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The Role of Heat-to-Power Technologies in Building Decarbonization

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ABSTRACT

The first major section of the manuscript is an abstract. The abstract should describe the contents of the paper, discuss the contribution to the field as well as present the most important results. Authors are responsible for typing accuracy and proofreading the manuscript. If accepted, the manuscript must be submitted for reproduction without being edited or retyped by the staff before printing. The manuscript must look professional and be technically correct in order to be accepted. This paper presents the energy, economic, and environmental benefits associated with different heat-to-power technologies such as Thermoelectrics, Thermophotovoltaics, Thermionics etc. Hybrid configurations consisting of heat pumps, heat-to-power systems, and renewable PV in cogeneration and trigeneration modes of operation will be presented. The role of such technologies in lowering the primary energy consumption, carbon dioxide emissions while improving the energy resiliency and serving the needs of underprivileged communities will be discussed. The key barriers of affordability and potential solutions for large scale implementation of these promising technologies are presented.

1. INTRODUCTION

Residential and commercial buildings in the US consumed 40 Quads of energy in 2018. This sector accounts for ~39% of annual greenhouse gas emissions (IEA, 2020). Energy efficient and sustainable technologies are necessary to not only lower the energy footprint but also lower the environmental burden. Many proven and emerging technologies are being pursued to meet the increasing energy demand while lowering the environmental footprint (Wei & Skye, 2021). Efficient utilization of available resources including renewable sources to support current and future building energy needs while targeting grid resiliency, energy, and environmental security, at an affordable cost via heat-to-power based approaches is an attractive option. This must include energy efficient technologies with fewer greenhouse gas emissions while optimized for cost, performance, and reliability. Energy resources such as grid electricity, renewable energy, waste heat compete in serving different applications. Their usage is primarily dictated by consumers and influenced by government policies. Other significant factors include efficiency, economics, and environment.

Electricity supply to the consumer comes at a premium value since almost 65% of the primary energy is lost during production and distribution stages (Energy Information Agency, 2020). Hence, the energy supplied to buildings must utilize it at highest possible conversion and utilization efficiency. Considering all the energy needs in a typical residential or commercial building, heating and cooling equipment consume up to 40% of the total energy supply (Agency, 2020; EIA, 2020), as shown in Fig. 1. Heating systems for instance utilize approximately 63% fossil fuels as the primary energy resource (Energy.Gov, 2020), as shown in Fig. 2. Globally, cooling demand is also on the rise, driven by population and income growth and accounting for ~ 20% of the total electricity used in buildings today (International Energy Agency, 2021b). Consequently, building energy usage accounts for approximately 40% of total annual carbon dioxide emissions, globally (International Energy Agency, 2021a). Considering the primary energy and carbon footprint impact combined with projected growth in energy demand, technology improvements to reduce the building energy consumption is of enormous value for a sustainable energy future without negatively impacting the environment.

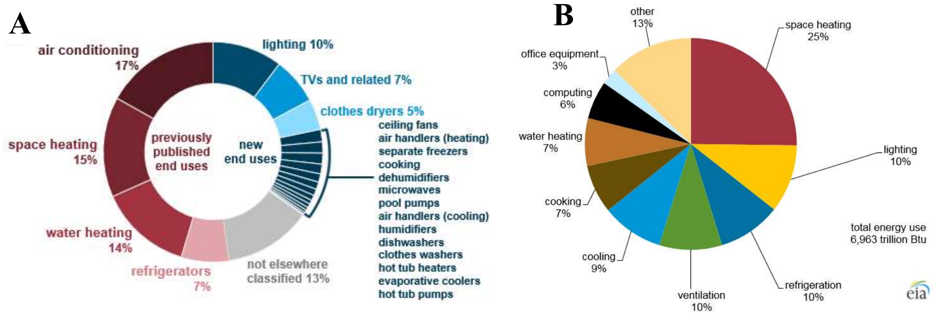

Figure 1: (A) Residential and (B) Commercial building energy consumption

Given the scale of thermal energy consumption in most sectors of the economy including buildings, the focus of this paper is to explore the application of heat-to-power technologies in lowering the primary energy consumption and carbon footprint. Waste heat to power has been recently reviewed by Garofalo et al. (Garofalo, Bevione, Cecchini, Mattiussi, & Chiolerio, 2020) where the authors discussed technologies, thermodynamic cycles, and energy conversion devices for utilizing low grade, low enthalpy waste heat resources for improving the primary energy efficiency. The focus of this review was on utilizing and converting industrial waste heat to useful electricity via traditional and emerging technologies. However, in the case of buildings, the enthalpy content and quality of waste heat is significantly lower and most of the technologies discussed are not suitable for practical applications. As shown in Fig. 2, greater than 60% of building heating needs are met by fossil fuels. It is possible to improve the primary energy efficiency and carbon footprint of fuel-based heating equipment while still utilizing the legacy energy supply infrastructure (for instance, gas pipelines) and enhancing the resiliency by generating useful electrical power during

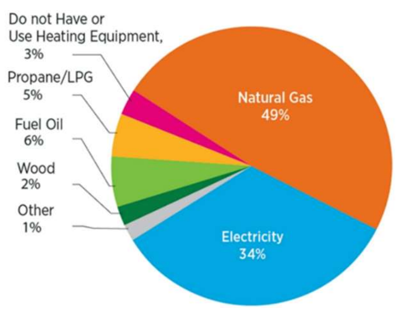

Figure 2: U.S. household heating systems' energy source

the thermal energy generation process (i.e., combustion). A survey of building scale heat-to-power technologies was recently reviewed where the authors identified technologies suitable for integration with gas heating furnace resulting in autonomous operation (no external electricity supply) (Abu-Heiba et al., 2021). This study demonstrated the suitability of thermophotovoltaic for such self-powered applications.

In this framework, the focus of the current investigation is to analyze three potential heat-to-power technologies which were shown to have the necessary features[10] to seamlessly integrate with traditional chemical energy-based building scale thermal systems (space and water heating). The key objective here is to assess the primary energy efficiency gain and associated carbon reduction potential of thermal systems integrated with solid-state technologies such as thermophotovoltaics (TPV), thermoelectric (TE) and thermionic emission (TIE) based power devices. Other potential heat-to-power technologies such as pyroelectrics, magnetocaloric, thermomagnetic hydrodynamic were not considered due to incompatibility with building heating equipment because of the scale of power produced, temperature requirement, cost, or technological readiness level. A TPV system consists of thermal emitter and photovoltaic diode cell to convert infrared frequency from thermal radiation directly to electricity. The photovoltaic diode absorbs the emitted photos in the infrared region similar to the optical energy absorbed by traditional photovoltaics. The emitter can be heated to temperatures in the range of 900 to 1300 °C to generate photons with desired frequencies. These temperatures are ideally suited for fuel-based heating systems where the combustion/burner module's flame is typically controlled in this range. TPV is very efficient at converting thermal energy to electricity, approaching 30% and beyond at heat source (emitter) temperatures above 1100 °C (Gamel et al., 2021). Temperature gradient across thermoelectric materials results in electromotive force (Seebeck effect) and causes charge carriers in the material to diffuse from the hot electrode to cold electrode. Materials with opposite Seebeck coefficients (n- and p- type materials) are joined at their ends to generate an electrical voltage as the temperature gradient occurs between the two sides. Typical electrical efficiencies of TE devices range from 3 – 10%, depending on the material set (Shittu, Li, Zhao, & Ma, 2020).

In a thermionic energy converter, electrons evaporate from a hot electrode (emitter) into a vacuum gap and are collected by a cooler electrode (collector), creating an electric current. The electron excitation in TIE occurs due to heat directly rather than through photons (Campbell, Celenza, Schmitt, Schwede, & Bargatin, 2021). The key advantage of a TIE device is its vacuum gap architecture, which reduces heat transfer to the cold side, allowing large temperature gradients between the electrodes (Campbell et al., 2020). The high operating temperature (>800 °C) and reasonable electrical efficiency (20-30% (Campbell et al., 2021)) of TIE is ideally suitable for integration with fuel driven thermal systems.

2. METHODOLOGY

The main methodology involved thermodynamic modelling of the integrated thermal energy system using process simulation software package CHEMCAD® (Version 7.1) to assess the thermal and electrical output for a given load demand in a building. Peng-Robinson equation of state was used for the global K-value and enthalpy models utilized in the process simulation models. The primary energy sources considered involved natural gas and/or hydrogen. The impact of different configurational aspects with TE, TPV, and TIE were studied in the case of residential scale buildings consuming various degrees of thermal energy, either as hot water or space heating. The model accounted for complete conversion of the fuel while exchanging the heat energy generated during combustion reactions in a primary heat exchanger as well as the heat-to-power device in serving the thermal load.

Primary components in these configurations included:

- Gibbs free energy minimization reactor (combustion)
- Primary heat recovery - heat exchanger
- Electrical heat pump consisting of compressor, expansion valve, and condenser, evaporator heat exchanger coils.
- Heat-to-power modules (TE, TPV, TIE)

Major design variables consisted of:

- Heat pump compressor work
- Kilo-watt rating of the power generation module
- Carbon intensity of the grid power supply

Carbon dioxide emission reduction is calculated based on the carbon factor (kg of CO_2 emitted per unit of fuel or kWh of electricity consumed) for the electrical grid supply and the local fuel consumption associated with both the power device as well as the water heater. Net annual emission reduction is calculated according to equation 1 by considering the carbon factor ($CO_{2,grid}$) of electrical grid, utility grid purchase offset ($kWh_{grid\ sales}$/yr), carbon intensity of fuel ($CO_{2,fuel}$), and the difference in fuel consumption between baseline and power device integrated equipment ($m^3_{fuel\ savings}$/year).

$$CO_{2,\ savings} = CO_{2,grid} * kWh_{grid\ sales} + CO_{2,fuel} * m^3_{fuel\ savings} \qquad (1)$$

Operational expenditure savings ($\$_{savings}$) are calculated according to equation 2 by considering the net expenses associated with on-site fuel consumption reduction ($m^3_{\text{fuel savings}}$/year), utility grid purchase offset ($kWh_{grid,\ sales}$), cost of grid electricity ($\$_{grid}$). Fuel savings is calculated based on the difference in primary energy efficiency estimated by the thermodynamic model.

$$\$_{savings} = \left(\$_{grid} * kWh_{grid\ sales}\right) + \left(\$_{fuel} * m^3_{fuel\ savings}\right) \qquad (2)$$

3. RESULTS

3.1 Case study: TE-Heat Pump-Water heater

Thermodynamic analysis of a water heater integrated with TE and heat pump was conducted using ChemCAD process simulation software. The model utilized for this study is depicted in Fig. 3, consisting of two major components: combustion module and heat pump module (coefficient of performance = 3). Soave-Redlich-Kwong equation of state (EOS) was used for the combustion sub-module while Peng-Robinson EOS was utilized for the heat pump module.

The two sub-systems were independently solved prior to connecting the fluid streams. The hot exhaust generated from the burner was supplied to a string of heat exchangers while the water stream temperature was gradually increased in a crossflow pattern, channelled through the heat pump's condenser coil as well as three heat exchangers (primary (PHX), TEG, secondary (SHX)). The model was constructed such that the compressor work was calculated using a feed-forward controller, tying the enthalpy change across the TEG heat exchanger (Equipment ID 4) to compressor work. An efficiency factor of 5% was assumed for the TEG heat exchanger power output while a 75% efficiency was assumed for the compressor. 70% of the power generated by the TEG was accounted for towards the compressor's actual power while the balance was assumed to be available for supporting rest of the system's parasitic demand or stored as useful electrical energy.

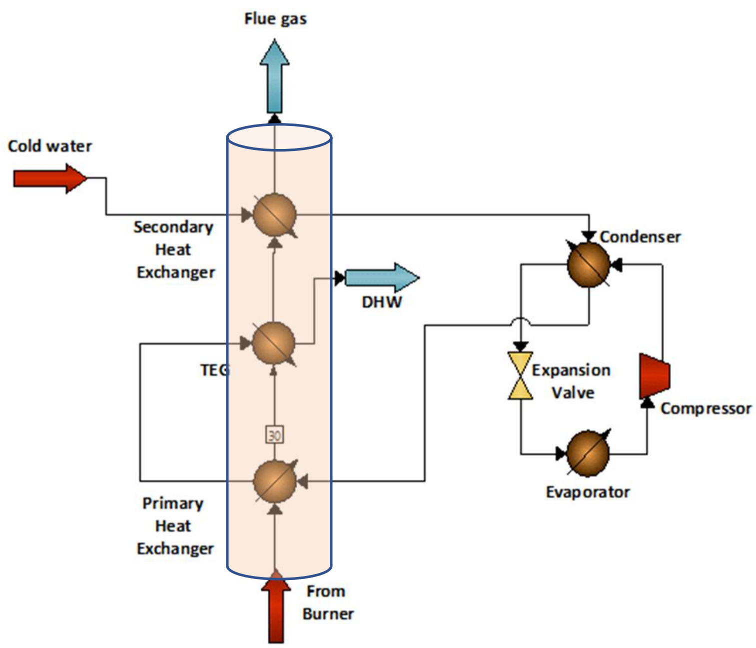

Figure 3: Integrated TE-water heater simulation model. 5% Efficient TE, T_{hot} – 350°C, T_{cold} - 100°C, Compressor efficiency of 75% (70W) and BOP = 30W.

Main fluid streams for the TE-water heater consist of (1) combustion products flowing through the primary, TE, secondary heat exchangers, and (2) water stream flowing through the heat pump condenser and cross flow through the three heat exchangers mentioned above. The flow sequence was varied while trying to converge the simulation and avoiding pinch points for all the heat exchangers. The key variable was water flow rate which was adjusted for the configuration considered. The combustion module was solved by supplying 10 kW of thermal energy (based on higher heating value, HHV of methane). Primary energy ratio (PER) is the ratio of the enthalpy change of the water stream over HHV of the supplied burner fuel. Analysis was conducted to identify a configuration suitable for implementation in a traditional water heater setup, as shown in Fig. 3. The key objective was to optimize the PER while considering the ideal location for physical integration of the TEG and meeting the operating temperature boundaries (T_{hot} – 350 °C, T_{cold} – 100 °C). The PER for the optimal configuration was calculated to be ~ 1.03, a 13% gain in primary energy efficiency compared to 90% efficient conventional water heaters in addition to generating 30 W of electrical power. Assuming a 30 kWh per day of hot water demand and a grid carbon intensity of 0.5 kg CO_2/kWh, this efficiency gain (plus additional power) translates to net yearly carbon dioxide emissions reduction of approximately 300 kilograms. Additionally, annual operational energy savings of ~ \$50 can be realized due to lower fuel consumption (\$0.3/m^3_{fuel}) and avoided grid purchases (\$0.15/kWh_{grid}) associated with higher efficiency of the TE water heater.

3.2 Case study: TPV-Furnace

Performance analysis of a space heating furnace integrated with TPV was also conducted. The main objective was to evaluate the integrated system from a thermal and material balancing standpoint while achieving optimal energy efficiency. The key requirement of generating electrical power in the desired range while utilizing all heat streams of varying temperatures was analysed at different power generation capacities. It must be noted that the model did not consider any physical or material constraints with regards to complete system integration particularly that of utilizing all heat streams and their temperatures. The temperature of the return air was assumed to be 30 °C while the flue gas exiting the furnace system was maintained at 150 °C. For the baseline case consisting of a natural gas fuelled furnace operated via electrical grid for supporting the parasitic load, the site delivery efficiency (electrical supply to the furnace for supporting the balance of plant) was assumed to be 33%. Efficiency calculations were performed using a lower heating value of 50 MJ/kg of fuel since the furnace system is a non-condensing design. Adiabatic flame temperature of the burner was assumed to be 1300 °C for all the results presented in this study. Chemical energy to radiant heat energy efficiency was assumed to be 75% while the radiant heat-to-electrical power conversion efficiency was assumed in the range of 35%. The total fuel energy supply to the furnace was fixed at 11.1 kW (LHV) with a total air flow rate of 800 CFM. The process flow diagram shown in Fig. 4 was utilized for analysing the integrated emitter-TPV-furnace configuration while accounting for heat recovery from the power generation module.

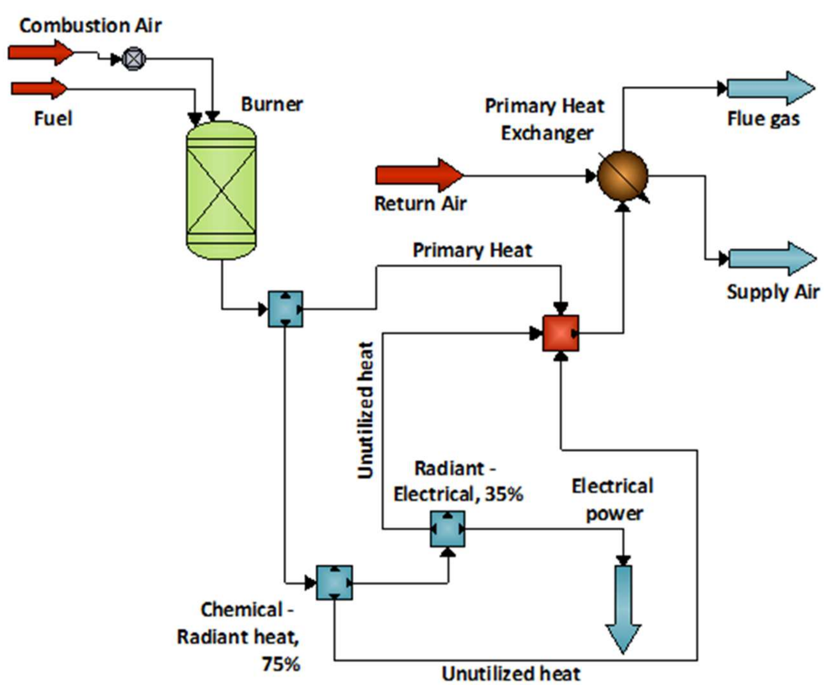

Figure 4: Thermodynamic simulation model of the integrated emitter-TPV-furnace system. Complete heat recovery from the power generation module.

Natural gas fuel supply was divided in to two streams to support a primary burner and a secondary TPV burner module. Both burners were operated at an equivalence ratio of 1.45 to maintain the burner temperature at ~1300 °C. Exhaust from the TPV sub-module was mixed with the combustion products generated from the primary burner. The required TPV operating temperature of 1300 °C on the hot side and 50 °C on the cold side was achieved using ambient air as the cooling medium while capturing the rejected waste heat (streams 82 and 87). System energy efficiency analysis for the configuration shown in Fig. 4 was conducted at power output in the range of 100 W to 400 W and compared with the baseline configuration of the same furnace using electric supply from the grid (no onboard power generation). Fig. 5 shows the primary energy efficiency of both systems as a function of different balance of plant power consumption. Heat recovery from the TPV module increases the primary energy efficiency significantly, across all power levels, achieving ~ 91% at 100 W and 88% at 400 W respectively. Compared with the baseline, at 400 W level, the TPV configuration with heat recovery can achieve ~ 6% higher performance while improving the resiliency. In a building with space heating thermal load of 100 kWh per day serviced by a 11.1 kW furnace consuming 400W of electrical power and an electric grid with a carbon intensity of 0.5 kg CO_2/kWh, this higher efficiency translates to an annual CO_2 emissions reduction by approximately 1100 kg per year. Additionally, annual operational savings of $275 can be realized due to lower fuel consumption ($0.3/$m^3_{fuel}$) and avoided electrical grid purchases ($0.15/$kWh_{grid}$).

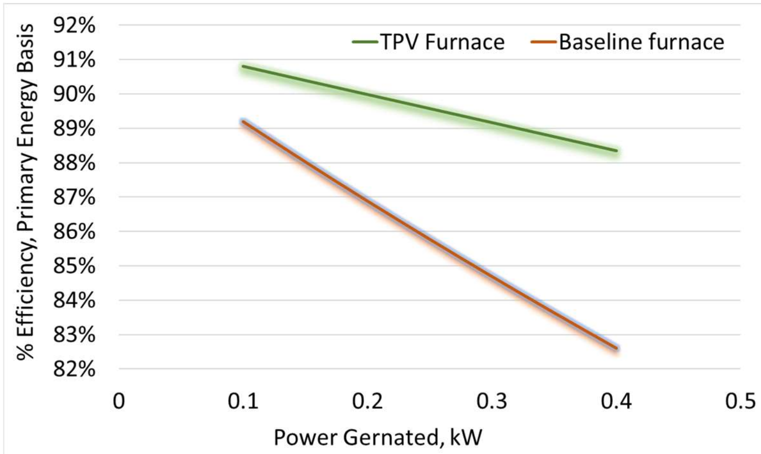

Figure 5: Primary energy efficiency comparison of a space heating system with and without onboard power generation via TPV.

3.3 Case study: TIE water heater

Process flow diagram and the simulation model utilized for this study is shown in Fig. 6. The model consists of three major unit operations: (i) a simplified generic Thermionic power module as the prime mover with defined electrical power output and efficiency, (ii) heat recovery system (heat exchanger) with defined thermal recovery efficiency and (iii) thermal energy storage system in the form of hot water storage tank.

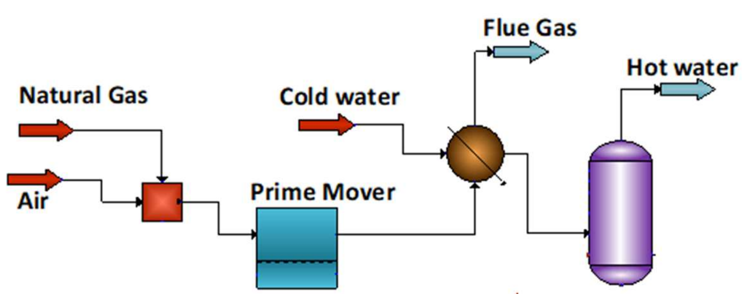

Figure 6: Thermodynamic simulation model of a TIE based water heater.

The model was subjected to sensitivity analysis by modulating the electrical efficiency of the TIE power device while assuming the heat recovery at 90%. The assessment was conducted for a daily hot water thermal demand of 30 kWh using a 250 W TIE operating continuously. Electrical energy generated was assumed to be either consumed directly to support base load or stored and utilized as necessary. Energy management strategies to use the available energy for such building applications in an efficient manner have been recently suggested (Cheekatamarla, 2020). The primary objective of this analysis was to investigate the overall merit of using a TIE based thermal provider with the rated power output and energy efficiency as a potential onsite energy resource to offset the energy and environmental burden of a residential building.

Fig. 7 displays the annual carbon dioxide emission reduction along with operational expenditure savings when utilizing a 250 W water heater integrated with TIE power device at electrical efficiencies in the range of 15% to 35%. Carbon intensity of the electrical grid was assumed to be 0.5 kg carbon dioxide per kilowatt-hour of electricity supplied while the cost of electricity was assumed to be \$0.15 per kilowatt-hour, and that of fuel was assumed to be \$0.3/m^3. As shown in the figure, annual carbon dioxide emissions decrease by up to 1000 kilograms as the electrical efficiency increases from 15% to 35%. Additionally, the operational expenditure saving varies from \$285 to \$310, annually, due to lower electrical grid purchases and fuel consumption. It must be noted that the daily thermal demand in this case study was fixed at 30 kWh. The power rating of 250 W for instance produces approximately 31 kWh of thermal energy at 15% electrical efficiency, accounting for the entire thermal demand. Higher electrical efficiencies however produce lower thermal energy, requiring additional fuel consumption. It is possible to configure the electrical power rating for specific thermal demand and electrical efficiency of TIE to achieve optimal economic and environmental benefits.

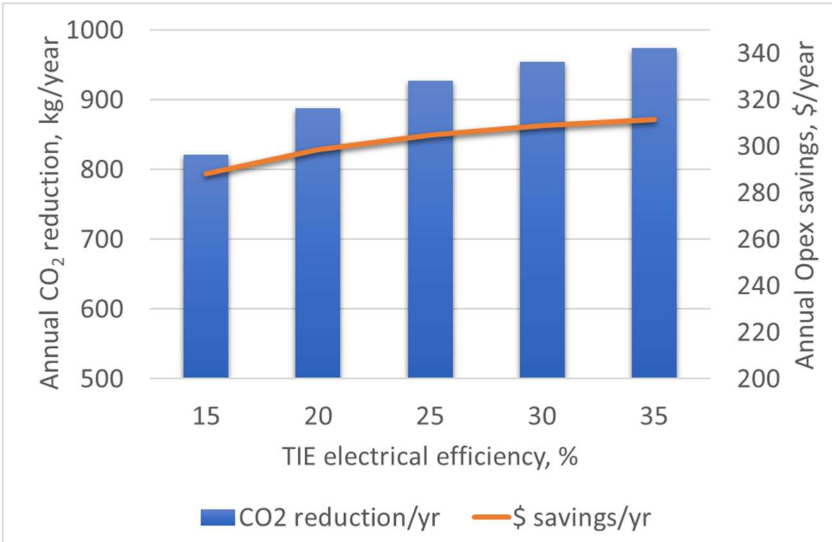

Figure 7: Impact of a 250 W TIE's electrical efficiency on operational savings and carbon dioxide reduction.

4. DISCUSSION

The energy and environmental gains coupled with cost benefits have been demonstrated for the three case studies discussed above, each with specific configurations. The potential for optimization has also been demonstrated. Nevertheless, other critical features necessary for a successful adoption of these technologies are (i) ease of manufacturability, (ii) material availability, (iii) integrability or retrofittability, (iv) cost, and (v) reliability. These technologies have their own strengths and weaknesses in meeting all five critical requirements, as discussed below.

Thermoelectrics have been in existence for more than hundred years and have proven their reliability in remote power generation applications (Bell, 2008). The maturity of the science has led to multiple commercial applications such as cooling, and niche applications such as space craft power (Jaziri et al., 2020). The electrical efficiency typically approaches 3 – 10% and the power density has been demonstrated at 1-5 W/cm^2 (Zhang et al., 2015). Emerging TE devices based on advanced materials such as skutterudites have shown significant increase in the volumetric power density, paving a path for integration with heating equipment (El Oualid et al., 2021). One of the unique advantages of TE is the flexibility in operating temperature range, which make them highly suitable for integration with thermal equipment, expanding the scope of energy harvesting with different grades of heat. Thermophotovoltaics on the other hand have great potential in a variety of building thermal equipment applications due to their scalability and temperature compatibility. However, low power density and high manufacturing costs are some of the challenges for large scale commercial applications. Additionally, high operating temperatures above 1200 °C present material challenges for physical integration of emitter and cell holder. Cold side temperature control for optimal performance requires complex cooling mechanism which further exacerbates the cost factor (Gamel et al., 2021). Cutting edge additive manufacturing methodologies are also being utilized in fabrication of TPV, TE devices to achieve lower manufacturing costs and improved reliability (Zhakeyev et al., 2017). Thermionic emission-based power generators are promising due to their high specific energy density and electrical efficiency. Key benefits of this technology include thermal compatibility with conventional flame based heating equipment, offering versatility and scalability.

Innovations in the vacuum gap technology enabled disruptive physical footprint facilitating the integration with residential scale heating equipment where factors such as physical footprint and drop-in replacement are crucial for adoption. Advanced micromachining and semiconductor device processing techniques are already improving the efficiency (Go et al., 2017). Wafer-based fabrication processes on the other hand are enabling ultra-small vacuum gap and enhanced thermal isolation structures improving both the performance and manufacturing costs (Rapp, 2020).

Another key advantage of these solid-state heat-to-power devices is their flexibility towards different fuels as they rely on the combustion energy. For instance, the transition towards renewable fuels such as hydrogen or blends of hydrogen with natural gas and/or biogas poses no challenges to the performance if the key operating temperature characteristic is achieved. A 30% renewable hydrogen blended natural gas for instance can further lower the carbon footprint reported in sections 3.1 to 3.3 by the same amount.

The environmental impact of employing heat-to-power technologies in buildings is higher in regions with higher electrical grid carbon intensities. For instance, 15 states in the USA in year 2020 had carbon emission factors above 0.5 kg CO_2 per kilowatt-hour (Energy Information Agency, 2021) considered in section 3. It is possible to further curtail the carbon footprint of building's thermal load if the generated power is stored and utilized during peak demand period when the marginal emissions are much higher compared to the average emission factor. Additionally, as shown in section 3.1, hybridizing the heat-to-power device with a heat pump offers significant benefits in completely realizing the full energy and environmental potential of such technologies.

As discussed above, one of the crucial factors for adoption of such technologies is the cost or alternatively, payback period. Target incremental capital cost of technologies analysed in sections 3.2 and 3.3 needs to be below $600 in order to achieve a payback period of 2 years without any subsidies/incentives. It must be noted that the cost of electricity considered in both cases is $0.15 per kilowatt-hour. However, in regions with higher cost of electricity (e.g., Massachusetts, USA), for instance at $0.22 per kWh, the payback period can be reduced to 1.6 and 1.3 years respectively. Alternatively, the capital cost can be increased by additional $50 if carbon emissions are taxed at $50 a metric ton. Such target costs are encouraging and can be implemented in disadvantaged communities, given the quick payback. Policy related amendments and incentives can further enable deep penetration of such technologies, particularly in regions with vulnerable grids where severe climate threatens the resiliency.

5. CONCLUSIONS

The primary objective of this study was to investigate the role of heat-to-power technologies in the ongoing energy transition towards sustainable, low/zero carbon building energy supply. Three different solid state energy devices capable of converting heat to electricity have been shown to be suitable for residential building applications, by integrating with conventional fuel-based thermal equipment. Thermoelectrics, Thermophotovoltaics, and Thermionic emission technologies have been shown to be capable of lowering the carbon footprint associated with thermal load while improving the resiliency and lowering the utility costs. It is possible to configure the electrical power rating for specific thermal demand and electrical efficiency of heat-to-power technologies to achieve optimal economic and environmental benefits. Target costs and other factors necessary for successful adoption of such technologies have been identified.

NOMENCLATURE

$	US dollar	
CO_2	Carbon dioxide	
CFM	Cubic feet per minute	(ft^3/min)
EOS	Equation of state	
HHV	Higher heating value	(MJ/kg)
kg	Kilogram	
kWh	Kilowatt-hour	
LHV	Lower heating value	(MJ/kg)
MJ	Mega joules	
PER	Primary energy ratio	
T	temperature	(C)

TE	Thermoelectric
TIE	Thermionic emission
TPV	Thermophotovoltaic
W	Watt

REFERENCES

Abu-Heiba, A., Gluesenkamp, K. R., LaClair, T. J., Cheekatamarla, P., Munk, J. D., Thomas, J., & Boudreaux, P. R. (2021). Analysis of power conversion technology options for a self-powered furnace. *Applied Thermal Engineering, 188*, 116627.

Agency, E. I. (2020). RESIDENTIAL ENERGY CONSUMPTION SURVEY (RECS). Retrieved from https://www.eia.gov/consumption/residential/data/2015/

Bell, L. E. (2008). Cooling, heating, generating power, and recovering waste heat with thermoelectric systems. *Science, 321*(5895), 1457-1461.

Campbell, M. F., Azadi, M., Lu, Z., Eskenazi, A. G., Jain, A., Bang, J. W., . . . Van Houten, K. C. (2020). Nanostructured Spacers for Thermionic and Thermophotovoltaic Energy Converters. *Journal of Microelectromechanical Systems, 29*(5), 637-644.

Campbell, M. F., Celenza, T. J., Schmitt, F., Schwede, J. W., & Bargatin, I. (2021). Progress Toward High Power Output in Thermionic Energy Converters. *Advanced Science, 8*(9), 2003812.

Cheekatamarla, P. (2020). Performance analysis of hybrid power configurations: Impact on primary energy intensity, carbon dioxide emissions, and life cycle costs. *International Journal of Hydrogen Energy, 45*(58), 34089-34098.

EIA. (2020). Commercial Buildings Energy Consumption Survey: Energy Usage Summary. Retrieved from https://www.eia.gov/consumption/commercial/reports/2012/energyusage/

El Oualid, S., Kogut, I., Benyahia, M., Geczi, E., Kruck, U., Kosior, F., . . . Koenig, J. D. (2021). High Power Density Thermoelectric Generators with Skutterudites. *Advanced Energy Materials, 11*(19), 2100580.

Energy Information Agency, E. (2020). EIA updates its U.S. energy consumption by source and sector chart. Retrieved from https://www.eia.gov/todayinenergy/detail.php?id=41093

Energy Information Agency, E. (2021). State CO2 Emissions. Retrieved from https://www.eia.gov/environment/emissions/state/

Energy.Gov. (2020). U.S. households' heating equipment choices are diverse and vary by climate region. Retrieved from https://www.eia.gov/todayinenergy/detail.php?id=30672https://www.energy.gov/energysaver/heat-and-cool/home-heating-systems

Gamel, M. M. A., Lee, H. J., Rashid, W. E. S. W. A., Ker, P. J., Yau, L. K., Hannan, M. A., & Jamaludin, M. (2021). A Review on Thermophotovoltaic Cell and Its Applications in Energy Conversion: Issues and Recommendations. *Materials, 14*(17), 4944.

Garofalo, E., Bevione, M., Cecchini, L., Mattiussi, F., & Chiolerio, A. (2020). Waste heat to power: technologies, current applications, and future potential. *Energy Technology, 8*(11), 2000413.

Go, D. B., Haase, J. R., George, J., Mannhart, J., Wanke, R., Nojeh, A., & Nemanich, R. (2017). Thermionic energy conversion in the twenty-first century: advances and opportunities for space and terrestrial applications. *Frontiers in Mechanical Engineering, 3*, 13.

IEA. (2020). Tracking Buildings. Retrieved from https://www.iea.org/reports/tracking-buildings-2020

International Energy Agency, I. (2021a). Buildings, A source of enormous untapped efficiency potential. Retrieved from https://www.iea.org/topics/buildings

International Energy Agency, I. (2021b). The future of Cooling. Retrieved from https://www.iea.org/reports/the-future-of-cooling

Jaziri, N., Boughamoura, A., Müller, J., Mezghani, B., Tounsi, F., & Ismail, M. (2020). A comprehensive review of Thermoelectric Generators: Technologies and common applications. *Energy Reports, 6*, 264-287.

Rapp, V. (2020). *Thermionic emission and energy conversion*. Retrieved from

Shittu, S., Li, G., Zhao, X., & Ma, X. (2020). Review of thermoelectric geometry and structure optimization for performance enhancement. *Applied Energy, 268*, 115075.

Wei, W., & Skye, H. M. (2021). Residential net-zero energy buildings: Review and perspective. *Renewable and Sustainable Energy Reviews, 142*, 110859.

Zhakeyev, A., Wang, P., Zhang, L., Shu, W., Wang, H., & Xuan, J. (2017). Additive manufacturing: unlocking the evolution of energy materials. *Advanced Science, 4*(10), 1700187.

Zhang, Y., Cleary, M., Wang, X., Kempf, N., Schoensee, L., Yang, J., . . . Meda, L. (2015). High-temperature and high-power-density nanostructured thermoelectric generator for automotive waste heat recovery. *Energy Conversion and Management, 105*, 946-950.

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