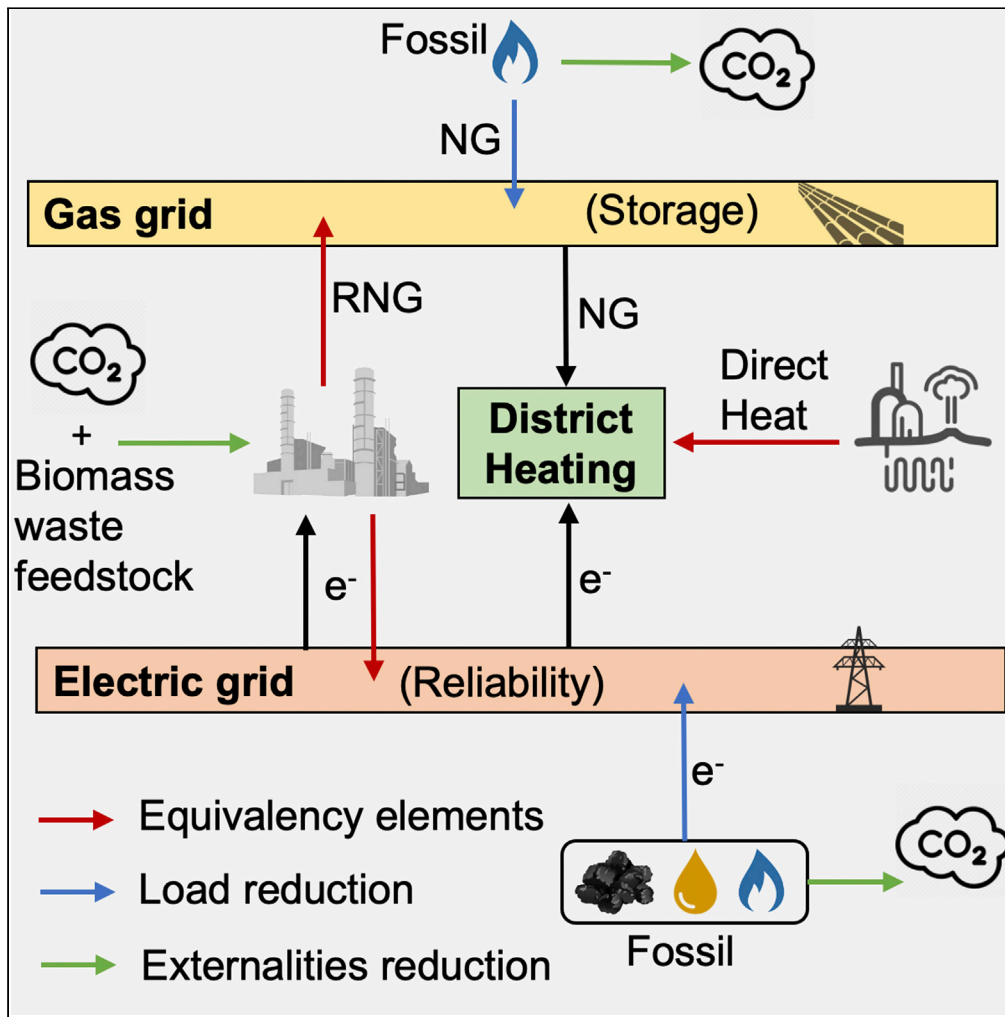


Article

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Nazih Kassem,  
Christopher R.  
Galantino,  
Jefferson W.  
Tester, C. Lindsay  
Anderson, Michal  
C. Moore

mcm337@cornell.edu

**Highlights**  
Methodology for  
calculating net carbon  
impact from energy  
systems is proposed

Alternative energy system  
contributions to the grid  
are evaluated

Reducing net carbon  
emissions using  
distributed energy  
resources are investigated

Electric capacity and heat  
offsets are offered as  
systems options for grid  
operators

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## Article

## Moving toward a framework for electricity and heat equivalence in energy systems analysis

Nazih Kassem,<sup>1,2</sup> Christopher R. Galantino,<sup>2,3</sup> Jefferson W. Tester,<sup>2,4</sup> C. Lindsay Anderson,<sup>2,3</sup> and Michal C. Moore<sup>2,4,5,\*</sup>

## SUMMARY

**Sustaining, maintaining, and upgrading the electricity grid, while meeting decarbonization goals is a challenge facing policymakers, regulators, grid operators, and investors. Simultaneously meeting demands for future capacity, retiring older inefficient technologies, and addressing externalities from energy production and use requires more diverse and inclusive technologies to avoid constraints and shortfalls in grid capability. Changing the energy production paradigm by encouraging alternative technologies was a key driver for FERC Order 2222. This stimulus for developing new small-scale generation will complement and supplement the existing fleet only if it attracts new investment. This investment must reflect technology that goes beyond the energy-only characteristics of traditional generation, creating systems where suites of energy-equivalent outputs are enhanced by environmental quality benefits and offsets. We use energy system designs to highlight the contribution that measuring and accounting for equivalency values provides net increases in capacity, electricity, and alternative fuels while simultaneously reducing carbon waste impacts.**

## INTRODUCTION

Electricity has emerged as the dominant and preferred means of distributing energy to consumers in both developed and developing countries. Current grid systems are relying less on hydrocarbon-based fuels in favour of renewables (Taneja et al., 2013; Nwaigwe et al., 2019; Toma and Gavrilas, 2014). Capacity needed to meet demand growth has been moderated through an emphasis on energy efficiency (Poudineh and Jamasb, 2014; York et al., 2019; Bao et al., 2017), effectively reducing average, and peak demand. Electricity, however, remains an inefficient substitute for heating (and cooling) in many regions and continued reliance on gas, heating oil and in some cases wood heating has contributed to significant impacts on air and water quality (Steubing et al., 2011; Gilmore et al., 2006; Plachinski et al., 2014; Mac Kinnon, Brouwer and Samuelsen, 2018).

Given the cost and lifespan of installed traditional generation technology, there is a natural preference for installed electric capacity that integrates gas turbines (Cheung and Rios-Zalapa, 2011; Eichman et al., 2013; Bitar et al., 2011), hydroelectric sites, solar PV, and wind energy for production. The choice of electricity as the dominant form of energy supplied will be tied closely to a future demand for new and more responsive battery storage capacity (Gilmore et al., 2010; Li et al., 2018; Nottrott et al., 2013), as well as regional variations such as heating demand in the Northeast that will not be efficiently met with electricity alone. Existing “system investment” is biased toward technology that excludes many smaller, scalable alternatives (Lozano and Reid, 2018; Cambini et al., 2020; Marnay et al., 2008; Willis and Scott, 2018).

Other alternatives (Wang et al., 2015; Eid et al., 2016; Kok et al., 2008; Colson and Nehrir, 2009) are available and can provide a range of benefits beyond electric energy alone. Direct heat offers the potential for net emissions reductions in carbon intensity, water quality enhancement, access to remote generation, and reduced demand for new transmission capacity. This compares with the overarching goal of assuring technology neutrality (Hoofnagle, 2018; Bushnell et al., 2021; Carton, 2016; Ebrahimi et al., 2018) based on output alone that can discount technologies with integrated emissions benefits (Tsikalakis and Hatzigiorgiou, 2007; Li et al., 2016). The additional layers of externality controls and charges can impede overall performance, diversity of technology, and resiliency (Johnson, 2017; Chanda and Srivastava, 2016; Yang et al., 2019).

<sup>1</sup>Department of Biological and Environmental Engineering, Riley Robb Hall, Cornell University, Ithaca, NY, USA

<sup>2</sup>Cornell Energy Systems Institute, Kimball Hall, Cornell University, Ithaca, NY, USA

<sup>3</sup>Systems Engineering, Rhodes Hall, Cornell University, Ithaca, NY, USA

<sup>4</sup>Smith School of Chemical and Biomolecular Engineering, Olin Hall, Cornell University, Ithaca, NY, USA

<sup>5</sup>Lead contact

\*Correspondence: mcm337@cornell.edu

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Future electricity capacity will be judged on its ability to deliver energy efficiently while contributing to lower net emissions in the process (Moslehi and Reddy, 2019; Tarroja et al., 2019). This has created a demand for tools such as environmental full cost accounting methods for identifying direct and indirect economic, environmental, health, and social costs of a project or action including externalities. Evidence suggests renewable technologies such as wind and solar PV will not be sufficient either in dispatchable capacity or performance capability, to fully meet future load demands. In terms of meeting climate quality goals, limits on the effectiveness of market and policy tools such as cap and trade (Colby, 2000; Schmalensee and Stavins, 2017), low carbon fuel standards (Lee et al., 2017; Banerjee, 2020), or regional emissions or carbon-emission charges will become apparent. However, standards based on these tools are difficult to apply and enforce in scale as an unintegrated amendment to current or emerging technologies.

An alternative system of encouraging, incenting, and creating “net” carbon reduction from energy production is needed. Such a systems-based approach can be initiated by recognizing and crediting unrecognized performance attributes (credits) from alternative energy generation complexes.

This credit can be calculated by using the concept of equivalency. With this metric, energy related co-products create potential beyond electricity generation that measure both energy availability as well as net emissions from alternative technologies. Using such a tool can result in additional capability that improves net storage, buffers intermittency, and reduces overall emissions; and co-products. Credits act as an accounting mechanism for energy production as well as potential offsets that reduce net load, creating a common denominator for comparing the net efficiency of electricity generation. Using equivalency as a performance measure contrasts with policy preferences that stress technology neutrality, where performance and dispatch based on available capacity are constrained externally by regulatory or policy prescriptions for content quality.

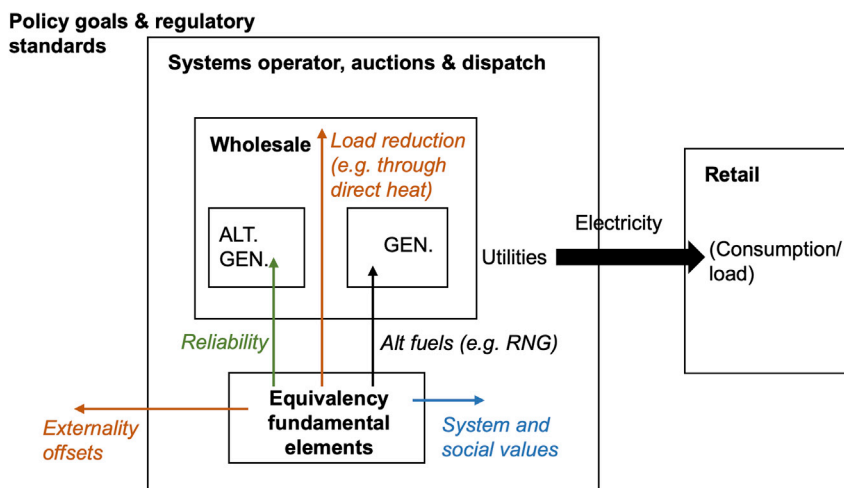
In this context, rule-based standards for limiting emissions typically focus on the existing technological pool of generation or consumption. In this context, the usual suspects have been hydrocarbon-derived fuels such as coal, fuel oil and natural gas. Tax incentives, consumption charges, carbon-limiting standards (e.g., LCFS, Cap and Trade programs, punitive regulatory limits for SO<sub>x</sub> and NO<sub>x</sub>) by design focus on industry wide or region wide average intensity to achieve mandated levels of compliance.

The goal of this paper is to illustrate the full potential of equivalency metrics to increase the attraction of alternative, distributed energy systems to enhance and enable the traditional electricity grid with added capacity and diversity needed for meeting future demand. We hope to initiate a debate regarding different methods and systems that will increase useful capacity while providing incentives and tools to decarbonize the electric grid. Rigorous quantitative estimations of the potential offered by an equivalency metric will define and refine the ultimate value for grid operations; that debate will ultimately involve and inform the corresponding policy and regulatory institutions.

Although it is important to diversify the existing grid (Aghaei and Alizadeh, 2013) by including new renewable and distributed generation technologies, that will not be possible without changes to corresponding policies, regulation, and compensation techniques to recover costs. These technologies represent far more than net generating capacity. By including alternative systems, future grid designs (Jairaj et al., 2016; Ela et al., 2019; Muhanji et al., 2019; Sorknæs et al., 2020) can include net benefits from improved performance and response times, net reductions in carbon-associated emissions, and co-benefits from reductions in air and water pollution in enterprises that must depend on extra-market support in order to reduce operating externalities.

### Traditional measures of performance

For consumers, the most ubiquitous energy product they consume is electricity, although most consumer reports address oil and fuel prices. Because electricity is functionally a carrier, the stock of generation technologies and fuels to meet demand vary widely. The result is a diverse mix of performance characteristics, pricing, and availability. Consumers see an average price paid to generators; this price (lagged because of billing delays) conveniently masks price volatility of electricity and the reserves necessary to serve instant changes in load. Electricity once generated is difficult to store and is dependent on secondary systems or technology from pump storage to batteries to be available for later use; even in large scale installations, batteries will still be limited in available capacity for dispatch.



**Figure 1. Stylized electricity grid, roles and actors**

GEN: existing generator, ALT: alternative or Distributed Energy Resource (DER). The electricity system operates within the context of policy and regulatory authority and rules. Within this context, permission for and standards governing technology, fuels and even consumer behavior interact broadly in an organized marketplace. Figure 1 illustrates the areas where changes in rules and standards affected by employing equivalency metrics would be concentrated.

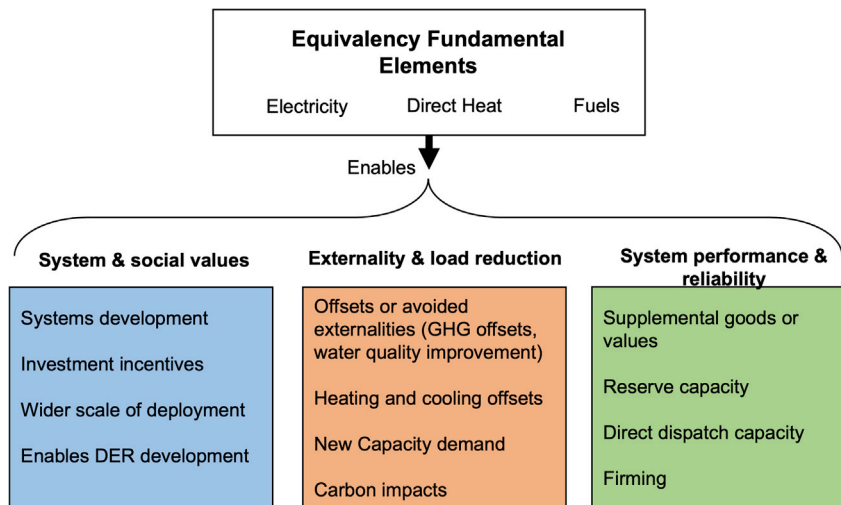
All energy systems reflect complex, interdependent and capital-intensive investments. The electricity system broadly includes electric power generation, direct thermal use, fuels for transportation, storage, and efficiency using so-called negawatt equivalents (Lovins, 1990) where the installed capacity is expected to perform over extended periods of time.

The least cost design (Ethier et al., 1997; Foley et al., 2010; Yousif et al., 2019) of electricity systems internalizes a suite of other characteristics such as social or policy preferences or managing externalities while still ensuring affordable supplies for consumers. Most electricity systems integrate some fraction of renewable energy technologies following policy mandates as well as programs to diminish reliance on fossil fuel-fired generation. Therefore, relatively expensive renewable generation is often built only after subsidies are applied or mandates such as portfolio standards have been met. The costs to meet these mandates are often internalized in user fees or taxes. In addition, a key characteristic of the modern electric energy system is a need for redundant capacity (reserves) ensuring continuous availability and reliability in both the short and long term that must be addressed and met.

Programs such as cap and trade, the Regional Greenhouse Gas Initiative (RGGI) or the Low Carbon Fuel Standard (LCFS) have succeeded in promoting technology-wide reductions in carbon emissions as well as diversifying the mix of generation in many regions (Lepitzki and Axsen, 2018; Yan, 2021; Yeh and Witcover, 2016). These rule-based top-down standards, however, have been less successful in the integrating potential of lesser scale alternative technologies, so-called Distributed Energy systems. For instance, air and water impacts are not always included in economic solutions focused on carbon mitigation, despite the urgency of mitigating them. Equivalency valuation can provide incentives for market intervention in this area by helping identify and qualify *attribute values* for combined technologies that offer *net* energy benefits from their operations.

When the full spectrum of net benefits is calculated, an active role for equivalency in alternative technologies will demonstrate and reward their use in grid operations and in the overall rate base, both in a physical and financial role. This role is apparent in Figure 1, showing the relationship of the policies and regulatory standards applied to electricity generation and delivery, including the potential of alternative energy resources, or equivalency agents to meet emissions goals.

Using equivalency metrics can refine this process by calculating and rewarding those attributes used or credited to meet these same goals or standards (see Figure 2). For instance, substitute fuels or heat sources



**Figure 2. Elements of equivalency in practice**

Equivalency simultaneously describes a characteristic or process that has value (utility) when applied to three primary components of the energy “system”. These elements, electricity, direct heat and fuels are the areas where equivalency can be applied most effectively in terms of systems operations. Figure 2 illustrates the nature of the benefit areas, including social policy goals, reduction of externalities and overall system performance where these benefits will be concentrated.

can reduce net carbon or other air pollutant emissions, create co-products with lowered environmental footprints or offset existing demand currently being met with natural gas or electric heating.

In Figure 2, we use equivalency to act as a catalyst and bridge between the “energy system” that includes both generation and offsets to introduce social values (policy related objectives) and reduction of externalities (typically a regulatory function) into the overall dynamic of system operation.

### The application and role of equivalency

The electricity capacity needed to meet forecast increases in demand (from shifts in transportation fuels, home and industrial facilities, and even agricultural production) will require gradual replacement of existing technology, new fuels as well as capacity expansion. This implies a continued reliance on natural gas (HNG) and combustion turbines that will be phased out over time (Ziegler et al., 2019). With such a fuel transition in mind, we have contrasted HNG or hydro-carbon derived natural gas using a technique such as reforming, with RNG or renewable natural gas derived from biogenic processing.

Improvements in technology have increased reliability and capacity utilization in the electric grid (simple cycle to combined cycle turbines, gas storage capacity in existing pipeline systems, deployment of solar PV, and wind farms) without succeeding in creating surplus capacity to match the combination of capacity retirement and growth in consumer demand. Creating the necessary incentives for alternatives during this transition period will demand new investment meeting the goal of increasing capacity while reducing overall carbon emissions.

Consequently, reducing dependence on traditional natural gas (HNG) will be an important part of this transition. For instance, substitution of bio-derived gas supplies for heating can be augmented with both biorefinery electricity and direct heat from geothermal sources (Reber et al., 2014; Litjens et al., 2018; Weer-atunge et al., 2021) and management of residual carbon waste can be integrated within refineries using organic production as a substitute for traditional hydrocarbons.

A systems approach, based on equivalency metrics such as net carbon emissions or equivalent offsets, will have to be authorized by policy initiatives and regulatory rules and standards. The accounting tool underpinning these credits must therefore reflect the net contribution of carbon-reducing attributes relative to a standard quantity, per megajoule (MJ), of dispatchable or saleable energy produced. In aggregate, the

outcome of using such a tool will measure the full or effective potential in new and replacement generation capacity in the electricity grid. An important byproduct will be more efficient use of alternative technology systems and net reductions in waste products from other energy intensive industries in agriculture and municipal waste disposal (Rajendran et al., 2021).

To illustrate this concept, we evaluate the potential of *equivalency metrics* to gauge the contribution of two alternative industries for carbon reduction when they are used in conjunction with traditional electricity dispatch. These examples, (i) direct heat offsets from geothermal wells using ground-sourced heat exchange, and (ii) energy production from region-specific biorefineries that integrate waste streams to generate dispatchable electricity and other energy products. We highlight the role of combining energy and co-products to offset the marginal cost loss when selling surplus electricity to the grid. In these conditions, revenue to support the gap between the system average price paid and the true Marginal Cost (MC) of generation is enabled through sales of a suite of co-products within a competitive integrated energy system.

The electricity grid, however, is aging (Energy Information Administration, 2020), and will need increased capacity, upgrades, and improved responsiveness to environmental externalities (Morvaj et al., 2017) in the future to meet projected increases in demand, while meeting quality and performance criteria from policy-makers and regulators (The National Council on Electricity Policy, 2009), as well as the investors who will enable the introduction of new technology. This need is daunting and will involve significant new capacity in every region of the country (Hostick et al., 2014) replacement of existing generation stock, increased reliance on low carbon technology combined with diverse renewable capacity, and the gradual reduction of overall emissions and other externalities from future operations (Energy Information Administration, 2021).

Electricity grids in virtually every region in North America have relied on a combination of new gas turbines, solar PV (some with battery storage to expand availability), and wind to meet near term expansion goals and begin retirement of existing stock. To diversify and expand the pool of technology available for generation, FERC has recently approved and sanctioned the use of Distributed Energy Resources (DER) (FERC Order 2222) to augment energy capacity and improve diversity of the installed base.

The grid is not designed to fully utilize or compensate low volume producers or alternative generation, despite outside extra-market subsidies, enforceable standards on fuel characteristics or even price augmentation using nodal prices adjustment or congestion compensation.

The reality is that a preference for new energy-only capacity discounts the choice and investment in alternative systems. When "energy only" is the dominant criteria for investment, policy tools such as cap and trade, relying on system averaged benefits, limit the incentive to develop integrated subsystems. This includes investment in technologies or processes to substitute technologies that shift or avoid load growth.

Creating new net capacity using these two examples illustrates the value of comparing *equivalency performance* across various technologies as a proxy for energy-based *full cost accounting*. Environmental costs are included as indirect costs throughout the lifecycle of these technologies and products in the system. Ultimately, of course, these metrics must be authorized or recognized as policy or regulatory instruments but applied in practice by generators and systems operators.

### Applying equivalency metrics

Equivalency is a policy-enabled tool that identifies attributes that have value in meeting social and environmental goals. Equivalency metrics (such the ratio of energy to associated emissions levels – positive and negative) creates incentives for alternative generation to operate as integrated systems where the benefits of sales or compensation for reducing emission levels offsets the potential loss from the energy component of electricity sales. This is similar to the situation in many existing markets where SO<sub>2</sub> or CH<sub>4</sub> levels are adjusted by the creation, sale, and elimination of offset credits that reflect lowered emissions elsewhere in the region and create compliance with standards. The result enables generators to sell electricity where their sales of attributes offset high marginal cost bids.

FERC Order 2222 has opened a door to allow generation from alternative energy systems to be included in unit commitment and dispatch. It is not clear, however, that the entrance of new energy capacity

from small(er) sources will be economically competitive or available without additional firming arrangements, subsidies, or other incentives. The capacity added by wind and solar facilities has been impressive (Energy Information Administration, 2021) but can complicate the ability of the systems operator to manage traditional technologies in meeting load shifts (Schmalensee and Stavins, 2017). This scenario has been explored in the past with some success (PV and wind integration), but the underlying intermittency characteristics have required continued dependence on firming and substitution from traditional sources such as NG turbines.

Credit or attribute compensation is available in some markets, where they trade on characteristics rather than performance, limiting the incentive to invest beyond the energy characteristics of these technologies. Sales of electricity alone may not cover marginal costs of generation and does not provide incentives for coterminous development of ancillary properties.

### Results and potential role of equivalency-driven capacity

Renewable energy generation, off grid, supplies and alternative combinations of generation for direct consumption exist in virtually every regional or meta-regional system. Many of these operations are not cost-effective enough to sell energy only to the grid at a competitive rate (Klavon et al., 2013; Aui et al., 2019; Usack et al., 2018). However, by combining their potential energy production net of other processing and co-product loads, it is possible to estimate net contributions to overall grid performance. Wood waste or municipal waste co-firing, methane capture from landfill sites, microturbines at neighborhood scale, avoided costs from scalable electricity parks with onsite generation, and the avoided cost of heat from direct geothermal heat substitution represent some of the potential resources available.

We illustrate these potential using two examples. First, we identify the functional equivalence values in a stylized biorefinery that processes dairy waste, and second, we use a scaled direct heat system to offset and replace heating and cooling loads in commercial and industrial load cents with either grid sourced electricity or bilateral service from independent generators.

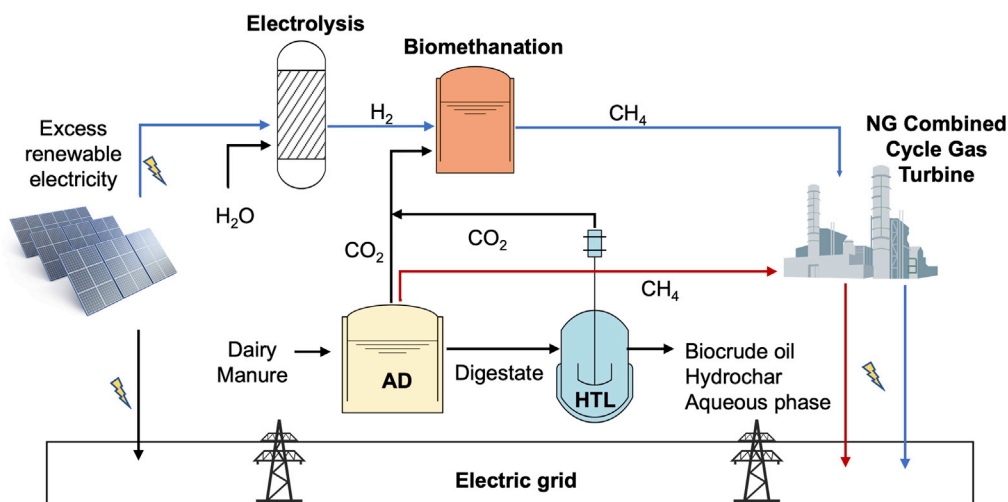
### Bioenergy refinery

A biorefinery is a facility typically located at or near operations that generate waste products. Biorefinery systems are based on a multi-step process that converts biomass wastes creating fuels, derivative products such as fertilizers and soil amendments and improving net water or air quality in the residual waste stream. In terms of GHG emissions, various sources of waste/manure products can be utilized as a platform for biomethanation including dairy, beef cattle, poultry, and swine farms. Liquid content of the manures in question changes the performance of the final products, but not the character of the waste stream utilized to offset net electrical loads and reduce net carbon emissions per MJ of electricity produced.

The refinery process can reduce net carbon emissions directly by substituting fuels or indirectly by reducing the quantity of fossil fuels supplied. The biorefinery evaluated in this study, adapted from Kassem et al. (2020a), relies on integrated anaerobic digestion (AD), hydrothermal liquefaction (HTL) and biomethanation (BM) components for processing manure from dairies (Figure 3).

In this example, Anaerobic Digestion, a biological process that uses anaerobic bacteria (methanogens) to convert organic matter into biogas (CO<sub>2</sub> and CH<sub>4</sub>), is the critical technology for converting dairy waste. The resulting biogas can be combusted to produce utility scale heat and electricity or can be upgraded to biomethane or renewable natural gas (RNG) for commercial applications (Table 1) (Usack et al., 2019; Ullah Khan et al., 2017). Anaerobic digestion is a well characterized process that includes co-benefits in terms of reducing GHG emissions and nutrient runoff (Usack et al., 2018; Angenent et al., 2018) by reducing direct land spreading of raw manure. The byproduct of this process, liquid digestate, can be further processed using HTL (thermochemical conversion at high temperature using pressurized water (Posmanik et al., 2018). Opportunities in remote or exurban areas that support poultry, fish, municipal wastewater treatment, or other concentrated operations can be imagined using similar integrated "refineries". Broad policy objectives dealing with air quality, water quality, or remediation are candidates for this approach and can be included in a net benefit calculation based on the ability to sell energy products from the complex (Table 1).

Commercial non-electricity grid products include Bio-crude oil sold to refineries for further processing into biodiesel, and hydrochar which can be used as a soil amendment product (Table 1). HTL also produces an



**Figure 3. Process flow illustration of a biorefinery system**

The biorefinery is an example of a complex system where coordinated processes create a suite of primary and secondary energy products. Figure 3 highlights the fact that although the electric grid is a principal beneficiary of dispatchable electricity, other products such as RNG indirectly support grid operations with a net benefit in terms of meeting capacity needs, responsive generation and more efficient operation to waste reduction performance when operated continuously.

aqueous phase containing dissolved NPK nutrients and organic compounds and a gaseous stream consisting primarily of pure CO<sub>2</sub> suitable for industrial processing (Table 1). The Biomethanation system uses microorganisms to convert CO<sub>2</sub> (sourced from AD and HTL) and H<sub>2</sub> (produced using water electrolysis) to produce additional methane (e-methane). The use of renewable electricity to power the electrolyzer ensures the production of carbon free e-methane (RNG as opposed to HNG derived from traditional sources).

The increased share of renewables in the electric power sector highlights the need for additional and reliable firming capacity to offset the intermittent characteristics of both wind and solar PV power. The integrated biorefinery described above, as a whole, can effectively act as a power-to-gas (PtG) system where excess renewable electricity can be stored in the form of RNG and used at a later time (Lewis and Nocera, 2006; Turner et al., 2008; Cook et al., 2010; Bockris, 2013; Pellow et al., 2015; Bailera et al., 2017) (see STAR methods).

Creating new supplies of RNG from facilities like biorefineries can augment short term storage for gas turbines adding capacity and improving peaking energy response times associated with peak demand or system outages (Balat, 2008; Qadrdan et al., 2015; Simonis and Newborough, 2017). The net outcome will improve the overall dispatch mix of future electric grid systems (Guandalini et al., Campanari, and Romano 2015); the net Renewable Natural Gas created is available for system-wide offset of seasonal storage, shortfalls in seasonal delivery or to offset the total natural gas demand for the system and act as a net credit for carbon emissions from HNG in addition to other fuels and products (Figure 4).

During peak demand periods short term capacity limits may affect systems operations. In this case, biorefinery capacity can provide a buffer, direct supply, or reserves enhancement. Conversely, in times of slack or regionally shrinking demand, underutilized pipe capacity offers an acceptable storage vehicle for RNG. As renewable electricity generation increases, we are likely to see an increased need for PtG systems for large scale electricity storage. In this case the PtG operators can become the existing natural gas utilities' marginal customers, paying a seasonal fee to 'store' their RNG in the grid. Here the legacy costs can be assessed and shared by PtG operators, supporting lower average gas bills for existing customers.

A biomass refinery adds both competitive and flexible capacity to support overall grid operations. It ultimately offsets total system costs, improving response times, firming capacity, and balancing. In addition to supporting electricity generation, the biorefinery contributes multiple environmental benefits, such as low (and sometimes negative) carbon intensity (CI) fuels, reduced net GHG emissions, reduced nutrient runoff, and river basin eutrophication. Furthermore, biomass waste feedstocks such as manure and food wastes



**Table 1. Market options for bio-refinery co-products**

Product	Characteristic	End user
Livestock waste (solid)	After dewatering, can be direct soil amendment	Reforestation Public Agencies
Electricity direct from methane combustion	Supplied to grid for dispatch on continuous basis	Sale to the Grid
RNG	Injected into the pipeline network for HNG supplement or replacement or for storage	Natural Gas System <sup>a</sup>
CO <sub>2</sub>	Credit cost per tonne needed to offset production	Electricity Producers
CH <sub>4</sub> for fertilizer	Ammonia production	Agricultural Operators
H <sub>2</sub>	Production cost per kg green	Chemical Industry
H <sub>2</sub>	Production cost per kg from clean hydrocarbon <sup>b</sup>	Commercial Interests
BioDiesel	For transportation substitute or additive	Transportation Fuel Companies
Bio oil	Substitute for heating oil	Rural Customers

Primary and secondary markets exist or are likely to emerge to support biorefinery operations. This is expected to occur when a refinery complex is supporting a system such as the electricity grid. The products will range from primary fuels to dispatchable electricity. Table 1 describes these products and suggests the likely end users and market niche for them.

<sup>a</sup>The natural gas system is widely used in power generation. The importance of substituting RNG is tied to the reduction of “net” emission characteristics.

<sup>b</sup>The production of H<sub>2</sub> using RNG (via steam methane reforming), is often considered “green” hydrogen since it is produced using RNG, as opposed to HNG. If fossil HNG were used as the source to produce H<sub>2</sub> along with CO<sub>2</sub> capture, then the H<sub>2</sub> is often referred to as ‘blue’.

are widely available and have predictable generation rates, ensuring a continuous RNG (biomethane) supply and helping to stabilize price levels.

### Gas/RNG/HNG

Natural gas (HNG) is typically supplied through a limited number of common hubs or exchanges (physically of course it may be delivered through far smaller or even local pipe and storage systems). The price and compensation are based on contracts for physical or financial delivery in forward (future), spot (physical) or reserve (storage) deliveries.

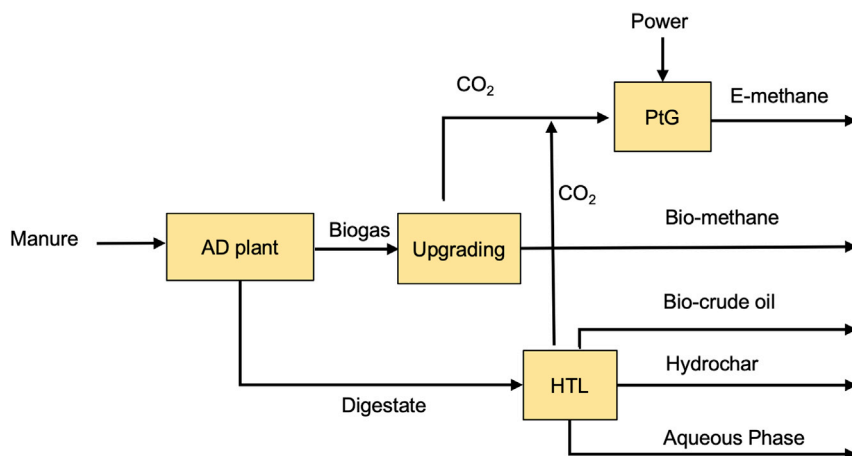
So, in general, we can say that the “value” of RNG is based on direct production costs minus equivalency payments (credits, RECs, cap and trade carbon values, and reserve payments, etc.) or even bi-lateral or direct use contracts in local markets.

The market for natural gas in general is diverse and complex, serving regional and local demands for heat, processing, and electricity generation. There are basically two opportunities to utilize RNG:

- self generation and on-site use (uncompensated by system operator)
- surplus beyond on-site use is sold into the regional NG system
  - to act as reserve or storage (daily competitive price plus credit or carbon value)
  - to augment current power demand
  - to offset short-term shortfalls
  - to offset or forestall future gas extraction

### Electricity generation supported by biogas (RNG)

Electricity can be generated and supplied via on-site turbines of some kind, and volume delivered is net of on-site (behind the meter) demands. The price obtained varies by hour or season but is based on either the



**Figure 4. Product streams available from dairy waste processing**

Dairy waste reflects an important area of emissions control concerns for policy makers and regulators. In Figure 4 we illustrate the additional products that emerge from the biorefinery and contribute to the overall economic viability of such an enterprise based on its total system performance. In this figure, the key component is a process that utilizes anaerobic digestion to break down the primary product, and other waste streams available in developed and concentrated feedstock operations.

behind the meter rate typical of solar PV based on peak system prices or a fixed bulk contract similar to wind producers.

Electricity generation is either used on-site or exported to grid operations. Only the net export volume receives payment.

- Payment is based on solar PV model, and pays system average peak price per kWh delivered
- Alternatively, payment can be for time of delivery, plus carbon offset value, which might result in profit for the refinery. An illustrative carbon offset pricing formula is shown in the [STAR Methods](#).

Biofuels – sold in separate industrial market at market clearing rates.

*Digestate* - is an intermediate product that is further converted into biooil and hydrochar through HTL. If the biorefinery consists of AD only, then digestate products can be sold.

*hydrochar* - sold as soil amendment in areas depleted or in need of remediation, as export product from the region where the refinery operates.

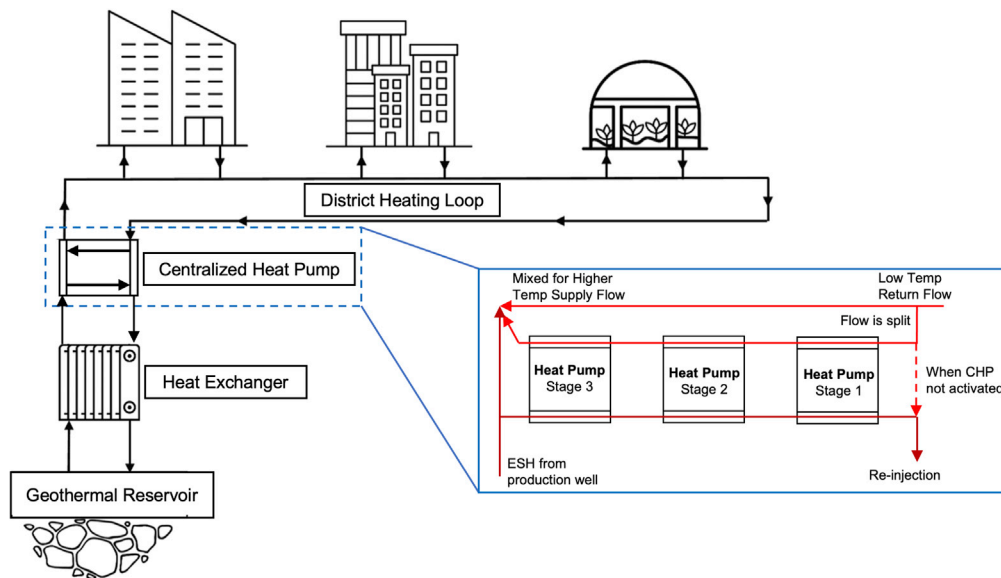
Direct Heat – delivered, metered, and sold by local utilities.

The value of direct heat (or cooling via chillers) represents an offset or avoided cost.

- for electricity offsets, it should reflect a credit or offset for use of resistive heat infrastructure
- for gas, it should be calculated on avoided demand and based on annualized savings

Both values should constitute a “levelized system benefit” calculation in order to merit area-wide installation, or for individual homeowners, a formula that assigns a system benefit value and monthly or annual credit.

In a news announcement Duke University ([Duke Today, 2021](#)) agreed to purchase RNG from a local RNG developer as a step to achieve its climate neutrality goals by 2024. The company operates at the local wastewater plant and uses vegetable waste to produce RNG and injects it into the existing NG pipeline.



**Figure 5. - Illustrative diagram of a direct heat geothermal system**

District heating systems can be developed either in the initial process of urban or commercial construction or in renewal projects for upgrading or replacing existing structures. The benefits, post construction, is a significant savings in serving heat loads, as well as offsetting the carbon emissions that would have been associated with using electricity to serve this demand. Figure 5 illustrates the relationship of the physical plant involved in such systems, using the common examples of residential, commercial and applied agricultural operations.

### Direct-use geothermal heating

Much of the debate over current electricity generation is focused primarily on the performance of the technology in the current fleet, including both renewable and non-renewable technologies. Most of this load is served utilizing natural gas. The demands for thermal processing in many sectors of the economy, however, represent a significant opportunity to avoid electric capacity associated with them, and replace that load with direct heat sourced from geothermal wells. A review of the current range of low temperature (<120°C) system demands, representing about 25% of US primary energy use (Fox et al., 2011) suggests an additional source of both energy and net carbon emission reduction.

Direct-use geothermal district heating (GDH) systems utilize one or more pairs of geothermal wells with a hot water distribution network to deliver renewable heat as a primary product (Tester et al., 2015; Jordan et al., 2020). Heat pumps (HPs) can be used in a direct-use system for resource augmentation to improve reservoir heat output and operation. A direct-use geothermal well-pair combines production and injection wells which circulate a geothermal fluid between a hot subsurface reservoir at a predetermined depth of reliable heat and a surface heat exchanger. This system transfers thermal energy to the surface where it is supplied to a nearby load source such as a commercial building or a city distribution "zone" using underground pipes, flow pumps, and heat exchangers. The geothermal fluid cools as heat is extracted from the heat exchangers and is then returned to the reservoir via the injection well to replenish subsurface fluids - completing a continuous loop. The centralized HP sub-system functions by "moving" energy from the return loop to the supply loop using pumps driven by grid-supplied electricity (Figure 5).

This type of system is functionally and financially attractive (Weijermars and van Harmelen, 2016; Zhang et al., 2019; Galantino et al., 2021) to augment or replace grid sourced electricity or natural gas for heating and cooling. Consequently, in appropriate climate-driven applications, such a system creates a net annual reduction in electricity and natural gas demand, with the ancillary benefit (Tester and Herzog, 1990; Beckers et al., 2014) of increased system reliability and security. The system relies on well characteristics in low enthalpy zones (temperatures not viable for electricity production) where they can be utilized for both heating and cooling applications, depending on the season. The characteristics of the piping and storage in the system result in short dispatch response (Buscheck et al., 2014), with capacity factors of approximately 98%

(the average capacity factor of the system can be expected to decline and approach 95% when used to support load following) (Jordan et al., 2020).

Direct-use technology depends on replication of suitable well-pair drilling with appropriate well spacing, reservoir design and performance validation (van der Zwaan and Dalla Longa, 2019; Soltani et al., 2021), and the installation of a dedicated underground pipe distribution system to deliver the heat to its points of use, (and/or utilization of existing district heating infrastructure). Systems may also require relatively scaled Heat Pumps, as well as grid-level electricity interconnects to support in-plant operations.

Benefits that reflect the potential for offsetting or substituting direct heat for heating and cooling loads supplied by grid-based electricity include net emissions reduction (Smith, 2019), renewable energy credits (REC's) to offset capital costs, as well as the net firming offset that represents renewable energy resources dispatched by the systems operator.

In terms of public health concerns or broader impacts on reaching climate change objectives, direct heat offsets must be calculated based on the emissions reductions at the time of operation to be fairly estimated in overall grid performance. Direct use of low-temperature geothermal well-pair provides reliable baseload heating and offsets or reduces but does not eliminate the need for electricity support in terms of pumping and heat recovery during heating or cooling operations, whereas electrified technologies operate to firm and handle variability in load.

With this technology installed, net associated emissions reductions provide a direct social benefit to communities that represent either credit value equivalency or the basis for estimating participation in existing support or public credit programs (further discussion of this issue is included in the STAR Methods). In the US "Rust Belt", these systems are included as part of the solution for remediating aging infrastructure with high maintenance and replacement costs (George, 2018).

### Potential direct heat offset value

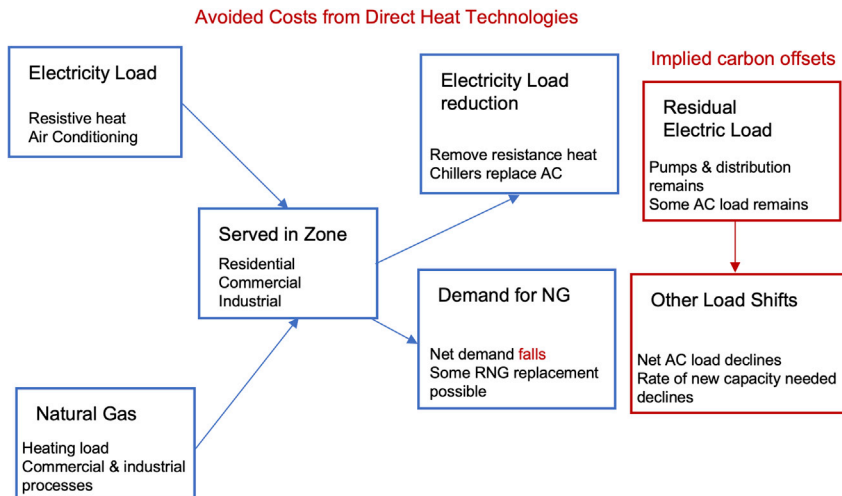
Direct heat from geothermal sources represents a fundamental change for most systems with a seasonal heating or cooling load. Installation and use of capacity based on avoided demand is not based on dispatch, because it is available continuously to serve variable load. In other words, with a direct heat system in operation, baseload conditions are reduced in response to moderating conditions in overall consumer demand. Diminished volatility will change the nature of that part of the demand curve associated with heating loads throughout the area served by the systems operator. This represents a net electricity savings potential district wide, but it is not eliminated completely. A residual or core demand for electricity exists to serve pumps, well maintenance and heat or cooling resource dispatch.

Integration of direct heating/cooling systems combined with this technology is equivalent to a net reduction in demand represented by existing electric heating and cooling demand (avoided costs) and in operating costs at the consumer level. Net avoided costs can be measured either as equivalent surplus generation capacity foregone or the calculated avoided costs of new electric generation dispatched at the margin (Zinaman, et al., 2020) during the day or by season.

Carbon reduction targets and benefits can be estimated and compared to existing demand only with a much generalized calculation. The behavior of current versus future consumers can only be measured in the aggregate and compared to expected growth in electric generation capacity within the service region at similar levels of estimation. The stylized relationship is shown in Figure 6.

### Direct-use geothermal heating cost/benefit summary

Investing in direct heat systems reflects the construction and operation of a dedicated system of wells, heat exchangers, pumps, and distribution pipes. The most likely locations that can benefit from the widespread use of this technology are in urban areas that experience annual periods of heating demand that would justify the infrastructure construction involved. At scale, however, in terms of urban budget cycles, we believe encouraging this type of investment in new construction or when urban renewal is undertaken, can result in substantial reductions in load over long periods of time; the offset of resistive heat avoided



**Figure 6. Illustrative value of direct heat offsets**

Once in place, direct heat installations can actively and passively affect heating loads. During operation, such a system requires minimal intervention and management by the electric or local systems operator, since the direct heating technology works by its nature smooths load to match ambient comfort levels for consumers. Figure 6 highlights the nature and effect of these characteristics on load to the electric systems and natural gas operators.

costs can be anticipated in reduction in electric load and correlated positively with reduced stress on both transmission and generation systems over time.

Such a geothermal system can substantially and positively affect the financial competitiveness of a municipality or service area. Successful development of such a system creates favorable conditions for improvement bonds that generate dedicated revenue for capital recovery as well as offsetting normal rates for ratepayers.

In such a case, the avoided cost of operations (including the potential for reversing the process and using chillers in warmer months) represents a potential net savings to grid operations. Beyond this though, such a technology can be used for net reduction calculations in terms of overall carbon reduction. Similar area-wide schemes exist to achieve compliance with standards such as  $\text{CO}_2$ ,  $\text{SO}_x$ , and  $\text{NO}_x$ , net reductions in these criteria pollutants can be the basis for tradable credits or permits.

### The case for including equivalency metrics in electricity dispatch

Significant progress toward controlling emissions from power generation facilities has been made utilizing market-based control programs such as carbon fuel standards, criteria pollutant regulation, and trading, the development of more efficient power generation that has displaced older technology and the impressive integration of wind, solar and more recently, advanced battery storage. However, a vast reservoir of distributed energy resources exist that include related environmental and social policy benefits available while creating net electricity benefits that can be deployed for grid dispatch.

Defining, monetizing, and mobilizing these benefits be important for improving existing electricity systems architecture. However, this process will not succeed without significant investment in local infrastructure and control technologies. These in turn will not generate the necessary investment interest without defining the role and credit available for small independent operators. Implementation of such a program, where credit values enhance the energy bid(s) from distributed systems will be the responsibility of systems operators. The authorization and structure of the values themselves require legislative or policy intervention. This will require proof of concept and a common metric of performance in meeting combined objectives of reliable and predictable delivered electricity supplies net of defined carbon reduction benefits for the system.

There is no established or common accepted term for equivalency in energy production and delivery. For distributed generation facilities, equivalency must result in a sustainable operation where saleable energy

is enabled by sales of associated products or credits assigned to avoided energy use or credit value assigned for social or grid benefits. Thus, credits such as REC's or offsets or banked values can be construed as having equivalency in terms of using one technology versus another in current operations or banked, sold, or traded to other participants in the market. This reflects the value of alternatives that have been underutilized or invested in the current grid operations in North America, namely geothermal, wind, and solar energy which represent not only energy to meet load, but the net avoided costs of externalities from using hydrocarbon thermal energy production as a primary source.

The use of specific equivalency measures has an historical precedent, for instance EPA captures emissions and generating characteristics in their EGRID tables (US EPA, 2020) and air quality characteristics of new generation are examined in a paper by the National Association of Clean Air Agencies (2015) where they specifically cite the benefits of including a measure of equivalency in determining merit order for electricity dispatch.

The grid balancing and power storage benefits of the biorefinery system can be utilized in places like California where an imbalance associated with solar generated electricity can overwhelm the backbone grid generation from natural gas in certain hours of the day, especially in summer months (commonly known as the 'duck curve' problem, see STAR Methods, Figures S2 and S3). The increasing share of solar during the day displaces at the margin gas turbines, but in the late afternoon hours, a new imbalance requires gas turbines to be brought back online to meet load. In this case, a PtG system could "store" solar electricity generated but not used during the day (curtailment) and restore it with RNG, at times of peak demand. Here, a 'systems' approach to meeting load, creating reserves, and managing carbon waste products addresses the 'duck curve', improving both planning and dispatch operations.

Equivalency here is a proxy of the potential or estimate of *total delivered energy* expressed or measured in a term like the Levelized Cost of Energy (LCOE), as the expected performance measure that combines dispatchability, availability, reliability, and avoided costs of externalities. Other metrics, such as the weighted average cost of capital (WACC) used in the investment community will ultimately reflect the ability of various DER facilities to generate competitive energy products within regional markets.

For instance, if equivalency characteristics were recognized widely, they would enable a wider use of energy to firm renewable technology intermittency already faced in grid operations, diminishing reliance on traditional HNG for meeting peak load in electricity dispatch or in supplementing local demand for heating using RNG. Equivalency in grid operations underpins the concept of achieving net carbon reduction wedges, reduces catastrophic remediation costs for water quality and can diminish impacts on rural agricultural land use.

### Compensation for equivalency

There are direct and indirect "compensation" mechanisms available to cover investment in alternative energy resources. We have used two examples for illustration in this paper. They are biorefineries using digesters and agricultural waste products, and local systems of direct heat exchange. The possible payment streams include:

- a. credits (sold, traded, or banked) for offsets or minimizing externalities
- b. auctions to establish value(s) which can fluctuate over various time periods
- c. direct payments based on spot prices or contracts
- d. assumed offset values purchased via annual must run/must take contracts

Taken alone, RNG, renewable electricity, and direct heat systems are not cost competitive if measured solely against an energy-only value to either the energy system (which includes transportation fuels as well as electricity) or the electricity system alone. Both require compensation or credit for attributes in order to operate and cover total costs. Because the range of "benefits" lies both inside and outside traditional electricity markets (the principal client or market destination), then acknowledging the utility of by-products and processes must be formalized (similar to the schemes used for wind or solar incentives) in order to justify investment in these technologies.

Consequently, accounting conventions must be adopted ahead of time that enable day ahead bidding similar to traditional generators and maintain uninterrupted supplies. Energy bids net of equivalency values and payments will be compensated at delivery by contract prices or system average costs in each hour dispatched.

## Conclusions

This paper is intended to initiate a dialogue and discussion that will include policymakers and regulators beyond the academic community. We believe such a dialogue will stimulate the development of rigorous models, rules, and standards necessary to add new and replacement capacity in the electric system. To be successful, the grid of the future must internalize the cost of carbon management, diversify the capacity available to meet load, and provide the incentives to invest in a broader range of technologies to support new, scalable, and integrated technologies.

The challenge that confronts policymakers and regulators and systems operators is clear and immediate. Net electricity demand is increasing despite credible and popular energy efficiency measures available to consumers to reduce or redirect demand. Simultaneously, improving electricity grid operations offers a unique opportunity to address the transition from traditional generation paradigms to more integrated designs that incorporate a combination of power generation (energy only) with programs that internalize and compensate for net emissions, allowing competitive distributed generation facilities to compete in the energy market.

The market for energy products is diverse enough to allow traditional and niche producers to simultaneously serve load, as well as creating a platform for internalizing the costs of dealing with a wide range of externalities such as water contamination and air pollution. However, to reach a common value that supports the full potential of distributed energy systems, it is important to estimate the market value of attributes beyond the embedded energy content of either electricity or gas markets alone.

In other words, the use of *energy content* alone does not fully recognize the potential of renewable and other alternative technologies to supply both energy and reduce system intensive externalities. Integration and coordination of these alternatives can support capacity growth, grid stability, energy system resilience, and responsive expansion of both transmission and storage facilities. Defining and including a metric that expands the definition of “energy” values for social, environmental and policy goals can bring new investment interest and support for the entire grid system. Ultimately this will require the identification and valuation of intangible benefits that result in new protocols for firming firm renewable supplies and creating new capacity. The result can enhance the value of rural agricultural systems and initiate a demand for untapped carbon offsets that support energy production. This in turn will begin to lower the amounts of spinning reserve and non-regulated capacity required, leading to lower consumer costs, and creating new investment opportunities for utilities.

These two technologies demonstrate viable business models for inclusion in grid operations. They do point out, however, that the functional value of the energy component in each depends on the inclusion of a suite of operational sub-functions, as well as viable compensation for attributes that meet social policy goals and standards.

Ultimately, adopting equivalency metrics does not eliminate least cost dispatch. It identifies attributes that cannot be fully valued or utilized outside of a small sub-system where direct energy generation is one by-product. By monetizing the suite of benefits net of operating costs creates a viable entity where the values support regional and local economic enterprise and offer extra-market benefits for controlling externalities that are not recognized in traditional dispatch models.

Attaining this goal will occur sooner, be more cost-effective, and provide investment incentives when separate attribute values are included in market-based bidding for electricity. Current policies and rules have evolved to apply programs such as cap and trade, SO<sub>x</sub> and NO<sub>x</sub> rule-based-limits to reduce average regional emissions. While this has reduced overall emissions, these programs are based on a historical least cost dispatch aggregate production model that ignores a more refined and focused incentive system for alternative energy production. The next generation of control can be designed to measure and assign a value (*Equivalency*) to co-products in small scale regional systems that can underpin a more efficient electricity grid in the future.

When the complete spectrum of net benefits is calculated, there clearly is an active role for using alternative renewable technologies for providing both heat and electric power. If equivalency metrics were employed to satisfy both load and policy requirements, it would expand the utility and revenue available from these renewable sources and establish an extended range of new direct and indirect energy supplies for grid operations. The outcome would be a more resilient and productive electric grid and heat distribution system operating in a combined physical and financial role.

The illustrative technologies here are intended to initiate and inform a debate that must involve legislative (policy) and regulatory rulemaking to enable use in day-to-day market operations. Standardizing estimates of carbon management or avoided costs is the key to enabling investor interest in implementing distributed generation alternatives, and underpin the ancillary support in transmission, storage and control facilities that will enable them.

### Limitations of the study

Equivalency is meant to target generation capacity that results from a suite of operations that integrate power generation with co-products that may or may not have direct sales potential as part of dispatchable energy supplies. Although one byproduct is clearly energy that can be transferred to consumers, a key and occasionally superior product is the net reduction in carbon emissions or the avoided use of carbon intensive electricity generation. The calculations are illustrative at this point, since this argument must travel a gauntlet beginning with policymakers and find definition and deployment with systems operators and cooperation from generators, utilities and independent power producers.

This paper is not intended to define or demonstrate the rigorous elements or framework of such a system. We believe that process will follow the initiation of an approach that recognizes our stated definition of the problem. As such, we only highlight the role and point of entry of equivalency in the system, (e.g., we do not develop a commitment dispatch model although that is a logical next step), since estimates of carbon offset value in bidding are not fully developed, nor is an estimate of the final market price of avoided carbon.

### STAR★METHODS

Detailed methods are provided in the online version of this paper and include the following:

- KEY RESOURCE TABLE
- RESOURCE AVAILABILITY
  - Lead contact
  - Materials availability
  - Data and code availability
- METHOD DETAILS
  - Nomenclature
  - Biorefinery capacity and costs
  - Grid balancing and storage – a California biorefinery implementation
  - Biorefinery illustrative pricing formula
  - Number of geothermal well-pairs and project costs
  - Geothermal well-pair case study: Buffalo, NY
  - Extension of model applicability

### SUPPLEMENTAL INFORMATION

Supplemental information can be found online at <https://doi.org/10.1016/j.isci.2021.103123>.

### AUTHOR CONTRIBUTIONS

N.K contributed the structure, functional description and operating characteristics of the biorefinery. C.R.G contributed data and operating characteristics of the geothermal heat program. C.L.A contributed fundamental work on the bidding and dispatch process for grid operations. J.W.T contributed fundamental work on biochemistry, geothermal heat exchange and offset principles. M.C.M contributed to the design of carbon exchange and valuation in grid operations. All authors contributed in writing and reviewing the paper.



## DECLARATION OF INTERESTS

The authors declare no competing interests.

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## STAR★METHODS

### KEY RESOURCE TABLE

REAGENT or RESOURCE	SOURCE	IDENTIFIER
<i>Deposited data</i>		
AD CAPEX & OPEX (Biorefinery case study)	<a href="#">Astill, Shumway and Frear, 2018</a>	<a href="https://csanr.wsu.edu/anaerobic-digestion-systems/enterprise-budget-calculator/">https://csanr.wsu.edu/anaerobic-digestion-systems/enterprise-budget-calculator/</a>
CHP CAPEX & OPEX (Biorefinery case study)	<a href="#">Astill, Shumway and Frear, 2018</a>	<a href="https://csanr.wsu.edu/anaerobic-digestion-systems/enterprise-budget-calculator/">https://csanr.wsu.edu/anaerobic-digestion-systems/enterprise-budget-calculator/</a>
HTL CAPEX & OPEX (Biorefinery case study)	<a href="#">Kassem et al., 2020b</a>	<a href="https://doi.org/10.1016/j.wasman.2019.12.029">https://doi.org/10.1016/j.wasman.2019.12.029</a>
Biomethanation CAPEX & OPEX (Biorefinery case study)	<a href="#">Electrochaea GmbH, 2019</a>	Personal communication
AEL electrolyzer CAPEX & OPEX (Biorefinery case study)	<a href="#">Electrochaea GmbH, 2019</a>	Personal communication
NYS Electricity price (commercial) (Biorefinery case study)	<a href="#">New York State Energy Research and Development Authority, 2020</a>	<a href="https://www.nyserda.ny.gov/Researchers-and-Policymakers/Energy-Prices/Electricity/Monthly-Avg-Electricity-Commercial">https://www.nyserda.ny.gov/Researchers-and-Policymakers/Energy-Prices/Electricity/Monthly-Avg-Electricity-Commercial</a>
Average hydroelectric PPA price (Biorefinery case study)	<a href="#">EIA, 2019</a> ; <a href="#">IRENA, 2019a, 2019b</a>	<a href="https://www.eia.gov/outlooks/archive/aeo19/pdf/electricity_generation.pdf">https://www.eia.gov/outlooks/archive/aeo19/pdf/electricity_generation.pdf</a> <a href="https://www.irena.org/costs/Power-Generation-Costs/Hydropower">https://www.irena.org/costs/Power-Generation-Costs/Hydropower</a> <a href="https://www.irena.org/publications/2019/May/Renewable-power-generation-costs-in-2018">https://www.irena.org/publications/2019/May/Renewable-power-generation-costs-in-2018</a>
Discount rate (geothermal case study)	<a href="#">Galantino et al., 2021</a>	<a href="https://doi.org/10.1016/j.enbuild.2020.110529">https://doi.org/10.1016/j.enbuild.2020.110529</a>
Inflation rate (geothermal case study)	<a href="#">Galantino et al., 2021</a>	<a href="https://doi.org/10.1016/j.enbuild.2020.110529">https://doi.org/10.1016/j.enbuild.2020.110529</a>
Project lifetime (geothermal case study)	<a href="#">Galantino et al., 2021</a>	<a href="https://doi.org/10.1016/j.enbuild.2020.110529">https://doi.org/10.1016/j.enbuild.2020.110529</a>
Electricity rate (geothermal case study)	<a href="#">Galantino et al., 2021</a>	<a href="https://doi.org/10.1016/j.enbuild.2020.110529">https://doi.org/10.1016/j.enbuild.2020.110529</a>
Well flow rates (geothermal case study)	<a href="#">Galantino et al., 2021</a>	<a href="https://doi.org/10.1016/j.enbuild.2020.110529">https://doi.org/10.1016/j.enbuild.2020.110529</a>
Drilling CAPEX (geothermal case study)	<a href="#">Galantino et al., 2021</a>	<a href="https://doi.org/10.1016/j.enbuild.2020.110529">https://doi.org/10.1016/j.enbuild.2020.110529</a>
Surface HX/pump facility CAPEX (geothermal case study)	<a href="#">Galantino et al., 2021</a>	<a href="https://doi.org/10.1016/j.enbuild.2020.110529">https://doi.org/10.1016/j.enbuild.2020.110529</a>
Stimulation CAPEX (geothermal case study)	<a href="#">Galantino et al., 2021</a>	<a href="https://doi.org/10.1016/j.enbuild.2020.110529">https://doi.org/10.1016/j.enbuild.2020.110529</a>
HP equipment CAPEX (geothermal case study)	<a href="#">Galantino et al., 2021</a>	<a href="https://doi.org/10.1016/j.enbuild.2020.110529">https://doi.org/10.1016/j.enbuild.2020.110529</a>
Interconnection CAPEX (geothermal case study)	<a href="#">Galantino et al., 2021</a>	<a href="https://doi.org/10.1016/j.enbuild.2020.110529">https://doi.org/10.1016/j.enbuild.2020.110529</a>
Labor OPEX (geothermal case study)	<a href="#">Galantino et al., 2021</a>	<a href="https://doi.org/10.1016/j.enbuild.2020.110529">https://doi.org/10.1016/j.enbuild.2020.110529</a>
Maintenance cost (geothermal case study)	<a href="#">Galantino et al., 2021</a>	<a href="https://doi.org/10.1016/j.enbuild.2020.110529">https://doi.org/10.1016/j.enbuild.2020.110529</a>

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REAGENT or RESOURCE	SOURCE	IDENTIFIER
Heat pump electricity OPEX (geothermal case study)	<a href="#">Galantino et al., 2021</a>	<a href="https://doi.org/10.1016/j.enbuild.2020.110529">https://doi.org/10.1016/j.enbuild.2020.110529</a>
Flow pump electricity OPEX (geothermal case study)	<a href="#">Galantino et al., 2021</a>	<a href="https://doi.org/10.1016/j.enbuild.2020.110529">https://doi.org/10.1016/j.enbuild.2020.110529</a>
NG consumption and related GHG emissions for residential, commercial and institutional sectors in Buffalo, NY (geothermal case study)	<a href="#">New York Power Authority, 2015</a>	<a href="https://www.nypa.gov/-/media/nypa/documents/document-library/operations/five-cities/2015-01-31-buffaloenergyplan.pdf">https://www.nypa.gov/-/media/nypa/documents/document-library/operations/five-cities/2015-01-31-buffaloenergyplan.pdf</a>
NG consumption GHG emissions for space and water heating (geothermal case study)	<a href="#">U.S. Energy Information Administration, 2015, 2016</a>	<a href="https://www.eia.gov/consumption/residential/data/2015/c&amp;e/pdf/ce4.2.pdf">https://www.eia.gov/consumption/residential/data/2015/c&amp;e/pdf/ce4.2.pdf</a> . <a href="https://www.eia.gov/consumption/commercial/data/2012/c&amp;e/pdf/e7.pdf">https://www.eia.gov/consumption/commercial/data/2012/c&amp;e/pdf/e7.pdf</a> .
Social cost of carbon (geothermal case study)	<a href="#">US EPA, 2017</a>	<a href="https://19january2017snapshot.epa.gov/climatechange/social-cost-carbon_.html">https://19january2017snapshot.epa.gov/climatechange/social-cost-carbon_.html</a>

**Software and algorithms**

Microsoft Excel	Microsoft	Excel v 16.52
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**RESOURCE AVAILABILITY**

**Lead contact**

Further information and questions for should be addressed to the Lead Contact, Michal C. Moore ([mcm337@cornell.edu](mailto:mcm337@cornell.edu)).

**Materials availability**

This study did not generate new materials.

**Data and code availability**

This paper analyzes existing, publicly available data. All data that informed or guided our research is available without restrictions from cited sources. The DOIs and URLs for the datasets are listed in the key resources table.

This paper does not report original code.

Any additional information required to reanalyze the data reported in this paper is available from the lead contact upon request.

**METHOD DETAILS**

**Nomenclature**

The definitions of all parameters appearing in the biorefinery pricing formula below.

Symbol	Definition
$CO_{RNG}$	Carbon offset value of RNG (\$/mcf, or \$/MJ)
$CO_{electricity}$	Carbon offset value of electricity (\$/kWh, or \$/MJ)
$MC_{RNG}$	Marginal cost of RNG (\$/mcf, or \$/MJ)
$MC_{electricity}$	Marginal cost of electricity (\$/kWh, or \$/MJ)
$P_{NG}$	Natural gas wholesale price (\$/mcf, or \$/MJ)

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Symbol	Definition
$P_e$	Electric wholesale price (\$/kWh, or \$/MJ)
sto	Storage value
x	RNG production (mcf, or MJ)
y	Electricity production (kWh, or MJ)

This paper proposes a new system for recognizing the capacity and net carbon offset values from alternative and distributed energy electricity systems. This section provides details for estimating capacity and equivalency pricing for two distributed energy resources: biorefinery and geothermal systems.

**Biorefinery capacity and costs**

The cost components of the biorefinery system are listed in the Key Resource Table and in Table S1. The infrastructure costs of the bioenergy system consist of the reactors capital and operating costs and the cost of imported electricity. Transportation costs are site and region specific, and reflect not only the nature of source materials, but the presence of storage facilities, seasonal production and are dependent on the capacity of the biorefinery system.

The capital and operating costs for a 10,000-cow system processing only dairy manure using an integrated anaerobic digestion-hydrothermal liquefaction-biomethanation system is shown in Table S2 of the SI. In calculating the electricity costs, we assumed a \$0.05/kWh hydroelectric PPA price (Energy Information Administration - Independent Statistics and Analysis, 2019; International Renewable Energy Agency, 2019a, 2019b), resulting in almost \$8 million. If we assumed commercial electricity prices (\$0.14/kWh) (New York State Energy Research and Development Authority, 2020), the electric cost would increase to \$22 million (Table S2). Total electric costs depend on the mode of operation of the electrolyzer. The electrolyzer can be run during times of excess renewable electricity, providing grid balancing and power storage services. In this case, the RNG stored in the pipeline can be used at later times using CHP to supply electricity during times of peak demand. On the other hand, the electrolyzer can run continuously using grid electricity (average fuel mix) to maximize RNG production (the e-methane in this case has a higher carbon intensity, since electric source is not 100% renewable). RNG injected in the pipeline can also be used to supply heat. The total RNG output for the 10,000 cows system is 18 MW (thermal) with biomethane and e-methane accounting for 8.5 MW and 9.5 MW respectively. The net electric power output was calculated at 5.5 MW (electric) assuming an average heat rate of a NG gas turbine (11,138 Btu/kWh ~31% efficiency), and at 8 MW<sub>e</sub> using the heat rate of a NG combined cycle gas turbine (7,627 Btu/kWh ~45% efficiency).

**Grid balancing and storage – a California biorefinery implementation**

The AD-HTL-BM biorefinery system generates two RNG streams, as shown in Figure S1 (red and blue streams). AD biomethane is continuously generated during normal processing, while e-methane generation rates depending on the mode of operation of the electrolyzer. For instance, the electrolyzer can (1) run only when excess renewable electricity is available, generating e-methane (zero carbon) during that time only, or it can (2) run continuously using grid electricity (or renewable power purchase agreements) to maximize e-methane production. As a base, RNG generation ultimately depends on the size of the system (e.g. number of cows) and volume of waste produced. In terms of grid offsets or sales, electric output and performance reflect the nature of the gas turbines employed in the grid system and their performance characteristics (i.e. efficiency and response rates).

A power-to-gas (PtG) system of distributed AD-HTL-BM biorefineries in California, with around 1.7 million dairy cows, would require 3115 MW electric to keep up with AD and HTL CO<sub>2</sub> generation rates (required electrolyzer capacity depends on CO<sub>2</sub> generation rates, such that a 1 MW<sub>e</sub> electrolyzer converts 50 Nm<sup>3</sup>/hr of CO<sub>2</sub> (Electrochaea GmbH, 2019)). To illustrate the grid balancing and power storage benefits of the system, we used load data from CAISO for March 31, 2020 (California Independent System Operator (CAISO), 2020a, 2020b) (Figures S2 and S3). Figure S2 shows the total electric demand (blue), while Figure S3 shows the renewables breakdown for that day.

As the share of solar increases during the day, the net demand to be provided by dispatchable resources decreases (solid green line in Figure S2). As the share of solar starts to decrease starting at 16:00, the net demand increases sharply, constituting the ramp rate. The average ramp rate needed between 16:00 and 19:00 is 10,325 MW<sub>e</sub>. To shorten that ramp, and reduce pressure on utilities, the PtG system can be used to store solar electricity during the day and use it later at times of peak demand (between 16:00 and 19:00). Assuming a curtailment period of 7 hours between 9:00 till 16:00, the amount of electricity that would be consumed by the electrolyzer would equal 3115 MW \* 7h = 21,805 MWh. This amount would be converted to e-methane (1606 MW \* 7h = 11,242 MWh) using biomethanation. This mechanism shortens the ramp rate as shown by the light green dotted curve in Figure S2.

At times of peak demand, the e-methane produced could be converted into electricity using Combined Cycle Gas Turbines, producing 718 MW \* 7h = 5,026 MWh of electricity in the period between 16:00 and 19:00. This mechanism would adequately address the generation deficit caused by the drop in solar production at the end of the day. In addition, 656 MW \* 3h = 1,968 MWh of electricity would be produced from AD biomethane, contributing in meeting the demand at that time.

### Biorefinery illustrative pricing formula

We show the basic equivalence accounting for a bio-refinery, where two of the energy outputs (electricity and gas) have economic value for dispatch, storage and avoided carbon costs in normal grid operations.

The biorefinery can sell electricity directly (produced from RNG) and indirectly using RNG (injected into the HNG grid). Assuming wholesale prices of P<sub>NG</sub> (\$/mcf) for RNG and P<sub>e</sub> (\$/kWh) for electricity sales.

In terms of gas production:

$$RNG\ revenues = (P_{NG} + CO_{RNG} + sto) \times x \quad (\text{Equation 1})$$

where x is the amount of RNG produced (mcf). CO<sub>RNG</sub> and sto reflect the carbon offset and storage benefits of RNG, respectively, and are in units of \$/mcf. To breakeven, the total revenues from a biorefinery must be equal to or greater than the marginal cost (MC) of production:

$$P_{NG} + CO_{RNG} + sto = MC_{RNG} \quad (\text{Equation 2})$$

where MC<sub>RNG</sub> is the marginal cost of producing RNG (\$/mcf). Knowing the MC of the biorefinery, the value of the total 'benefits' brought by the system (carbon and storage) can be calculated by:

$$CO_{RNG} + sto = MC_{RNG} - P_{NG} \quad (\text{Equation 3})$$

Similar for electricity:

$$revenues = (P_e + CO_{electricity}) \times y \quad (\text{Equation 4})$$

where y is the electric production (kWh). CO<sub>electricity</sub> here is in \$/kWh. To breakeven, revenues must at least equal marginal cost:

$$P_e + CO_{electricity} = MC_{electricity} \quad (\text{Equation 5})$$

The carbon offset value for electricity can then be calculated by:

$$CO_{electricity} = MC_{electricity} - P_e \quad (\text{Equation 6})$$

If, however, an overall singular carbon offset (CO) value were to be calculated for the entire biorefinery instead, then the total biorefinery revenues (from RNG and electricity) should at least equal the total marginal cost:

$$(P_{NG} + CO + sto)x + (P_e + CO)y = MC_{electric} + MC_{RNG} \quad (\text{Equation 7})$$

Solving for CO, we get:

$$CO = \frac{MC_{electric} + MC_{RNG} - (P_{NG} + sto)x - P_e y}{x + y} \quad (\text{Equation 8})$$

Since price values were given in different units for gas and electric (\$/mcf and \$/kWh, respectively), P<sub>NG</sub>, P<sub>e</sub> and all other parameters in Equation 8 need to be converted to a unified \$/MJ equivalent. In this equation, MC<sub>electric</sub> and .. are the cost of production in \$/MJ, P<sub>NG</sub> and P<sub>e</sub> are the wholesale prices of NG and



electricity in \$/MJ, respectively.  $x$  and  $y$ , the volume of RNG and electricity generated respectively, are also given in MJ units.  $sto$  is an assumed storage value.

For simplification, we can remove storage values ( $sto$ ) from the equation, and attribute all benefits to CO only (Equation 8). Then becomes:

$$CO = \frac{MC_{electric} + MC_{RNG} - P_{NG}x - P_e y}{x + y} \quad (\text{Equation 9})$$

Using this formula we can calculate the carbon offset 'value' of a biorefinery by knowing: the marginal costs of production for gas ( $MC_{RNG}$ ) and electric ( $MC_{electric}$ ) for the biorefinery, the wholesale prices of gas ( $P_{NG}$ ) and electricity ( $P_e$ ), as well as the amount of gas ( $x$ ) and electricity ( $y$ ) produced. This represents the minimum value, or credit needed (in \$/MJ) to break even, where MJ represents total energy generation in both delivered electric power and system-available natural gas.

### Number of geothermal well-pairs and project costs

The capital costs and operating and maintenance costs for different well-pair amounts for the proposed geothermal heating system can be found in Table S3. Values are the averages across all scenarios tested at subsurface temperatures between 83.6 and 87.5°C, reinjection temperatures between 20 and 40°C, and well flows between 30 and 70 kg/s. Table S4 depicts the financial parameters and assumptions used for the geothermal system (also listed in the Key Resource Table).

### Geothermal well-pair case study: Buffalo, NY

Buffalo, NY can be used as a brief example to illustrate the impact that geothermal well-pairs can have on energy consumption and GHG emissions with respect to heating needs alone. According to the Five Cities Energy Plan released by NYPA in 2015, a total of 24,132,709 MMBTU was consumed via the combustion of natural gas (NG) by the residential, commercial, institutional, and industrial building sector (New York Power Authority, 2015). Using a NG emissions factor of 53.06 kg CO<sub>2e</sub> per MMBTU from the EPA (Environmental Protection Agency, 2014), this is equivalent to 1,280,492 MTCO<sub>2e</sub> or over 68% of Buffalo's total energy consumption emissions (New York Power Authority, 2015). Table S5 shows which of those emissions are from NG consumption by sector (excluding industrial) and attributes which portions are approximately from space and water heating, according to EIA's RECS and CBECS tables for the Northeast (U.S. Energy Information Administration, 2015, 2016). It is assumed that commercial and institutional buildings have the same end-use breakdown.

A single well-pair utilizing an 84.4°C geothermal resource at 50 kg/s of well flow and a reinjection temperature of 30°C can provide 13.3 MW of thermal capacity for space and water heating (Galantino et al., 2021). With a capacity factor close to 98%, as shown to be possible through this system, this is the equivalent of about 110,680 MWh (377,655 MMBTU) of produced thermal energy in a single year, or 20,038 MTCO<sub>2e</sub>, assuming the staged HP system of the geothermal well-pair is powered by 100% clean electricity. Hypothetically, a direct use geothermal well system such as the one being studied at Cornell can pair nicely with residential, commercial, or institutional building use, or a combination. Table S6 below represents GHG reduction potential of geothermal well-pairs for each sector's building stock along with the monetary benefit of abated emissions based on the 2030 value for the social cost of carbon (\$50/MTCO<sub>2e</sub>) (US EPA, 2017). It's important to note that each additional well-pair may be used less frequently given seasonal heating demand from the hypothetical district. To represent this concept, the hourly use of each additional well-pair is depicted in Figure S4 and is the assumption used for the purposes of this thought experiment.

From this case study, it evident that the strategic placement of geothermal systems can play an integral part in a renewable future where conventional heating infrastructure is being challenged by solar, wind, and battery technology applications. Direct use of low-temperature geothermal well-pair provides reliable baseload heating while electrified technologies may make up the difference and handle variability in end-use demand. Further, different district configurations that explore a combination of residential, commercial, and institutional building distribution can maximize well-pair utilization, resulting in nearly 0.5 GWh of delivered thermal energy and 82,688 MTCO<sub>2</sub> of emissions reductions annually for Buffalo, NY (~6.4% of Buffalo's NG emissions and 4.4% of Buffalo's total emissions in 2010). For a major metropolitan city, these are substantial permanent emissions reductions and energetic performance that improve

public health and safety, spur job growth, and improve energy independence – factors that can be measured and compared in the proposed equivalency metric.

### **Extension of model applicability**

Traditional electricity grid capacity is judged using traditional metrics of levelized cost, reliable power delivery and access. Equivalency metrics add a dynamic framework for adding capacity from smaller systems where the benefits include energy, net carbon reduction per kW, alternative fuels such as green natural gas as a fuel and offset and externality reduction in related systems such as water quality.

Treating the development of new distributed energy resources with a “systems” view can justify the investment in, and dispatch of, resources that have been judged as inefficient in the past. Gaining net contributions to carbon management through this process adds another source of payment to improve the competitive value to these resources.

Integrating agricultural operations such as dairies and swine farms not only supports an alternative energy resource but highlights the need to combine energy production with diminished environmental impacts. We show how a combination of energy, environmental and social values, creates a competitive new source for improving grid operations including regulation power, offsets and displaces inefficient load for heating, reduces the need for spinning reserves and creates new carbon credits that help achieve air quality goals.