Transforming energy performance of new homes using a thermodynamics systems paradigm

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Abstract

The current climate emergency calls for an "all-hands-on-deck" approach to transforming many aspects of our lives in order to reduce and reverse global warming. Homes and the energy consumed in daily living are a non-trivial contributor to climate change. A current technological trajectory is to use solar photovoltaic panels and batteries to address the problem. However, they both use toxic substances in their production, have critical material supply concerns, have relatively short productive lifetimes, and lack proven plans for recycling. The ways in which home building envelopes are constructed today are very inefficient compared to the Passive House standard. If this standard were applied to the construction of every new single-family home, the energy required for the operation of all new homes would be drastically reduced. Then, the use of solar and ground sourced thermal energy using existing technologies may provide the heating, cooling, and electrical energy needed without the use of photovoltaic panels. Thermal energy storage, coupled with compressed air energy storage, may provide long-term energy storage without the need for batteries. Existing literature on these lower ecological footprint technologies will be reviewed through a thermodynamics systems lens.

Introduction

This poster will cover three key points. First, that the current paradigm of using primarily solar photovoltaic panels and batteries in modern construction is not sustainable. Second, a paradigm leveraging the thermodynamic properties of key renewable energy system components is proposed. Third, the potential impact of widespread adoption of the paradigm on climate change targets will be discussed.

The Current Paradigm is Not Sustainable

Two key aspects to the current paradigm include energy intensity required by "modern" home construction practices, and the sustainability of the materials used for energy system components.

The energy demands of current buildings far exceed what is needed compared to demand when Passive

House standards are applied to the building envelope. The typical Energy Performance Index of buildings in various countries is contrasted in Figure 1.

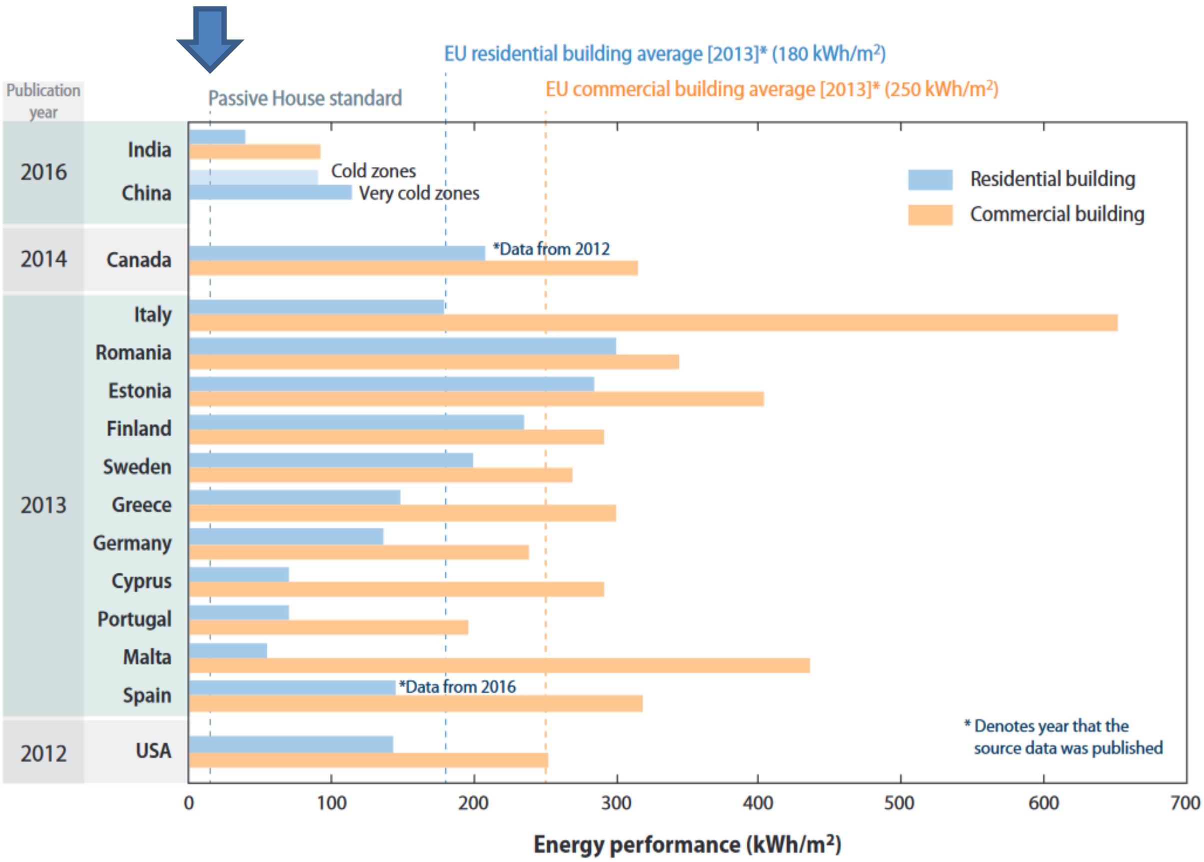

Figure 1. Energy performance indexes for residential and commercial buildings (Ürge-Vorsatz *et al.*, 2020)

With an annualized 916,000 new single-family homes built in the United States ('United States Housing Starts', 2022), the opportunity to avoid excessive energy demand by applying Passive House standards is rather significant.

Key quotes from relevant literature regarding environmental and supply issues with solar photovoltaic panels and batteries include:

- The increase in PV panel waste is anticipated to reach over 60 million tonnes by 2050, mostly disposed of in landfills where groundwater and soil contamination may occur (Franco and Groesser, 2021, p. 1). "A similar growth/waste scenario is expected for lithium-ion batteries" (ibid., p 22).
- "Claims about the sustainability of PV [photovoltaic solar panel] technologies cannot be fully supported until efficient and environmentally-friendly recycling processes for them have been developed and are deployable" (Ardente *et al*., 2019, p. 166).
- "To be comparable with renewable energy systems, hydroelectric, wind, biomass, geothermal and solar (4–76 g CO2 eq kWh−1), 300 folds reduction in the GWP [global warming potential] of BESS [battery energy storage systems] will be necessary" Sadhukhan and Christensen (2021).
- The future availability of critical raw materials for solar PV panels is in question (Cristobal et al., 2020), so much so that some researchers are investigating extraterrestrial bodies as another source (Dallas et al., 2021).

Reducing the building energy intensity required by nearly an order of magnitude through the use of Passive House standards enables the use of approaches to renewable energy systems design that were not previously economical. In addition, it provides the opportunity to revisit the paradigm applicable to their design.

Hypothesis

For new builds of single-family homes using the Passive House standard it is practical to reduce energy demands to the point where it is possible to apply thermodynamic principles to the design of renewable energy systems which would not require the use of photovoltaic panels nor batteries. Figure 2 provides a simplified conceptual perspective.

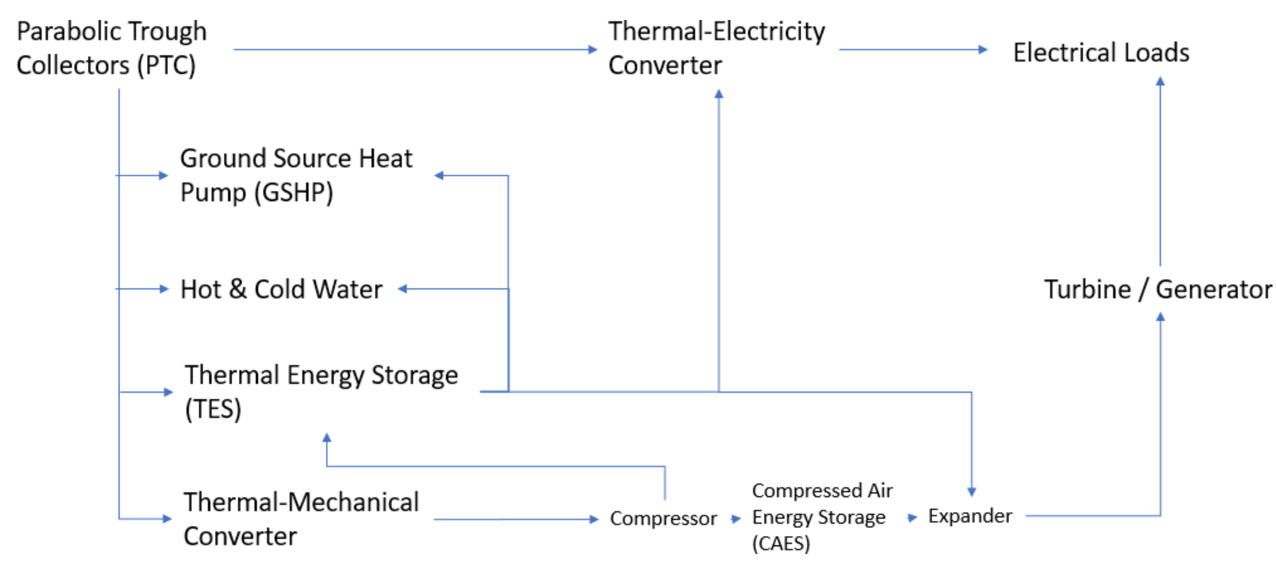

Figure 2. Simplified Energy Flows without Controls

The Role of Thermodynamics in a Renewable Energy System

The research led to considering the following key components:

- Solar thermal collectors (parabolic trough collectors)
- Ground Source Heat Pumps
- Thermal Energy Storage (TES)
- Stirling and Organic Rankine Cycle Engines (for energy conversion)
- Compressed Air Energy Storage (CAES), plus expander and turbine/generator

When implementing these, there are numerous ways to select and configure them as a system. Key principles to keep in mind include:

- The sun is the primary source of heat (and is variable and intermittent).
- The ground is a primary source of cold (more or less constant).
- The air can be a source of hot or cold and is variable.
- Temperature sources are best used for temperature-based applications.
- Hot and cold temperature sources should both be stored separately.
- Hot and cold sources may be shared to heat or cool air and water.
- Hot and cold sources may be added together in their storage, or at the time of use.
- Heat is the primary source of electricity by way of Stirling or ORC engine & generator/inverter.
- Hot and cold sources may include energy system components themselves.

- Certain functions may not yet be economically feasible using a thermodynamics approach.
- Thermal energy may be converted to mechanical energy using a Stirling or ORC engine.
- Compressed Air Energy Storage persists longer than Thermal Energy Storage.
- CAES is used for generating electricity only after TES has dropped below a certain level.
- Solar collectors and compressed air tanks require sufficient physical space.

Highlights of Key Component Characteristics

Stirling Engines to Convert from Heat to Electricity

A number of solar power implementations use Stirling or Organic Rankine Cycle (ORC) engines to directly couple to solar collectors to convert thermal energy to electricity. A variety of systems in the 1 to 3.2 kWe range are commercially available, have as high as 24% net system efficiency and operate on as little as 725 W/m^2 Direct Normal Irradiance (DNI) (Giovannelli, 2015, p. 610). Most notable is the EU Project DiGeSPo, using parabolic trough collectors (PTC) and a Stirling engine, that demonstrated 3 kWe output with 12-15% electrical efficiency using a 250-350°C temperature source (ibid.; Crema *et al*., 2014, p. 32). Using numbers from Orosz *et al*. (2009), with 1,130 sq. ft. of PTC array area, an ORC system cost of $14,400 yielded a 3 kWe system.

Thermal Energy Storage (TES)

One study used readily available HVAC components for a 2.8kWe PTC-ORC system with pebble-bed thermal energy storage (TES) (Dickes *et al*., 2014). Typical costs of building scale TES systems are around $30 USD /kW h_{th}, making them cost-competitive with battery energy storage systems (Odukomaiya *et al.*, 2021, p. 5321). Storage timeframes for TES systems are typically around 12 hours.

Ground Source Heat Pumps, Plus Solar Assistance

Ground Source Heat Pumps (GSHPs) are not installed as often as Air Source Heat Pumps (ASHPs) because of the cost of excavation. However, GSHPs have a payback period of 5-7 years (Turpin, 2014), 30-80% savings over conventional approaches, including ASHPs, and average at least 50% less greenhouse gas (GHG) emissions than ASHPs (Aquino *et al*., 2021). An indirect expansion solar assisted GSHP in parallel mode was able to attain an overall coefficient of performance (COP) of 3.96 (Nouri, Noorollahi and Yousefi, 2019, pp. 227, 229). '2022 Geothermal Heat Pump Cost & Heating System Installation Prices' (2022) suggests that excavation, equipment and installation of a standard GSHP is $4,000 to $8,000 USD per ton.

Ground Source Heat Pump with Thermal Storage

Pairing GSHPs with thermal energy storage (TES) using salt hydrate Phase-Change Materials (PCM) could reduce the cost of excavation by 50%, and decrease energy consumption between 12.8 to 32%, while achieving a coefficient of performance (COP) of 2.0 to 6.49 (Aquino *et al*., 2021; Zhu *et al*., 2014, p. 150). According to the author's calculations, it appears that for the same cost as a standard GSHP, it is possible to include the TES at no additional cost.

Converting Thermal Energy into Compressed Air Energy Storage (CAES) for Later Electricity Generation

The act of compressing air results in heat that should be stored. Upon expansion, the heat may be retrieved and added back to the air. This is known as adiabatic CAES. It is not straightforward to use thermal energy from solar collectors coupled to a Stirling or ORC engine to mechanically compress air into a storage tank because of the increasing pressure in the tank, although multistage Stirling engine based thermocompressors are in the early stage of development (Fischer and Kuehl, 2021). CAES is capable of storing energy longer than TES and batteries.

A few studies have focused on small-scale CAES using compressed air tanks. Rukh and Khattak (2020) studied the discharge power characteristics for a system rated at 4kW. Castellani *et al*. (2018) demonstrated that at an operating pressure of 225 bar stored in a volume of 0.25 m^3, it was possible to produce 1.273 kWh, covering 26% of the 4.6kW energy demand (i.e., during times of low or no sun, or high demand). Although CAES is not as efficient in charging as batteries, batteries have a lifetime of about five years, while a CAES has lifetime exceeding 20 years—suggesting that a Life Cycle Assessment (LCA) comparing the two is needed (Castellani *et al*., 2018). Maia *et al*. (2016, p. 359) suggests that a 10 kW CAES turbine generator system may be constructed for under $5,000.

Discussion

Assuming a 2,200 sq. ft. home in central Pennsylvania in the U.S. built to Passive House standards, typical GSHP COP of 3.89 and improved COP of 6.49 using TES, only a 1-ton GSHP would be required based on the author's calculations. Considering the cost of modern home with a solar photovoltaic and battery solution today, use of the Passive House standard and components described above may eliminate or minimize the need for PV panels, batteries, and grid-tie—at an equal or lower cost.

Assuming 10 million net new homes being built per year globally to meet population growth, with a current typical 8 tons of CO_2 being emitted per home under "modern" building practices, adoption of a Passive House building standard using an integrated thermodynamics systems approach may avoid adding 80 million tons of CO_2 per year at a time when we are trying to reduce emissions each year.

Conclusion

This poster covered three key points:

- The current paradigm of adding solar photovoltaic panels and batteries to construction that does not minimize operating energy intensity is not sustainable.
- A thermodynamic systems paradigm was proposed to leverage the properties of key renewable energy system components, and is cost-competitive.
- The potential impact of widespread adoption of the paradigm on climate change targets is significant.

Further research is required to model the various components and ways to connect them together. Certain components may not be available at the desired scale. Other components may need to be designed, or re-designed to support efficient integration. There are numerous opportunities for integrating these technologies to achieve a multiplier effect of increased efficiencies.

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