Renewable Thermal Energy Systems: Systemic Challenges and Transformational Policies (Report 2)

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National Renewable Energy Laboratory

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Preface

This report is Part 2 of a three-report series that evaluates the provision of renewable heat for industry and buildings via current and prospective renewable thermal energy systems (RTES) technologies. The RTES project has undertaken initial research focused on technologies that could be suited for industrial process heat applications at different temperature levels, and, where possible, gathered performance and cost data for these technologies. This project neither directly evaluates RTES for distributed residential or commercial applications nor includes documented cases or modeling of RTES using geothermal, biomass, waste heat, renewable fuels like renewable natural gas, or hydrogen production.

The three technical reports are summarized as follows:

- *Renewable Thermal Energy Systems: Characterization of the Most Important Thermal Energy Applications in Buildings and Industry (Report 1)*: summary of thermal demands of U.S. industry and buildings, and relevant hybrid RTES configurations. Available at: https://www.nrel.gov/docs/fy23osti/83019.pdf.
- ***Renewable Thermal Energy Systems: Systemic Challenges and Transformational Policies (Report 2)*, this report: discussion of socio-technical characteristics of RTES, innovation challenges, and supporting policies.**
- *Renewable Thermal Energy Systems: Modeling Developments and Future Directions (Report 3)*: Energy yield and performance modeling of RTES, techno-economic analysis via case studies, and proposed development of a user decision support tool. Available at: https://www.nrel.gov/docs/fy23osti/83021.pdf.

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NREL does not endorse the companies specified in this report, and any mention is strictly for research purposes only.

List of Acronyms

Btu	British thermal unit
CO_2	carbon dioxide
CO_2e	carbon dioxide equivalent
CapEx	capital expenditures
CSI	California Solar Initiative
CPUC	California Public Utilities Commission
DOE	U.S. Department of Energy
EU	European Union
EIA	U.S. Energy Information Administration
EaaS	energy as a service
EERE	Office of Energy Efficiency and Renewable Energy
ESCO	energy service company
EEaaS	energy efficiency as a service
GWh_{th}	gigawatt-hour thermal
HPA	heat purchase agreement
HaaS	heat as a service
IEA	International Energy Agency
IPH	industrial process heat
ITC	investment tax credit
kW	kilowatt
kW_{th}	kilowatt thermal
kWh	kilowatt-hour
MW_{th}	megawatt thermal
MWh	megawatt-hour
NREL	National Renewable Energy Laboratory
PV	photovoltaics
PBI	production-based incentive
quad	quadrillion BTU
RECs	renewable energy certificates
RPS	renewable portfolio standards
RTES	renewable thermal energy systems
SWH	solar water heating
SIPH	solar industrial process heat
TIS	technology innovation system
U.K.	United Kingdom
U.S.	United States

Executive Summary

The provision of heat for industrial processes is a central driver of industrial energy use and carbon dioxide emissions, both globally and for the United States. The need for renewable heat in industry is vital, either directly or indirectly through electrification with renewable electricity generation, both for decarbonization and for the reduction in the use of fuels with historically volatile prices. Relatively recently, the slow pace of decarbonizing heat has prompted a much broader conceptualization of renewable thermal energy systems (RTES) that expands beyond discussion of physical technologies. These perspectives view RTES not as isolated pieces of equipment, but as being embedded in a socio-technical system comprising physical and knowledge infrastructures, markets, institutions, and actors, among other aspects.

Given the country's challenge of rapidly achieving economy-wide net-zero emissions, and the current pervasive use of fossil fuels to provide heat, RTES offer one promising technology pathway. However, to achieve RTES deployment at scale, several challenges must be met. A broad socio-technical perspective is helpful in framing these challenges in terms of improving the technical performance of RTES. This perspective also extends to the ability of society to imagine and create a range of possible solutions that are capable of overcoming passive and active resistance to the diffusion and widespread use of RTES within a required emissions reduction timeline.

Two important challenges for RTES are the need for significant further innovation and deployment, particularly in the United States. In the face of continued success of other renewable energy technologies, such as solar photovoltaics (PV) and land-based wind energy for electricity, it is worthwhile to evaluate the current state of select RTES technologies in the context of technology innovation systems and energy transitions.

This report marks a departure from the existing body of research we are aware of and have contributed to relating to RTES applications for industrial process heat in the United States. Our objectives for this report are fourfold:

1. Begin considering the challenges of RTES deployment in the United States through application of socio-technical and transitions frameworks
2. Begin applying the theory of RTES as configurational technology innovation systems in the United States and for industrial process heat specifically
3. Review RTES innovation, policies, and market formation activities in the contexts of Objectives 1 and 2
4. Identify future paths for RTES research.

Ultimately, the challenges associated with scaling the deployment of RTES in the United States are related to the need to develop a well-functioning innovation system that can overcome resistance from a highly stable socio-technical regime within a shrinking window of time to address the climate crisis, U.S. industrial competitiveness, and volatile energy commodity price shocks. Current efforts toward scaling for RTES applications in industry and buildings emphasize the need for further cost reductions, but not for interventions that support actors and their interactions and that increase the legitimacy of the technologies. As a result, there are significant opportunities to analyze the social contexts of RTES that can then be used to inform

the design of effective, transformational policy portfolios. Moving the discussion and analysis of RTES, which has historically been dominated by techno-economic framing, into socio-technical analysis frameworks may be necessary to accelerate the decarbonization of heat. We identify and expand on three focus areas suggested for future RTES research: innovation systems, user perspectives, and transitions.

- **Innovation systems:** Develop appropriate delineations for renewable thermal energy innovation systems, identify their system functions, focusing on identifying actors and interactions, and evaluate how well the innovation systems are functioning.
- **User perspectives:** Identify and examine the roles of industrial users in evaluating and implementing RTES.
- **Transitions:** Frame decarbonization with RTES as a socio-technical transition, identifying niche formation activities, analyzing the stability of existing technical regimes, and exploring the potential for transformative innovation policy mixes specifically for industry.

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1 Introduction

From 2009 to 2019, the estimated total global annual final energy demand increased from 320 to 381 exajoules (EJ; equivalent to 303 to 361 quadrillion British thermal units [Btu]) (REN21 2021). During the same time period, the percentage of renewable energy meeting end-use demands grew from 8.7% to 11.2%. The total consumption of fossil fuels has increased globally, yet the percentage share of fossil fuels meeting final energy demands has essentially not changed: it was 80.3% in 2009 and 80.2% in 2019 (REN21 2021).

Today's industrial energy is overwhelmingly supplied by the burning of fossil fuels, principally natural gas, and other combustible fuels to produce the heat or steam used in industrial processes (Akar et al. 2021a). In the United States in 2020, 63% of the energy consumed by the industrial sector came directly from fossil fuel sources such as natural gas and coal (EIA 2022). As the world looks to decarbonize, the reduction of fossil fuels through renewable alternatives is becoming increasingly important, though the industrial sector has experienced little change to date. The power sector in the United States, as one example, has seen rapid deployment of renewable energy—in 2020 renewable energy generation met 20% of U.S. needs (EIA 2021a). Relative to this sector, direct industrial uptake of renewable energy, and particularly renewable heat, is much lower.

Total energy delivered to the four end-use sectors (residential, commercial, transportation, and industrial) decreased by ~10% in 2020 compared to 2019 levels due to significantly less demand in response to COVID-19 (EIA 2021b). The industrial sector in 2020 consumed approximately 31.2 quadrillion Btu, or "quads," which was about a 4.5% decrease from 32.7 quads in 2019 (EIA 2022). The expectations are that industrial energy consumption will return to 2019 levels and continue to rise through 2023 at a faster rate than other sectors (EIA 2021c). Beyond this short-term outlook, U.S. industrial sector energy use is projected to increase nearly 30% to 40.34 quads from 2023 to 2030 (EIA 2021b). In this time, the use of fossil fuels for the industrial sector is projected to increase from 19.8 to 27.2 quads (EIA 2021b), unless there is significantly increased adoption of renewable heat, renewable electricity, and energy efficiency.

The use of renewable heat in industry, either directly or indirectly through electrification with renewable electricity generation, is vital both for decarbonization and for the reduction in the use of fuels with volatile prices. The provision of heat for industrial processes is a central driver of U.S. industrial energy use and carbon dioxide (CO_2) emissions (McMillan et al. 2016) and is the keystone for decarbonizing industry (Thiel and Stark 2021). It was estimated that in 2020, global industrial heating applications consumed approximately 20% of the total global energy demand (IRENA 2019a). In 2019, this was approximately 76 EJ (72 quads). At present, the CO_2 emissions associated with direct energy-related activities in industry is estimated to be close to 24% of the global total (REN21 2021).

The need for thermal energy in industry and buildings can be broken out into energy end uses, such as space heating, cooking, and process heat, as discussed in the first report of this series (Kurup, McMillan, and Akar 2023). For industrial process heat (IPH) it is important to consider the temperatures and other process characteristics (e.g., heat transfer medium and mechanism, physical properties of the material to be heated) required for various processes. In the United States, approximately two-thirds of IPH demand in 2014 was used for processes at temperatures of 300°C or below (McMillan et al. 2021), shown in Figure 1. Much of the IPH demands within this temperature range are met by steam produced by conventional boilers or in cogeneration systems.

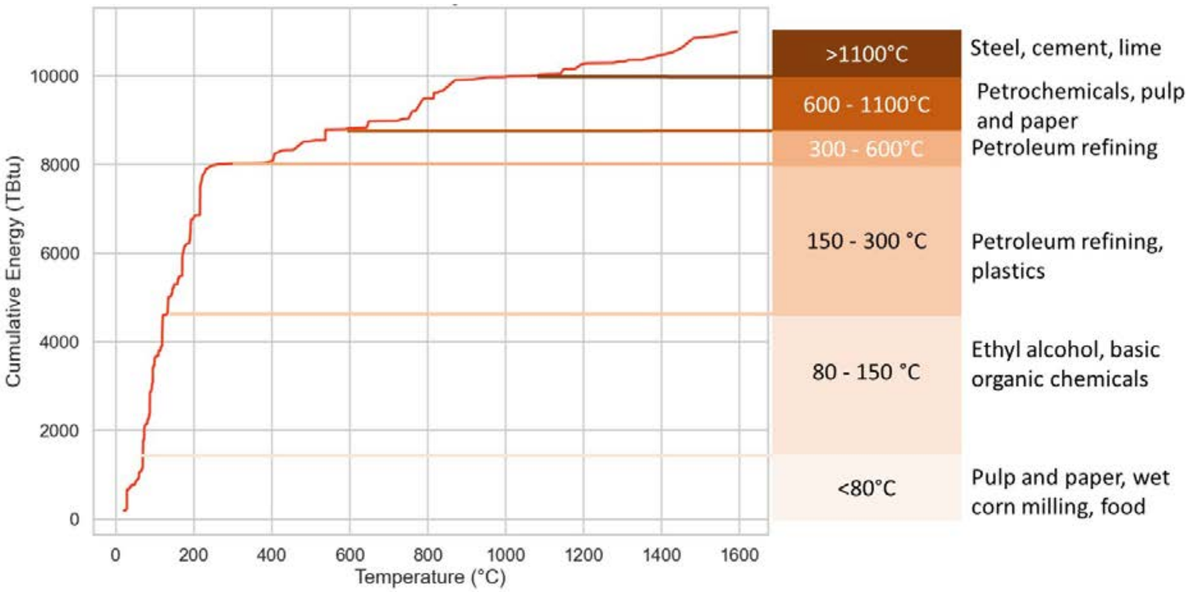

Figure 1. Cumulative energy used for industrial process heat in 2014 and typical process temperature ranges of corresponding example industries.

Data from McMillan (2019)

Renewable thermal energy systems (RTES) could play a significant role in decarbonizing thermal demands for industries and for buildings, as has been shown in certain European countries. RTES, in both stand-alone and hybrid configurations (e.g., concentrating solar thermal [CST] collectors with and without flat plate collectors), have already been commercialized; however, current use of these technologies globally is relatively insignificant. This is particularly true in the United States. Given the country's challenge of rapidly achieving economywide net-zero emissions and the current pervasive use of fossil fuels to provide heat, the accelerated, widespread deployment of RTES to help address the climate crisis, improve U.S. industrial competitiveness, and reduce the impact of fossil fuel price volatility requires more systematic analysis and framing of key challenges and opportunities.

Using an approach that combines a literature review, consideration of the current state of RTES markets and policies, and a brief analysis of learning curves, this report marks a departure from the existing body of research we are aware of, and have contributed to, related to RTES applications for IPH in the United States. We start by emphasizing the social contexts of technology and innovation in general. This socio-technical approach, however, has been accepted more slowly and incompletely in some circles than others: "In short, it appears that the critical debates about science and society that have emerged within the halls of academia during the last several decades have, for the most part, taken place beyond the earshot of practicing scientists and policymakers" (Smirnov and Willoughby 2021, p. 2).[1]

As the United States grapples with large-scale energy transitions that include the decarbonization of heat, there could be significant opportunities to view energy technologies in their social contexts, as well as to follow similar ends for related policy development (Miller et al. 2015). We begin this process for RTES by expanding the definition beyond technical terms and introduce the technology innovation system (TIS) (Carlsson and Stankiewicz 1991; Markard and Truffer 2008; Wieczorek and Hekkert 2012), which has been used to analyze the interrelationships of technology and society. Then, by introducing the evaluation of TIS using system functions (i.e., Hekkert et al. 2007), we discuss current market status, evaluate technology learning curves, and discuss existing and emerging supporting policies and heat business models for RTES in both domestic and international settings. This leads to a discussion of the systemic challenges facing RTES, after which we conclude with a set of options for consideration to support the role of RTES in decarbonizing heat.

The remainder of the report describes the conceptual RTES framework (Section 2), the current RTES market status (Section 3), and RTES learning curves (Section 4). Section 5 considers policy support for RTES, Section 6 highlights business models of heat, and Section 7 highlights key challenges. Options for future research follow in Section 8.

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[1] It is beyond the scope of this report to cover the debates about science and society beyond pointing the reader to several relevant references, which include Marx and Smith (2011); Pinch et al. (1987); and the second chapter of Winner (1977).

2 Viewing RTES From a Technology Innovation Systems Perspective

We start the process of conceptualizing RTES from a purely technical definition: RTES are technologies that either directly or indirectly[2] use renewable energy to provide useful thermal energy. This includes not only the equipment that generates the heat itself, such as concentrating solar thermal collectors, but also heat transfer fluids, thermal energy storage, and renewable combustion fuels.

This initial definition results in a wide range of technologies and applications. For that reason, this report does not address biomass, renewable fuels like renewable natural gas, and hydrogen production. Additionally, given the low adoption rates and breadth of challenges, we focus on industrial RTES (i.e., RTES for IPH) and on solar thermal systems. However, we also utilize insights from the research of RTES for distributed residential and commercial applications, as well as district heating systems, because these systems have received much more attention to date.

Relatively recently, the slow pace of decarbonizing heat has prompted a much broader conceptualization of RTES that expands beyond the discussion of physical technologies. For instance, decarbonizing heat has been cast as a "wicked" problem[3] (Cowell and Webb 2021) and as an issue of path-dependency[4] (Gross and Hanna 2019). These perspectives view RTES not as isolated pieces of equipment but as being embedded in a socio-technical system composed of physical and knowledge infrastructures, markets, institutions, and actors, among other aspects. With a socio-technical framing, decarbonizing heat is a challenge not only in terms of the technical performance of RTES, but in the ability of society to imagine and create a range of possible solutions that are capable of overcoming passive and active resistance to their diffusion and widespread use within a required emissions reduction timeline.

Before continuing any further with our discussion of RTES, we first introduce several concepts that are used in the report. These concepts reframe technology by explicitly considering its social dimensions. We start by expanding the discussion of RTES innovation by introducing the TIS[5] framework (Carlsson and Stankiewicz 1991; Markard and Truffer 2008; Wieczorek and Hekkert 2012). Markard and Truffer (2008) define a TIS as "a set of networks of actors and institutions that jointly interact in a specific technological field and contribute to the generation, diffusion and utilization of variants of a new technology and/or a new product" (p. 611). The authors also

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[2] The European Union's Renewable Energy Source Directive has classified heat pumps with "output that significantly exceeds the primary energy needed to drive [them]" as renewable energy (European Parliament 2009, p. L 140/19).

[3] Cowell and Webb (2021) use the qualities of wicked problems defined by Rittel and Webber (1973), such as not being susceptible to either a single definition or linear cause-effect solutions, and possible solutions that are contentious due to the different views and values of the actors involved.

[4] Gross and Hanna (2019) define path-dependency as the increasing returns achieved by technologies or systems through scale and learning economies, adaptive expectations, and coordination effects.

[5] A similar framework developed later for energy technologies—the energy technology innovation system (ETIS) (Gallagher et al. 2012; Grübler et al. 2012). For this report we use the TIS framework, which is considered to be more expansive than the ETIS (Truffer et al. 2012).

establish four minimum conditions that a TIS must meet: although different actors pursue different innovation strategies or control different resources, they share expectations or vision; actors are subject to a division of labor of different innovation tasks; a variety of institutions exist, of which internal institutions that arise from actor activities are central; and market transactions occur between customers and multiple, competing suppliers. Wieczorek and Hekkert (2012) later distill the structure of a TIS down to four aspects—actors, interactions, institutions, and infrastructures—which are described in Table 1.

Table 1. Identification and Description of Structural Aspects of a TIS (Wieczorek and Hekkert 2012)

Aspect	Description
Actors	Individuals, organizations, or networks categorized by their role in economic activity (e.g., government, companies, universities, nongovernmental organizations, banks, consultants)
Interactions	Dynamic relationships that occur between individuals or within networks
Institutions	The shared concepts and habits (i.e., soft institutions) that are set by legislation, standards, and strategies (i.e., hard institutions)
Infrastructures	Structural components that include the physical, knowledge, and financial (e.g., grants and subsidies)

The activities occurring in TIS to drive the creation and diffusion of innovations that result in technological change can be mapped to seven core functions (Hekkert et al. 2007). These functions, summarized in Table 2, include the activities of entrepreneurs, knowledge development and diffusion, allocation of human and financial capital through resource mobilization, and the acceptance of an innovation by creating legitimacy. A well-functioning TIS exhibits these system functions, while systemic weaknesses impede innovation system functions (Jacobsson and Bergek 2011).

Table 2. TIS Functions (Hekkert et al. 2007)

Innovation System Function	Function Definition
Entrepreneurial activities	New or incumbent actors that turn potential innovations into new business opportunities
Knowledge development	Generation of knowledge through learning-by-searching and learning-by-doing
Knowledge diffusion through networks	Exchange of information through learning-by-interacting and learning-by-using
Guidance of search	Selection of specific technology options to receive an allocation of limited resources for further development
Market formation	Creation of opportunities for innovations to compete with existing technologies
Resource mobilization	Allocation of limited human and financial capital
Creation of legitimacy	Acceptance of an innovation, resulting from either incorporation within or disruption of an existing regime

Analyzing the social and material infrastructures of specific technologies is the important undertaking for studying technological change (Winner 1986). Examples of more applied analysis of innovation system functions include Wesseling and Van der Vooren (2017), who find that innovations for clean concrete in the Netherlands face structural problems related to risk aversion of concrete procurers, little public pressure on cement companies, a strong and well-coordinated industry lobby, a lack of policy support, large capital requirements of cement production, and the focus of incumbent cement companies on proven technologies. The authors conclude that interwoven policies that support diffusion of knowledge between procurers and suppliers, create a market for clean concrete, and mitigate the power of vested interests could be helpful for improving innovation.[6] In another example, Reichardt et al. (2016) trace the developments and interdependencies of the German offshore wind TIS and its policy mix, finding that early policies responded to a lack of regulations for responding to offshore wind permission requests, which supported entrepreneurial activities. Later, market formation and guidance of search functions were supported by adjustments to demand pull policy instruments, such as a feed-in tariff. Additional examples of applied analysis can be found for the Swedish iron and steel industry (Karakaya et al. 2018) and for Chinese solar PV (Huang et al. 2016).

We begin the process of evaluating the functioning of RTES by discussing the United States in the context of international developments regarding market formation (Section 3 and Section 5), knowledge development (Section 4), and entrepreneurial activities (Section 6).

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[6] We note that recently a group of European construction companies, architectural and engineering firms, and other concrete procurers have created the ConcreteZero initiative that aims to develop markets for low-emission concrete (Climate Group 2022).

3 Current RTES Market Status

The market penetration of RTES at an aggregate level can be gauged by the portion of heat demand met by renewable energy. According to REN21 (2021), as of 2019, renewable energy constituted nearly 15% of global industrial energy demand and 10% of building heat. In the EU, where some member states have set specific targets for renewable heat, about 23% of total heating and cooling demands (including industry and buildings) came from renewable sources in 2020, up from about 12% in 2004 (Eurostat 2022). Renewable shares in 2020 for EU member states ranged from 6% in Ireland to 66% in Sweden. For the United States, only 7% of industrial energy use came from renewable energy, of which the overwhelming majority was biomass (EIA 2022).

A lack of availability and transparency of RTES deployment data, including system costs and performance, as well as the challenge of lowering system costs, is a persistent problem (IRENA 2021). On a global level, the International Energy Association (IEA) Solar Heating and Cooling Programme publishes "Solar Heat Worldwide" annually, noting new installations and cumulative statistics on solar thermal (Weiss and Spörk-Dür 2021). The IEA has also compiled a database of existing solar heat installations for industrial processes (SIPH) as part of Task 49 (https://www.ship-plants.info), which currently includes details for 346 plants as of 2021. Weiss and Spörk-Dür (2021) estimate the total number of installations as more than 891; the 19 installations in the United States amount to about 11 megawatts thermal (MW_{th}). China leads globally in the number of installations, but SIPH capacity/production is dominated by a single facility in Oman attached to petroleum production. The plurality of global installations in the database are in the food and beverage sectors (Weiss and Spörk-Dür 2021).

Most solar thermal industrial systems installed globally are relatively small—less than 0.35 MW_{th}—and cover an area of less than 500 square meters (m^2). For comparison, in the United States the average installed capacity of natural gas boilers is 30 metric million Btu per hour (MMBtu/h) (about 8.8 MW_{th}) (Schoeneberger et al. 2022).

Two exceptions to the lack of cost and performance data are California's Solar Initiative (CSI) Thermal Program (California Public Utilities Commission 2021), which is primarily a program for residential and commercial buildings, and the United Kingdom's Renewable Heat Incentive (HM Government Department for Business, Energy & Industrial Strategy 2022) The CSI Thermal Program approved 12,354 applications in 2021, which at the time of writing are estimated to have achieved cumulative savings of 953,448 MMBtu of natural gas, 755,607 kilowatt-hours (kWh) of electricity, and 50,878 metric tons of carbon dioxide equivalent (CO_2e) (CPUC 2021).

The International Renewable Energy Agency (IRENA) has undertaken efforts to fill data gaps and has reported cost and performance data for commercial and industrial solar thermal systems above a 50-m^2 collector area. The data collected by IRENA are divided into five groups by application and location: district heating in Denmark; large-scale thermal (i.e., central hot water and space heating, district heating, and process heat) in Austria, Germany, and Mexico; and district heating systems in Europe.

Reductions in total installed cost and levelized cost of heat are given for each group from the earliest year (2010, 2013, or 2014) to 2020. For example, total installed costs of district heating in Denmark declined by about 29%, from $573/kW in 2010 to $409/kW in 2019 (amounts in 2020 U.S. dollars), corresponding to an experience rate of about 17% (IRENA 2021). Installed costs for commercial and industrial-scale projects in Austria and Germany declined even more dramatically, falling by 55% for Austria from 2013 to 2020 and by 45% for Germany from 2014 to 2020 (IRENA 2021). As Section 7.2 discusses, however, the transition to decarbonized heating in Germany has significantly lagged the transition to renewable electricity.

Prior NREL work has highlighted that for parabolic trough collector technology in California (based on 2019 industrial natural gas prices), the installed cost of the solar field would need to be cheaper than \$150/m^2 for competitive projects compared to natural gas (Kurup and Turchi 2020). This was estimated to be at least 50% less expensive than the current \$300/m^2–\$400/m^2 needed to install the technology when the engineering, procurement, and construction costs are also included in the installation (Kurup and Turchi 2020).

4 RTES Learning Curves

Technology costs can be reduced through learning, or the knowledge accrued through experience with a technology (Grübler et al. 1999). The relevant processes for driving cost reductions can be categorized in terms of learning-by-researching, learning-by-deployment (including learning-by-doing, learning-by-using, and learning-by-interacting), economies of scale, and markets (Elia et al. 2021). Learning curves are a common method for estimating the effects of these learning processes and for evaluating the knowledge development function of a TIS (Hekkert et al. 2007). Learning curves have typically been used as single-factor representations that aggregate the effects of learning-by-doing, learning-by-using, and learning-by-interacting (Elia et al. 2021). These single-factor representations relate technology costs to cumulative production or deployment.

Expressing technology cost solely as a function of cumulative deployment is a convenient yet grossly oversimplified representation of the processes of technological learning. Critiques of the approach have been mounted from various perspectives, including the role of policy as a factor in both technology costs and deployment (Breetz et al. 2018), and the constraints imposed by raw material prices (Hsieh et al. 2019).[7] Other approaches for assessing learning, such as patent analysis and expert elicitation, are not covered in this report, but have recently been reviewed by Lewis and Nemet (2021) in the context of low-carbon innovation.

Solar PV can be held up as a prime example of the cost of an energy technology declining substantially with increasing deployment. For example, the unsubsidized capital cost of utility-scale PV declined by more than 80% from 2010 to 2020, reaching approximately $\$1/W_{DC}$ (Ardani et al. 2021). From 1976 to 2020, global PV module costs have, on average, dropped in price by about 22% for every doubling of cumulative shipments (Feldman et al. 2021). Costs are projected to fall further—for example, capital expenditures (CapEx) and operations and maintenance costs are expected to be $0.78/W and $16.64 kW/year, respectively, in 2030 (NREL 2021)[8].

The literature on learning curves for solar thermal technologies is not nearly as broad or as deep as that of solar PV, and costs and their components are not tracked as systematically. Part of the explanation, at least in the United States, may be linked to the history of solar water heating (SWH) in California. A handful of technological improvements in the 1970s that were the result of federal R&D programs were followed by installation tax credits that included California Public Utilities Commission (CPUC) SWH credits (1977–1983) and federal tax credits (1979–1985) (Taylor et al. 2007).

The market evaporated once these credits were removed, which had implications that reverberated decades later: sales fell from about $1 billion in the 1980s to $30 million at the end of the 2000s (Nemet 2013). Although there were no technological improvements noted in the

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[7] Additional critiques are discussed by Elia et al. (2021).

[8] Utility-scale PV under the Moderate scenario and R&D case. Expressed as a levelized cost of energy, utility-scale PV is projected to reach 2.068¢/kWh for Class 5 resources. This essentially matches the 2030 goal of the U.S. Department of Energy's Solar Energy Technologies Office (https://www.energy.gov/eere/solar/goals-solar-energy-technologies-office).

1980s, learning-by-doing accrued by experienced installers during this period contributed to improved system performance over the initially poor reliability (Taylor et al. 2007). However, the removal of the tax credits prevented this accrued knowledge from being codified and retained as installers exited the market (Taylor et al. 2007). Without being codified, the knowledge of proper installation and operation of these technologies was partially lost, a process formally known as knowledge depreciation (Grübler and Nemet 2013).

Importantly for the RTES, knowledge depreciation is more problematic for system integration than for individual system components (Nemet 2013). SWH was also subject to negative perceptions that persisted for some time, which may have negatively influenced the diffusion of SWH and may have had spillover effects for other technologies (Nemet 2013). The role of industry discontinuities and changes in policy regimes in contributing to knowledge depreciation for a solar thermal technology is also documented in the case of concentrating solar power by Lilliestam et al. (2017).

Nearly three decades after the CPUC SWH incentives disappeared, the California Solar Initiative Thermal (CSI-Thermal) Program was created. The CSI-Thermal Program promoted SWH by providing direct financial incentives to retail customers, training for installers and building inspectors, and a statewide marketing campaign (California Public Utilities Commission 2021). It is worth quickly exploring how learning curves have progressed over the course of the CSI-Thermal Program, relative to the generally increasing cost trends found for SWH (Taylor et al. 2007). To our knowledge, only learning impacts of the CSI solar PV program have been evaluated (e.g., Bollinger and Gillingham 2019).

We use the wealth of data on installations (http://www.csithermalstats.org/download.html) to calculate and plot the installed cost (in 2019 U.S. dollars per megawatt[9]) and cumulative installed power (in megawatts) for each major system technology type, as shown in Figure 2. We then use a simple log-fit to estimate learning curves and associated experience rate[10] for each technology. Indirect forced circulation, which is the largest technology type by number of applications and makes up 43% of applications, is estimated to have an experience rate of approximately 4.5%. Technologies "not specified" account for 90% of the size of applications and are estimated to have an experience rate of about 3.8%.

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[9] System capacity is not included in the CSI database. Using the PVWatts® application programming interface (https://developer.nrel.gov/docs/solar/pvwatts/v6/), we query the daily average solar irradiance (in kilowatt-hours per square meter per day) at the latitude and longitude of each application to convert reported collector area to megawatts. This differs from the approach of Taylor et al. (2007), who converted collector area to megawatt thermal using a constant factor of 0.7 kW/m^2.

[10] The experience rate is the rate at which costs decrease for each doubling of cumulative deployment.

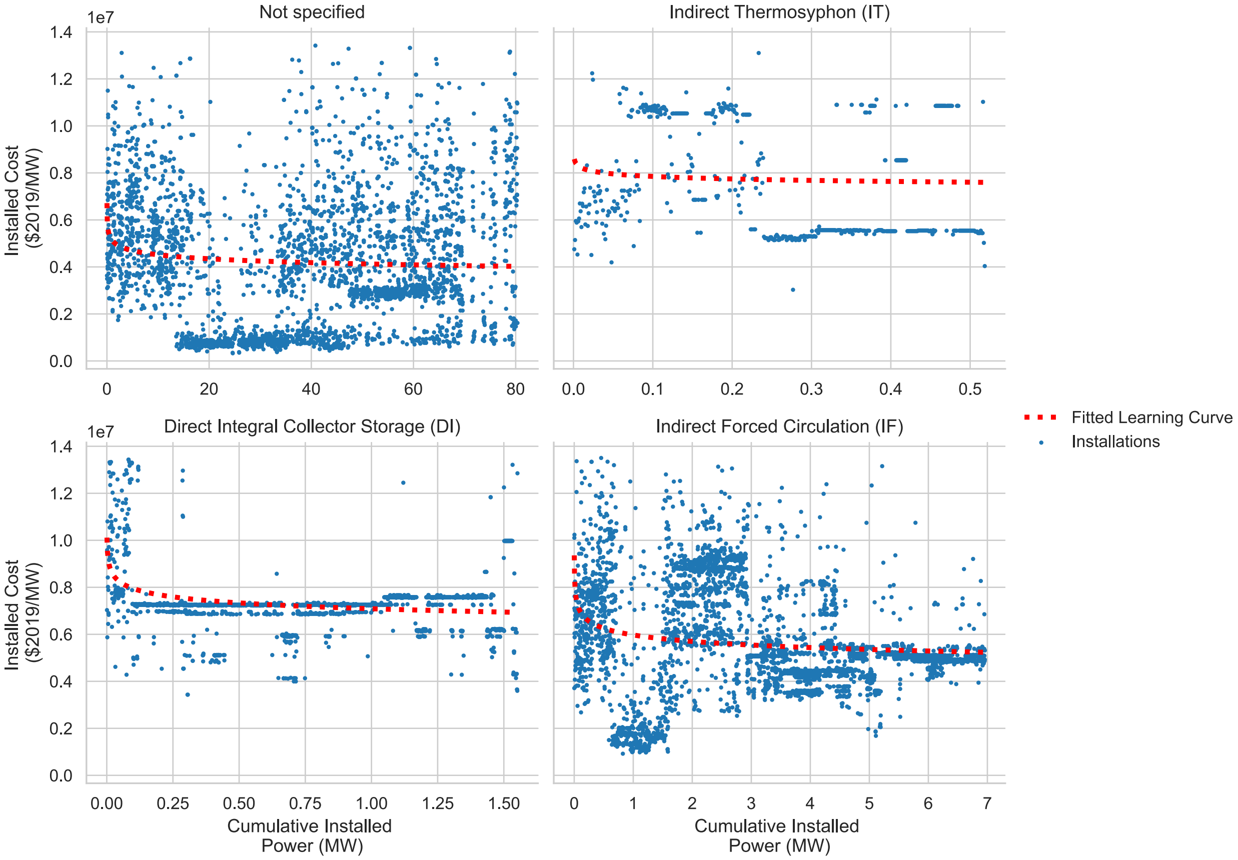

Figure 2. Estimated learning curves of solar water heating by technology for systems installed under the California Solar Initiative Thermal Program. The estimated experience rates of these technologies over the life of the program were relatively small. The most significant technologies by number of applications and cumulative installed capacity—indirect forced circulation and "not specified"—had experience rates of 4.5% and 3.8%, respectively.

Noting the differences in experience rates across geographies (e.g., Elia et al. 2021), we compare the CSI-Thermal Program to solar thermal installations in the United Kingdom. Analysis by Renaldi et al. (2021) of experience rates of residential heating technologies includes solar thermal collectors installed during a period that overlaps with the CSI-Thermal Program. From 2010 to 2019, the experience rate for flat-plate collector equipment costs was about –2% (indicating an increase in costs) and 3% for evacuated tube collectors; the experience rate for the total installed costs for the two technologies was about 13%.

As an additional attempt to evaluate the current state of innovation in North American RTES, we constructed a learning curve for a supplier of concentrating solar thermal systems used to provide IPH in Mexico. Figure 3 shows this learning curve fitted to the roughly 3,500 kW of cumulative installations. Fitting a logistic curve to the cumulative installed capacity and installed costs (in U.S. dollars per kilowatt) yields an experience rate equal to –64%. This is a notably large negative experience rate. A cursory examination of the installations does not indicate changing trends in characteristics such as mounting type (roof or ground), supplied temperature, or type of storage tank. Inspection of additional installation details, discussions with the manufacturer, and other efforts necessary for identifying factors behind this experience rate, however, are outside the scope of this report. Instead, we propose that this, along with our analysis of the CSI-Thermal Program learning curves, is additional evidence that renewable may be best characterized as a configurational TIS, which faces innovation and diffusion challenges due to the highly location-dependent nature of installation and use, as well as the wide variety of available technologies and fragmented actors (Wesche et al. 2019). We discuss the nature and implications of configurational TISs in Section 7.1.

We stress that knowledge development is only one example of TIS functions. Although it is not framed as such, Taylor et al. (2007) analyze government actions in the U.S. SWH market and incidentally provide a blueprint that could be applied for the solar IPH TIS, as well as other RTES TISs. For example, Taylor et al. quantify knowledge development by R&D spending and patenting activity, knowledge diffusion through networks by quantifying conferences and publishing, and resource mobilization by evaluating the importance of various innovation policies.

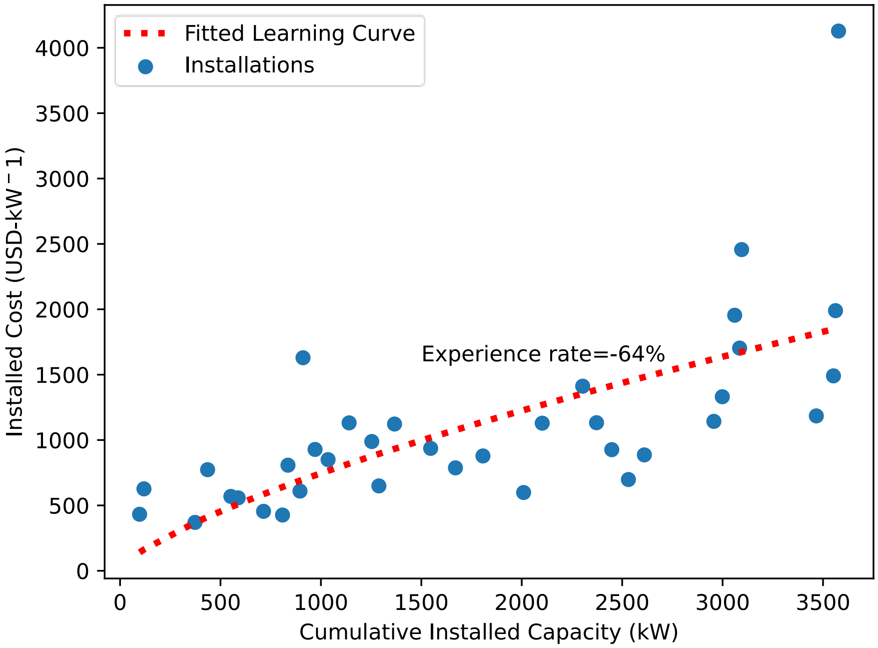

Figure 3. Estimated learning curve for a solar industrial process heat developer in Mexico. Total installed costs have been converted and deflated from Mexican dollars to 2019 U.S. dollars.

Costs include collector field and circuit, solar storage tank, and planning and installation costs. Costs for integration equipment, financing, and value added tax, as well as any subsidies, are excluded.

5 Policies to Support RTES

5.1 United States Federal and State Policies

Key enablers for the industrial sector identified by IRENA include regulatory support, incentives for renewable energy and efficiency measures, and market design (IRENA 2019b). This section highlights some of the U.S. incentives, policies, and regulatory support that are either currently used or could be used in the future to increase RTES uptake for industry. In our TIS framing, these policies and incentives represent the hard institutions and financial infrastructure, respectively, that are currently used for RTES in the United States. These also reflect the ability of RTES actors to mobilize resources to support innovation and to foster legitimacy.

Federal and state incentives are available for heat and heat services generated from renewable energy in the United States; however, the incentive can vary based on the type of renewable energy used. This policy summary discussion includes biomass[11] and geothermal technologies in addition to solar thermal. At the federal level, most of these technologies are incentivized through an investment tax credit (ITC). The ITC provides a tax credit for a specific percentage of qualified expenditures associated with the installation of certain renewable energy technologies.[12] The tax credits are not currently refundable or transferable but may be applied over multiple years. Still, the credits are generally more accessible to higher-income households[13] and businesses with sufficient taxable income. That said, third parties can own the renewable energy system on a residential or commercial property, claim the tax credit, and sell the heat or lease the equipment. This model is particularly popular for solar PV but has also been used for industrial process heat. Table 3 summarizes these incentives by owner type.

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[11] Biomass in gas (e.g., biogas made from animal or food waste), liquid (e.g., biodiesel, plant-matter-based ethanol), or solid state (e.g., wood chips or pellets).

[12] The ITC provisions described here do not reflect updates that may be included in H.R.5376 - Inflation Reduction Act of 2022 (https://www.congress.gov/bill/117th-congress/house-bill/5376).

[13] Barbose et al. (2022) found that residential solar PV adopters span all income ranges but generally skew high, likely due to the capital cost and the tax credits.

Table 3. Summary of Investment Tax Credit Availability by Technology and Owner Type

	Solar Thermal	Geothermal	Biomass
Residentially owned and used	Solar water heater (not for swimming pools or hot tubs): 26%[a] for systems placed in service from 2020 to 2022; 22% for systems placed in service in 2023.	Heat pump: 26% for systems placed in service from 2020 to 2022; 22% for systems placed in service in 2023.	
Business-owned	Water/space/process heat: 26% for systems beginning construction from 2020 to 2022; 22% for systems beginning construction in 2023. All systems must be placed in service before 2026.	Heat pump: 10% for systems beginning construction from 2020 to 2023 and, generally, installed within 4 years.	Combined heat and power, 50 MW or less, using biomass as 90% or more of the system's energy source: 10% for systems beginning construction from 2020 to 2023 and, generally, installed within 4 years.

[a] Unless otherwise noted, percentages in table reflect the percentage of a qualifying project's total eligible costs that the owner can claim in the form of a tax credit. *Source: DSIRE (NC State University, 2021)*. Note restrictions for the suitability of tax credits apply; see source for more information.

At the state level, a significant portion of incentives for renewable heat and heat services is driven by state renewable portfolio standards (RPS), which mandate a certain percentage of electricity sold within a state be generated from renewable sources. In roughly half the states with RPS, renewable thermal technologies are incorporated into an RPS[14] program (Donalds 2018). As with the federal ITC, program eligibility varies by technology, as summarized in Table 4.

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[14] Because RPS are for electricity, and thus measured in megawatt-hours, states have developed methods for converting thermal heat to equivalent megawatt-hours. Some states use a Btu-to-MWh conversion (or "electric equivalency basis," which is frequently 3,412,000 Btu = 1 MWh), whereas other states calculate RECs based on the megawatt-hours of conventional electricity displaced by these thermal renewable energy sources.

Table 4. States That Include Renewable Thermal Technologies in Their RPS

All	Solar Thermal	Biomass	Geothermal
AZ, IN, MA, MD,NH, TX, VT, WI	AZ, DC, IN, MA, MD[a], NV, NH, NC, PA, TX,UT, WI	AZ, IN, MA, MD[b], NC[3], NH, OR[c], TX,WI	AZ, IN, MA, MD, NV,NH, TX, WI

[a] Solar hot water only

[b] Excludes woody biomass

[c] Only useful thermal energy that is produced as a byproduct by biomass electricity generators is eligible

Source: Clean Energy States Alliance (Donalds 2018)

A key issue is that solar thermal technologies (and renewable heat technologies in general) are inconsistently classified as either a renewable energy technology or an energy efficiency technology. A lack of state-level policy has meant most states do not have renewable heat targets and goals, compared to most states utilizing RPS for renewable electricity.

5.1.1 Other State Incentives

Although design details vary considerably, RPS policies typically rely on RECs, up-front cash grants, performance-based incentives (PBIs), state and local tax credits, and/or feed-in tariffs to promote deployment and facilitate compliance (Feldman and Bolinger 2016).

Renewable Energy Certificates

RECs are tradable, intangible certificates that represent proof that energy was generated from an eligible renewable energy resource. RECs are classified in many different ways, depending on the year the REC was generated, the facility location, and the type of renewable generator. These certificates can be sold, traded, or bartered, and the REC owner holds claim to the renewable attributes of the underlying energy (Feldman and Bolinger 2016). Utilities purchase RECs to satisfy state RPS requirements. The price of a REC will depend on the relative supply and demand of the specific vintage of the REC. Often, electric utilities within these states satisfy RPS requirements by purchasing RECs, which gives them credit for having generated a certain unit of energy (typically, 1 REC = 1 MWh, or an equivalent thermal amount). Thus, renewable generation sources can sell RECs as a way of defraying the cost of building and maintaining these assets; however, due to the market-based element of RECs, there can be great uncertainty about the value of the credits over the system lifetime.

State Tax Credits

Some states offer tax credits for installing a renewable energy system. Homeowners or businesses can deduct a portion of the system cost from their state tax bills. These amounts vary significantly by state and may have system size, dollar amount, or ownership limitations. To claim the credit, a person or business must have enough tax liability to offset in that state.[15]

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[15] That is, unless the credit is refundable, in which case the amount of any credit in excess of taxes owed is refunded to the taxpayer in cash. Certain states use the tax code to incentivize solar in other ways, such as prohibiting the value of renewable energy systems from being included in property tax assessments or exempting renewable energy equipment from state sales taxes (Feldman and Bolinger 2016).

Arizona, Iowa, Massachusetts, Montana, New York, South Carolina, and Utah all have tax credits applicable to some form of renewable thermal energy (NC State University 2021a).

Grants, Rebates, or Performance-Based Incentives

PBIs differ from grants and rebates in that funds are distributed over time based on the performance of the system, instead of in one lump sum at the beginning of the project. PBI programs are typically administered by state clean energy funds and are funded by utilities and/or ratepayers through alternative compliance payments and system benefit charges on electric bills (Feldman and Bolinger 2016). A PBI was used in California's CSI-Thermal Program for gas displacement in the industrial sector. This is a useful example of the impact of an uncertain incentive time horizon on investors and project developers. This PBI was specifically suited for industrial end users to receive rebates of \$10.10/therm (\$0.3446/kW$_{th}$) of natural gas displaced, up to a maximum of \$800,000 when the installed SIPH system could show metered reductions in natural gas consumption (CPUC 2017; Esfahani et al. 2021).

In 2017 the PBI for industrial end users was expected to end (Kurup and Turchi 2020), though with the extension of Bill AB-797 in late 2017, the PBI was extended by 2 years from 2018 to 2020 (Esfahani et al. 2021). The use of the PBI was dependent on providing measured natural gas displacement savings; as such, the new SIPH plants would need be constructed by the end of 2018 in order to qualify, effectively resulting in only a 1-year extension of the build period. The uncertainty faced by solar developers and industrial end users in late 2017 and a 1-year window to build the plant could have dissuaded industrial consumers from proceeding with SIPH upgrades. Discussions with RTES and concentrating solar thermal developers who were aiming to execute projects in California, such as Rackam, confirm that even with the lucrative incentive, the industrial end user was unwilling to take on a new project given the doubts in the length of the financial incentive.

Subsidized Loans

Subsidized loans may be made available by a governmental entity, nongovernmental organization, utility company, or private entity and feature significantly reduced interest rates. Generally, subsidized loans are available only in a few areas and for a limited time. Often, the low interest rates are made available by states offering credit subsidies to the lender, effectively "buying down" the interest rates.

Property-Assessed Clean Energy Programs

In Property-Assessed Clean Energy (PACE) programs, municipal financing districts lend the proceeds of bonds or other funds to property owners to finance end-user renewable energy and energy efficiency improvements. The property owners then repay these loans over 15–20 years via annual assessments on their property tax bills. One benefit of PACE programs is that the repayment obligation of the loan stays with the property and does not move with the homeowner or business.

Beyond direct financial incentives, states can enable the deployment of renewable heat systems with improved permitting processes, reductions of fees, and increased quality assurance for the installation (EPA 2012).

Certain renewable energy projects qualify to receive cash rebates that encourage deployment and reduce the up-front cost to the end consumer. Grants and rebates may be available from states, municipalities, utility companies, and other nongovernmental organizations. These options for financial support can be used to address the up-front CapEx, longer payback periods, and potential investor aversion to deploying renewable heat technologies. A key to state policy best practices is the long-term financial viability of an incentive (EPA 2012). The CSI-Thermal Program, one part of the overall CSI, tried to reduce natural gas use by providing financial incentives for end users/sectors, such as commercial/multifamily residential, commercial pools, and industry (Esfahani et al. 2021). From 2010 to 2020 in the CSI-Thermal Program, approximately $162 million of incentives were approved (out of a maximum total of $250 million). Out of the 11,757 approved applications in 2020, only one was for the industrial sector, with the single project receiving $753,000 in incentives (Esfahani et al. 2021). Considering the relative savings of the CSI-Thermal Program as of 2021, of the approximately 9.5 million therms of energy savings from the program, ~300,000 was from the industrial sector, or 3% of the total (CPUC, 2021).

5.2 International Renewable Heat Policies

As with the case of tracking cost and performance of RTES, a lack of renewable heat data hampers analysis of policies, in terms of both their effectiveness and comparisons between approaches (Collier 2018). It is important to first note that even from an international perspective, policies that specifically target renewable heat are much less common than policies for overall use of renewable energy or renewable electricity generation. As of 2020, 161 countries had overall renewable energy policies, 60 countries had heating and cooling policies, and only 32 countries had a heating or cooling policy related to industry (REN21 2021). Similarly, of the 165 countries having renewable energy targets, 137 countries had renewable electricity targets and only 19 countries had renewable heating and cooling targets (REN21 2021). REN21 summarizes these targets: the 2020 targets for shares of renewables in heating and cooling of EU member states range from 8.5% for Luxembourg to 62.1% for Sweden.

Several efforts have been made over the last few years to review existing renewable heat policies, principally from a perspective of best practices that may be applicable to decarbonize heating demands in the U.K. building stock (Hanna et al. 2016; Kerr and Winskel 2021; Vivid Economics and Imperial College 2017a). Although these policies were developed in European contexts and primarily address heat demand in buildings, there are many lessons that could be applied to the United States and for industry demands.[16]

The reviews of renewable heat policies make no attempts to quantify the effectiveness of individual policies, or even packages of policies, given the lack of consistent data on technology deployment and heat demand. Nonetheless, the policy reviews share several observations and conclusions regarding what has made for effective policies. These studies find overall that a

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[16] On one hand, the United States may share similarities with individual countries: U.S. residential buildings use natural gas for 65% of space and water heating demands (EIA 2018), compared to 53% in Germany, 85% in the United Kingdom, and 94% in the Netherlands (Kerr and Winskel 2021). On the other hand, given the United States numerous climate zones and variety of building stock as well as the different concentrations of industries, it may be more appropriate to make subnational comparisons between the United States and EU member states.

foundation to decarbonizing heat is built with a mixture of market-based incentives (e.g., rebates, grants, loans) and strong government intervention. However, we highlight that unlike policies tailored for the buildings sector, all renewable heating or cooling policies for industry are currently economic incentives (e.g., tax credits, grants, fuel or carbon taxes, subsidies, or loans) (REN21 2021).

Common drivers of successful adoption of renewable heat technologies found in reviews of renewable heat policy include (Kerr and Winskel 2021; Vivid Economics and Imperial College 2017a, 2017b; Collier 2018; Hanna et al. 2016)

- Policy consistency
- Longstanding, clear targets for emissions reduction, fossil fuel reduction, or renewable heat adoption
- Fossil fuel taxes, either by fuel or by carbon content
- Complementary policies for energy efficiency and building codes
- Packages of synergistic policies (e.g., integrating renewable heating and energy efficiency policies), as opposed to single, isolated policies
- Innovation support through the development of test facilities
- Robust actor networks and interactions of manufacturers, industry associations, installers, utilities, research institutes and government to generate and share knowledge
- Information dissemination through consumer awareness campaigns, technology standards, installer certifications.

Several countries consistently stood out in these policy reviews: Germany, Sweden, and Finland. Sweden and Finland are notable for their early use of carbon taxes, emissions reduction goals, and noneconomic renewable heat policy support. Germany has been discussed as a country struggling to decarbonize its heat use (e.g., Frank et al. 2020; Wesche et al. 2019). In order to compare policies across these three countries, we have summarized heat policy literature in Table 5. We note that this is not an exhaustive summary and we have focused our efforts on the most recent policies. We note that although the effectiveness of one specific policy might be subject to criticism, it may contribute in aggregate to the achievement of the overall policy goal.[17]

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[17] See, for example, the discussion of residential heat pump developments in Sweden by Nilsson et al. (2005).

Table 5. Summary of National Contexts and Renewable Heat Policies in Germany, Sweden, and Finland

	Germany	Sweden	Finland
National target: greenhouse gases emissions	Net zero by 2045	Net zero by 2045 (legally binding)	Net zero by 2035
National target: renewable heat	15.5% by 2020	62.1% by 2020	47% by 2020
Renewable share of heating and cooling[a]	2004: 7.2% 2020: 14.8%	2004: 45.9% 2020: 66.4%	2004: 39.5% 2020: 57.6%
National target: technology deployment	nf	nf	5-terawatt-hour heat pumps 2020
National carbon tax[b]	nf	\$129.89/tonne CO_2e (USD)	\$58.58/tonne CO_2e (USD)
National energy taxes: industry[c]	Natural gas: 18.1% Light fuel oil: 19.3 % Electricity: 51%	Natural gas: 25.1% Light fuel oil: 55.4% Electricity: 6.1%	Natural gas: 41.6% Light fuel oil: 45.4% Electricity: 10.4%
National energy taxes: households[c]	Natural gas: 24.1% Light fuel oil: 28.2% Electricity: 53.2%	Natural gas: 43% Light fuel oil: n/a Electricity: 39.9%	Natural gas: n/a Light fuel oil: 55.9% Electricity: 31.6%
Subsidies: capital	Heat networks, based on length and diameter of pipes	nf	Replacement of oil-based heating; adoption of efficient wood-fired heating[d]
Subsidies: installation	nf	Tax incentive of 50% of labor costs for heat pumps installation; tax reduction for installation of "green technology"	Tax incentive of 60% of labor costs for heat pumps
Grants	Small-scale renewable heat systems. Heat pumps must meet minimum coefficient of performance. Additional support for innovative technologies or combinations (Market Incentive Program of the Renewable Energy Heat Act [EEWärmeG])	Homeowners up to 30% of material and labor costs to replace oil or resistance heating with heat pump, district heating, or biomass (2006–2010)	nf
Loans	Low-interest loans for large systems for industry and district heating (Renewable Energy Heat Act [EEWärmeG])	nf	nf
Technology prohibitions	Ban on oil central heating in buildings to begin in 2026. At least 50% of heat load in new residential buildings to be supplied by renewable sources (EEWärmeG)	nf	nf

	Germany	Sweden	Finland
Complementary energy efficiency[e]	Various, including efficiency standards for new and existing construction (Energy Efficiency Ordinance [EnEV])	Various, including efficiency standards in Swedish Building Code (Svensk Bygg Norm [SBN]) and buildings with very low energy use LÅGAN)	Various, including nearly-zero energy buildings standards for new construction
Technology standards and labeling	Heat pump seasonal performance factor of 3.3–4; Heat pumps must be certified with EHPA Quality Label	Heat pump eco-label (Swan); heat pump quality label (P-Label); installation standard for geothermal systems (Normbrunn-97)[f]	Certifications for heat pumps and installers; established national quality committee
Government testing facilities	nf	Research Institutes of Sweden (RISE)	nf
Industry or user groups	German Heat Pump Association (IWP)	Swedish Refrigeration and Heat Pump Association (SKVP); Swedish District Heating Association (now Energiföretagen Sverige [Swedenergy])	Finnish Heat Pump Association (SULPU); user internet forums
Information campaigns	Heat pump information campaigns from energy agencies and utilities	Various information and awareness campaigns	Various information and awareness campaigns

nf = none found; examples may exist

Sources: Collier (2018); Hanna et al. (2016); REN21 (2021); Vivid Economics and Imperial College (2017) unless indicated otherwise)

[a] Eurostat (2022). Reported as gross final consumption of energy for heating and cooling. See source for additional information.

[b] Germany ETS price of $33.16/tCO_2e. Data from https://carbonpricingdashboard.worldbank.org/map_data.Implemented pricing. Nominal price on April 1, 2022.

[c] Tax in 2Q2020 for light fuel oil and in 2019 for all other energy carriers. Percentage represents total tax, which includes national and subnational-level taxes and accounts for tax exemptions and returns. Data from International Energy Agency (2020).

[d] Kern et al. (2017)

[e] Enerdata (2022)

[f] Kiss et al. (2013)

6 Business Models for Heat

6.1 Energy Service Companies

Energy service companies (ESCOs) offer energy savings through designing, financing, and installing energy-efficient equipment and building retrofits, thereby avoiding the need for customers to provide significant up-front CapEx (Stuart et al. 2021). ESCOs use energy service performance contracts, which guarantee annual financial savings in reduced utility bills or other added value that covers the equipment financing and installation costs and remunerates ESCOs based on metered performance (DOE EERE 2020; NAESCO 2021).

There are several aspects of ESCOs, including their historical development, that are worth discussing in the context of their relevance as a possible business model for industrial heat in the United States. First and foremost, ESCOs have primarily served institutions in the public sector (e.g., federal and state government, schools, and universities); public and institutional markets composed 94% of U.S. ESCO revenues in 2018 (Stuart et al. 2021). Initial formation of the U.S. ESCO industry was supported by the use of financial incentives offered by electricity and natural gas utilities, which helped address customers' initial concerns about the financial and technical performance of energy-efficient equipment (Carvallo et al. 2019).

As the ESCO model has evolved, it has gone from primarily electricity projects to more complicated projects involving fuel. This increase in complexity has come with increases in payback periods, which grew from 1.9 to 3.2 years for private sector projects and 5.2 to 10.5 years in public sector projects over the course of about 10–15 years (Larsen et al. 2012). For U.S. industrial sites, it has been found that approximately 70% of the energy efficiency and energy savings opportunities require significant CapEx (NAM 2014).

Initially, the concept of using the ESCO model to support renewable energy was rare and not well understood (Putz 2015). Although the model's features of reducing risk and uncertainty and avoiding customer capital investment would seem to address barriers for RTES adoption in industry, there are challenges in industry that may limit ESCO success. For example, manufacturers may be wary of providing energy and process information that they feel is confidential, and large, energy-intensive industries may already have the financial and technical resources to implement projects on their own (Putz 2015).

The last several years have seen the ESCO model applied in practice for renewable heat provision to industries in Germany, Sweden, France, and Spain. For example, Absolicon, the Swedish concentrating solar thermal collector manufacturer, has begun construction of a €1.6 million (or $1.95 million as of December 2020 [X-Rates 2020]), 1.5-MW_{th} parabolic trough collector field (~3,000 m^2) for a demonstration solar district heating system in Sweden (Epp 2020). Absolicon will serve as the ESCO, with ~48% of the CapEx coming from the Swedish Energy Agency and 52% coming from Absolicon. The heat purchase agreement (HPA; a heat contract to sell heat at a fixed price) is between Absolicon and the end user, the district's utility Härnösand Energi & Miljö.

In Spain, a specific national incentive scheme named Solcasa has helped fund more than 42 heat ESCOs and 18 projects with loans and low-interest financing (Epp 2015). The Solcasa funding offered to these companies from Spain's Institute for Diversification and Saving of Energy, has helped provide an energy service model where the end user pays for the heat delivered with at least a 10% savings of fuel compared to prior consumption, thereby simplifying the end user's operations without having to pay up-front CapEx or operate the heat system to reduce their natural gas consumption. Through government incentives, this heat-specific ESCO in Spain can take on the project development, CapEx, and operations risks to help the end user make the purchase decision. The ESCO owns and operates the heat system, and through the HPA the ESCO can gain back the investment through the 10%–15% fuel savings (Battisti 2019).

By fixing the monthly price to the end user without any capital outlay (and thereby the ESCO making the difference between the normal price with fuel consumption and the fixed price), there could be an uptake in the U.S. industrial sector. Although a key difficulty in executing an HPA via an ESCO is the financing and ensuring the offtake for several years. HPAs, for example, generally have a 20-year term (Solar American Solutions 2015). This can be overcome, for example, through local government or federal incentives and access to low-cost financing.

6.2 Heat as a Service and Energy as a Service

Heat as a service (HaaS) and energy as a service (EaaS)[18] are developing models that could have significant benefit for the industrial sector. Heat is currently charged for industry and commercial purposes as a purchase or consumption of the fuel (e.g., natural gas in dollars per thousand cubic feet or dollars per therm consumed). A HaaS model is being deployed in trials for residential U.K. users to test the idea that customers will pay for an experience and a warmth/comfort level, instead of the unit of energy consumed (Energy Systems Catapult 2021). Trial data are then analyzed to understand customer preferences and willingness to pay.

HaaS is a customer-focused model and has several benefits. These include the HaaS provider taking the financial and credit risk of providing a device or system without the CapEx needed by the end user, the operations and technical risks to install and operate the system, and even the fuel price fluctuations risk because the consumer is paying for the service rather than the device and system (Pieterse 2019). EaaS can be seen as the next step after HaaS, as EaaS typically includes the heating and the energy/efficiency measures (Pieterse 2019).

An alternative financial approach for RTES, instead of using commercial banks and institutions for lending, is the use of a financial entity skilled and experienced in specifically financing renewable heat projects. This can provide low-cost financing to reduce the risk of the project. One of the key leaders in this area is Kyotherm. As of 2020, Kyotherm has financed and contracted approximately 100 MW_{th} of renewable heat and energy efficiency projects, mainly in Europe, leading to the generation of approximately 250 gigawatt hours thermal (GWh_{th}) of renewable heat per year (Kyotherm 2020a). Energy efficiency projects make up approximately 24% of the Kyotherm portfolio, with approximately 76% for financing solar thermal, geothermal, and biomass heat generation and integration projects (Kyotherm 2020b). Kyotherm is also investing in heat pumps as part of their portfolio (Renewables Now 2021).

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[18] The DOE Better Buildings program is also highlighting energy efficiency as a service (EEaaS) (DOE 2021), which is similar in nature to EaaS.

Kyotherm has recently financed one of the first dedicated SIPH sites, a 10-MW_{th} flat plate collector project expected to produce 8–9 GWh_{th} per year, equivalent to about 10% of a malt facility's annual thermal demand of 80 GWh (Epp 2019). Details of the project are summarized in Table 6. The French national energy agency (ADEME) also provided a 60% CapEx grant for the flat plate collector system. When the financing and project structure are considered, the client was able to receive an agreed-upon HPA of €26/MWh (\$29/MW_{th}) with inflation over 20 years. It is important to note that the HPA price was approximately 20% less than the average price of natural gas that the malting facility would normally pay (Epp 2019).

Table 6. Amended Project Financing Details for Kyotherm SIPH Project (Epp 2019)

Project Area	Value and Units[a]
Field size of water-driven flat plate collectors	14,252 m² (~10 MW_{th})
Size of solar storage tank	3,000 m²
CapEx, including solar field, storage tank and integration into factory's hot air system	€5.8 million (\$6.3 million)
Specific installed costs of flat plate collectors	€400/m² (\$441/m²)
Financing structure	10% equity when construction starts, bank refinancing at a later stage
ADEME (France's national energy agency) grant	60% of CapEx, which corresponds to €20/MWh (~\$22/MWh) over 20 years
Annual heat demand from malt business	80 GWh as hot air between 50°C and 85°C
Expected solar yield	8 to 9 GW_{th}
Specific solar yield	561 to 632 kWh/m²
HPA with client	€26/MWh (~\$29/MWh) plus inflation over 20 years
Commissioning scheduled	May 2020

[a] All dollar amounts are converted to 2019 USD using X-Rates (2019)

Kyotherm has begun funding projects within the United States, the first being with the energy service company Skyven. Skyven, the project developer, will work with Bay City Boilers to install a condensing economizer at a California Dairy Inc. site in Visalia, to reduce the natural gas consumption by approximately 9% of the current natural gas boilers (Kyotherm 2021). The EaaS approach will be used to provide a 10-year energy service agreement, where the California Dairy Inc. facility will not bear any of the up-front capital or operations risk, and the savings will be used to pay for the system and operations (Kyotherm 2021). With support from the California Energy Commission, this type of model and energy service contract could be suitable for other food and dairy producers.

6.3 Green Bonds

Europe and other areas in the world are looking at using green bonds and green thermal bonds to help increase the funding for renewable heat projects for IPH application. A green bond, either issued by a private company or a subgovernment entity (such as a municipality) is a bond instrument that provides a fixed income to raise funds specifically for projects contributing to sustainable development goals and climate action (Iberdrola 2021; ICMA 2017). Within the United States, green bonds are already utilized for financing PV electricity projects, and as of 2019 the U.S. green bond market was worth over $250 billion (Smith and Davies 2020). This mechanism is well understood and low risk for PV companies today. Out of the six states that offer energy efficiency and renewable energy bonds, only Hawaii (the Green Infrastructure Bonds) and Illinois (the Renewable Energy and Energy Efficiency Project Financing) have offered bonds for the industrial application of renewable heat (NC State University 2021b).

Few companies today offer or issue green thermal bonds. For example, the company Energy From Waste Gmbh issued in 2021 a €400 million green bond to finance and refinance waste heat recovery projects (Recycling Magazine 2021). Kyotherm is currently also the only renewable heat generation finance institution that has utilized a corporate green thermal bond for renewable heat and efficiency projects. The company has developed and issued a green bond to Edmond de Rothschild Asset Management and Johes for €30 million (Kyotherm 2020a), or $35 million as of 2020 (X-Rates 2020). This type of bond then allows specific renewable heat and energy efficiency projects to be funded.

6.4 Alternative Approaches

The Swedish company Absolicon has also opted for an alternative idea. This includes selling the automated production lines of the parabolic trough collector alongside developing projects (Absolicon 2021a, 2021b). At full utilization, this semiautomated mass-assembly line can assemble, verify, and produce approximately 50 $\mathrm{MW_{th}}$ or 100,000 $\mathrm{m^2}$ of the patented and certified Absolicon T160 collectors (Absolicon 2021b).[19] The first production line was set up in China (Absolicon 2018).

The setup of a production line allows for local manufacturing capacity expansion and jobs and the ability to minimize the transport and logistics of the collectors needed for projects (Absolicon 2021c). The assembly line is sold through a framework agreement, which has three main components. The first is the sale of the hardware, training, and support for the line at approximately €4 million to €5 million or ~$5 million to $6 million as of 2021 (X-Rates 2021); the second is a monthly license fee of €30/collector sold (~$36/collector sold in 2021 [X-Rates 2021]); and the third is a materials supply contract where approximately 30%–40% of the materials needed for the collectors built would be sourced through Absolicon (Absolicon 2021d). For a fully utilized production line, Absolicon cost estimates of the needed material could be between €10 million and €15 million per year (Absolicon 2021d), or $12 million to $18 million in 2021 (X-Rates 2021). Reports indicate framework agreements have been signed in countries such as Canada, France, Botswana, and Italy (Absolicon 2021d, 2021e, 2021f). This way of selling their manufacturing line adds revenue, but also allows the company to license their certified technology into new markets (Absolicon 2021d, 2021e, 2021f).

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[19] These specific details have not been verified by NREL.

7 Challenges for RTES

7.1 Innovation Challenges

Emerging research indicates that RTES technologies should be treated differently than renewable electricity generation technologies in terms of the functioning of their TISs and ultimately in the development of effective policy packages. Wesche et al. (2019) propose an explanation for why, despite the success of renewable electricity generation, renewables continue to remain a low fraction of German space heating and warm-water heating and cooling. The authors identify that the renewable heat TIS is much more dependent on local contexts (e.g., physical characteristics of buildings and their equipment, occupancy behavior, variety of renewable heat technologies) and features a wider variety and more geographically dispersed set of actors than renewable electricity TISs (i.e., solar PV and land-based wind). Wesche et al. formally distinguish renewable electricity as a generic TIS and renewable heat as a configurational TIS and examine the implications for system functions of each.

As a configurational TIS, renewable heat is characterized by a larger portion of knowledge development that occurs at the point of deployment, rather than a focus on upstream component integration; a broader and less well-defined set of actors, which hinders knowledge diffusion and standardization; a lack of market formation, despite the availability of technologies; a smaller pool of financial support; and low legitimacy and support from advocacy groups (Wesche et al. 2019). The technology dimensions and their definitions are summarized in Table 7. These aspects of configurational TIS make it more difficult for RTES to have well-functioning innovation systems, which, in turn, hinder their ultimate adoption and diffusion.

Table 7. The Characterization of Renewable Heat as a Configurational TIS

Technology Dimensions[a]	Dimension Definition[a]	Configurational Description[b]
Technological identity	Standards that specify the functions and performance of a technology	Weak technological identity due to need to configure each deployment
Technological systematicity	Standard plans that are based on standard parts	Local contexts require adaptation of components, precluding a dominant design at systems level
System development dynamic	Existence of an unambiguous development trajectory	Ambiguous development trajectory stemming from weak technological identity and systematicity
Flow of information	Sources and transfer of information about user requirements and conditions of operation	Diverse, diffuse flows of information that are difficult to centralize
Innovation pattern	Location and dependence of innovation and diffusion	Innovation and diffusion are concurrent, with supplier and user innovations, in addition to producer innovations

[a] Fleck (1993)

[b] Wesche et al. (2019)

Although the concept was developed from the perspective of heat demand in buildings, we see many analogs for RTES applications for IPH. Foremost is the concept of the need for site-specific knowledge to successfully configure and integrate a renewable heat technology and the concept of technology legitimacy, or the social acceptance by institutions of actors and technology in a new TIS that enables mobilization of resources, generation of market demand, and establishment of legitimacy (Bergek et al. 2008). It is likely true in most instances that the need for site-specific knowledge is even more significant for industrial applications of RTES than for buildings. For instance, the solar thermal integration process outlined by Muster et al. (2015) involves a detailed characterization and implementation of heat recovery opportunities, which introduce the need for additional analysis for the technology developer, as well as the need for adoption of additional technologies or practices on the part of the customer (Lauterbach et al. 2009). One approach that may help this integration process is the development of a decision support tool that enables prospective industrial users to evaluate the broad range of RTES that may be applicable to their operations. The concept and proposed development of a decision support tool is discussed in more detail in the third report of this project.

A separate yet complementary framework has been devised by Malhotra and Schmidt (2020) to aid in explaining differences in experience rates using a technology typology. Technologies are categorized on the dimensions of design complexity and the need for customization. Design complexity is used to capture the number of design components and the degree of their interaction. The need for customization encompasses how much a technology needs to be adapted to its use environment, which is characterized in terms of user preferences, regulatory contexts, and physical environment. These dimensions are then used to define a spectrum of decreasing experience rates, from Type 1 to Type 2 to Type 3 technologies. Type 1 technologies represent relatively simple products that have little need for customization and can be mass-produced (e.g., solar PV modules). Type 2 technologies involve more design complexity and/or need for customization (e.g., rooftop solar PV). Type 3 technologies represent the greatest need for customization (e.g., building envelope retrofits) and/or design complexity (e.g., thermal power plants).

As with Wesche et al., Malhotra and Schmidt's examples are primarily drawn from energy generation technologies that are not specific to the industrial sector. That said, given the observations of RTES made elsewhere, it is possible to propose a rough classification based on Malhotra and Schmidt's typology. The need for extensive customization, combined with low to medium design complexity, indicates that solar IPH systems, as well as other industrial RTES, may be Type 2 (i.e., standardized or mass-customized design-intensive products, such as electric vehicles and concentrating solar power, respectively, or mass-customized simple products, such as rooftop PV) or Type 3 technologies (i.e., complex designs that span standardized, mass-customized, and customized products, such as combined cycle gas turbines, small modular nuclear reactors, and nuclear power plants, respectively; design-intensive customized products, such as geothermal power; and simple, customized products, such as building envelope retrofits), although a more complete analysis, including associated policy implications and identification of ways to reduce the need for customization, is warranted.

The innovation implications of Malhotra and Schmidt's typology can be summarized as more complex, and customized technologies are more likely to be characterized by lower experience rates. Additionally, technologies that require more adaptation to their use environments, which we propose include RTES, may exhibit higher experience rates at local levels than globally. This is an outcome of barriers to learning-by-using and more dispersed knowledge spillovers that may characterize Type 3 technologies. Type 2 technologies, which are less complex and less customized than Type 3, may have core components that have shown high experience rates and related cost reductions. Therefore, the balance-of-system components, which are necessary for successfully adapting the technologies to their local contexts, become the focus of innovation and cost-reduction activities. This is consistent with how Fleck (1993) identifies the possibility of individual components of configurational technologies achieving dominant design and standardization, while the complete system of components remains configurational.

7.2 Policy Challenges

To aid our discussion of policy challenges, we introduce the concept of lock-in as it relates to decarbonizing technologies. Carbon lock-in is a condition where interactions between technologies, organizations, and institutions create systemic market and policy barriers to low-carbon alternative technologies (Unruh 2000). Path-dependency, a force behind carbon lock-in, has been analyzed in the context of natural gas central heating in the United Kingdom and district heating and heat pumps in Sweden (Gross and Hanna 2019). According to this framing, these technologies became dominant in their respective countries by achieving increasing returns through scale and learning economies, reduced consumer uncertainty and improved acceptance (i.e., adaptive expectations), and interconnection with other, related technologies and broader infrastructure (i.e., network externalities). For example, the U.K.-supported network externalities and coordination effects through a nationalized ownership structure for natural gas were able to centrally coordinate building a transmission network, converting appliances, and consumer outreach for the benefits of central heating. Sweden supported scale and learning economies through the Swedish District Heating Association, which set standards for technology performance and interoperability.

Even for countries that have been identified as having successful renewable heat policies, this was not necessarily always the case, and for most countries the transition to renewable heat remains underway. There are multiple examples of RTES markets collapsing due to technology legitimacy being negatively impacted by combinations of poor product quality, installation, and maintenance standards. These include German heat pumps (Vivid Economics and Imperial College 2017b), Finnish ground-source heat pumps (Heiskanen et al. 2011), SWH in California (Nemet 2013), and Swedish heat pumps (Nilsson et al. 2005). Even though subsequent efforts may remedy poor quality and performance, the perception of these issues can persist, negatively impacting legitimacy, resulting in knowledge depreciation (e.g., Grübler and Nemet 2013), and hindering market development. Fostering and maintaining technology legitimacy appears to be a crucial aspect of RTES policy.

Ultimately, the policy challenges facing RTES in the United States are related to the need to develop a well-functioning TIS that can overcome resistance from a highly stable socio-technical regime within a shrinking window of time. Given these features, RTES face the challenge of creating transformative decarbonization policy, where government policy interventions are made to actively steer and accelerate transformational change (Frank et al. 2020), and developing polycentric governance, which incorporates multiple stakeholders operating over multiple scales (e.g., Sovacool and Martiskainen 2020).

In order to enable radical[20] innovation and system transformation, Frank et al. (2020) point to eight governance activities that indicate the transformative ambitions of policy mixes. These activities can be grouped into three categories: knowledge and governance capacities, vision and strategy development, and a policy mix for innovation and phase-out of unsustainable infrastructure (exnovation). At least in the case of decarbonizing building heating in the United Kingdom and Germany, it has been challenging to implement policies that systematically create opportunities for investment in decarbonized heating options and to develop policies for phasing out fossil fuel heating (Frank et al. 2020).

Another transitions perspective indicates that the challenge for RTES policy can be related to governance of polycentric systems, which are systems governed by multiple authorities that span various scales (Ostrom 2010). In the instances where deep and rapid (i.e., within 18 to 35 years) heat transitions have recently occurred, governance has taken a polycentric form (Sovacool and Martiskainen 2020). This has involved coordinated activity spanning local to international levels, equitable allocation of costs and benefits, and willingness of a central state to coordinate and guide policies, and purposefully facilitate the roles of various nongovernment actors.

Given the observed importance of polycentric governance, it should be noted in addition to the virtual absence of federal renewable heat policy in the United States, several states are actively resisting a transition to RTES. For example, as of April 2022, twenty states have passed laws that in some form prevent municipalities from restricting natural gas utility service, such as prohibiting natural gas service to new buildings (DiChristopher 2022). Together these states represent about 27% and 26% of natural gas and petroleum products use, respectively, for commercial and residential buildings; for the industrial sector the states represent 60% and 73% of natural gas and petroleum products use, respectively (EIA 2021d).

These policies should also be understood in the context of analysis of successful renewable heat policies. The prohibition of natural gas and fuel oil heating in new construction, either directly or indirectly through building energy performance standards, has been identified as an aspect of breaking free of existing fossil fuel infrastructure (Kerr and Winskel 2021) and as an indicator of a policy's transformative potential (Frank et al. 2020). Frank et al. also call out the removal of a building refurbishment package and zero-carbon standards for new construction by the U.K. government as undermining its own vision for decarbonization.

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[20] The term radical innovation is used in contrast to incremental innovation, but the terms are not strictly defined and may represent only one axis for categorizing innovation (Henderson and Clark 1990). Ettlie et al. (1984) point out the distinction between radical and incremental innovation can be made in terms of marking a clear break from existing practices, if the technology is novel to its adopters and their referent organizations, or if the technology dictates changes to processes and production or services. Whether or not an innovation is deemed radical or incremental has implications for its adoption (Dewar and Dutton 1986) and may require unique organizational capabilities (Ettlie et al. 1984). Abernathy and Utterback (1978) predate these examples and describe radical and incremental innovation as capturing the two, albeit neither completely independent nor fixed, extremes of innovation patterns. The distinctions between radical and incremental innovations have formed the basis of research relevant to decarbonization such as carbon lock in (Unruh 2000) and reconfiguration of sociotechnical systems (Geels 2002).

8 Potential Future Research in the Role of RTES for Decarbonizing Heat

Based on the low penetration of renewable heat to date, RTES technologies are at very early stages of adoption in the United States The concept of renewable heat as configurational TIS may prove to be a key to understanding how RTES could be successful in helping decarbonize IPH, as well as building heating. The aspects of a configurational TIS have ramifications for achieving experience rates on par with what has been observed for other renewable energy technologies, such as solar PV and for developing effective policy measures. The low and negative experience rates estimated in this report for the CSI-Thermal program and for a North American concentrating solar power developer provide further support for the hypothesis that renewable heat systems function as configurational TIS. This in turn supports the need to explore the implementation of different policy mixes.

Ultimately, moving the discussion and analysis of RTES, which has historically been dominated by techno-economic framing, into socio-technical analysis frameworks may be necessary to accelerate the decarbonization of heat. We identify and expand on three focus areas suggested for future RTES research: innovation systems, user perspectives, and transitions.

8.1 RTES Innovation Systems

The third report in this RTES series, *Renewable Thermal Energy Systems: Modeling Developments and Future Directions (Report 3)*, demonstrates through case studies the improvements to simulation and techno-economic analysis of hybrid RTES (Akar et al. 2023). This is a fundamental piece of providing information about their techno-economic performance. However, framing cost as the paramount measure of performance for new energy technologies (e.g., International Energy Agency (2000)) is an incomplete and ahistorical perspective that may be insufficient for increasing RTES adoption and meeting greenhouse gas reduction targets on time and may lead to policies that have some negative unintended consequences. Certainly, making RTES cost-competitive and cost-advantageous relative to incumbent fossil fuel combustion technologies is an important part of decarbonization transition. Declining relative costs are part of the definition of a new techno-economic paradigm, which encompasses the guidelines for technological and investment decisions made by manufacturing firms (Perez 1985) and scale and learning economies are an aspect of path-dependency (Arthur 1989).

With few deployed RTES examples (either in stand-alone or hybrid configuration) for industrial applications in the United States, this report and others in the series begin addressing key challenges faced by technology developers, technology end users, and policymakers. Much of the discussion to date from a U.S. perspective has focused on the techno-economic challenges of RTES, such as the difficulty with finding suitable alternatives to high-temperature processes (Friedmann et al. 2019; McMillan et al. 2016; Sandalow et al. 2019). Other techno-economic challenges for RTES discussed elsewhere (i.e., Akar et al. 2021b, 2021a; McMillan et al. 2021b; Schoeneberger et al. 2020) have been mapped to a TIS aspect in Figure 4.

As Figure 4 shows, most of the focus has been on the physical infrastructure challenges related to the potential applications of RTES (e.g., the diversity of industries and their processes and operational requirements), siting constraints, and the competition with lower-cost fuels, such as natural gas. The lack of challenges identified in terms of actors, interactions, hard institutions, (e.g., codified standards and legislation)) and knowledge and physical infrastructures indicates the need for additional, wider-ranging efforts to characterize RTES TISs.

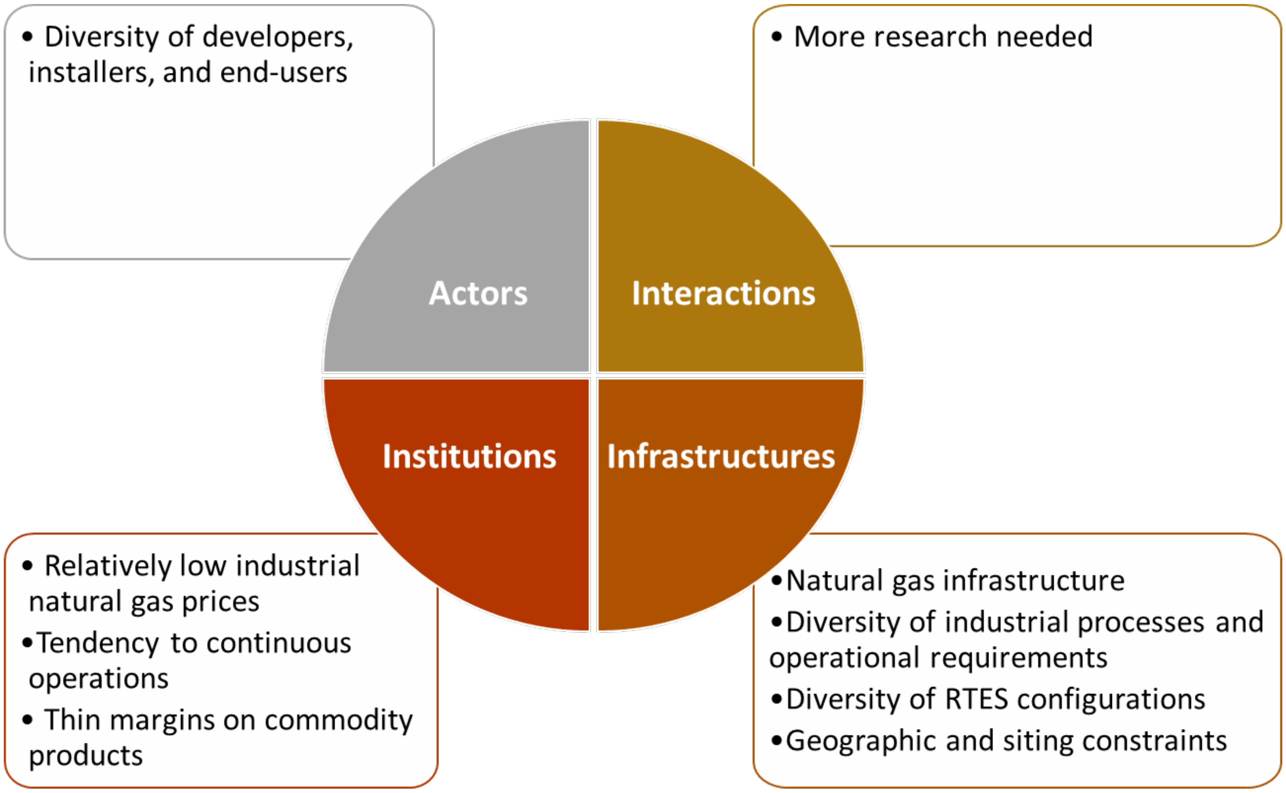

Figure 4. Previously identified challenges for RTES categorized by TIS aspect. Note that the emphasis to date has been on soft institutions and physical infrastructure, rather than actors, interactions, hard institutions, and knowledge infrastructure. No examples of interactions were identified.

A critical aspect of countries that have deployed significant amounts of RTES, such as heat pumps, has been the presence of supporting policies for standardizing technologies and installation practices to codify knowledge and for creating legitimacy for RTES. U.S. renewable heat policy is nearly nonexistent[21] relative to leading countries and particularly suffers in terms of lacking a national renewable heat target, using noneconomic instruments, taking an energy systems approach by integrating energy efficiency policies, and collecting deployment data (Collier 2018). Current efforts for solar for IPH emphasize cost reductions, but not building up actors and interactions and increasing legitimacy of the technologies.

Our preliminary exploration of the RTES TIS in the United States suggests that the TIS is functioning poorly. Of course, additional efforts that use much more thorough analyses are needed to make a final determination. One of the most fundamental and important observations

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[21] The words "renewable heat" and "renewable thermal," for example, do not appear in the U.S. Long-Term Strategy (The White House 2021). However, Horowitz et al. (2022) in a subsequent modeling discussion identify biomass, but not solar thermal, as part of industrial energy mix, an albeit shrinking one, under decarbonization.

to take from the existing literature on renewable heat system deployment and associated policies is the heterogeneity of the actors and technologies. Although these observations have largely come from analysis of buildings, there are many similarities with industry that are already apparent and more may be identified with further analysis.

8.2 RTES User Perspectives

As Wesche et al. (2019) indicate, a key to accelerating development of a configurational TIS is overcoming fragmented, dispersed actors and knowledge development. What is perhaps diminished by their focus on residential heating is Fleck's original emphasis on the key role of users and their involvement in technology development (Fleck 1993). Fleck, who instead references industrial technologies (e.g., robotics and material requirements programming systems), identifies users as the owners of knowledge about local practices and requirements. Active user involvement is seen as being critical for successful implementation of configurational technologies; more extensive user participation may be required in cases of very novel technologies, where users are potentially the sole source of information about how these systems may perform.

In additional to approaching RTES as configurational technologies, it may be fruitful to also consider the implementation of RTES more broadly through a lens of mutual adaptation of technology to the user environment (i.e., Leonard-Barton 1988). Here, adaptation is seen as a necessary process for fitting a new technology to its intended use environment. Throughout this process, misalignments related to technical requirements, delivery system performance, and organizational values drive adaptations and ultimately determine the success or failure of a technology. Future research activities for RTES could study previous adaptations of heating technologies (including failures as well as successes) to identify potentially significant misalignments.

Another path for future research would be to analyze from the user perspective the roles of innovation system actors in influencing the adoption of RTES. For this path, Cowan (1987) proposes analysis using the "consumption junction," the time and pace at which an end user evaluates and chooses between technology options. This approach recognizes that end users are "embedded in a network of social relations that limits and controls the technological choices that [they] are capable of making" (Cowan 1987, p. 262).

Regardless of the theoretical framing, a broader analysis of why potential RTES users may or may not adopt a new technology is not only important but currently lacking. Existing analysis tends to focus on market barriers, such as capital costs or levelized costs relative to incumbent combustion technologies. However, early in the adoption of a new technology potential users may be more interested in the technical performance benefits of a technology than its cost relative to the incumbent technology (Fouquet 2010). This observation also appears, among other places, in the form as a grand pattern of energy technology change: "attractive beats cheap, at least initially" (Grübler et al. 2012, p. 1674); in historical analysis of the Corliss steam engine and its performance benefits in the textile and primary metals industries (Rosenberg and Trajtenberg 2004); and in historical analysis of early electrification in U.S. manufacturing subsectors (Goldfarb 2005). Additionally, Nye finds early on in the electrification of manufacturing that "savings in energy costs were considered to be of no great importance" due to power costs typically accounting for 1%–3% of production costs (Nye 2001, p. 141).

8.3 RTES Transitions

The socio-technical systems of heat use in industry and buildings have developed and evolved over time. A historical perspective has been used to understand how the entrenchment of these existing systems has led to their path-dependency (Gross and Hanna 2019) and to identify ways that decarbonization efforts are met by passive and active resistance (Dewald and Achternbosch 2016; Geels 2014). Using a historical perspective is likewise helpful for understanding the possibilities of heat transitions and the success of renewable heat policies (Sovacool and Martiskainen 2020). Other countries that have not experienced the same increase in domestic production of natural gas and petroleum as the United States can still face significant barriers to developing supportive RTES policies posed by the configurational nature of renewable heat TISs and path-dependency of fossil fuel heating.

The radically different nature of providing heat through RTES may mean it is more appropriate to move from an emerging technology perspective offered by the TIS to framing the RTES innovation system in combination with a transition perspective, such as the multilevel perspective, as proposed by Markard and Truffer (2008). The multilevel perspective considers technology transitions as complex, interacting processes that occur on three levels: micro-level niches, meso-level technical regimes, and the macro-level socio-technical landscape (Geels 2002). Radical innovations begin and develop at the niche level, which provides learning opportunities and supporting social networks. A successful innovation stabilizes into a dominant design over time and, within a window of opportunity provided by changes in the existing regime and landscape, becomes established in a regime. The changes within macro-level landscape (e.g., decarbonization efforts) can exert pressure on the existing regime, which are typically concerned with incremental technology developments and may actively, as well as passively, resist destabilization from innovative (e.g., decarbonized) technologies (Geels 2014).

8.4 Socio-Technical Analysis for RTES

Overall, we suggest continued socio-technical analysis of RTES and their role in the decarbonization transition as characterized by the multilevel perspective. Given the evidence discussed so far regarding the path-dependency of existing fossil fuel heating technologies and distinguishing socio-technical aspects of renewable heat technologies, much work remains for characterizing RTES technologies and how best to accelerate their adoption for decarbonization. This is acutely true for RTES for energy-intensive industries, which suffer from a lack of research on carbon lock-in (Janipour et al. 2020; Wesseling and Van der Vooren 2017) and socio-technical transitions (Svensson et al. 2020; Wesseling et al. 2017).

We have organized proposed future socio-technical analysis according to the three areas discussed at the beginning of this section:

1. Innovation systems
    - Develop appropriate delineations for RTES TIS and identify their system functions, focusing on identifying actors and interactions, and evaluate how well the TISs are functioning
    - Inventory recent coverage of RTES in U.S. trade journals and related media (i.e., evaluate the guidance of search function)

    - Conduct network analysis of recent conferences, workshops, and similar gatherings related to RTES (i.e., evaluate the function of knowledge diffusion through networks)
    - Identify subnational policies that might inhibit or promote the adoption of RTES, such as site planning and permitting requirements (i.e., evaluate the market formation function)
    - Analyze activities of RTES interest groups and of existing regime interest groups focused on maintaining the status quo (i.e., evaluate the creation of legitimacy function)
    - Interview RTES developers and adopters to gauge opinions on sufficiency of existing financial and human capital (i.e., evaluate the resource mobilization function).
2. User perspectives
    - Conduct interviews of current and perspective RTES users to understand dynamics of configuring industrial process heat technologies
    - Evaluate existing methods and, where appropriate, develop new methods of capturing the dynamics of user configuration.
3. Transitions
    - Explore the use of the multilevel perspective[22] for analyzing RTES transitions and as a complement to the TIS framework, identifying relevant strengths and weaknesses
    - Evaluate historical lessons learned from transitions involving RTES and other relevant technologies (e.g., rooftop PV) in buildings and how they could be relevant to industry
    - Identify niche formation activities of RTES, such as the adoption of solar industrial process heat by food and beverage manufacturers (Schoeneberger et al. 2020)
    - Identify active and passive resistance from current socio-technical regimes, such as the prohibition of fossil fuel bans and other efforts to protect public health and transition to clean energy systems
    - Understand how current technical assistance approaches that support the implementation of energy efficiency in industry (i.e., the Industrial Assessment Centers[23]) could be leveraged for RTES transitions
    - Conduct additional analysis of alternative business models for RTES and their promotion
    - Explore the potential for transformative innovation policy mixes as discussed by Frank et al. (2020) specifically for industry.

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[22] Aspects of Markard and Truffer's (2008) integrated framework has so far been applied to RTES of ground source heat pumps in Finland (Lauttamäki and Hyysalo 2019), legitimacy of biogas technology in Germany (Markard et al. 2016), and industrial heat pumps in the Netherlands (Wesseling et al. 2022).

[23] https://iac.university/

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