (retail store refrigeration) would be different. However, in general, MUBs would be able to make PV roof solar available to neighborhood users as discussed for MFRs. In the US out of 128.505 million residential units, 81.744 million (63.6%) are single family residences, 39.968 million (31.1%) qualify as multifamily, while 6.793 million (5.3%) qualify as manufactured /mobile homes, trailers, boats, RV or other *(29).* According to an EPA IO-LCA report *(124),* single family homes are estimated to last 50 to 200 years with a more narrowly estimated lifespan between 50 and 70 years. For its IO-LCA study, the EPA study used a service life of 51.6 year as found for a survey for non-residential wooden buildings between 2000 and 2003. Another study indicated factual life spans between 25 – 100^{+} years with the largest group (37% of 227 demolished buildings) to be demolished after 76 – 100 years *(123).* Little is known about the life span of commercial buildings. One non-peer reviewed source reports the age of commercial buildings by end 2023 to vary between 26 and 83 years with an average of 55 years *(30).* Another non-peer reviewed source states that commercial buildings need significant maintenance and upgrades 50 to 60 year after initial construction *(31).* If correct, this would imply that except for historic buildings, residential and commercial buildings are on average demolished within 100 years and undergo major reconstruction within about 50 years. During such major reconstruction, insulation can be brought up to sustainable standards while, roofs can be simplified with mainly South facing sections after which roof PV solar and (geothermal) heat pumps can be installed. The additional energy cost savings using geothermal HPs powered by PV roof solar systems is likely to lead to earlier major renovation. Where such renovation is not cost effective, buildings should be replaced by well-designed and well-sited new buildings. Over time (50 – 100 year) all buildings would be rebuilt or completely renovated meeting new building standards requiring good insulation, mostly south facing roofs, (geo)-HPs for all heating and cooling needs and PV solar panels covering most or all of the sun exposed roofs. The electrical power grids would provide community power sharing at no or very low costs.

3.4. How Much Electricity Can Roof Mounted PV Solar Provide?

The residential and commercial sector used respectively 39 and 35% of all US electricity in 2022. Using the models for SFRs and MFRs, the electricity consumption for SFRs and MFRs is anticipated to increase respectively by a factor 1.44 and 1.15 for the future RE case. This increase in due to the conversion from fossil fuels for heating and transportation by using HPs and E-cars. For office space and hotels, the analogy with MFR would be reasonable, but commercial buildings include high energy users like automated car washes, laundry/dry cleaners, supermarkets with large freezer and refrigeration sections and computer data centers. Comparing these residential with the commercial and industrial buildings sectors (and in this order), the building floor area goes down steeply and the energy use per unit floor area goes up steeply (figure 3.3). Where not yet used in the commercial sector, the electricity needs for heating and cooling could be reduced by replacing fossil fuel heating systems and ICE-cars by air source HP and E-cars and by further upgrading systems to geothermal HPs (including for freezers and refrigeration). Since the extent to which this already took place is unknown, I will add the full primary energy amount used in 2022 as additional electricity used in a RE society for the commercial sector. For the optimum future case of 100% south facing roofs and 100% PV roof coverage, the three sectors would produce 2.6 times the electricity the US used in 2022 (96% from residential). Some of the heating needs of the commercial and industrial sectors can be efficiently met using ASHPs, GSHPs, High Lift and Very High Temperature Heat Pumps (VHTHPs) *(93, 94).* High lift heat pumps use the double acting Stirling cycle, can both heat and cool in the same process and have an operating range of 34 – 183 ^{o}C. Depending on source and sink temperatures, COPs range from 1.7 – 2.6. In an example given they can be used to generate 10 bar steam from low grade waste heat rejected by air conditioning systems *(94).* VHTHPs can deliver heat up to 500 oC and (depending on source and sink temperatures) have COP up to 3.5 *(108).*

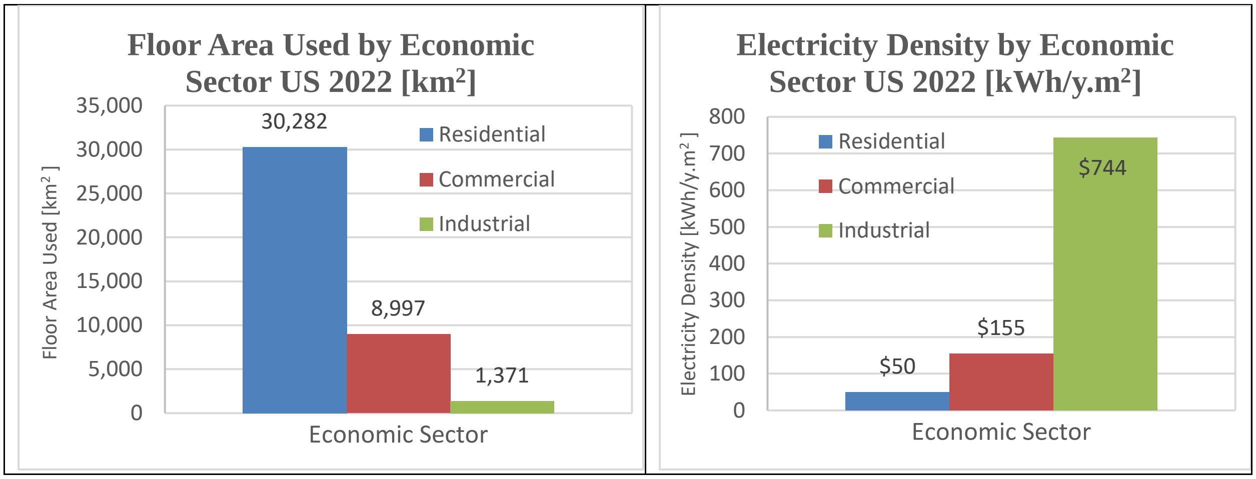

Figure 3.3: US 2022 floor area used by economic sector (left) and energy density (energy used per unit floor area in kWh/y.m^2, left). *(88, 109, 134).* See *(134)* sheet "E-Density".

However, since the fraction of process heat that can be provided by HPs is unknown, I will assume that all primary energy needs for the industrial sector (as per 2022) will be met in the future using green H_2 (produced using RE) and directly used for process heat. In addition to the H_2 needs for process heat, the PV solar electricity generated varies daily, with seasonal variations everywhere (except for locations along the equator). Heating and cooling demands can be roughly in sync (at low latitudes) or very much out of sync (higher latitudes) with the seasonal variations in PV solar. For the Case Zero SFR in the Philadelphia area, the shortfall of PV solar electricity, measured over monthly periods, was 27% for 2020 – 2022, but varies somewhat annually due to varying weather conditions. For a constant monthly electricity demand the seasonal electricity storage is calculated to be 16%. Values of 27% are used for the residential sector and 16% for the commercial and industrials sectors (table 3.9). At low heat pump and roof PV solar installation levels, the excess solar electricity is consumed by neighboring electricity users (lowering power plant production), while the solar shortfall over the winter is covered by additional power plant production. At high heat pump and roof PV solar installation levels and, this is no longer possible. For a RE society, fossil fuel power plants are obsolete and the excess solar electricity needs to be converted to H_2, compressed and stored seasonally and converted back to electricity once needed. For the US, the amount of electricity that need to be converted to H_2 to be used as process heat is twice the US electricity produced in 2022.

Future US Renewable Energy (RE) Use Excluding H_2 Conversion Losses		**Residential [kWh/y]**	**Commercial [kWh/y]**	**Industrial [kWh/y]**	**Total [kWh/y]**	**2022 Elect. Multiple**
2022 US electricity consumption		1.51E+12	1.39E+12	1.02E+12	3.92E+12	1.00
RE replacing 2022 Primary Energy (heat & transport)		4.92E+11	1.41E+12	6.59E+12	8.50E+12	2.17
RE_{Excl} : RE needed (excl. conv. losses)		2.00E+12	2.80E+12	7.61E+12	1.24E+13	3.17
Max roof solar potential		9.08E+12	1.10315E+12	9.157E+09	1.02E+13	2.60
Needed as H_2 fuel (heat and transport)		0	1.41E+12	6.59E+12	8.00E+12	2.04
Seasonal electricity storage as H_2 [%] (4)		27%	16%	16%		
Seasonal electricity storage as H_2		5.40E+11	2.23E+11	1.63E+11	9.26E+11	0.24
$H_{2,\,Excl}$: Total H_2 needed (excl. conv. losses)		5.40E+11	1.63E+12	6.76E+12	8.93E+12	2.28
$H_{2,\,Excl}$ as % of RE_{Excl}		4%	13%	54%	72%	

Table 3.9: Future US RE use excluding H_2 conversion losses based on 2022 consumption. The residential sector roof PV solar provides 2.6 time the 2022 electricity sold. The amount of H_2 needed by the commercial and industrial sectors is twice the 2022 electricity sold. For the residential sector, about 27% of the RE needed annually needs to be stored as H_2 to cover winter PV solar shortfalls for the Philadelphia area. For the commercial and industrial sectors, a constant monthly electricity consumption is assumed resulting in an estimated 16% seasonal storage (Philadelphia area). See *(134)* sheet "Total Energy".

The additional amount of H_2 needed for seasonal storage is relatively small, resulting in a total of H_2 needed equivalent to 2.3 times the 2022 US electricity production. Expressed as a percentage of the RE needed, the total amount of energy to be made available as H_2 is small for the residential sector (4%) but increases to respectively 13% and 54% for the commercial and industrial sectors; overall 72% of all RE must be made available as H_2.

The conversion of electricity to H_2 and back has significant conversion losses, which need to be covered by additional H_2 stored, requiring additional RE. Some efficiency losses can be reduced by better processes, but such improvements are not possible for physical processes like truck or pipeline transport of H_2. Due to the low energy density per unit volume of H_2 compared to natural gas and other fossil fuels at the same pressure *(89),* the transport of H_2 will remain inefficient in comparison, and energy can be more efficiently transported by cable (electricity) than as H_2 by tank or pipeline. H_2 generating electrolyzers and H_2 storage should be installed at location of use like H_2 refueling stations and local energy storage and distribution centers instead of transporting the H_2 there, preventing transportation losses. Even then (and based on current commercially available technology), energy losses of H_2 fuel cell cars add up to 68%, leaving 32% for traction, compared to the 31% loss for EVs, leaving 69% for traction *(89).* Except for heavy trucks driving long distances, driving on H_2 is currently not an attractive or sustainable solution. Based on 2006 process efficiencies for the various process steps associated with the use of H_2, the RE needed for electricity use and H_2 would be about 5 - 6 times the US 2022 electricity produced.

Future US Renewable Energy (RE) Use, Including H_2 Conversion Related Losses	**Loss (1) %**	**H_2 stored [kWh/y]**		**2022 Elect. Multiple**	**Loss (2, 3) %**	**H2 stored [kWh/y]**		**2022 Elect. Multiple**
Starting H_2 amount stored in kWh and %		1.84E+13	100%	4.7		1.13E+13	100%	2.9
AC-DC conversion losses [%] and kWh/y and % left	5%	1.74E+13	95%	4.4	5%	1.08E+13	95%	2.7
Electrolysis losses [%] and kWh/y and % left	25%	1.31E+13	71%	3.3	5%	1.02E+13	90%	2.6
Compression Losses [%] and kWh/y and % left	10%	1.18E+13	64%	3.0	10%	9.20E+12	81%	2.3
Transport/transfer losses [%] and kWh/y and % left	20%	9.41E+12	51%	2.4	0%	9.20E+12	81%	2.3
Fuel Cell losses [%] and kWh/y and % left	50%	8.93E+12	49%	2.3	28%	8.93E+12	79%	2.3
		Energy Used and Stored [kWh/y]	**[%]**			**Energy Used and Stored [kWh/y]**	**[%]**	
Total direct used RE		3.49E+12	16%	0.9		3.49E+12	24%	0.9
Total Energy needed for H_2		1.84E+13	84%	4.7		1.13E+13	76%	2.9
Total RE needed		**2.18E+13**	100%	5.6		**1.48E+13**	100%	3.8
Overall H2 economy efficiency		57%				84%		

Table 3.10: Future US RE use including H_2 conversion and related losses. Using 2006 efficiency estimates *(89),* about 5 – 6 times the 2022 electricity production would be needed for a RE H_2 society. Cars and light trucks are assumed to be E-cars and E-trucks. Heavy trucks are assumed to use H_2 fuel cells. Using the results from laboratory scale efficiency improvement since 2006 *(90, 91, 92)* and eliminating H_2 transport/transfer losses (green highlighted values), this would drop to 4 times the 2022 US electricity production. Fuel cell losses only include losses for utility electricity generation, and thus exclude fuel cell losses in cars and trucks *(98, 134).* See *(134)* sheet “Total Energy”.

These efficiencies remain essentially unchanged per April 2024 and thus reflect the current state of commercial technology. Due to efficiency improvements in electrolyzer and fuel cell technology since 2006 *(90, 91, 92),* and by eliminating H_2 transport/transfers in favor of local H_2 generation and storage, the RE needed for electricity use and H_2 could be reduced from 5 - 6 to about 4 times the US 2022 electricity production (table 3.10). These efficiency gains represent laboratory scale results; no commercial scale electrolyzers and fuel cells with these higher efficiencies are yet built, efficiencies may not be reproduced on commercial scales and the true commercial costs are yet unknown. The US DOE (97) expects significant fuel cell efficiency improvements for heavy trucks by 2030 and later (68 -72%). This would make H_2 fuel cells much more efficient (42%) than diesel engines (~ 30%), but less efficient than E-cars (69%) *(89).* This combination of improved efficiencies, limitation to local H_2 production, storage and use and the use of E-cars would represent a future lowest energy requirement case. The energy losses for conversion to H_2 and back where needed (the H_2 economy), correspond to 43% of the future RE to be generated based on current commercially available technology and could drop to 16% based on recent laboratory scale improvements. In a future H_2 economy, for respectively current and future efficiencies, only 16 – 24% of all RE will be used directly as electricity while 76 - 84% will be used for the conversion to H_2. Roof solar could potentially supply 47 - 69% of all RE needed based on respectively commercially available technology and laboratory scale efficiency improvements, leaving the remainder to be generated using wind power.

3.5. How much land area is needed using only ground mounted PV solar?

Solar and wind power are the two lowest cost renewable energy sources *(32).* Suppose we would use only ground mounted PV solar as renewable energy (RE) source; how much land area would be needed? The total US RE use for a H2 economy (including H_2 conversion losses) and a constant US population was calculated in table 3.10. Under those conditions, the land areas needed in order to meet the RE requirements using only solar farms would require a land area of 200,000 – 300,000 km^2 for the US alone. For solar farm investors it is often attractive to locate solar farms close to urban areas, reducing costs and regulatory hurdles of installing power lines. Solar farms pop up on lands prior used as cropland and meadows. The total global cropland area changes annually due to population growth and market demand for food. In addition, the estimated cropland area varies based on methods used *(75, 102)*. Using the most recent data (2022), the globally available crop area is 12,440,000 km^2 *(75)*. The US solar farm area needed would be equivalent to 1.6 – 2.4 % of global croplands, or 48 – 71% of the land area in the state of California. In order to reduce poverty and improve human conditions globally, the per capita incomes of poor and middle-income counties need to increase. In the ideal case, the average per capita incomes would be globally the same. This would be reflected in a per capita global consumption and RE use identical to high income countries.

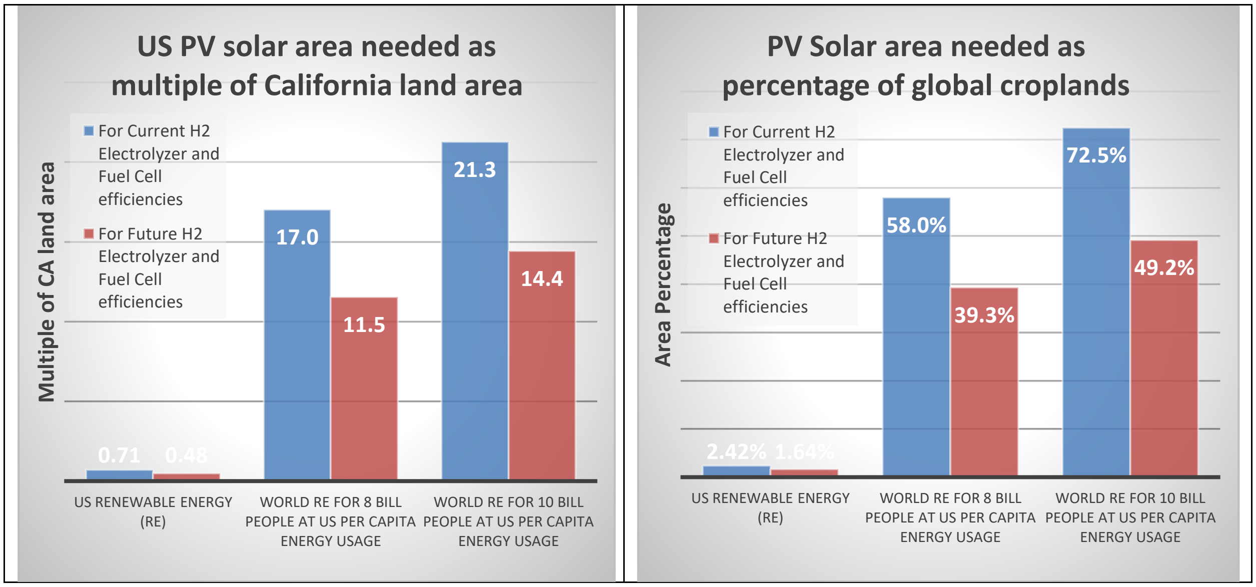

Figure 3.4: Land area needed for a carbon neutral society if all renewable energy (RE) would be provided by PV solar for current and future H_2 electrolyzer and fuel cell efficiencies. The left chart shows total land area needed for solar farms expressed as a multiple of the state of California land area, while the right chart shows the same expressed as a percentage of the world crop land used. For both charts, the left bars reflect US RE needs. The middle and right bar sets reflect the world at US per capita energy use for respectively 8 and 10 billion population. In reality larger areas would be required, to cover additional RE needs for carbon sequestration (DACCS) and reverse osmosis (RO) water. Energy use data and derived RE requirements are based on US data for residential, commercial and industrial floor areas and on Philadelphia weather data (see section 3.4), will vary across the US and the world and are not an accurate average for either the US or the world (136). See *(136)* sheet “PV_Area_2”.

Using the US as the comparator rich country, on a global basis and for an 8 billion world population, the total solar farm area would require 5 to 7 million km^2; equivalent to 11 – 17 times the CA land area or 39 – 58% of all global croplands. This would increase to 14 – 21 times the CA land area or 49 to 72% of the world crop area for a 10 billion world population (figure 3.4). In reality larger areas would be required, to cover additional RE needs for carbon sequestration (DACCS) and reverse osmosis (RO) water. Energy consumption data and derived RE requirements are based on US data for residential, commercial and industrial energy consumption and floor areas and on Philadelphia weather data (see section 3.4), will vary across the US and the world and are not an accurate average for either the US or the world. Even so, the data give an indication that the area that would be needed for PV solar are huge, if all RE energy would be installed as PV solar.

Overnight energy needs for the residential and commercial sector can in most cases be covered by future low costs battery systems, but this will not be the case for seasonal storage. After providing overnight battery storage, for the Case A SFR (Philadelphia area) about 27% of the annual solar electricity needs to be stored (excess power produced in the summer needs to be stored for the winter) if no net metering were available. This will vary greatly with geographic location. In “hot” states, most of the HVAC duty is for AC and little for heating. The PV solar peak, both daily and seasonally, matches well with AC demands and less seasonal storage is needed. The opposite is the case for the northerly contiguous US states and for Alaska, where most energy collected over the summer needs to be stored for the winter season. In addition to the conversion losses, large amounts of electricity are needed for carbon sequestration (DACCS). If these additional energy needs and conversion losses were included, the land area needed would be much larger than shown in figure 3.4. The cultivated area currently used needs to be reduced in order to allow the required increase of wildlife area. According to the Global Footprint Network and Statistica *(63)*, humanity would need about five planets Earth if the entire world population would live like the richest countries currently do (4.9 and 4.8 planets Erath for respectively the USA and Denmark). This is based on 2022 data and a world population of 8 billion. For a world population growing to 10 or 12 billion, humanity would need 6 – 7.5 planets Earth. However, this would not yet account for the space requirements for comprehensive biodiversity protection where the fraction of protected wildlife area would be expanded from 15 to 50% of all terrestrial area. Even without any ground mounted PV solar there will be pressure on existing biodiverse wildlife areas and it will be hard to expand existing areas and protect new areas. Crop and meadow lands are needed to feed the world. A fraction of global farmlands would need to be taken out of cultivated use in order to expand existing wildlife areas and conserve global biodiversity. Farmland can be reduced by consuming less meat, but it will not be easy for consumers to make this change and its effects will in part me muted by a still growing and developing world population. Any area used for ground mounted PV solar on farm and commercial forests lands, puts further pressure on such lands and in turn on wildlife areas and is thus unsustainable, unless the land area under the solar panels can be used for farming without a significant reduction of production. Use of land area below solar panels as farmland (agrivoltaic (AV) systems) can result is almost comparable to improved yields for some crops, while reducing water consumptions and providing shade for livestock *(100).* While spacing between solar panels for AV systems needs to be increased, crop yields were reported to be 80-99% for lettuce (France) and consuming 20% less water, while corn grown in Japan had a 4.9% higher biomass and 5.6% higher yield than grown under full sun conditions. Where the use of AV systems would not significantly decrease crop yield, the use of solar panels in areas otherwise used as cropland or meadow areas would be sustainable. Fortunately, wind power can provide an almost unlimited amount of energy with almost no footprint compared to ground mounted PV solar. With the unsubsidized (2022) costs of on-shore wind power at 24 to 75 $/MWh (versus utility PV solar at 24 to 96 $/MWh) *(32),* and with the need to protect a much larger fraction of almost all ecoregions, there are (with a few exceptions) no long-term benefit but instead ecological damage for utility scale ground mounted PV solar. The exceptions are: AV systems and PV solar farms installed in areas (e.g. deserts) where a sufficient fraction of the ecoregion is already protected as wildlife area and cultivated area is still sustainable available for use as solar farms. This is different for built-up areas, where all new building should be built with South facing roofs and 100% covered with PV solar. The PV area can be expanded drastically by covering streets and squares using a 25 to 50% coverage to allow sufficient light to penetrated ground areas.

3.6. Cost of Carbon Neutral Heating and Cooling Systems

To become carbon neutral, we need to switch from fossil-fuel based heating and power generating systems to heat pumps powered by renewable energy (mostly solar and wind). How much does that cost or save? The investment costs and resulting savings for this transition depend on the costs of the fossil fuels saved, the electricity used and on the installation costs of heat pump (HP) and PV solar systems. For building and hot tap water heating, natural gas is the most used energy source in the US and the EU and will be used here for the fossil fuel case. Nearly 90% of all US homes *(39)* and almost all businesses use air conditioning. Focusing on US residences, 66% use central air conditioning (AC) equipment. HPs can be divided in air source HPs (ASHP) and ground source HPs (GSHP). HP and AC systems use mostly the same type of parts. HPs differ from ACs mainly in one aspect; they have an additional freon reversal valve (retailing at about $ 150) that allows the unit to work in both cooling and heating modes. Both AC and HP systems with cooling mode use the same central air ducting system, which is typically used for both (gas furnace) heating and cooling. GSHP manuals recommend the same air flows for heating and cooling and no ducting changes are needed for HP use if the ducting was properly designed for classic AC systems *(71).* AC and HP systems are available in different efficiencies and at different prices, but compared at the same coefficient of performance (COP) and the same reliability (quality), their prices should not differ significantly in a competitive marketplace. For the cost comparison I will assume that the equipment and installation costs for high efficiency versions of AC + gas furnace, ASHP and GSHP are the same *(125).* GSHPs are designed to fit in the same spaces used for classical gas furnace, circulation blower and AC evaporator. Typically, if any, only minimal ducting changes are needed. These costs are small compared to the new system costs and are ignored in the cost evaluation. For geothermal GSHPs the transitional costs are different; in addition to the actual GSHP, GSHP systems extract heat from the ground, which requires a field loop with (typically) circulating water. Unless already present (GSHP replacement), this field loop needs to be installed. For new construction using full basements, horizontal field loops can be installed at little additional costs (~ $2500 total) when integrated with pouring of the foundation footer for the basement *(127).* However, this is typically only an option for new single-family residences with sufficiently large building lots. For existing buildings or small lots, vertical field loops (≥ 60 m deep) with one U-tube per bore are a better option. Competitive cost for installing vertical field loops in loam and sand in Delaware (2020 price level) are about $2000 per 60 m deep U-tube *(40),* but prices are likely to vary per state and even county and are strongly a function of competition. Drilling in rock will be more expensive *(129)*. For a well-insulated residence (Case A) of 407 m2 (including conditioned basement), 3 to 4 loops are needed. Larger and less well insulated residences need larger field loop systems. An undersized or otherwise less well-designed field loop system may require the use of antifreeze and will lead to underperformance and higher operating costs. While around for a long time (invented in 1857), GSHP systems are still considered a “luxury item”, with insufficient competition, and the range for price quotes for residential systems can be large. The levelized cost of thermal energy from the field loop are calculated for a vertical field loop system in sand/loam using a 50-year life time, resulting in costs of 0.0035 $\$/kWh_{th}$ which drops to 0.0025 $\$/kWh_{th}$ after application of a 30% tax rebate (US only). These costs are about ten times lower than the costs of utility scale wind and solar. While wind and solar farms can produce electricity at costs lower than produced by fossil fuel power plants, end-use consumers do not benefit from this. In most cases consumers cannot chose what type of electricity they want to use and even if they can, the prices of renewable energy types are about the same as for fossil fuel-based electricity. In order to benefit from the low cost of renewable energy, end-users need to install PV solar on roofs or ground mounted racks (or have wind turbines) on their premises. Roof mounted solar is in most cases the most practical and lowest cost option. The end user cost of roof mounted solar in turn depends on latitude, cloud cover and azimuth of the PV system. The costs of heating and cooling are compared for three scenarios:

#	System Type	Energy Source	Costs [$/y]	Relative Costs to #18	Relative Costs to #1	CO_2 [kg]	Relative CO_2 to #18
1	Geothermal HP	PV, South facing, 30 % tax rebate	566	20%	100%	0	0%
2	Geothermal HP	PV, E - W facing, 30 % tax rebate	732	25%	129%	0	0%
3	Air Source HP	PV, South facing, 30% tax rebate	747	26%	132%	0	0%
5	Geothermal HP	Utility, 30% tax rebate, Lowest Cost State	815	28%	144%	5,322	79%
7	Air Source HP	PV, E - W facing, 30% tax rebate	996	35%	176%	0	0%
10	Air Source HP	Utility, Lowest Cost State	1,120	39%	198%	7,979	119%
12	Geothermal HP	Utility, 30% tax rebate, US Average	1,435	50%	253%	2,497	37%
14	Air Source HP	Utility, US Average	2,049	71%	362%	3,743	56%
15	Natural Gas	NG, electric HW, lowest cost Utility electric	2,201	76%	389%	8,230	122%
16	Natural Gas	NG all heat and lowest cost Utility electric	2,518	87%	445%	8,406	125%
17	Natural Gas	NG, electric HW and average Utility electric	2,682	93%	474%	6,039	90%
18	Natural Gas	NG all heat and average Utility electric	2,885	100%	510%	6,730	100%

Table 3.11: Annual costs for home heating and cooling for Case A SFR over the 25-year system life of PV solar and HP systems calculated using the levelized cost of energy. Annual US costs for heating and cooling and CO_2 emissions using GSHP and ASHP, powered by PV solar or utility electric are compared to systems powered by natural gas for heating and utility electric for AC. Installation costs for the three types of systems, GSHP (without field loop), ASHP and natural gas with AC systems are assumed to be the same. Natural gas prices for residential US consumers have historically fluctuated, but increased between 1970 and 2022 from 1.09 to 14.75 $ per thousand cubic feet *(129)* corresponding to an average annual cost increase of 5.14%; well above inflation. To be conservative for calculations used, natural gas prices are assumed to rise no more than 3% per year over the next 25 years, leading to a levelized cost of natural gas (LCNG) of 21.34 $ per thousand cubic feet over the next 25 years. For PV solar systems, the 30% tax rebate option is applied to the PV solar system cost as part of the calculation of the $LCOE_{PV}$. For GSHP systems the tax rebate option is only applied to the field loop system as part of the calculation of the $LCOE_{TH}$ for the thermal energy extracted from the ground. Cases without CO_2 emissions are highlighted in green *(132)*. See *(132)* sheet “GeoPV_Summary”.

A. Natural gas scenario, using natural gas (NG) for space and hot water heating and utility electricity for AC.
B. Air source heat pump (ASHP) scenario, for space heating & cooling and using ASHP hot water heater.
C. Geothermal heat pump (GSHP) scenario, for space heating & cooling and using ASHP hot water heater.

In total eighteen scenarios are evaluated of which six have tax rebate options.

The eighteen cases are compared with their results distributed over two tables; table 3.11 including 30% tax rebate cases reflecting the US and table 3.12 excluding tax rebate cases, reflecting other countries. The results for the three scenarios show that GSHP systems provide the lowest cost option when powered by South facing roof PV solar systems. Using GSHPs with East – West facing PV solar systems increases the costs by 29%. The costs for classic natural gas heating using utility electric AC (case 18) are 3.7 (no tax rebate case) to over 5 times higher (30% tax rebate) compared to the lowest cost GSHP option. Using the highest efficiency ASHPs available and powered by roof solar, the cost of heating and cooling using ASHPs are 32 – 76% higher compared to the lowest cost GSHP options. Using US average costs of electricity, heating and cooling using GSHPs is 86 – 153% more expensive than using South facing PV solar. Using US average costs of electricity, heating and cooling using ASHPs is 162% more expensive than using GSHP with South facing PV solar. Using the lowest cost utility electricity Wyoming), the costs of heating and cooling using GSHPs is 7 – 44% more expensive than South facing PV solar and still has 79% of the worst-case CO_2 emissions. None of the GSHPs or ASHPs using utility electricity are sustainable due to the CO_2 emissions, unless these emissions are immediately and fully neutralized by CO_2 sequestration.

#	System Type	Energy Source	Costs [$/y]	Relative Costs to #18	Relative Costs to #4	CO_2 [kg]	Relative CO_2 to #18
4	Geothermal HP	PV, South facing, No tax rebate	783	27%	100%	0	0%
6	Geothermal HP	Utility, No tax rebate, Lowest cost utility electric	841	29%	107%	5,322	79%
8	Geothermal HP	PV, E - W facing, No tax rebate	1,007	35%	129%	0	0%
9	Air Source HP	PV, South facing, No tax rebate	1,034	36%	132%	0	0%
10	Air Source HP	Utility, Lowest cost utility electric	1,120	39%	143%	7,979	119%
11	Air Source HP	PV, E - W facing, No tax rebate	1,369	47%	175%	0	0%
13	Geothermal HP	Utility, No tax rebate, US average utility electric	1,460	51%	186%	2,497	37%
14	Air Source HP	Utility, US average utility electric	2,049	71%	262%	3,743	56%
15	Natural Gas	NG, electric HW, lowest cost utility electric	2,201	76%	281%	8,230	122%
16	Natural Gas	NG all heat and lowest cost utility electric	2,518	87%	321%	8,406	125%
17	Natural Gas	NG, electric HW and average utility electric	2,682	93%	342%	6,039	90%
18	Natural Gas	NG all heat and average Utility electric	2,885	100%	368%	6,730	100%

Table 3.12: Table description as for table 3.6 but without 30% tax rebate (reflecting non-US cases). Cases 6, 10, 15 and 16 reflect countries with low-cost electricity and high CO_2 emissions per kWh comparable to Wyoming. Cases 13, 14, 17 ad 18 reflect countries with cost of utility electricity and CO_2 emissions per kWh comparable to the US average *(132).* See *(132)* sheet "GeoPV_Summary".

3.7. GDP Savings from Transitioning to Carbon Negative Buildings

The total 2021 US expenditures on primary energy and electricity represent 5.65% of the US GDP (table 3.13). The total economy is divided in four sectors: residential, commercial, industrial and transportation. The transportation sector represents all transportation used by the first three sectors. In table 3.13 the transportation expenditures are divided among the first three sectors *(107).* Including transportation (but excluding aviation) the residential and commercial sectors expenditures on primary energy and electricity correspond to respectively 2.83 and 1.29%. Most of the heating needs of the commercial sector and for some of the industrial sectors can be efficiently met using ASHPs, GSHPs, Very High Temperature Heat Pumps (VHTHPs up to 200 °C) *(93)* and High Lift heat pumps (up to 550 °C) (*94, 108, 118).* For the residential sector an 80% reduction in the cost of energy is possible using GSHP and South facing PV solar. This could save 2.26% of GDP. The commercial sector uses less than 1/3 of the residential floor area and it is not clear which fraction is temperature conditioned. As a conservative approach I could assume that only the savings resulting from South facing roof PV solar could be claimed (at 50%). The same approach could be followed for the industrial sector. That would lead to a combined 1.36% GDP savings, bringing the total to 3.62% of US GDP. This percentage will be larger if savings due to the use of GSHPs, High Lift HPs and VHTHPs and savings in the transportation (driving electric or on H_2) for the commercial and residential sectors, are included. While the current costs of green H_2 are estimated to be 3 - 7 $/kg with *(113),* the costs are expected to drop to around $ 1.50/kg by 2030 *(110, 111)* and possibly drop below $ 1/kg by 2050 *(112).* With a caloric value of 39.2 kWh/kg, H_2 prices of $ 1.50/kg and $ 1/kg correspond to 0.038 and 0.026 kWh/kg. Compared to 2021 prices for natural gas at $ 0.039/kWh *(115)* and fuel oil at $ 0.028/kWh *(116),* green H_2 would become competitive with both after 2050. For cost of H_2 comparable to natural gas after 2050, the spending on energy as percentage of GDP would remain the same or lower, but would be higher until the parity pricing is reached. In combination with the growing demand for electricity (between 3.8 – 5.6 times the 2022 US sales see table 3.10), the latter could mean that potential energy savings using roof solar and GDHPs might save more than the above 3.62% of GDP.
Expressed as percentage of income, the spending on energy represents 31%, a very high percentage, especially compared to the 3.0% of income spent on energy in the residential sector. Comparing the three sectors, the commercial sector has the highest current energy spending as percentage of income (31%). For 50 – 80% energy savings, the savings would correspond to 16 – 25% op profits.

Spending on Energy, US 2021 (Million Dollars)	**2021 Income or profits (3) [Mil $]**	**Primary Energy Ex Transportation**	**Primary Energy Transportation Ex Aviation**	**Electricity**	**Aviation**	**Total Spending [Mil $]**	**Total Energy Spending as % of Income (3)**	**Total Energy Spending as % of GDP**
Table E10. Residential Sector Expenditure Estimates, 2021	21,410,000	81,407	368,464	200,834		650,705	3.04%	2.79%
		12.5%	56.6%	30.9%		100.0%		
Table E11. Commercial Sector Expenditure Estimates, 2021	949,972	49,994	97,382	149,008		296,384	31.20%	1.27%
		16.9%	32.9%	50.3%		100.0%		
Table E12. Industrial Sector Expenditure Estimates, 2021	1,860,028	162,956	96,448	68,816		328,220	17.65%	1.41%
		49.6%	29.4%	21.0%		100.0%		
3-Sector Totals Excl. Aviation & Transp. Sector Electricity		**294,357**	**562,294**	**418,658**	**0**	**1,275,309**		**5.47%**
Aviation & Electricity for Transport Sector				646	41,143	41,789		0.18%
3-Sector Totals Incl. Aviation & Transp. Sector Electricity		**294357**	**562294**	**419304**	**41143**	**1317098**		**5.65%**
		1.26%	2.41%	1.80%	0.18%	5.65%		
Other	-910,000							
US GDP 2021	23,310,000							

Table 3.13: US 2021 spending on energy based on EIA data. All transportation section spending is divided over the three other sectors by assigning all gasoline sales to the residential sector and all diesel fuel sales to the commercial sector *(107).* The "Total Energy Spending as % of Income" reflects the taxable income; gross revenues after deduction of tax-deductible costs before taxation. Note the high spending of the commercial sector on energy expressed as a percentage of profits *(130, 137).*

3.8. Value of CO_2 Emissions Avoided

Direct air carbon capture and storage (DACCS) is an essential tool to limit global warming to 1.5 degree or less. *(41).* Large scale DACCS facilities (≥ 1 million tCO_2/y) are currently under construction *(129).* Many thousands of such facilities are needed to capture the CO_2 amounts needed to keep global warming to less than 1.5ºC. For each additional facility added, the CO_2 captured and stored will need to be purchased by businesses and governments (the "society"). This is not only needed to minimize loss of biodiverse wildlife areas and the ecosystem services they provide, but is also cost effective, since the costs to society for the *"business as usual"* (BAU) scenario are much higher than for cost prevention *(83, 129).* While the DACCS costs are expected to fall drastically over the next 20 years, they are currently still very high. Fasihi *et al.* (2019) estimated the costs of DAC for 2020, 2030, 2040 and 2050 for different process types (high versus low temperature) and for conservative and base case scenarios *(16).* However, the DAC costs estimated do not include costs for CO_2 transportation (4.4 – 14 \$/tCO_2) *(16),* permanent underground storage (~ 10 \$/tCO_2) *(16)* or a profit margin. Including transportation and long-term storage costs at 9 and 10 €/tCO_2, a 20% profit margin and conversion to dollars at the 1.33 \$/€ exchange rate used by Fasihi *et al.* (2019), the DACCS prices paid by buyers are calculated for the same years (table 3.14). PV solar systems producing electricity avoid the CO_2 emissions that would otherwise be generated by fossil fuel power plants. Each ton of CO_2 not emitted due to the use of renewable energy, reflects the cost avoided at the time of energy production. Using linear regression for the six price development cases, the DACCS price per ton of CO_2 can be estimated for each year of the 30-year period. This in turn allows the estimation of average DACCS price for an equal weighted mix of

Year	**HT DACCS CS [$/tCO₂]**	**HT DACCS BS [$/tCO2]**	**LT DACCS CS $/tCO2]**	**LT DACCS BS $/tCO2]**	**LT DACCS CS - FH [S/tCO2]**	**LT DACS - BS - FH [$/tCO2]**
2020	458.1	458.1	384.6	384.6	242.6	242.6
2030	242.6	207.5	197.9	164.4	126.1	92.6
2040	175.6	145.2	140.4	114.9	94.2	68.6
2050	143.6	116.5	116.5	91.0	81.4	55.9

Table 3.14: Levelized costs of DACCS calculated from Fasihi *et al.* (2019) *(16)* after addition of transportation (at 9 €/tCO_2), permanent underground storage (at € 10/tCO_2) and a 20% profit margin. HT and LT stand for respectively the high and low temperature processes used, CS stands for conservative scenario, BS stands for base scenario, FH stands for free waste heat available *(134).* See *(134)* sheet "DACCS 4-Pt").

all price development cases over the 30-year period. This average DACCS price can be used to estimate the costs avoided for each ton CO_2 not emitted due to the use of renewable energy. The 2022 fraction of buildings where all heating took place using ASHPs is very small and the fraction using GDHP is even smaller. The fraction of utility electric used to charge electric cars in 2022 was also still very small. The fraction of utility scale PV solar electricity used for building and hot water heating is very small and hardly any of the CO_2 emissions avoided due to HPs

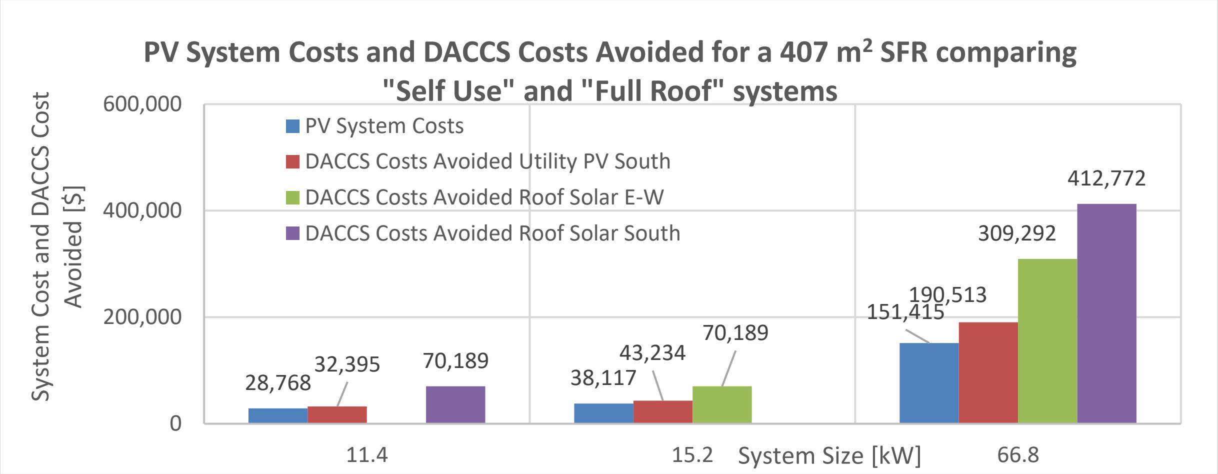

Figure 3.6: The chart shows the costs of 11 - 67 kW PV systems installation and the value of CO_2 emissions avoided (DACCS) for roof mounted system installed on a 407 m^2 single family home (SFR) (255 m^2 discounting basement), over the 25 year system lifetime. For systems just large enough to provide all SFR and EV power, the CO_2 costs avoided are the same, but the system size is smaller for a South azimuth. For the full roof system (66.8 kW), excess PV power is sold to neighbors under a *"community production and use agreement"*. These neighbours are assumed to live in similar energy efficient SFHs and driving EVs, and have therefore the same CO_2 emissions prevented per kWh used, but without PV solar panels on their own roofs (insufficient roof area, shade, unfavorable azimuth). The DACCS cost avoided for average use of utility PV power are 1.1 - 1.3 times as large as the installation cost of roof mounted PV systems. For roof mounted systems used to power energy efficient carbon neutral or carbon negative MFRs, the DACCS costs avoided are 1.8 - 2.0 (E - W azimuth) and 2.4 - 2.7 times the PV system costs (South azimuth).

and E-cars can be assigned to utility scale solar; I will ignore this fraction by setting it to zero. This is different for energy efficient carbon neutral or carbon negative buildings, where in addition to the CO_2 emissions avoided by using roof PV solar electricity for "classic" electricity uses, additional CO_2 emissions are avoided by no longer using fossil fuels for building and tap water heating and for E-cars. Figure 3.6 shows the PV systems costs and the DACCS costs avoided for the Case A SFR with a system size to only provide enough energy for the SFR itself and for a PV system using the entire roof area. Comparing azimuths, the same energy is used by the SFR, but a larger systems size (15.2 versus 11.4 kW) is needed (and larger system costs result) for East or West azimuths. The ratio of DACCS costs avoided over system costs is 1.8 – 2.0 for E-W and 2.4 -2.7 for the South azimuth.

In case the entire roof is covered with PV solar panels, the electricity produced by the roof mounted PV system, but not used by the SFR itself (the excess), can be purchased by neighbors. In case the neighbors live in similar insulated and GSHP conditioned residences and drive EVs, but lack roof PV systems (insufficient roof area, shade, unfavorable azimut) the ratio of DACCS costs avoided over roof PV system costs are 2.0 for East and West azimuths and 2.7 for South azimuths (right section of 66.8 system size bar charts in figure 3.6). In case the neighbors live in homes still using fossil fuels for heating, less CO_2 avoidance can be claimed and all CO2 emission avoidance of excess SFR electricity should be treated as for utility solar (the red bars in figure 3.6). Depending on the PV array azimuth, the ratio of DACCS cost avoided over roof mounted PV system costs are 1.9 to 2.8. Similar values are found for MFRs (figure 3.7). For new construction all PV systems could be desigend with South azimuths resulting in a the ratio of DACCS cost avoided over roof pmounted PV system costs of 2.5 – 2.8.

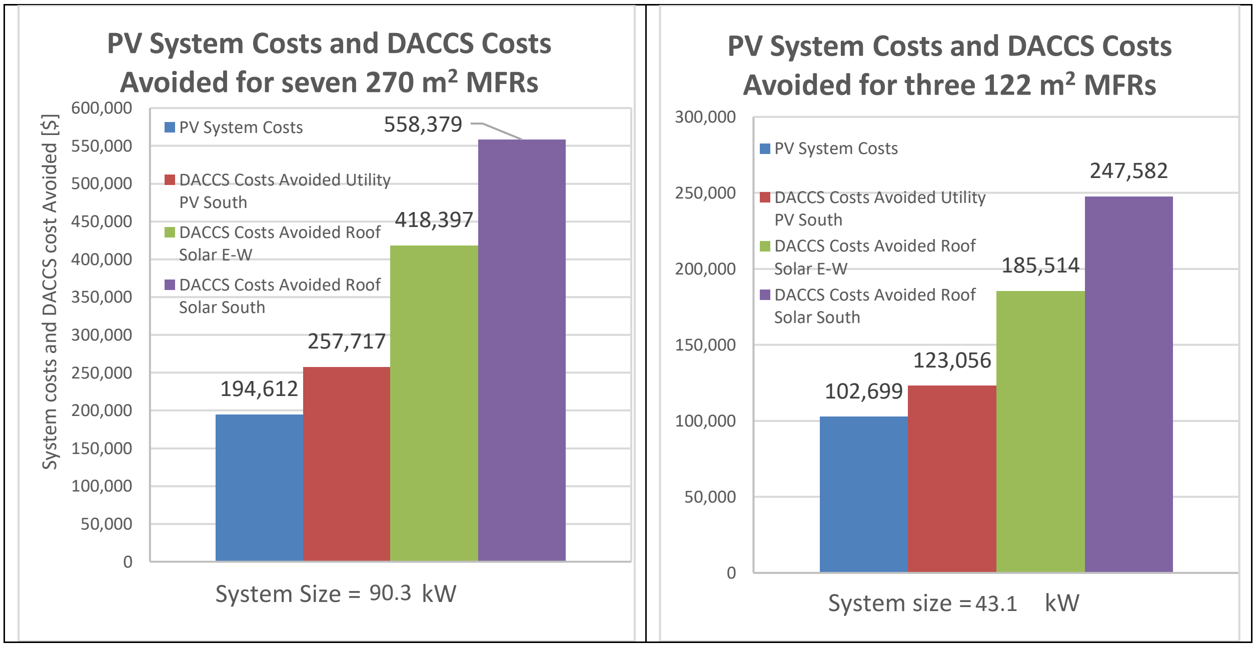

Figure 3.7: The left chart shows the costs of roof PV system installation and costs of CO2 emissions avoided over the 25-year system lifetime for the Case B MFR with five 257 m^2 MFRs above each other. For systems just large enough to provide all MFR and EV power, the CO_2 costs avoided are the same, but the system size is smaller for a South azimuth. For the East-West azimuth system, all roof overhangs need to be extended (by about 88 cm) to allow for the larger PV system. The DACCS cost avoided for the average use of utility PV power are 1.3 times the installation cost of roof mounted PV systems. For roof mounted PV systems used to power energy efficient carbon neutral or carbon negative MFRs, the DACCS costs avoided are 2.1 (E - W azimuth) and 2.8 times the PV system costs (South azimuth). The right chart is similar the left chart, but applies to the Case B MFR with eight MFRs of each 127 m2. The ratio of DACCS costs avoided over installed PV system costs over 25-year are 1.3 for utility scale PV (South azimuth), and 1.9 (E - W azimuth) to 2.5 for (South Azimuth) for roof solar.

3.9. Neighborhood Power Sharing at No Additional Grid Costs

For new developments, all residential and commercial building can (and should) be built carbon negative using roof PV solar and heat pumps. For a 50 – 100-year building life, new construction would correspond to 5 – 10% of buildings. For the exiting building inventory, buildings either need a major energy overhaul (wall insulation, new windows, HPs and roof PV solar) or need to be rebuilt. The typical urban area will thus be a patchwork of new of renewed carbon neutral and carbon negative buildings in an environment of older energy inefficient carbon emitting buildings. A delayed or slow implementation of this urban renewal process will lead to higher global warming induced economic damage due to increased biodiversity damage *(129)*. The average life span of HVAC systems is about 20 years. It would make sense to replace each system at the end of its life cycle with a combined HP and PV solar systems such that the building becomes carbon neutral/negative especially since that reduces the buildings levelized cost of energy by a factor 3 to 5. That would correspond to growth rates of roof PV solar and HP installation much higher than historical rates. The only way to do that is to reduce the costs for building owners in every aspect possible. The factor 3 to 5 reduction in the cost of energy can only be reached by using roof PV solar, since the energy costs for using utility power are 2.6 to 3.6 times higher than for PV solar with a south azimuth (see tables 3.5 and 3.6). Residences and other buildings in built-up areas with no or insufficient South or East -West facing roof area need access to low-cost roof PV solar at the same costs per kWh as for owners of PV solar roofs with South or East -West azimuths. The only way this can be done is to create *"Roof Solar Production & Use Associations"*, (RSP&UAs) where electricity can be transferred free of cost via the local electricity grid. Net-metering agreement policies need to be extended to groups of building owners who co-own PV solar systems on their homes, without any charge for the amounts fed in or out. This would allow building owners with unfavorable roof azimuths (many older buildings) or in the shade of taller buildings, to invest in and use PV solar electricity at the same low cost as for buildings with favorable oriented roofs. *"Roof Solar Production & Use Associations"*, would invest in PV systems on their association member roofs and give their member access to fractions of the power generated. These lower costs would allow them to more quickly earn back investments in building insulation and geothermal HP systems and would accelerate the conversion towards a carbon neutral society, saving costs for the society as a whole. Except for the changed software required, there would be no additional costs for the electricity distributor. RSP&UAs are different from "Community Solar Associations", where the gird operator charges the usual electricty price but applies a cost reduction. In the latter case the energy savings are reported as 5 – 20%, much less than the levelized costs of roof PV solar of 50 – 64% (see table 3.4). Laws and policies need to be changed to facilitate such cost free use of the power grid between RSP&UA members. In addition to the direct costs savings for residential and commercial users, roof mounted PV solar systems also reduce the investment for street power cable upgrades, since a large fraction of the solar power produced on a sunny day is consumed by the neighbors (both RSP&UA members and others) compared to remote utility scale solar and wind farms for which no large fraction of electricity can be used by local neighbors due to their remote location. Within neighborhood PV power generation thus saves money for the collection of electricity grid owners, compared to the same amount of electricity fed in via remote utility scale solar and wind farms. Compared to grid connected remote utility scale PV and wind farms, peaks in the power generated by residential roof PV systems are shaved off, by the producing residences and by neighborhood users and reduce "grid congestion". In contrast to popular belief, the same applies to electric car with power to grid functionality (PTG). Under time variable pricing (TVP), E-cars with PTG functionality can discharge their electricity to the grid during hours of peak demand and recharge at time of low demand. TVP and can be combined with smart grid electricity users (laundry dryers, washing machines and dishwashers) for which the program start can be delayed to a time with lower power costs. Electric car owners would get paid more for electricity charged into the gird at high demand (and cost) hours than they are paid at low-cost hours. According to a recent study *(33),* at higher levels of participation and higher utilization rates all short-term (4-hour) power storage needs can be met by 2030, while by 2040-2050 all power needs can be met even at lower levels of participation and lower utilization rates. In addition to batteries in fully functioning E-cars, retired E-car batteries would be utilized for this purpose *(33).* This will further reduce grid congestion and lower costs for electricity distributors. Since in a non-sustainable world, higher costs lead to lower sustainability *(1, 2, 3, 4, 5)*, in order for E-cars to be "more-sustainable", the PTG functionality would be required for all E-cars. Although such neighborhood RSP&UAs power exchange mechanism will reduce grid expansion costs, it will also reduce the sale of electricity by the electric utilities and put pressure on their profit margins, likely causing pushback.

3.10. The Changing Roles of Electric and Gas Utilities

The change to a RE society should be driven by the need to minimize ecological damage (biodiversity loss), human suffering, loss of human life and economy damages that would result from following the business-as-usual (BAU) energy generation and use scenario. It should not be driven by desires of the utility industries to maintain or increase profits, or by government desires to extract taxes from energy generation and distribution. For the Case Zero SFR, the seasonal energy storage requirements correspond to 27% of the annual power needs (11.4 MWh). This would in turn corresponds to a seasonal storage amount of 78 kg of Hydrogen. Costs of electrolyzers and fuel cells are still very high, but will come down. Even at 50% conversion losses (power → H_2 → power) the amount of hydrogen that would need to be stored remains small and could be stored in metal-hydride based storage system *(131).* Alternatively, with the costs of PV solar continuing to drop, building owners may decide to install enough roof PV solar to provide most or all winter electricity needs. While speculative that the costs of metal-hydride H2 storage or of roof PV systems will come down sufficiently to make this attractive soon, this opens a future for "off grid" RE building operation. The classic electric utility both produces and distributes electricity to end users, while the classic natural gas utilities only distribute natural gas to end-users. In an efficient and low cost RE society, the role of electric and natural gas utilities will need to be different. Independent utility scale wind and solar farms with generate electricity and sell this to the electric utilities, who will distribute it to end-use consumers. Natural gas utilities, with their experience in handling flammable gasses, may be best suited to take on H_2 generation, storage, distribution to industrial end-users and conversion back to electricity when demand for electricity is not met by RE supply. Those H_2 facilities will most likely be installed close to their largest customers (steel and chemical plants and electric utility substations). Electric utilities' role will change from one producing and distribution of electricity to one of only electricity distribution. Building owners will increasingly install (by then likely Sodium based) low costs battery systems to cover nightly and (a few day) cloudy weather conditions. With the bulk of building electricity provided by roof solar, both electric and gas utilities will mainly provide power at times of peak demand. This will increase the costs of power per kWh delivered. Change is in many cases hard for both individuals and organizations. Nevertheless, changes to a RE society are needed and could best be carried out following a path that saves money for home and other building owners and the society as a whole. Such a cost saving path accelerates the overall RE transition minimizing ecological damage (biodiversity loss), human suffering, loss of human life and economy damages that would result from following the business-as-usual (BAU) energy generation and use scenario.

4. Discussion and Conclusions

The low end levelized costs of electricity for both PV solar and wind energy are lower than for fossil fuels generated electricity (unsubsidized 24 $/MWh for utility scale PV solar and wind versus 39 $/MWh for Gas combined Cycle and 68 $/MWh for new coal plants). While the lower costs of RE could lead to lower prices for utility provided RE for end user consumers, this is unlikely to happen. For the currently mostly fossil-fuel-based electricity, only a fraction of the price paid by residential end user consumers reflects the costs of the electricity produced. The rest reflects the costs of electricity distribution, profit margin, fees and taxes. Electric utilities need to phase out fossil fuel systems and invest in carbon neutral systems (H_2 generation, H_2 storage, H_2 fuels cells, batteries) and upgrade the electrical distribution grid capacity (for L2 and high-speed E-car chargers). This requires investments in such new systems and a phase out of fossil fuels systems (gas and coal power plants) faster than anticipated under the current BAU scenario. In addition, with the bulk of power used by buildings generated by PV solar on their own roofs, electric utilities power demand will shift towards periods of peak demand, increasing costs. These costs will be passed on to the end-user, leading to higher costs per kWh delivered. The levelized cost of electricity for roof mounted PV solar systems are significantly lower compared to the current US average price of utility provided electricity. In the US, cost savings for roof mounted PV solar vary from 51 – 64% for residential systems and are similar for commercial and industrial roof mounted systems *(103).* For the EU, with typically higher utility electricity prices compared to the US average and where PV solar system costs appear to be significantly lower, the savings of roof mounted PV solar electricity appear to be even larger. For a future carbon neutral society, all fossil fuel energy use needs to transition to RE. This can be done using heat pumps and E-cars, but requires a large increase in the use of RE. In addition, a large amount of CO_2 needs to be removed (DACCS) from the atmosphere, to allow a return to pre-industrial atmospheric conditions and minimize the biodiversity loss due to climate change. This requires an additional large amount of RE. The society thus needs to become and then remain carbon negative for (likely) decades, before a relaxation to carbon neutrality can take place. With the inclusion of the additional electricity needs for HPs, hot water and E-cars, the household electricity usage will strongly increase using GSHP (by about 44% for a new SFR), but stronger using ASHPs. The total costs paid for energy are determined by the combination of energy systems used. Comparing the overall costs to operate energy systems in the US, the “classic” natural gas (NG) heating and utility powered AC systems cost about 5 times (with tax rebate) or 3.7 times (without tax rebate) as much compared to using geothermal GSHP HVAC and GSHP/ASHP hot tap water systems powered by roof mounted PV solar systems. The installation and maintenance costs of GSHO energy systems for HVAC and hot water are roughly the same as for the classic whole house AC system and NG furnace, with the exception of the additional field loop costs for geothermal systems. While the field loops add upfront system costs, the levelized costs of geothermal heat ($LCOH_{Field}$ in $/kWh) they collect corresponds to only 11 – 14% of the LCOH of the GSHP (electricity used) for field loop system life of 50 year. These field loop costs drop to half if the building (and loops) last 100 years. For the EU, with on average higher utility electric prices (and recently also much higher NG prices), the differences are even larger. Compared to the minimum cost scenario (GSHP using South facing PV solar), E – W facing PV solar and air source heat pumps (ASHP) each cost about 30% more. Note that in the comparison used, only ASHPs with the highest COPs are compared against a good (but not the best) GSHP and the differences will be larger for the average ASHP installed. Overall, for the example cases used, the energy use for E-cars and hot water varies from 48% - 62% *(104)* of total for respectively SFRs and MFRs. To maximize energy cost savings, 100% of the roof areas should face South and covered with PV solar. Under those conditions, the average carbon negative SFR with a ground level 2 car garage would only need 17% of its annual power generation for “itself” and can sell 83% to its neighbors. For MFRs, the amount of roof PV solar is a function of floor area per MFR; the larger the floor area, the more levels can be stacked and/or the more power can be made available to neighbors. For MFRs of 270 m^2 each, 10 layers can be stacked, versus 5 layers for 122 m^2 MFRs, while just using all available power for the building’s residents. Note that this is only an example of “stacking” residences without attached neighbors. In reality, MFRs are (and will be) built in blocks, further reducing heat gains and losses. Building codes should require that all fossil fuel-based energy systems must be replaced with systems that would be carbon neutral using RE. Since NG furnaces, water heaters and AC systems last about 20 years, annually 5% would be replaced, leading to 100% replacement in 20 years. Buildings last 50 to 100 years and major changes in roof angles (to South azimuth) would take much longer than 20 years. In the meantime, renovated buildings (insulation, GSHPs) without adequate roof area for PV solar would benefit from using PV solar power generated on roofs of their neighbors sold at low cost or used as co-owned neighborhood roof PV systems. In addition to the above, the amount of roof mounted PV solar electricity could be increased strongly by using optimized building designs. For example, building walls, with azimuth between 90 and 270 degrees, could be covered with Building Integrated Photo Voltaic (BIPV) surfaces *(70).* In addition to designing 100% South facing roofs, with the optimum roof pitch, solar panels carrying surfaces could be extended downwards on the South side of buildings using 50% transparent PV solar panels, creating covered patios and covered gardens (for SFR and MFRs) or covered public spaces (for public areas like streets, squares and parking areas). Panels with 50% transparency are still in development but are expected to reach 15 to 20% power conversion efficiency (PCE) *(80, 81)* in a few years. The currently (2024) most efficient PV cells are perovskite tandem cells with a PCE of 33% *(82).* Depending on the climate and the need for ventilation, such additional PV solar covered areas can be either open (hot climates) or enclosed (colder climates). Such use of urban area for utility PV solar covering relatively large public areas with PV solar could be sustainable alternatives for utility scale PV solar investors.

RE production (especially solar and wind) is intermittent and energy storage systems are needed for off grid use to cover energy needs during nights and low wind periods. However, at the current low fraction of RE generated, grid connected end-users should not install battery storage systems, since the same monies spent on additional PV solar panels or HPs would lead to more sustainable outcomes. Utilities could invest in battery systems as a quick solution to ease power distribution capacity and spread distribution cable upgrades over a longer period. This will change at high fractions of RE generated and when RE battery costs come down by an order of magnitude over the next two decades. Once most energy used is RE, batteries should be used to provide power at night and for short daily periods. By then the use of Real Time Pricing (RTP) should be implemented (where prices charged and reimbursed to end user consumers will vary hourly with supply and demand. Under RTP end-users could earn money by storing utility power when costs are low and sell it back when prices are higher. Even when on average enough RE is produced to cover the annual US electricity needs, the periodic RE production and consumption do not match daily, weekly or monthly; energy needs to be stored to cover daily to seasonal fluctuations in RE supply and user demands. Energy can be stored in water reservoirs, using H_2, methanol or other synthetic CO_2 base carriers. To cover the conversion to RE, the US would need about 2.3 times the electricity sold in 2022 in absence of conversion losses. Including H_2 conversion losses, the US would need almost 4 times the 2022 electricity sold. US Roof PV solar in the residential, commercial and industrial sectors could potentially supply 2.6 times the 2022 US electricity sold, of which most would be supplied by the residential sector. The remainder could be supplied by wind energy or as utility scale solar mounted in areas not suitable for agriculture. If all US RE would be provided as solar electricity, the US land area needed would vary between 48 – 71% of the state of California land area, depending on electrolyzer and fuel cell efficiency. On a global scale the solar RE needs would require 39 -58% of the globally available croplands for 8 billion population and 49 -72% of the globally available croplands for 10 billion people if I assume the world to have the same per capita energy needs as the US had in 2022. Such an assumption is needed to lift global living conditions to those of the rich countries. Alternatively, rich countries could show that a much lower energy consumption is possible, after which other countries can follow their example and need less space for solar RE. However, we need these croplands to feed the world. The world population is too large to both protect biodiversity and meet the cultivated land use needs of a growing and more prosperous population; the world population needs to shrink. A still growing and “richer” (or “less poor”) world population is likely to use more, not less agricultural products. With the urgent need to minimize biodiversity losses, wildlife areas need to be expanded globally using land hitherto used for agriculture. Using any agricultural lands for PV solar alone would be unsustainable. AV (agrivoltaic systems) can be used if these result in comparable to improved crop yields. Otherwise, utility scale solar systems can be installed in deserts or other areas after a sufficient fraction of the ecoregion is adequately protected as wildlife area. Wind power has an almost unlimited potential, similar low costs per kWh produced and should be used for the balance of RE needed.

In 2021, excluding aviation fuels and electricity use of the transportation sector, 5.55 % of US GDP was spent on energy as direct cost of fuels and electricity. With the future sunk costs (fossil power plants) and investments needed in the electric utility industry (H_2 electrolyzers, H_2 fuel cells, electricity distribution networks, battery systems) it is unlikely that end-user RE electricity costs will drop anytime soon. Instead, they are more likely to rise. Combining all RE types and all energy saving systems (mostly different types of heat pumps and E-cars), about 3.6% of US GDP could be saved annually. Similar savings are likely for rich countries globally. Note that these potential savings are larger than the average annual costs of DACCS (0.7 – 1.8% of global GDP) for a return to pre-industrial atmospheric conditions in 40 years *(138, 139).* Note that the 3.6% potential GDP savings only result from roof PV solar and not from field mounted utility scale PV solar or wind energy.

For the residential sector alone, the use of GSHPs in combination with South facing PV solar would save 80% compared to the continued use of natural gas and utility electricity, corresponding to about 2.3% of GDP. Using ASHP and RE utility electric, the average energy savings would drop to 29%, resulting in savings of 0.8% of GDP. The use of roof PV solar in combination with GSHPs in the residential sector alone, compared to the best RE system alternatives, thus reflects savings of about 1.5% of US GDP.

Large scale carbon sequestration using DACCS is needed to limit the global temperature increase to less than 1.5 °C. The society as a whole (either individuals, corporations or governments) will need to pay for these costs. Since low- and middle-income countries have insufficient means to help pay for DACCS, these costs will primarily fall to rich and upper middle-income countries. All CO_2 emissions avoided also avoid spending on DACCS. Expressed as the ratio of DACCS costs avoided over PV solar system costs paid over the typical 25-year lifetime of PV solar systems, this ratio is 1.1 – 1.3 for utility scale PV solar. For rooftop PV solar systems powering GSHP systems, this ratio is 1.8 – 2.0 for E – W azimuth and 2.4 – 2.7 for South azimuth. The society as a whole thus saves money by making this transition ASAP. The faster the transition to 100% PV solar on all roofs takes place, the larger the savings will be. The 30% US tax credit is mainly an interesting option for those who can pay cash for their roof PV solar system. At 11.0 – 14.6 kW (table 3.11) systems sizes for carbon neutrality at respectively E-W and South azimuths, the average SFR system costs of $ 27,800 – 36,800 are much more than most families have available as cash or easily liquifiable assets. Families often lack the financial means to directly pay for roof PV solar systems, while commercial loans lengthen pay-back times and eat away at the return on investment. This leads to a much slower than possible transition to 100% roof PV solar, costing money for both households and the society as a whole. Even if governments would pay the full costs of roof PV solar, the societal savings in DACCS costs avoided would be 1.4 to 1.7 times larger over the 25-year period than the PV system costs. Government supported payment systems should be created to make roof PV solar affordable for families who cannot pay cash for their systems or include them in their home mortgage.

New SFRs and MFRs with South facing 100% roof covering PV solar systems can provide much more electricity than these buildings need for their own use and can do so at much lower costs than utility provided electricity. Current net-metering policies allow the building owner to feed-out any excess electricity to the grid and feed-in an equal amount of electricity at a later date without any charge for the amounts fed in or out. Net-metering agreement policies need to be extended to groups of building owners who co-own PV solar systems on their homes, without any change for the amounts fed in or out. This would allow building owners with unfavorable roof azimuths (many older buildings) or in the shade of taller buildings, to invest in and use PV solar electricity at the same low cost as for buildings with favorable oriented roofs. Such *"Roof Solar Production & Use Associations"* (RSP&UAs), would invest in PV systems on their own and neighbors roofs and give their members access to fractions of the power generated. The drive to lower costs would accelerate the rate of roof PV solar installation and increase their size. Except for the software required, there would be no additional costs for the electricity distributor. Such improved net-metering agreements for RSP&UAs would require national or state legislation.

Comparing the three sectors, the commercial sector has the highest current energy spending as percentage of income (31%). For 50 – 80% energy savings, the savings would correspond to 16 – 25% op profits. While such energy spending may vary widely within the sector, converting to carbon neutral operations would save large amounts of money. Participating carbon neutral operating sellers could use these savings towards DACCS vouchers (covering the remaining historic emissions), lower prices to increase market share and collect the rest as profits.

Overall, electric and natural gas utilities will need to transition to their future sustainable renewable equivalent. Due to the much lower costs, energy systems of buildings will transition from almost 100% relying of electric and natural gas utilities to almost fully relying on roof mounted PV solar, with partial seasonal storage of energy. Electric power generating and natural gas producing and distribution companies will need to transition from proving base load electricity and natural gas, to providing medium (days, weeks) and seasonal term electricity storage, using batteries, H_2 electrolyzers, pressurized H_2 storage and H_2 fuel cell systems.

This study was carried out using solar irradiation and climate data for the Philadelphia area. Solar irradiation and heating and cooling days vary with latitude and local climates and thus vary across the US. While the number of annual heating and cooling days each vary 2 to 3 orders of magnitude between US states, their sum is much more constant. The sum of heating and cooling degree days for the actual "Case Zero SFR" location used are within 1% of the US average *(105)*, while the average number of heating days is 6% higher than the US average. The results should be recalculated (by others) for all US states to provide more accurate local predictions and to calculate population weighted US averages *(106)*. However, based on the small deviation from average US heating and cooling days and the HVAC fraction being limited to 13 – 34% (MFR – SFR) of the energy budget, other energy use aspects (especially E-cars) carry more weight and the building heat and cooling demands used are a good approximation of the US average.

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